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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

This is the final number of *Climatological Bulletin*. Thanks to all our readers, contributors, reviewers, and the Editorial Board. We wish every success to the new *CMOS Bulletin*.

Ce numéro est le dernier du *Bulletin climatologique*. Merci à nos abonnés, auteurs et arbitres et au comité de rédaction. Bon voyage au nouveau *Bulletin SCMO*.

Alec Paul
Editor/Rédacteur en chef

Cyclone Climatology of Southeastern Canada

*Maria Cintia Piccolo**
and
Mohammed I. El-Sabh
Centre Océanographique de Rimouski, Université du Québec à Rimouski, 310 Allée des Ursulines, Rimouski, Québec G5L 3A1, Canada
[Original manuscript received 3 October 1992;
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ABSTRACT

Annual, seasonal and monthly cyclone, cyclogenesis and cyclolysis frequencies were analyzed for 2.5° latitude by 5° longitude grid cells in eastern Canada for the years 1972–1990. The mean feature of the study area is the storm frequency maximum of the Gulf of St. Lawrence. Summer and winter mean cyclone patterns are not similar, because a great part of the sea water of the study region is ice covered in winter. A general decrease during the study period in the number of cyclones per year was found over the entire area.

A principal component analysis was performed for the 24 grid cells. The first principal component indicates the cyclone frequency variability of the Gulf of St. Lawrence and surrounding coastal regions. The second principal component contrasts cyclone frequencies in Atlantic Ocean waters with continental zones. Years with storm frequencies above average over the Atlantic waters also show minimum frequencies north of Quebec province.

RÉSUMÉ

Les fréquences annuelle, saisonnière et mensuelle de la cyclone, cyclogénese et cyclolyse ont été analysées sur une grille possédant une maille de 2.5° de latitude par 5° de longitude pour l'est du Canada durant les années 1972 à 1990. La caractéristique principale de la région étudiée est le maximum de la fréquence de tempête du Golfe Saint-Laurent. Les patrons moyens des cyclones en hiver et en été ne sont pas similaires. Une décroissance générale durant la période étudiée du nombre de cyclones observés par année a été remarquée sur toute la région.

Une analyse en composantes principales a été faite pour les 24 mailles de la grille. La première composante principale indique la variabilité de la fréquence des cyclones du Golfe Saint-Laurent et des régions côtières avoisinantes. La seconde composante principale montre le contrast entre les fréquences des cyclones dans les eaux de l'océan Atlantique et les zones continentales. Les années avec des fréquences de tempêtes au-dessus de la moyenne sur les eaux de l'Atlantique présentent aussi des fréquences minimum au nord de la province de Québec.

*Permanent address: IADO, Av. Alem 53, 8000 Bahia Blanca, Argentina

1. INTRODUCTION

The weather in temperate zones is marked by a succession of large-scale migratory cyclones that undergo pronounced seasonal variations in frequency and intensity. Frontal activity and inclement weather commonly associated with these low pressure systems make them an important component of climate. Considerable effort has been expended to accurately chart their spatial and temporal distribution. Cyclone frequency maps can be used to identify areas that most frequently experience cyclone weather, preferred paths followed by storms, and long-term trends in cyclone climatology (Reitan, 1974, 1979; Resio and Hayden, 1975; Zishka and Smith, 1980; Mooley, 1980; Hayden and Smith, 1982).

Continental shelf and coastal waters along mid-latitude western oceanic margins are greatly influenced by weather. Because these waters are shallow, they are readily affected by atmospheric forcing such as heating and cooling and turbulent mixing process. The Atlantic provinces and the Gulf of St. Lawrence show the most active and variable winter regimes in Canada. Matheson (1967) carried out a detailed study of airflow types on the Gulf of St. Lawrence region. The airflow types were determined based on daily surface and 500 mb charts. He found that year-to-year variation in ice severity was related to the types of winter circulation (Barry and Perry, 1973). Three streams of cyclones converge on the region (Hare and Thomas, 1974). Consequently, some work has been done on the frequency and tracking of low pressure systems travelling over the area, but mostly related to severe storms (Archibald, 1969; Lewis and Moran, 1984; Brown, et al., 1986) or general circulation models (Lambert, 1988) where some detailed features are lost because of the global scale analysis.

The purpose of this investigation is to determine the climatology of cyclones over southeastern Canada with special emphasis on the maritime areas for the period November 1971 –June 1991. Spatial and temporal variations in cyclone frequency are examined and also the geographical distribution of cyclone development and dissipation areas. In this study we try to document and update the knowledge of the synoptic climatological variability of the region.

2. CYCLONE CLIMATOLOGY

2.1 *Analytical procedures*

The data used in this study were derived from monthly maps of cyclone tracks published in the *Mariners Weather Log* (NOAA, 1991) for November 1971–June 1991. Locations for pressure centers are given on these charts for 0000 and 1200 GMT for centers having at least one closed isobar and whose lifetimes are at least 24 hrs. Methodology, source and analysis are presented in the mentioned journal, and therefore will not be explained here. To study the horizontal

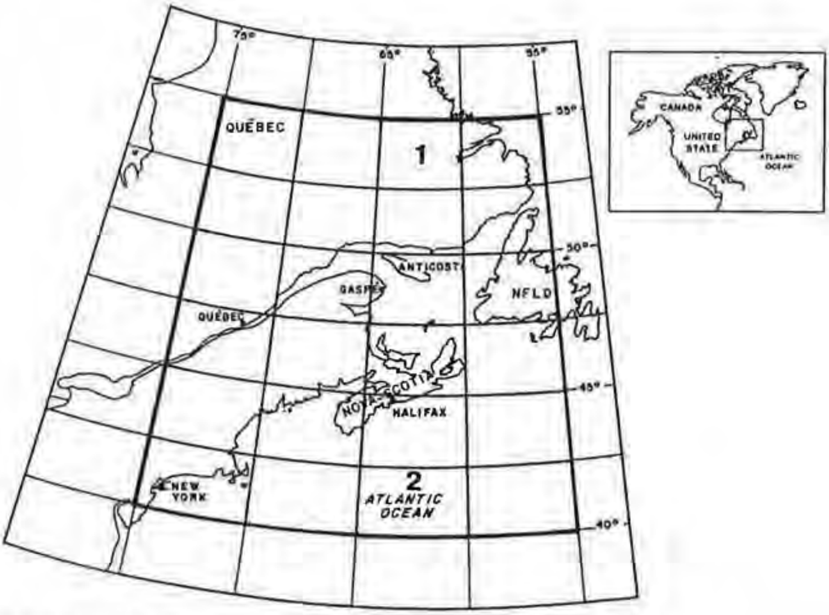

FIGURE 1 Map showing the study region and the grid used in the analysis.

distributions, 2.5° latitude by 5° longitude grid cells were prepared (Figure 1), and cyclone frequencies were determined by counting the number of cyclone tracks that passed through each quadrangle in a particular month and year. Multiple entries of a given storm were ignored (Hayden, 1981a).

Tabulations of the total number of cyclones, cyclogenesis and cyclolysis for each grid cell were completed for each of the individual months and years. The values were then summed over the 19 year period and analyzed to yield distributions of cyclone events, as well as cyclogenetic and cyclolytic phenomena. In the present study a cyclogenesis event is considered when a well defined cyclone track begins on the monthly cyclone tracks map, and a cyclolysis event where the storm track finishes.

Although the area enclosed by the quadrangles decreases with increasing latitude, no areal corrections are made, thus avoiding a latitude dependent bias (Zishka and Smith, 1980; Hayden, 1981b). Quadrangles of this size were used to avoid qualitatively noisy fields which resulted from using smaller areas.

2.2. *Total period statistics*

Figure 2a shows the mean annual frequency of cyclones for the period 1972–1990. The frequency notably increases over the coastal and oceanic waters.

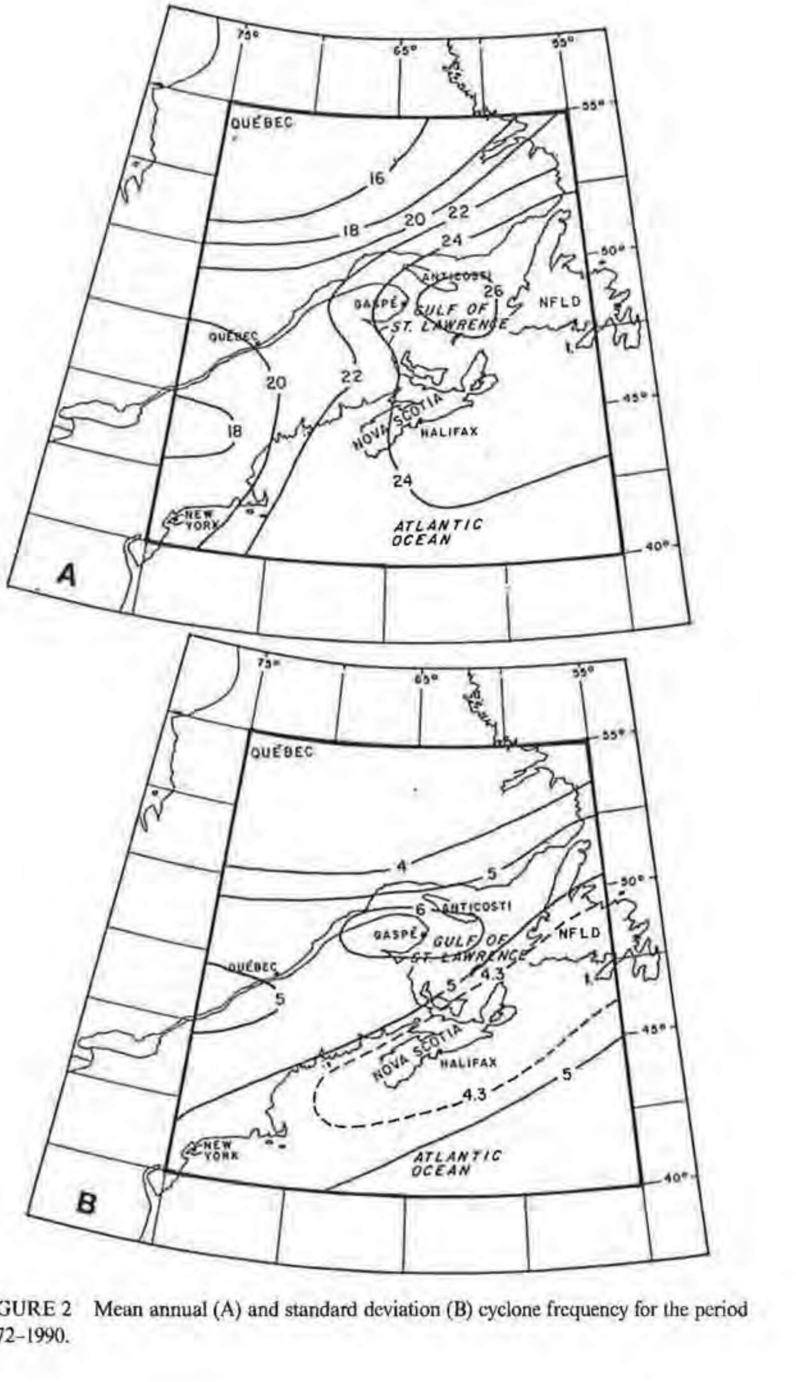

FIGURE 2 Mean annual (A) and standard deviation (B) cyclone frequency for the period 1972–1990.

The maximum frequency is found over the Gulf of St. Lawrence (GSL) and the Scotian continental shelf. The frequency of cyclones decreases over continental areas. A mean period of 10–11 days was found for storm passages over the study zone. The standard deviation of annual cyclone frequencies is presented in Figure 2b. The dominant feature is the standard deviation maximum located in the Gaspé peninsula - GSL area.

One physical reason for the variation in cyclone routes may be found in the changing land-sea contrast associated with the complex topography of the region. Archibald (1969) described the preferred tracks of severe storms over the study region. He found two spatially-varying forcing patterns: a) *northern storms*, propagating from the west to the northeast with their centres lying to the north of the gulf; b) *southern storms*, propagating from the south to the northeast with their centres lying over the Scotian shelf. Archibald (1969) also described a less frequent storm track that trends across Nova Scotia and across the GSL. Brown et al. (1986) showed that severe storms, causing significant wave events in the region, were mostly southern ones.

Two new forcing patterns should be added to this analysis. Besides the described ones, it was found that storms crossing the GSL from west to east or to the northeast, with their centres lying over the gulf are also important. Some of these storms are generated by the northward (southward) displacement of southern storms (northern storms) over the GSL region. The standard deviation maximum is between the northern and southern storm tracks. Storms crossing the gulf from south to north were less frequent but noticeable.

Figure 3 shows the mean winter and summer frequencies of cyclones per grid cell for the period 1972–1990. Winter was considered from October to March and summer from April to September. The summer and winter patterns have distinct differences, the cyclones being more frequent in winter. In the winter mean field, the axis for the maximum frequency is along central Nova Scotia and across Newfoundland, with frequency decreasing northward. In the mean summer pattern the axis of the maximum frequency has shifted northward to lie over the Gaspé Peninsula and northern Newfoundland. The location of the frequency maxima is associated with the baroclinic effects of the coastal zone. An important factor that has to be taken into account to explain the movement of the cyclone frequency maxima is that during the winter season a great part of the marine areas is ice covered, and therefore, the baroclinic effects of the GSL area decrease. Minimum summer frequencies are found inland from the Atlantic coast and northward over the province of Quebec. The results are comparable with those of Hayden and Resio (1982), although they analyzed a different period and larger area.

Identifying specific monthly features allows a better insight into the governing physical mechanisms of the study zone. Higher temporal resolution of cyclonic routes leads to a better estimation of the variation of climatic variables associated with them. In Figure 4 the total zonal frequencies between 65° and

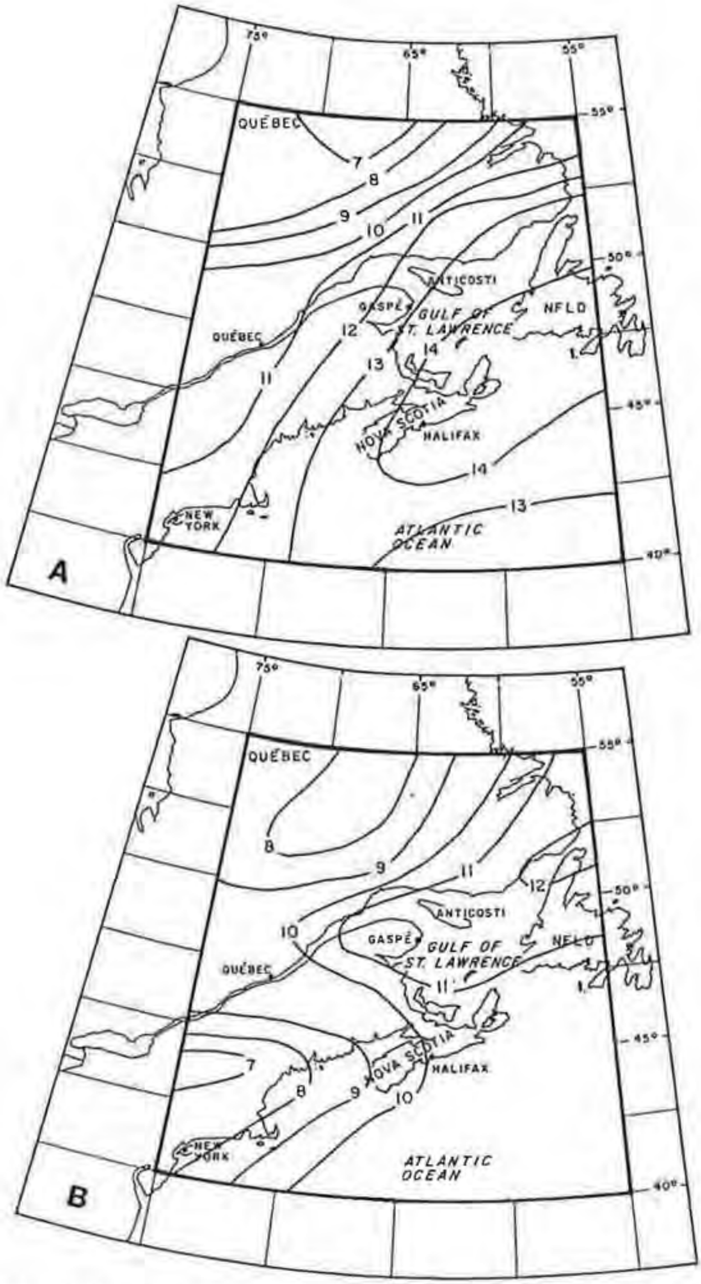

FIGURE 3 (A) Mean winter (October to March) and (B) summer (April to September) cyclone frequency for the period November 1971–June 1991.

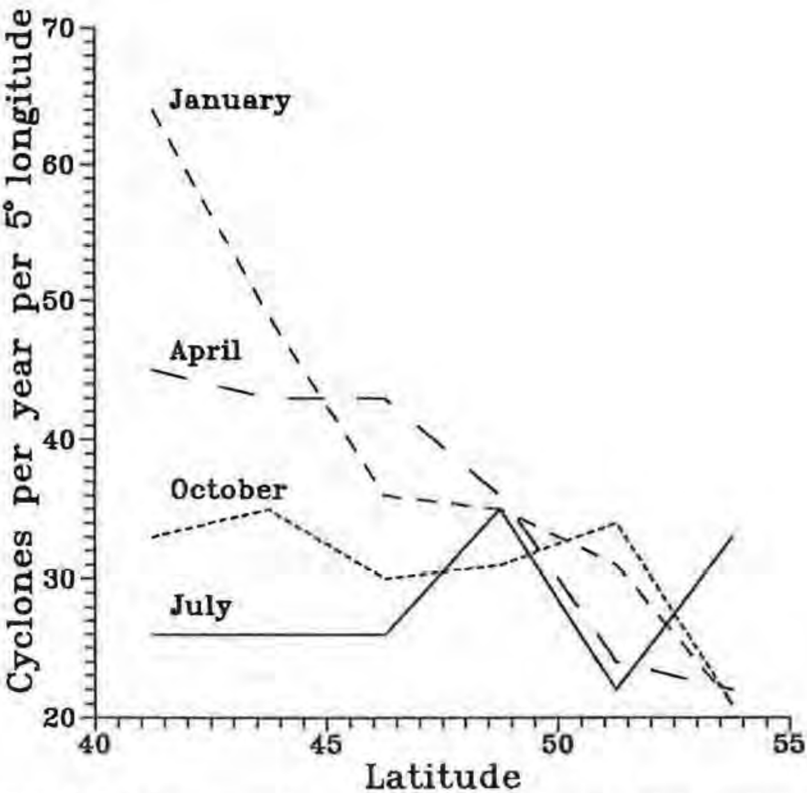

FIGURE 4 Total storm frequency between 65° and 70° W as a function of selected months and latitude for the study period

70° W are presented as a function of the latitude for selected months. In general, the frequency decreases with latitude. There is a remarkable seasonal variability at low latitudes. the cyclone frequency is greatest in January and decreases gradually to less than half of the winter values in July. The latitudinal gradient at high latitudes is roughly constant for all months, except for July, when an increment is found over the Chaleurs Bay - Gaspé Peninsula area.

The study region shows very distinct features due to the contrast between land and marine waters. Therefore, the data set was divided temporally and spatially. The temporal variations were studied by examining year-to-year fluctuations (Figure 5) of the number of cyclones in two selected grid cells (Figure 1), at the same longitude interval (60° – 65° W). One grid cell (cell 1) is located at high latitude over a continental area of Quebec province (52.5° – 55° N) and the other one (cell 2) over the Atlantic ocean (40° – 42.5° N). In 1974/75 and 1984/87 frequency maxima are found over the Atlantic Ocean (Figure 5) and relative minima over the continent. Another significant feature

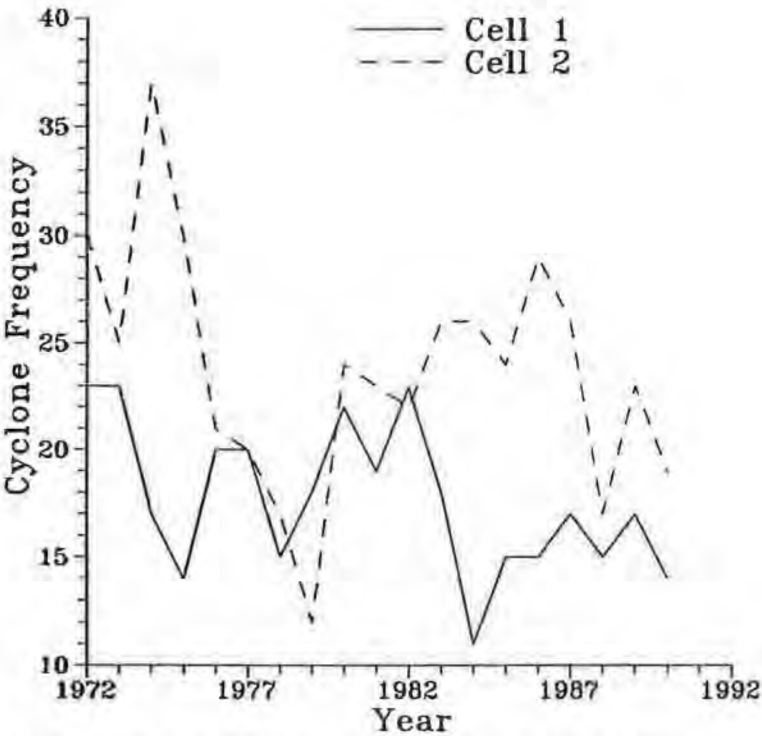

FIGURE 5 Time series of annual cyclone frequency for two selected grid cells.

is the large year-to-year cyclone frequency fluctuations over the Atlantic Ocean. In 1974, 37 cyclones crossed over the area and five years later only 12.

2.3 *Cyclogenesis and cyclolysis events*

In recent years, considerable attention has been devoted to the phenomenon of cyclogenesis (Jury and Laing, 1990). Operational weather forecasters have long been aware of these events in cold air masses over open water. They often evolve quickly and can result in adverse weather conditions that affect the safety of operations at sea. While cyclogenesis can and does occur from time to time in any area of the extratropics, there are preferred geographical locations for its occurrence. Figure 6a shows all cyclogenesis events for the study period. There is a southward increase in frequency with maximum values along the eastern coast of the U. S. A.

Western ocean regions are preferred areas for cyclogenesis (Zishka and Smith, 1980). These are regions with significant air-sea surface temperature contrasts at a given latitude, particularly during the winter seasons. These zones,

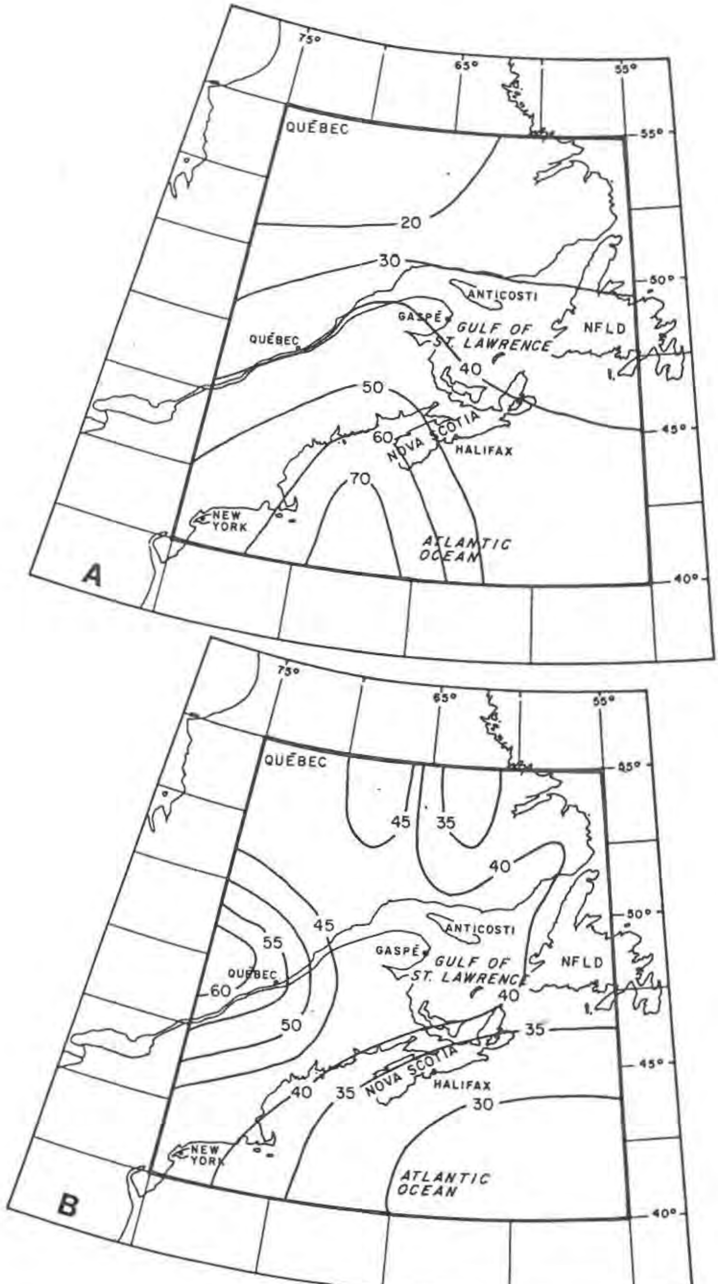

FIGURE 6 Total cyclogenesis (A) and cyclolysis (B) events for period November 1971–June 1991.

where diabatic processes are important, have stronger mean baroclinicity than many other areas. Thus, the cyclogenetic maximum found in the study area is in general agreement with the findings of Zishka and Smith (1980) and Whittaker and Horn (1981).

Compared to cyclogenesis, less attention has been given in the scientific community to the cyclolysis phenomenon. Naturally, these events do not impede human activities. However, from a physical point of view, they can bring some insight on the dynamical processes that characterize a particular region. Figure 6b shows the total cyclolysis events for the study period. A zone of maximum cyclolysis is found over the Quebec City area and extends into the GSL. These results show the possible role of Gaspé Peninsula orography as a barrier to western cyclone movement, which also helps to explain the maximum variability found in the mean fields (Figure 2b). Using the vorticity theorem (Hess, 1979), when airflow crosses a barrier, there is a decrease in the magnitude of the vertical perturbation of the air as it moves over the barrier. An increase of anticyclonic curvature develops in the wind side of the barrier and a cyclonic curvature on the lee side of it. Some cyclones are strong enough to continue their movement to the east while others dissipate their energy over the area.

3. PRINCIPAL COMPONENTS ANALYSIS OF ANNUAL FREQUENCY DATA

Principal components analysis (PCA) has successfully resolved the variance structure in multivariant geophysical data (Resio and Hayden, 1975), and provides a method for determining patterns in large data fields (Hayden, 1981a). The objective of the analysis is to isolate characteristic, recurrent and independent modes of covariance among variables into a new set of independent variables. PCA provides a description of the major modes of variability in the data set. Typically, each component is identified with some property of the data field. The analysis also provides an index which measures the importance of each component within each year. Finally, the analysis provides an estimate of the total percent of variance in the data set which can be explained on the basis of each component (Hayden, 1981a; Hayden and Smith, 1982). The first application of PCA in meteorology appears to have been made by Bryan and Gordon in 1948 (Preisendorfer, 1988) to develop a short-term prediction method for sea level atmospheric pressures over the Northern Hemisphere. PCA is a tool for the analysis of the spatial or temporal variability of physical fields.

In the present study, to prevent those grid cells with high mean cyclone frequencies from dominating the total variance and consequently from dominating the eigenvector forms, the correlation matrix rather than the covariance matrix was used. Only the first two eigenvectors were statistically significant in terms of the Rule N test (Overland and Preisendorfer, 1982). The fact that only the first two eigenvectors are significant may be the result of the small sample size. The percentage variance and the cumulative

TABLE 1 The percentage of the total variance for the first two eigenvectors

Eigenvector number	Percent variance explained	Cumulative percent variance explained
1	31.6	31.6
2	20.1	51.7

percentage of variance explained by the two eigenvectors are given in Table 1.

The eigenvectors corresponding to eigenvalues 1 and 2 were mapped in Figure 7. The first eigenvector (Figure 7a) has positive values over the entire field. The dominant feature of its distribution is the maximum value centred over the Magdalen shallows area. The pattern is rather similar to the standard deviation map of the annual mean fields of cyclone frequencies shown in Figure 2b. Therefore, the first principal component indicates the storm variability of the study region. In positively-weighted years, a general increase in cyclone passages will occur over the GSL and in negatively-weighted years fewer than average cyclones will characterize the area.

The second eigenvector (Figure 7b) indicates the contrast between southern and northern storms (*sensu* Archibald, 1969). In years with positive weightings, storms are more frequent than average in Atlantic oceanic waters. Negativelyweighted years show an increase in storm frequency over continental areas at high latitudes.

The first two eigenvectors of annual cyclone frequencies constitute two new orthogonal axes which account for nearly 52 % of the variance in the original data (Table 1). In general, weightings on these two vectors for the 19 years of record varied between –5 and +5. The time series of eigenvector weightings for each year for the two eigenvectors are shown in Figure 8. The annual weightings of the first eigenvector (Figure 8a) exhibit a change from positive to negative values after 1976. This variation indicates that during years with positive weightings the cyclone frequency increases over the GSL and coastal provinces areas, and during years with negative ones, the storm frequency decreases. Inspection of the year-to-year variation of storm frequency over the area indicates that after 1976 the cyclone frequency decreases over the GSL area to values below the average and in 1988 and 1989 the frequency increases notably when the annual weighting of the first eigenvector also becomes positive again.

The annual weightings of the second eigenvector (Figure 8b) exhibit a short time scale of variation from positive to negative values. The figure indicates an increase in cyclone frequency over the oceanic zone of the study region and a corresponding decrease over the GSL and continental areas for positively weighted years. This variation suggests that up to 1977 and from

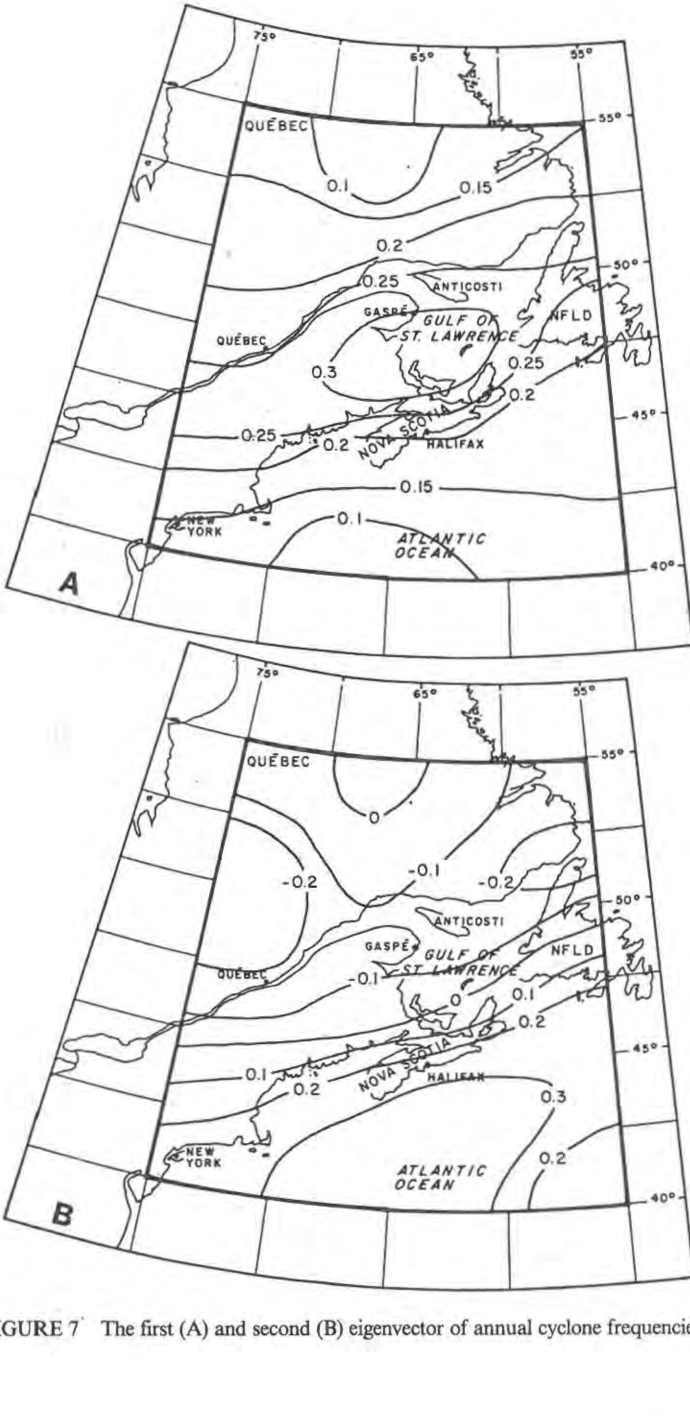

FIGURE 7 The first (A) and second (B) eigenvector of annual cyclone frequencies.

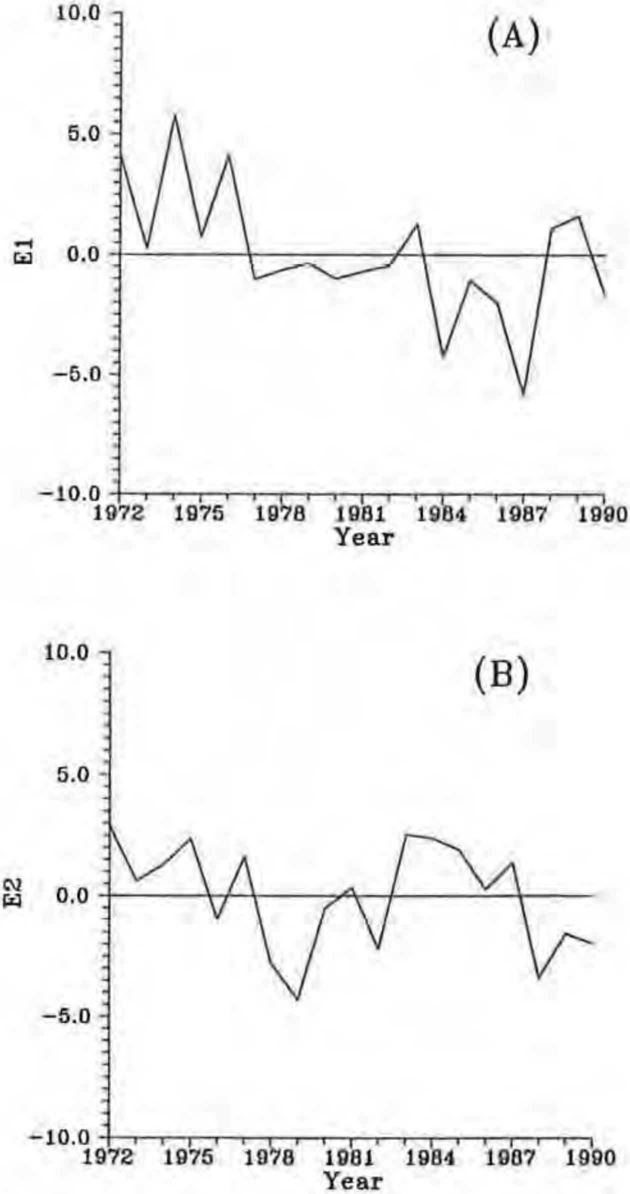

FIGURE 8 Time variation of the annual weightings of the first (A) and second (B) eigenvectors.

1983 to 1987 the cyclone frequencies declined over the region northward of the St. Lawrence River (considering the study zone) and increased over marine areas. This conclusion is consistent with the results presented in Figure 5.

4. CONCLUSIONS

Based on 19 years of data, a storm track climatology of southeastern Canada with special attention to the marine waters was presented. The analysis of the frequency of cyclones has revealed several noteworthy features involving its geographical, seasonal and secular characteristics. Convergence of most major eastward moving storms occurs over the study area. The variance in cyclone frequency is maximal over the GSL-Gaspé Peninsula area. Much of this variance could be explained by the northward (southward) displacement of storm tracks from southern (northern) storms described by Archibald (1969). It appears that this variation is produced by changes in the intensity of the east coast baroclinic zone resulting from the Gulf Stream and by shifts in the North American long-wave location associated with blocking in the high latitudes as suggested by Resio and Hayden (1975).

Over the study period the annual cyclone frequency for the entire area decreased, with the exception of 1988 and 1989 where frequencies increased. This finding is in agreement with the results presented by Zishka and Smith (1980) for the period 1950–1977. Therefore for the study region, it appears that there was a general decrease in cyclone frequency from 1950 to 1990.

A maximum of cyclogenesis was found in the latitude zone 40°–42.5° N. A maximum in cyclolysis was found westward of the Gaspé Peninsula. This indicates that possibly the orography that characterizes the peninsula plays a significant role in blocking the storm passages, thus contributing to the variability of cyclone climatology in the GSL.

ACKNOWLEDGEMENTS

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Zonage du Risque Agroclimatique Durant la Saison Froide au Québec Méridional: II-Endurcissement, Déchaussement et Prise des Racines dans la Glace

Philippe Rochette[1]
et
Pierre-André Dubé[2]
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RÉSUMÉ

Le but de cette étude est 1) d'exprimer, à l'aide de variables climatiques, le risque de dommage aux plantes pérennes résultant d'un endurcissement inadéquat, du déchaussement et de la prise des racines dans la glace, et 2) 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'endurcissement automnal inadéquat exprimé par la durée de la photopériode au moment du premier gel automnal et par l'accumulation de degrés-froid au-dessous de 5°C entre le début août et la date où la température minimale atteint -10°C pour la première fois; la perte d'endurcissement hivernale exprimée par les degrés-jours au dessus de 0°C accumulés au cours des mois de décembre, janvier et de février; le gel printanier des bourgeons exprimé par les degrés-jours au-dessus de 0°C accumulés entre le premier mars et le dernier gel printanier; et le déchaussement et la prise des racines dans la glace exprimés par un indice intégrant le rôle de la pluie hivernale, de l'absence de couverture de neige et du dégel hivernal.

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 rendent ainsi possible la généralisation à l'ensemble de la zone, des observations sur les dommages aux plantes faites en un point de cette zone.

ABSTRACT

The purpose of this study is to determine the spatial pattern of the climatic risk of damage to perennial plants caused by inadequate cold hardiness, soil heaving and ice encasement in southern Québec, Canada. The causes of plant damage and the climatic

1 Centre de recherches sur les terres et les ressources biologiques, Direction de la recherche, Agriculture Canada, Ottawa (Ontario) K1A 0C6.
2 Département de phytologie, Faculté des sciences de l'agriculture et de l'alimentation, Université Laval, Sainte-Foy (Québec) G1K 7P4

variables used to describe their intensity are: the inadequate acquisition of cold hardiness in the fall expressed by the length of photoperiod at the time of the first fall frost and by the accumulation of cold degree-days below 5° C between August 1st and the first occurrence of an air temperature equal to or below -10° C; the loss of cold hardiness during winter expressed by the degree-days above 0° C accumulated during the winter months; the spring freezing of buds expressed by the accumulation of degree-days above 0° C between March 1st and the date of the last occurrence of spring frost; and soil heaving and ice encasement expressed by the integrated effect of rainfall, winter thaw and snow cover during the winter months.

The maps produced show the spatial gradients of the climatic risk for each cause of plant damage. They permit the generalization of observations on plant damage in one location to the whole zone to which the site belongs.

INTRODUCTION

Les conditions climatiques de la saison froide sont régulièrement responsables de dégâts importants aux plantes pérennes au Québec méridional (Brown & Blackburn, 1987). Les causes de dommage sont nombreuses et n'affectent pas toutes les plantes avec la même sévérité (Sakai & Larcher, 1987). Une étude a donc été entreprise afin de définir le patron de variation spatiale de chaque cause climatique de dommage au Québec méridional (Rochette & Dubé, 1993). La démarche adoptée consiste dans un premier temps à identifier les causes de dommage, puis à choisir les variables climatiques exprimant l'intensité de chaque cause et finalement à déterminer leur variation spatiale. L'action du froid hivernal sur les plantes pérennes a été étudiée récemment (Rochette & Dubé, 1993). Le présent article présente les résultats relatifs à l'endurcissement inadéquat des plantes, au déchaussement et à la prise des racines dans la glace.

REVUE DE LITTÉRATURE

La survie des plantes suite à leur exposition à de basses températures dépend de leur degré de résistance au froid. Or, la capacité d'acquisition de cette résistance est fonction du stade de leur développement (Levitt, 1980). Chez la plupart des plantes, elle est maximale aux stades de la dormance et de la quiescence (Levitt, 1956). Sous nos latitudes, la rusticité d'une plante pérenne est donc d'abord conditionnelle à la coïncidence de sa période de repos avec la saison froide (Sakai & Larcher, 1987).

Induction de l'endurcissement automnal

A l'automne, les premiers froids peuvent endommager les plantes qui ne sont pas encore assez endurcies. Or, en conditions naturelles, l'induction de l'endurcissement automnal est provoquée, chez les tiges des plantes ligneuses, par le raccourcissement de la photopériode (Weiser, 1970). Howell & Weiser (1970) ont observé que les jours courts favorisent l'endurcissement du pommier mais qu'ils ne sont pas essentiels à son acclimatation. Sakai & Larcher (1987) considèrent toutefois les premiers gels automnaux comme une pression sélective importante vis-à-vis des génotypes de plusieurs plantes ligneuses. En effet, une même espèce peut peupler des milieux où la longueur de saison sans gel est différente, par des génotypes dont les réponses photopériodiques sont appropriées (Pauley & Perry, 1954). Il est donc important, lors de l'introduction de certaines plantes ligneuses dans un nouveau milieu, de s'assurer de la concordance entre la date à laquelle s'y observent les premiers gels automnaux et la réponse photopériodique de la plante.

Degré d'endurcissement automnal

Chez les plantes herbacées, telles que la luzerne et les céréales d'hiver, le rôle de la photopériode est secondaire et l'accélération de l'endurcissement coïnciderait avec la baisse de la température de l'air (Paquin, 1984). Woolley & Wilsie (1961) ont en effet noté une forte corrélation entre le degré d'endurcissement de la luzerne et l'accumulation des degrés-froid au-dessous de 15,5°C à 10,2 cm sous la surface du sol. Sakai & Larcher (1987) ont, quant à eux, identifié à 5°C le seuil de température au-dessous duquel les plantes entrent dans le deuxième stade de leur endurcissement.

Perte d'endurcissement hivernale

En hiver, les plantes dont le niveau de résistance au froid est plus sensible aux fluctuations de température seront plus vulnérables (Levitt, 1980). Paquin (1985) a observé, chez certaines plantes fourragères et chez les céréales d'hiver cultivées au champ, que la résistance au froid obtenue était plus grande lorsque les plantes étaient exposées à des températures plus basses et plus constantes. De leur côté, Gusta & Fowler (1977) ont mis en évidence une baisse de la résistance au froid du blé d'hiver après son exposition à deux cycles de gel/dégel. Selon Sakai & Larcher (1987), la résistance au froid des plantes suit les fluctuations de la température et 0°C représente un seuil général au-delà duquel les plantes commencent à perdre leur endurcissement. L'exposition des plantes à de telles températures n'entraînerait toutefois une perte de résistance significative que si elle survient après la levée de leur dormance vraie. Or, cette dernière serait, pour la plupart des arbres de nos latitudes, terminée à la fin du mois de décembre (Perry, 1971). Chez les plantes herbacées, la dormance vraie, lorsqu'elle existe, est levée plus rapidement et les conditions climatiques de décembre doivent aussi être considérées.

Endurcissement printanier

Au printemps, la résistance au froid des bourgeons foliaires et floraux, s'il y a lieu, diminue avec leur débourrement. Ces derniers sont alors d'autant plus vulnérables au gel qu'ils ont atteint un développement plus avancé (Levitt, 1980). Les gels tardifs peuvent donc tuer la plante entière ou certains de ses organes si la reprise de l'activité de la plante est trop hâtive au printemps. A cet effet, Rousselle (1983) rapporte une mortalité variant de 25% à 100% des bourgeons floraux des pommiers McIntosh dans les vergers québécois à la suite des gelées tardives du printemps de 1981. Sakai & Larcher (1987) ajoutent que les gels tardifs printaniers représentent la plus grande menace du gel pour les plantes pérennes des zones au climat tempéré.

La vitesse de sortie de la phase de quiescence dépend avant tout de la température de l'air chez un grand nombre de plantes. En effet, cette relation a été établie pour le cornouiller (Reader, 1975; Kobayashi & Fuchigami, 1983), le pommier (Anstey, 1966; Bidabe, 1967), le lilas (Hickin & Vittum, 1976), l'épinette (Cannel & Smith, 1983) et de nombreuses plantes à floraison printanière (White, 1979). Au Québec, Castonguay et al. (1984) ont montré que les développements foliaire et floral printaniers de deux chèvrefeuilles (Arnold Red et Zabeli) et d'un lilas (Red rhotomagensis) pouvaient être prédits par l'accumulation des degrés-jours à partir du premier mars. Dans leur étude, la température seuil pouvait varier entre 0° C et 5° C sans engendrer une perte significative de précision dans la prédiction.

Prise des racines dans la glace

La présence de glace dans les champs de plantes fourragères et de céréales pendant l'hiver est souvent associée à une plus grande mortalité hivernale (Smith, 1964; Rohweder & Smith, 1978; Pomeroy & Andrews, 1983). L'action nuisible de la glace serait de deux ordres. D'une part la glace augmenterait, par sa plus faible perméabilité aux gaz, la concentration en CO_2, en éthanol, en acide lactique et en acétylène (Smith, 1964; Pomeroy & Andrews, 1978; Barta, 1980; Suzuki, 1981) à des niveaux toxiques pour la plante. D'autre part, par sa grande conductibilité thermique, elle favoriserait la pénétration plus profonde du gel (Smith, 1975; Paquin, 1984).

Vasil'yev (1961) affirme cependant que la seule présence d'une couche de glace à la surface du sol ne cause pas de dommages au blé d'hiver cultivé en contenant. Il affirme même qu'en absence de neige, l'isolation procurée par la couche de glace est préférable à l'exposition directe du sol à l'air ambiant. Suzuki (1977), de son côté, a montré que la luzerne pouvait survivre deux mois à la présence d'une couche de glace de dix centimètres d'épaisseur à la surface du sol si ce dernier était gardé relativement sec.

Paquin (1985), dans une revue des facteurs de mortalité hivernale des plantes pérennes, explique cette contradiction apparente par la distinction entre les situations où il y a uniquement une couche de glace à la surface du sol et celle où il y a prise des racines dans la glace. Citant ses travaux et ceux de Suzuki (1977), il souligne que la seule présence d'une couche de glace n'est associée à un taux élevé de mortalité qu'en absence d'une couche de neige suffisante, alors que la prise dans la glace des racines et de la couronne ou du collet est presque toujours mortelle. Paquin (1984) ajoute que le type de glace, la texture et le tassement du sol sont également des facteurs qui influencent l'action nuisible de la présence de glace sur la survie des plantes à l'hiver.

Les plantes n'ont pas toutes la même sensibilité à la prise de leurs racines dans la glace. Andrews & Gudleifsson (1983) ont montré que la fléole des prés peut y résister deux fois mieux que le blé d'hiver, alors que la différence entre leur résistance au froid n'était pas aussi importante. D'autres conséquences indirectes de la présence de glace peuvent contribuer à augmenter la mortalité hivernale. En effet, la prise des racines du blé d'hiver dans la glace, même pour une courte période peut entraîner une baisse de sa résistance au froid (Andrews & Pomeroy, 1975). De plus, une couche de glace en surface du sol permet plus facilement au vent de balayer la neige tombée, augmentant ainsi l'exposition des plantes à l'action des basses températures de l'air (Vasil'yev, 1961).

La présence d'eau en surface, dont le gel subséquent entraîne la formation d'une couche de glace, peut être le résultat de conditions automnales très humides et de pluies ou de dégels hivernaux (Vasil'yev, 1961; Smith, 1964; Ouellet, 1977; Pomeroy & Andrews, 1983). Paquin (1984) souligne cependant que la présence d'une couche de neige ou d'un sol gelé au moment de la chute de pluie peut réduire sensiblement l'action nuisible de cette dernière.

Déchaussement

L'alternance de gels et de dégels peut causer le déchaussement des plantes pérennes croissant sur des sols humides lorsque l'épaisseur de la couche de neige est insuffisante (Rohweder & Smith, 1975). Selon les conditions du sol et du climat, deux types de déchaussement peuvent être observés. Le premier n'implique que le soulèvement de la plante et résulte de la formation de cristaux de glace sous son collet ou sa couronne et autour de ses racines. On observe ce genre de déchaussement sur les sols lourds dont la couche superficielle est très humide. Le deuxième type de déchaussement est caractérisé par le soulèvement de la couche superficielle du sol qui entraîne avec elle la végétation qu'elle supporte. Il est généralement causé par un gel sévère et rapide suivi d'un dégel lent (Smith, 1964).

Les couronnes et les racines des plantes soulevées par le déchaussement sont ensuite endommagées par leur exposition directe à l'action desséchante et gélive de l'air ambiant. Selon Rohweder & Smith (1978), les plantes à racines pivotantes comme la luzerne sont plus susceptibles au déchaussement que celles ayant un système radiculaire fasciculé comme les graminées.

Plusieurs chercheurs ont identifié le déchaussement comme une cause de mortalité hivernale de la luzerne au Québec (Ouellet, 1977; Pesant et al., 1978). Pesant et al. (1978) ont mis en lumière, pour le Québec, une corrélation entre la mortalité de la luzerne par déchaussement d'une part et l'abondance de pluie hivernale et la faible couverture de neige d'autre part. Les conditions favorisant le déchaussement des plantes herbacées sont donc fort semblables à celles conduisant à la prise de leurs racines dans la glace.

Cette revue des causes de dommage associées à un endurcissement inadéquat des plantes, au déchaussement et à la prise des racines dans la glace a permis de préciser les conditions climatiques qui favorisent leur occurence. Le choix des variables climatiques exprimant la menace que représente chacune de ces causes sur les plantes pérennes tiendra compte de cette information.

MATÉRIEL ET MÉTHODES

Le territoire couvert par cette étude est celui où se pratique l'agriculture dans la province de Québec (Canada). Les observations météorologiques journalières utilisées ont été celles de la température minimale et maximale de l'air de même que celles des précipitations sous forme de neige et de pluie. L'étude a porté sur une période de 11 ans (1972 à 1982), et plus de 200 stations du réseau climatologique du Ministère de l'Environnement du Québec ont été utilisées (figure 1).

Calcul des variables climatiques

Les variables 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. La longueur de la photopériode a été identifiée au nombre d'heures d'ensoleillement théorique et a été calculée à l'aide d'un programme conçu à cette fin par Audet (1975). Le calcul des degrés-jours et des degrés-froid journaliers intervenant dans la détermination de plusieurs variables a été fait à l'aide d'une approche sinusoïdale. L'algorithme choisi a été celui développé par Watanabe (1978) et n'exige que la connaissance des températures minimale et maximale journalières. La cartographie a été réalisée à l'aide du logiciel "SYMAP" (Dougenik & Sheenan, 1975).

Indices de synthèse agroclimatique

La plupart des causes de dommages peuvent être exprimées à l'aide d'une seule variable climatique. Leur expression est donc facile et directe. Le déchaussement

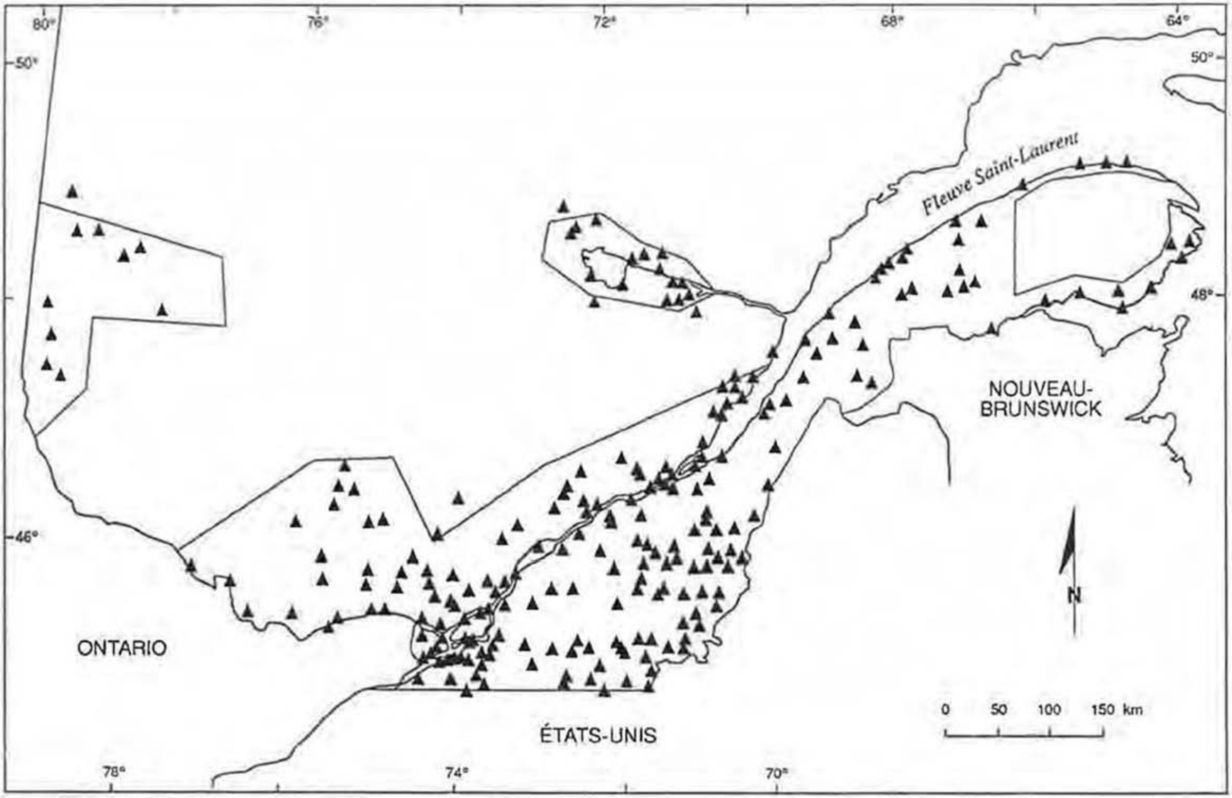

FIGURE 1 Stations météorologiques utilisées et territoire couvert par l'étude des conditions agroclimatiques de la saison froide.

et la prise des racines dans la glace sont pour leur part associés à plusieurs variables climatiques. Leur expression nécessite donc la détermination de la résultante de l'action individuelle de chaque variable climatique impliquée. Dans cette étude, le calcul de cette résultante a été fait à l'aide d'un indice de synthèse agroclimatique. Cet indice ne donne pas la valeur absolue réelle de l'intensité de la cause de dommage à une station donnée mais en permet une mesure relative par rapport à d'autres endroits.

L'expression de l'indice de synthèse agroclimatique à chaque station est:

$$I_{d,j} = \sum_{i=1}^{n} a_i V_{i,j}$$

où:

$I_{d,j}$ = indice de l'intensité relative de la cause de dommage à la station "j";
n = nombre de variables climatiques utilisées;
$V_{i,j}$ = valeur transformée de la variable climatique "i" à la station "j";
a_i = coefficient pondérant le rôle joué par la variable "i" dans l'expression de l'intensité de la cause de dommage. Il satisfait la condition:

$$\sum_{i=1}^{n} a_i = 1$$

Transformation des variables

Les variables climatiques ont été transformées dans le double but d'éliminer l'effet dû à leurs unités de mesure différentes et d'exprimer l'effet particulièrement important des conditions climatiques extrêmes sur la survie à l'hiver. La transformation est effectuée de la façon suivante:

$$V_{i,j} = \overline{E+M}$$

où:

$$E = \frac{E_{i,j} - E_{imin}}{E_{imax} - E_{imin}}$$

et

$$M = \frac{M_{i,j} - M_{imin}}{M_{imax} - M_{imin}}$$

$E_{i,j}$ = valeur extrême (minimale ou maximale) prise par la variable "i" sur la période étudiée à la station "j", et correspondant à sa contribution maximale à l'intensité de la cause de dommage;
E_{imin} = plus petit $E_{i,j}$ dans l'échantillon de stations;
E_{imax} = plus grand $E_{i,j}$ dans l'échantillon de stations;

$M_{i,j}$ = valeur moyenne de la variable "i" sur la période étudiée à la station "j";

M_{imin} = plus petit $M_{i,j}$ dans l'échantillon de stations;

M_{imax} = plus grand $M_{i,j}$ dans l'échantillon de stations.

Les valeurs moyenne et extrêmes des variables au cours de la période étudiée sont d'abord identifiées à chaque station et la valeur minimale prise par chacun des paramètres dans l'échantillon de stations leur est soustraite. Les différences obtenues sont ensuite divisées par l'écart maximal observé dans le même échantillon. Les valeurs de "E" et "M" varient donc de 0 à 1 sur l'ensemble des stations. Au besoin, elles ont été ajustées de la façon suivante:

$E = |(E - 1)|$ et $M = |(M - 1)|$

afin de faire correspondre la station où l'intensité de la cause de dommage est la moins forte à 0 et celle où elle l'est le plus à 1. Elles représentent donc la position relative de la mesure de chaque station par rapport aux valeurs moyennes et extrêmes observées dans l'ensemble des stations. La moyenne des deux fractions est ensuite calculée et constitue la valeur transformée des variables ($V_{i,j}$). Dans notre étude de zonage des conditions agroclimatiques du Québec méridional, les valeurs extrêmes (E) ont été considérées en raison de l'influence d'événements exceptionels sur le choix d'une culture pérenne en un endroit.

L'estimation de l'indice I_d pose le problème de la pondération de l'importance du rôle joué par chaque variable climatique dans l'expression de l'intensité relative de ces causes de dommage. L'importance de la contribution d'une variable d'entrée "i" dans la détermination d'un indice est exprimée par le coefficient "a_i". Nous avons tenté de réduire à son minimum le rôle de la subjectivité dans ces prises de décision en tenant compte des observations, des opinions et des résultats publiés par les chercheurs oeuvrant dans le domaine de l'agrométéorologie et de l'écophysiologie végétale.

RÉSULTATS ET DISCUSSION

Induction de l'endurcissement automnal

"Le nombre d'heures d'ensoleillement potentiel au moment du premier gel automnal" (PHOTO) a été retenu pour décrire la sévérité des conditions relatives à l'induction de l'endurcissement automnal des plantes ligneuses. Ce paramètre varie de façon importante dans le territoire étudié (figure 2). Il passe, en effet, de 11,1 heures sur l'île de Montréal à 14,2 heures dans certaines parties de l'Abitibi, du Lac St-Jean, des Laurentides et des Appalaches. Les plantes ligneuses dont l'induction de l'endurcissement automnal dépend d'un signal photopériodique sont donc plus exposées à des dommages causés par les premiers gels automnaux dans les régions plus éloignées de la vallée du St-Laurent. L'influence de l'inertie thermique des masses d'eau comme le St-Laurent sur le patron de variation

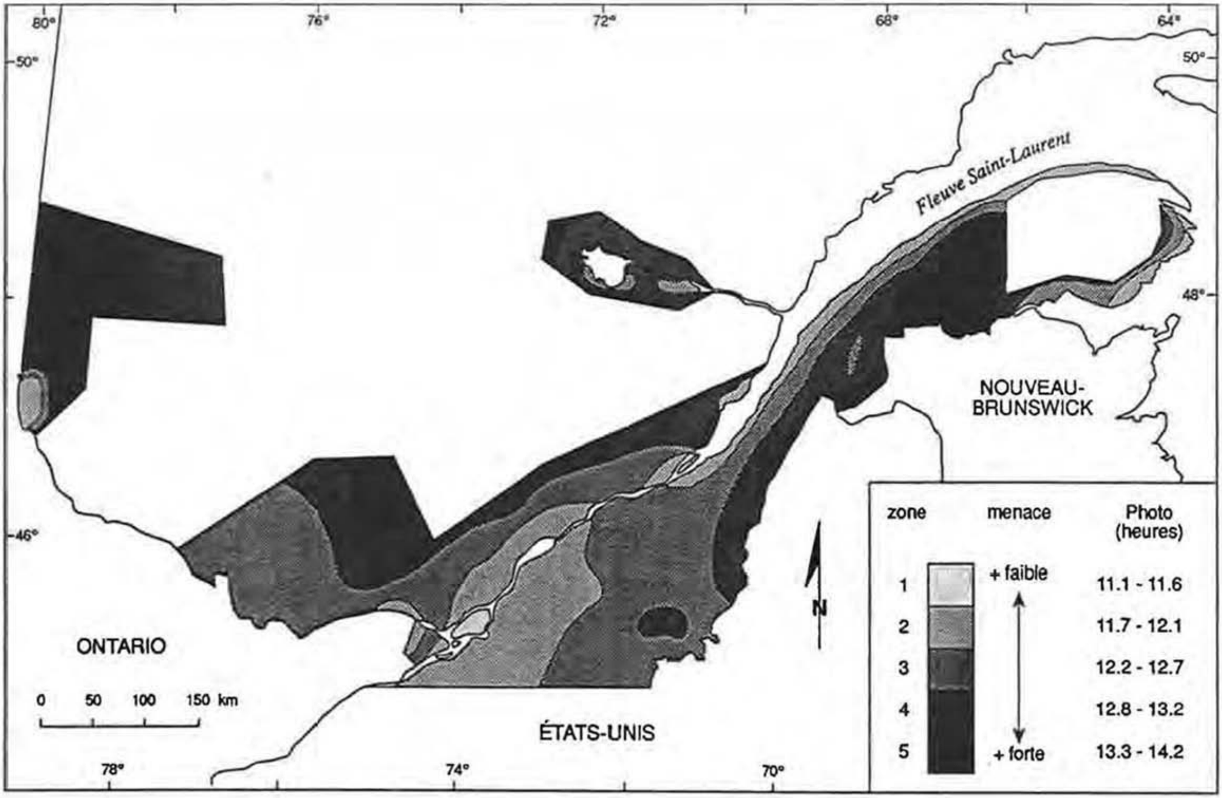

FIGURE 2 Variation spatiale de l'induction de l'endurcissement automnal au Québec méridional (1972-1982). L'intensité relative de la menace exercée par une induction inadéquate de l'endurcissement automnal a été exprimée par la longueur de la photopériode au moment du premier gel automnal (PHOTO).

spatiale est très nette. Il est également possible que l'îlot de chaleur urbain caractéristique des agglomérations urbaines importantes joue un rôle significatif dans la détermination des conditions de l'île de Montréal.

Nous n'avons pas trouvé d'études où étaient déterminées les longueurs critiques de photopériode auxquelles l'endurcissement automnal de diverses plantes ligneuses était induit. Des travaux ont d'ailleurs démontré que cette longueur pouvait varier de façon importante entre les génotypes d'une même espèce (Pauley & Perry, 1954). Il nous est donc impossible d'utiliser immédiatement l'information de la figure 2 dans le but d'estimer les limites d'adaptation de certaines plantes aux conditions automnales qui prévalent au Québec. La connaissance de ces dernières permet toutefois d'identifier les régions où les gels automnaux hâtifs sont les plus susceptibles de causer des dommages aux plantes ligneuses. On peut aussi déduire, du succès d'adaptation d'une plante à ce stress dans une zone, sa résistance à cette même cause dans une zone inférieure. Ce zonage pourra également permettre l'utilisation pratique immédiate des exigences d'une plante donnée dès qu'elles auront été déterminées expérimentalement.

Degré d'endurcissement automnal

Le degré d'endurcissement automnal atteint par les plantes pérennes, en un endroit donné, a été associé à leur exposition à des froids d'intensité moyenne avant l'arrivée de températures potentiellement dommageables. Nous avons donc choisi "l'accumulation de degrés-froid au-dessous de 5° C entre le premier août et la date où la température minimale atteint -10° C pour la première fois" (DFA), comme la variable climatique exprimant le degré d'endurcissement relatif permis par le climat automnal d'un endroit donné. Le zonage de ce paramètre est présenté à la figure 3.

Les degrés-froid passent de 87 unités dans les Laurentides au nord de Montréal, où ils sont les moins abondants, à un maximum de 152 sur la côte gaspésienne du golfe St-Laurent. La plaine du St-Laurent et les Appalaches sont caractérisées par des conditions près de la moyenne provinciale. On y observe cependant certaines enclaves où les conditions sont relativement moins favorables.

La région des Laurentides est celle où le refroidissement est le plus rapide et où les plantes bénéficient des pires conditions d'endurcissement au Québec méridional. Or, cette région est aussi parmi celles qui subissent les froids hivernaux les plus intenses (Rochette et Dubé, 1993). La combinaison de ces deux conditions fait donc, de cette région, un territoire où le risque de dommage par le froid hivernal est particulièrement élevé.

Perte d'endurcissement hivernale.

Le potentiel du climat d'un endroit à affecter le niveau de résistance au froid des arbres et des plantes herbacées durant l'hiver a été respectivement exprimé par

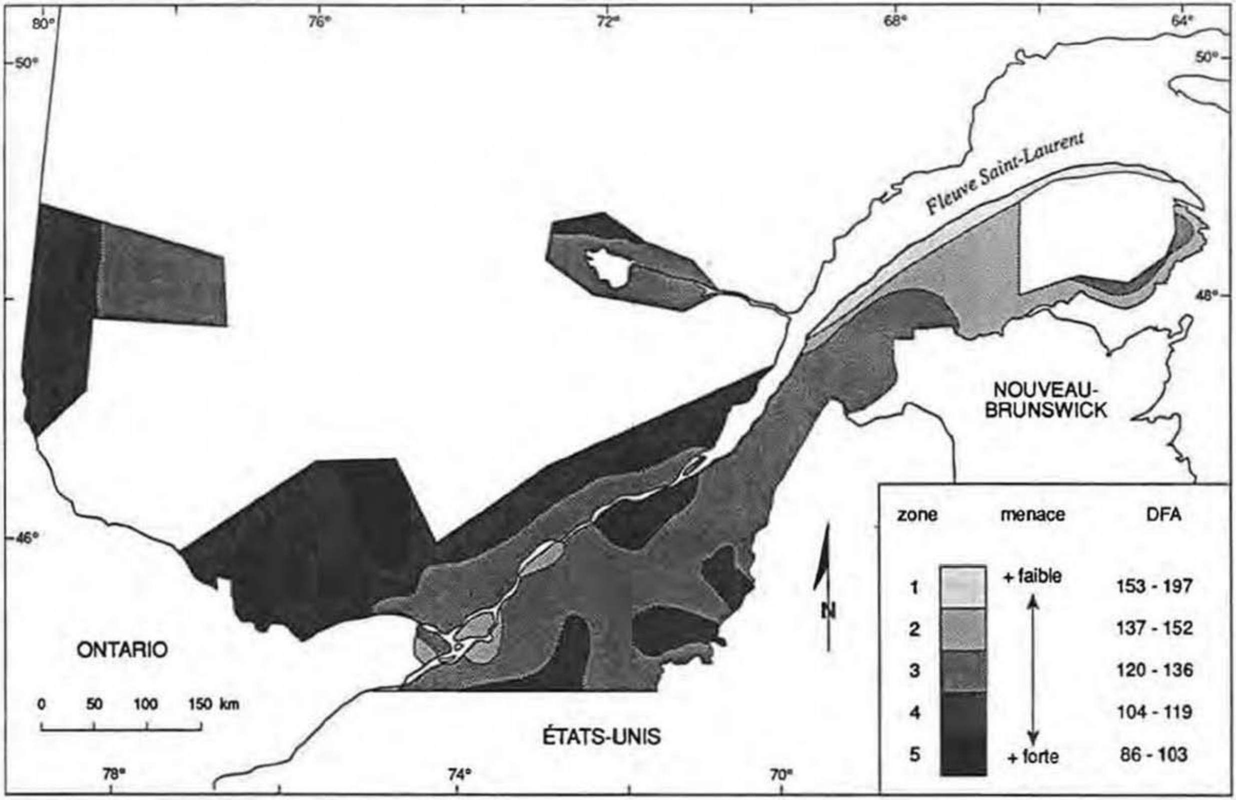

FIGURE 3 Variation spatiale du degré d'endurcissement automnal au Québec méridional (1972-1982). L'intensité relative de la menace exercée par un endurcissement automnal inadéquat a été exprimée par le nombre de degrés-froid (5° C) accumulés entre le premier août et la date de la première observation d'une température ≤-10° C (DFA).

"les degrés-jours au dessus de 0° C accumulés au cours des mois de janvier et de février" (DEG-I) et "ceux accumulés de décembre à février" (DEG-II). La variation spatiale des deux sommations s'est avérée identique et est présentée à la figure 4.

La majeure partie du territoire étudié est relativement peu susceptible de connaître des dégels significatifs durant la saison froide. En effet, seules la plaine de Montréal et la région des Appalaches au sud de la Beauce connaissent, en moyenne, des dégels relativement plus importants. Les valeurs moyennes des variables DEG-I et DEG-II y atteignent respectivement un maximum de 33,5 et 55 unités alors qu'elles sont négligeables en Abitibi-Témiscamingue.

Endurcissement printanier

Le risque de dommage aux plantes associé à un gel tardif printanier a été exprimé par la moyenne des "degrés-jours au-dessus de 0° C accumulés entre le premier mars et le dernier gel printanier" (DJP). La variation spatiale de ce paramètre est présentée à la figure 5.

Les degrés-jours accumulés varient beaucoup dans le territoire sous étude. Ils passent d'environ 200 unités sur la rive sud du St-Laurent en aval de Québec à plus de 500 en Abitibi-Témiscamingue, au nord-est du lac St-Jean, dans les Laurentides au nord de Montréal et à certains autres endroits des hautes terres des Appalaches. Les rôles joués par l'inertie thermique de la masse d'eau du fleuve St-Laurent et par le relief de sa vallée sont encore ici très évidents. On observe, en effet, un net gradient perpendiculaire à l'axe du fleuve.

Le zonage produit présente plusieurs points communs avec celui proposé par Langlois (1985) pour les risques de gels printaniers des bourgeons des pommiers au Québec. En effet, les zones à plus faible risque identifiées par Langlois correspondent assez bien avec celles de plus faible accumulation de degrés-jours printaniers au dessus de 0° C. Ainsi, la délimitation de la zone 1, tout juste au sud de Québec, de même que les influences du lac St.-Pierre et du fleuve St-Laurent se retrouvent sur les deux cartes. Les zones de plus grand risque de dommages printaniers aux pommiers suivent également d'assez près celles de plus forte accumulation de degrés-jours 0° C. Langlois suggère cependant un patron beaucoup moins uniforme pour les régions du lac St-Jean et de l'Abitibi-Témiscamingue, de même qu'un gradient plus faible dans les Appalaches au sud-est du St-Laurent entre Québec et la frontière américaine.

Déchaussement et prise des racines dans la glace

Nous avons choisi les valeurs moyennes de "la hauteur de précipitations sous forme de pluie pour la saison froide (décembre, janvier et février)" (PLHI), de "la sommation des degrés-jours au dessus de 0° C accumulés entre le début du mois

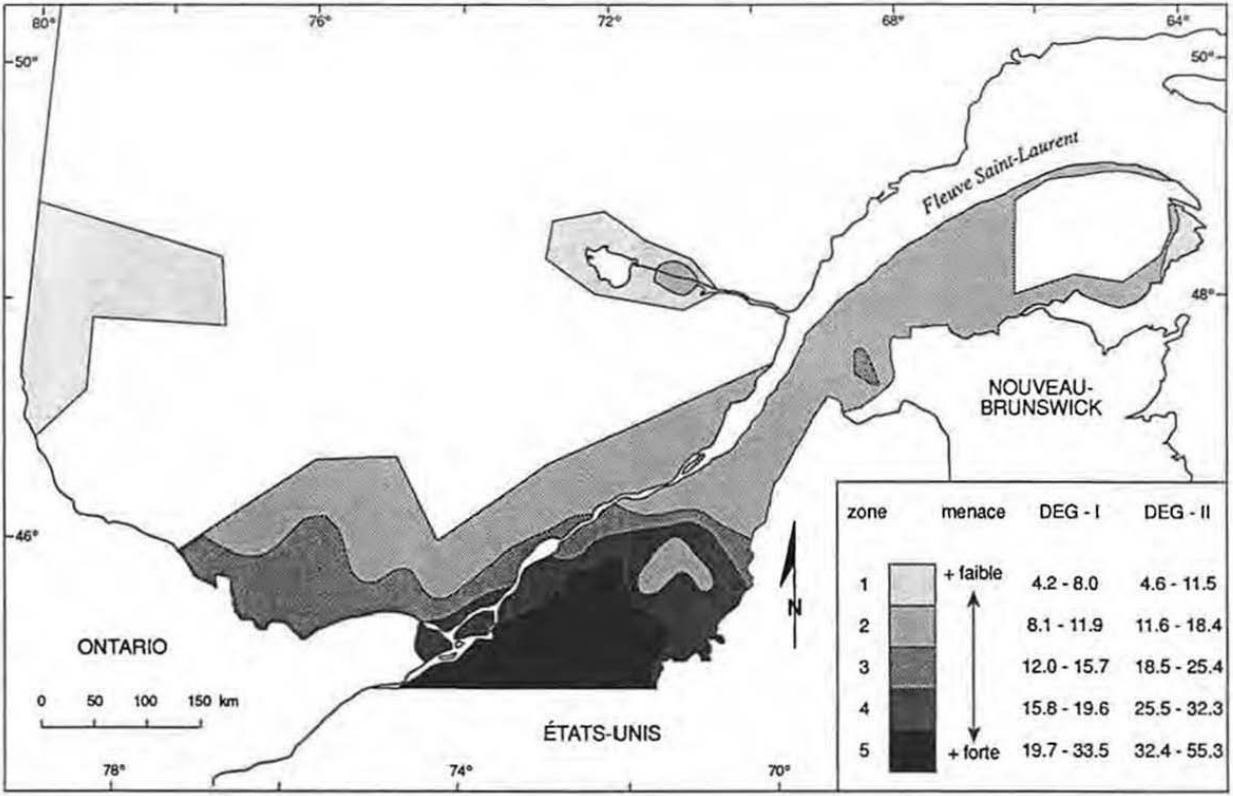

FIGURE 4 Variation spatiale de la perte d'endurcissement hivernal au Québec méridional (1972-1982). L'intensité relative de la menace exercée par la perte d'endurcissement hivernal est exprimée par le nombre de degrés-jours (0° C) accumulés de décembre à février (DEG-I) et en janvier et février (DEG-II).

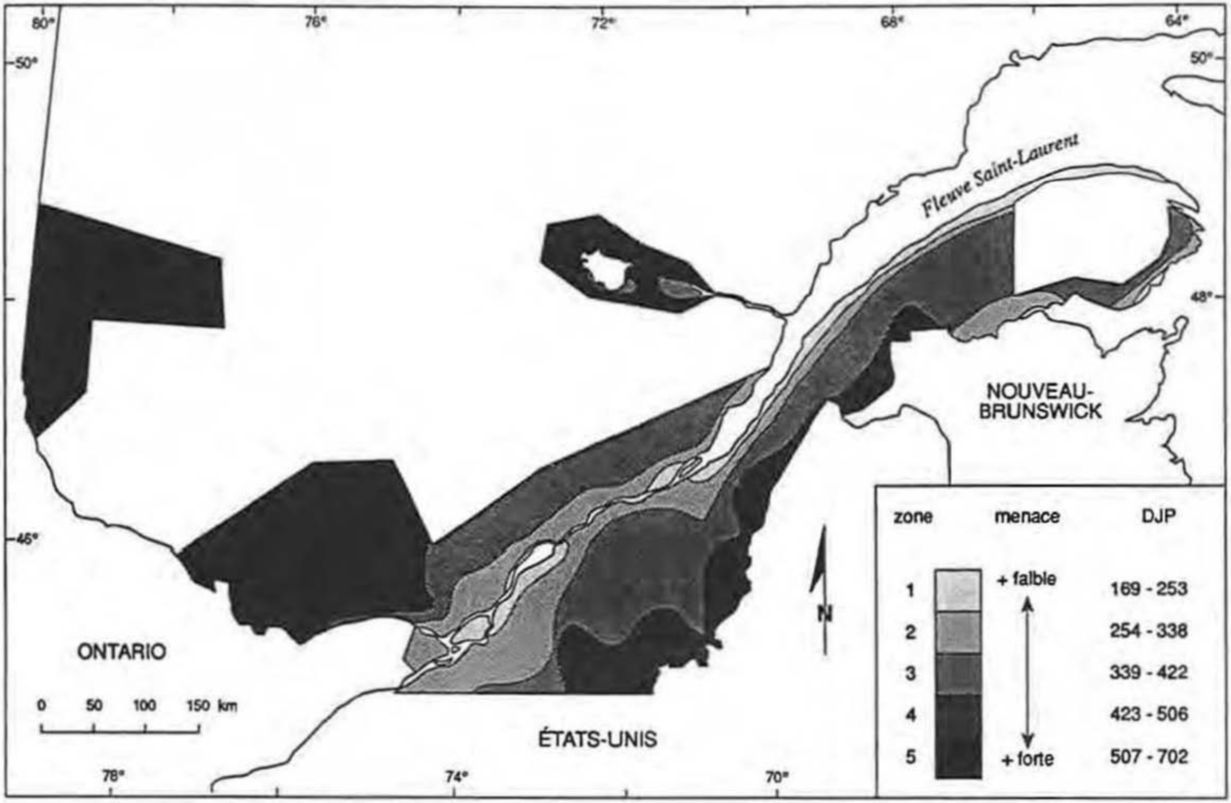

FIGURE 5 Variation spatiale du gel printanier des bourgeons au Québec méridional (1972-1982). L'intensité relative de la menace exercée par le gel printanier des bourgeons est exprimée par le nombre de degrés-jours (0° C) accumulés entre le premier mars et la date du dernier gel printanier (DJP).

de décembre et la fin du mois de février" (DEG-II) et de "la différence entre la durée de la période de froid et le nombre de jours d'enneigement" (DNF) (Rochette et Dubé, 1993) comme étant les variables permettant de représenter le mieux les conditions influençant les dommages causés aux plantes herbacées par le déchaussement et la prise de leurs racines dans la glace. L'intensité de ces causes de dommage a été exprimée par le même indice (I_d) impliquant les variables DEG-II, PLHI et DNF. On a jugé, que la pluie et le dégel hivernaux ont un effet d'importance semblable favorisant ces causes de dommage et que l'absence d'une couverture de neige au sol a un effet approximativement égal à la somme des deux premiers dans l'expression du phénomène. Les valeurs des "a_i" affectés aux variables DEG-II, PLHI et DNF ont donc été respectivement de 0,25, 0,25 et 0,5.

La variation spatiale de la pluie hivernale (PLUIE) est présentée à la figure 6. On y distingue deux régions de plus forte précipitation. Ce sont celles de Montréal et celle de la pointe de la Gaspésie où la valeur moyenne de pluie atteint jusqu'à 88 mm. Les régions de l'Abitibi-Témiscamingue et du lac St-Jean sont, au contraire, celles où la pluie hivernale est la plus faible (8 mm).

Le zonage de l'intensité relative des phénomènes de déchaussement et de prise des racines dans la glace est présenté à la figure 7. La région de la plaine de Montréal s'y révèle être celle où la menace est la plus grande pour les plantes herbacées. Ce résultat est en accord avec les observations faites par Pesant et al. (1978) et Paquin (1985), sur les dommages causés à la luzerne par le déchaussement.

La rive sud du golfe St-Laurent, de Rivière-du-Loup à la pointe de la Gaspésie, est la région la moins susceptible d'être touchée par le déchaussement ou la prise des racines dans la glace. La différence entre le nord et le sud de la Gaspésie est principalement due à l'abondance des pluies hivernales dans la partie méridionale.

Selon Paquin (1984), les conditions les plus favorables à l'observation du déchaussement sont celles où des excès d'eau sont présents à la surface d'un sol sans couverture de neige, lorsque surviennent les premiers froids importants de l'hiver. L'absence de données annuelles sur la couverture de neige pour l'ensemble de la période considérée et l'impossibilité d'estimer correctement le contenu du sol en eau à cette période de l'année nous ont cependant empêchés de considérer ce scénario pour exprimer l'action du déchaussement sur les plantes herbacées.

CONCLUSIONS

Cette étude avait pour but de définir les risques climatiques de dommages aux plantes pérennes relatifs à un endurcissement inadéquat, de même qu'au déchaussement et la prise des racines dans la glace. Les zonages produits présentent la variation spatiale de l'intensité relative (entre stations) du risque

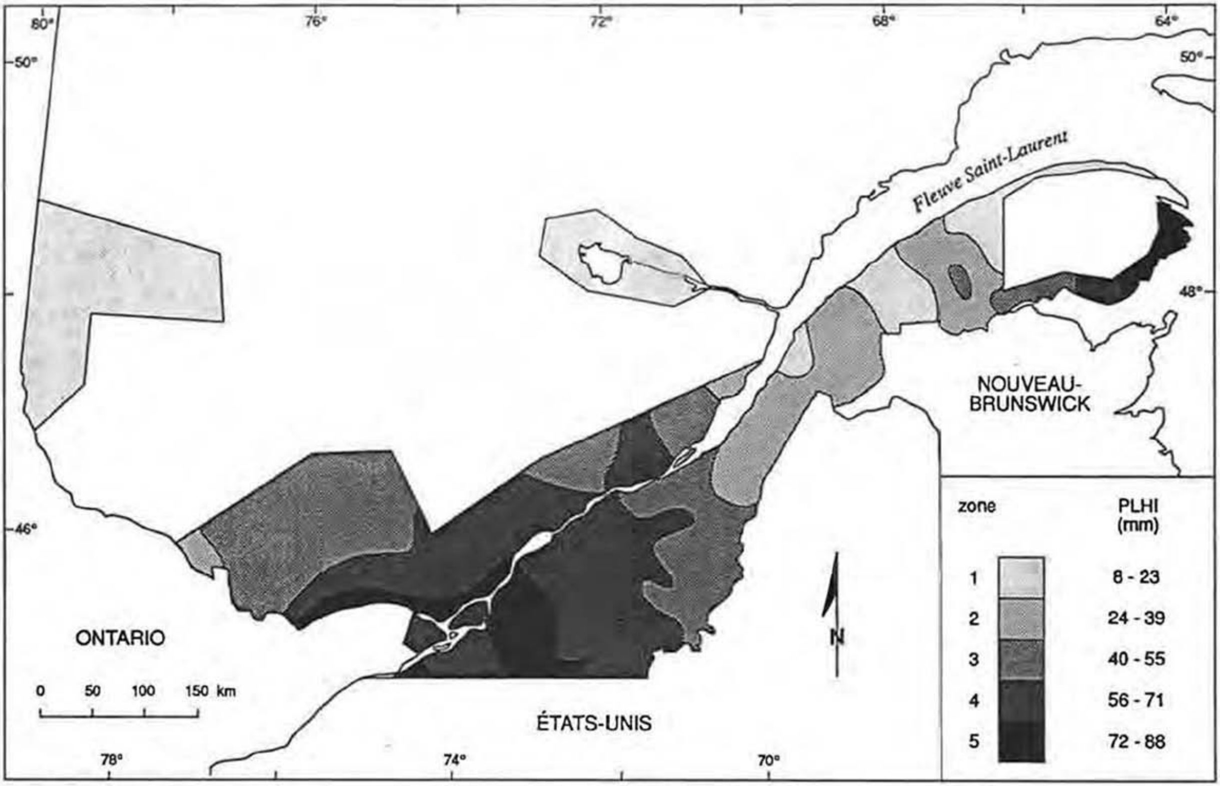

FIGURE 6 Variation spatiale de la hauteur de pluie reçue de décembre à février au Québec méridional (1972-1982) (PLHI).

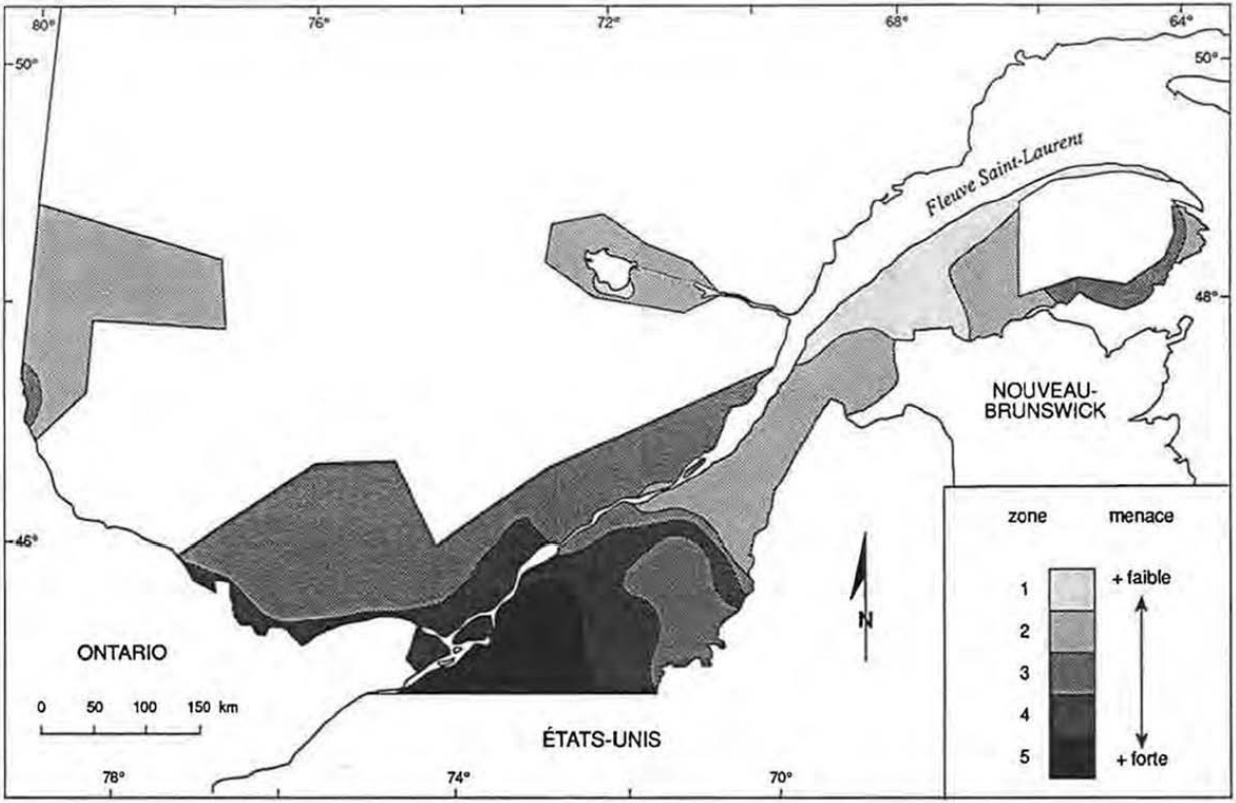

FIGURE 7 Variation spatiale du déchaussement et de la prise des racines dans la glace au Québec méridional (1972-1982). L'intensité relative de la menace exercée par le déchaussement et la prise des racines dans la glace a été exprimée par un indice pondérant le rôles de la couverture de neige, de la pluie et du dégel hivernaux.

de dommage associé à chaque cause climatique. Ils permettent de comparer dans l'espace la menace exercée par chaque cause de dommage. L'étude a également permis une mesure plus absolue des conditions agroclimatiques associées à certaines causes de dommage. C'est le cas de la perte d'endurcissement printanière pour laquelle la réponse du développement des bourgeons au réchauffement de l'air a été définie chez de nombreuses espèces et du degré d'endurcissement automnal dont la corrélation avec l'exposition à des froids modérés a également été étudiée quantitativement.

Un indice de synthèse agroclimatique a été proposé pour l'estimation de l'intensité relative de la menace de dommage exercée par le déchaussement et la prise des racines dans la glace. Ces causes de dommage ne peuvent être associées à une seule variable climatique et la pondération du rôle joué par chaque variable impliquée a été établie à la lumière des résultats expérimentaux publiés. Cette démarche a la faiblesse de reposer sur une appréciation quantitative d'observations nonquantitatives. Son utilisation a cependant permis de proposer, pour la première fois, une mesure de l'intensité de la menace exercée par le déchaussement et la prise des racines dans la glace et de leur variation spatiale au Québec méridional.

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Hydrometeorological Zoning of the Savanna Belt of Nigeria for the Growth of Maize (Zea Mays)

N.J. Bello
Department of Agrometeorology and Water Management,
University of Agriculture, P.M.B. 2240, Abeokuta, Nigeria.

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ABSTRACT

The hydrometeorological zoning of the savanna belt of Nigeria for maize cultivation was attempted in this study using regression and cluster analysis. The result of the regression analysis of moisture variables with maize yield showed that the critical hydrometeorological indices for the growth of maize are interdiurnal variability of rainfall during the establishment stage, evaporation during the vegetative stage, mean length of dry spells and total rainfall during the grain filling stage, and relative humidity during the ripening stage.

Emerging from the results of the cluster analysis are 4 hydrometeorological zones of different potential for maize cultivation in the savanna belt of Nigeria. The potential hydrometeorological zones vary with latitude up to 10° N, beyond which they follow lines of longitude.

A comparison between the potential hydrometeorological zones and the present cropland under maize in the study area showed a marked disparity. This disparity is more glaring in the southern half of the study area where conditions are favourable for the crop. Thus while spatial expansion of the cropland under maize in the southern half of the area is quite feasible up to 10° N, such an endeavour is not encouraging in areas beyond latitude 10° N. Rather, intensive cultivation of drought resistant and extra early maturing cultivars should be encouraged. Generally good maize yield can be achieved by adopting appropriate agronomic practices such as mulching and irrigation in the area.

RÉSUMÉ

On a amorcé l'étude du zonage hydrométéorologique des cultures de maïs dans la région de savane du Nigéria, à l'aide de régression et d'analyse de groupement. Les résultats de l'analyse de régression des variables d'humidité en fonction du rendement des cultures de maïs indiquent que les indices critiques affectant la croissance du maïs sont la variabilité journalière de pluie durant le stade de l'établissement, l'évaporation durant le stade de végétation, la durée moyenne de la sécheresse et les précipitations totales durant le stade de la maturation de l'épi et l'humidité relative durant le stade du mûrissement.

À partir des résultats de l'analyse de groupement, on a identifié 4 zones hydrométéorologiques avec des potentiels différents, pour la culture du maïs dans la région de savane du Nigéria. Le potentiel des zones hydrométéorologiques varie en fonction de la latitude jusqu'au 10° N et, selon la longitude, au-delà de ce parallèle.

Si l'on compare le potentiel des zones hydrométéorologiques à l'étendue actuelle des cultures de maïs dans la zone étudiée, on observe des inégalités marquées. Ces inégalités sont encore plus frappantes dans la partie sud de la région étudiée où les conditions sont favorables à cette culture. Bien qu'il soit faisable d'accroître l'étendue de la culture du maïs dans la partie sud de la région, jusqu'au 10° N, on ne recommande pas une telle initiative au-delà du 10° N de latitude. On devrait plutôt encourager la culture intensive d'espèces résistantes à la sécheresse et d'espèces possédant une maturation très rapide. Généralement, on peut obtenir de bonnes récoltes de maïs en adoptant des méthodes agronomiques convenables comme le paillage et l'irrigation, dans la région.

INTRODUCTION

According to Whitmore (1957) farming potentialities of any area tend to be determined not so much by favourable as by the adverse or restrictive qualities of the agroclimatic environment. It is therefore not surprising that agrometeorological literature in the tropics has, over the past few decades, become replete with the assessment of the influence of hydrometeorological factors (rainfall, evaporation and relative humidity) on agriculture. Among research endeavour in these areas are those of Robinson and Glover (1954); Dagg (1965 and 1970); Oguntoyinbo (1967); Kowal and Andrews (1973); High et. al. (1973); Detlief Schreiber (1981); Jatzold (1981); Wolfgang (1981); Olaniran (1983) and Bello (1987).

Plants germinate, blossom and ripen in different phases according to seasons and not according to the calendar (Sanderson, 1957). But it is observed that using the calendar year as the basic unit of data analysis pertaining to the influence of hydrometeorological variables on crop growth tends to dominate research work done in agrometeorology in Nigeria [Ojo, 1970; Oyebande and Oguntoyinbo, 1970; Igeleke, 1974; Odumodu, 1983]. Most of such studies lack detailed quantitative characterization of the agroclimatic environment for agricultural production. Consequently, attempts at climatological classification for agricultural land use planning and zoning of crops have failed. For instance, despite the technological advancement in crop husbandry, cases of crop failure and poor yields, particularly in the savanna belt of Nigeria, have become an annual phenomenon. In order to avert this situation, the plant environment has to be adequately defined in terms of the critical hydrometeorological factors for crop production.

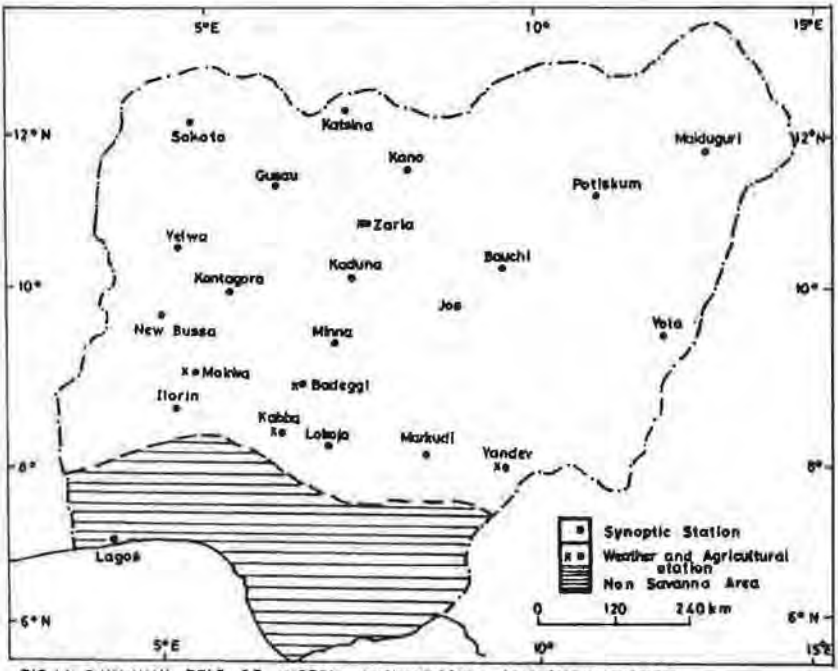

FIG 1: SAVANNAH BELT OF NIGERIA SHOWING DATA COLLECTION STATION

Based on the foregoing, the aims of this study are:

(i) to determine the critical hydrometeorological indices for the growth of maize during the different phenological stages in the different climatic regions of the savanna belt of Nigeria and

(ii) using the results in (i) above, to derive an optimal zoning of the area for the growth of maize.

This study focuses on maize because it is an important multi-purpose crop for man and livestock (Miracle, 1966; Agbola, 1979), and also because maize plays an important role by filling the food gap during the hunger season occurring between the end of the food stocks of the previous season and the harvest of local sorghum and millet in Nigeria (Tatum 1971, IITA maize research programme annual report, 1983–1985). More specifically, maize is the only food crop that can be planted and harvested twice in a given year and is also normally the earliest food crop that can be harvested after the beginning of the wet season in a given year in Nigeria. Thus maize plays a role in reducing the length and severity of food shortage that may be caused by insufficient reserves carried over from the previous season.

The savanna belt of Nigeria lies between latitudes 6° 58′–13° N and longitudes 3°–14° E (Fig. 1). Soils of sandy surface horizon underlain by weakly-

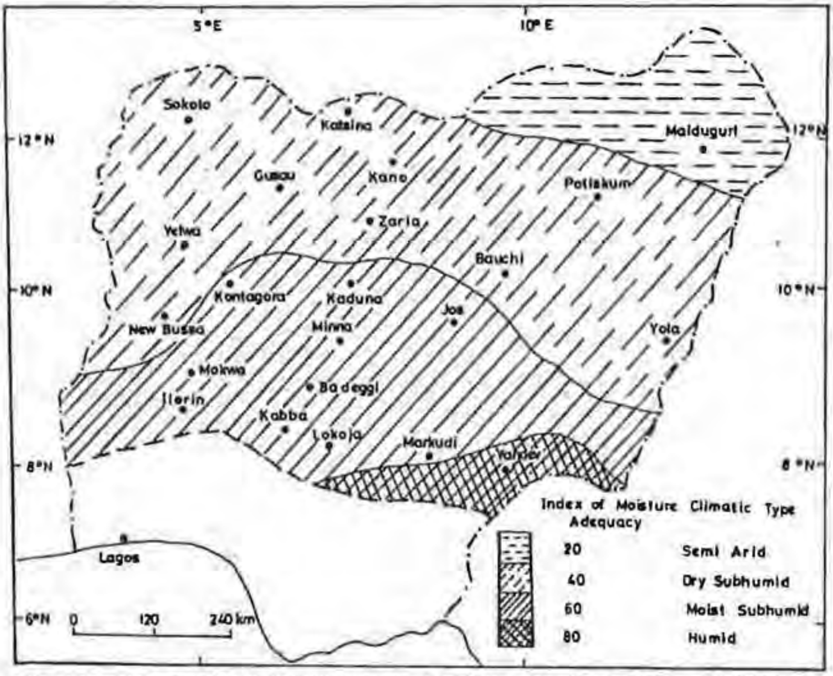

FIG 2: MOISTURE ADEQUACY REGION OF THE SAVANNAH BELT OF NIGERIA ACCORDING TO AYOADE (1973)

developed clayey, mottled and occasionally concretionary sub soils (Ferruginous Tropical Soils) cover the most extensive parts of the savanna belt of Nigeria (Agbola, 1979).

Thus for most parts of the savanna belt of Nigeria, a dry spell of more than 5 days will dry out the top soil and therefore constitutes a threat to crop yields.

The region receives abundant insolation (425 cal $cm^{-2}day^{-1}$) and therefore temperatures and photo periods (day length) are high throughout the year. The mean monthly temperature varies between 25–28° C while average annual photo period is between 12.0–12.5 hours per day.

Fig. 2 shows the climatic classification of the area into moisture adequacy regions (Ayoade, 1973). The index of moisture adequacy is a measure of moistness of an area. But these moisture adequacy regions for the growth of specific crops are yet to be adequately defined. Thus this study attempts to zone the savanna belt of Nigeria into potential hydrometeorological regions for the growth of maize. By relating the results of this study to the present land use under maize, we shall be able to ascertain whether optimal use is being made of arable land or whether there is the possibility for spatial expansion.

MATERIALS AND METHODS

(a) Type and Source of Data

Meteorological and maize yield data are utilized in this study. The meteorological data utilized are rainfall, pan evaporation and relative humidity which are together referred to as hydrometeorological indices. The maize yield data utilized are the grain yield of maize (kg/ha). Both the meteorological and maize yield data were collected for a period of 20 years (1971–1990), the longest period for which consistent records of maize yield and meteorological data are available simultaneously at all stations (Fig. 1). The data for each of the stations shown in Fig. 1 were obtained from the Institute of Agricultural Research, Ahmadu Bello University, Zaria and Nigerian Meteorological Office headquarters, Oshodi, that used to coordinate and collect local agricultural data and weather information from the agrometeorological stations shown in Fig. 1. Furthermore, in order to be able to process the data into phenological stages, information on calendar of maize farming (planting and harvesting dates and length of each phenological stage) was also utilized. It should be noted that the dates of planting and harvesting are not the same for all the stations. This is due to the variation in the onset of the rains. However the duration of growth of the maize cultivar studied does not vary, thus the phenological time scale is constant. For instance the establishment stage which covers 20 days from planting date applies to all the stations.

(b) Data Processing

The raw data for each growing season at each station were first processed using the phenological stages of maize as the basic time scale. The phenological stages of the maize cultivar studied (high-yielding late maturing cultivar with a growing period of about 135 days) are:

(i) the establishment stage (includes the periods of germination and emergence of seeds to the time of jointing when two nodes can be seen, that is, the beginning of shooting). This covers about 20 days from planting date.

(ii) vegetative period covering 35 days (periods of shooting, that is, stage of elongation of internodes and increase in leaf numbers).

(iii) flowering stage of a period of 25 days (divided into periods of tasseling and silking which are the times of appearance of male and female flowers respectively).

(iv) grain filling stage extending for a period of 35 days (time of grain development from fertilization) and

(v) ripening stage covering 20 days (period of enlargement of grains to the normal grain size of the cultivar).

Rainfall data were not only processed in terms of total amount received during each phenological stage but also into interdiurnal variability and mean length of dry spells. According to Nieuwolt (1972) the interdiurnal variability of rainfall is the sum of the absolute values of the differences between consecutive daily rainfall totals. The relative value of interdiurnal variability of rainfall is known as the interdiurnal variability index (IVI). This index relates the interdiurnal variability to the total rainfall recorded during the same perid. The IVI (%) is computed according to the formula

$$IVI = \frac{VIs}{2TRs} \times 100 \ldots\ldots\ldots \text{equ (1)}$$

where

VIs = interdiurnal variability of rainfall during the reference period(s) (s = phenological stage)

and it is the sum of the absolute values of the difference between consecutive daily rainfall (mm) recorded during the reference period.

TRs = Total rainfall (mm) during the same period(s) under reference.
2 = a constant factor because daily amounts of rainfall are considered twice in the process of computing VIs.

According to Nieuwolt (1972), an IVI of 100% indicates the maximum possible variability of rainfall. Thus the lower the IVI at a place, the higher the consistency of rainfall.

Usually, in the rain-fed agricultural tropics, a value of 2mm of rainfall defines a rain day. According to Oliver (1972) 2mm of rain is the minimum threshold required to meet the evaporative demand of the atmosphere. Nieuwolt (1977) noted that daily rainfalls of less than 2mm are insignificant in warm climates as such small amounts largely evaporate before infiltrating into the soil.

According to Olaniran (1983) a dry spell of 5 or more days could dry out the top soil and constitute a hazard to physiological growth of field crops. Thus in this study a dry spell is defined as a consecutive period of 5 days or more, each with less than 2mm of rainfall. The mean length of dry spells ($\overline{Ld}$) during each phenological stage is expressed according to Oliver (1972) as

$$\overline{Ld} = \frac{\Sigma Lifi}{\Sigma fi} \text{ (days)} \ldots\ldots\ldots \text{equ. (2)}$$

where

$\overline{Ld}$ = average length of dry spells (days)
Li = length of spell (days)
fi = frequency of length of spell.

(c) Data Analysis

Regression and cluster analysis are used in this study. Simple regression analysis was first done for each of the selected stations in order to determine the statistically critical hydrometeorological parameters for maize growth. The variables used for the simple regression analysis are total rainfall (mm), interdiurnal variability of rainfall (%), mean length of dry spells (days), evaporation (mm) and relative humidity (%). Because of the need to ascertain the worth of the critical hydrometeorological variables for utilization in the cluster analysis for the purpose of zoning, the combined effect of these parameters on maize yield was next investigated for each station using the multiple regression techniques. However, only the hydrometeorological indices that were each significantly correlated with maize yield at a minimum of 95% probability level in at least 2 different climatic regions or 50% of the selected stations were included in the multiple regression analysis. Similarly such variables were utilized in the cluster analysis. Good discussions of cluster analysis method as a tool of regionalization or zoning have been made by Gower (1961), Cole and King (1970), Anderberg (1973), Bohif (1973) and Everitt (1974).

RESULTS AND DISCUSSIONS

The results of the simple regression analysis have been summarised as presented in Table 1, while the results of the multiple regression are presented in Table 2.

(1) *Establishment Stage*

Table 1 shows that mean length of dry spells during the establishment stage is significantly correlated with maize yield at the 90% probability level in all climatic regions whilst interdiurnal variability of rainfall was found to be significantly correlated with maize yield at the 95% probability level in the humid and at 99% level in the dry subhumid and semi arid climates.

The significant negative correlation between maize yield and interdiurnal variability of rainfall during the establishment stage indicates that the lower the interdiurnal variability of rainfall (or in other words, with a reliable onset of the rains and fair distribution of rainfall) the higher the yield of maize. It should be noted that low interdiurnal variability of rainfall implies regular occurrence of rainfall, and therefore availability of water needed for the development of better root system and growth of maize during this stage (Semb and Gerberg, 1969).

On the other hand the significant negative correlation between maize yield and interdiurnal variability of rainfall can be interpreted to mean that the higher the interdiurnal variability of rainfall during the establishment stage, the lower is the maize yield. This should not be surprising because a high

TABLE I Summary of the Result of Correlation Between Maize Yield and Hydrometeorological Variables for Different Phenological Stages of Maize in the Savanna Belt of Nigeria

Phenological Stage	Hydrometeor-ological Variables	Level of Significance and Climatic Region	Types of Relationship
ESTABLISHMENT			
STAGE	TR	Not Significant	Positive
	IVR	95% in humid and moist-sub-humid climates	
		99% in semi-arid and Dry sub-humid climate	Negative
	MLDS	90% in all climatic regions	Negative
	E	Not significant	Negative
	RH	Not significant	Positive
VEGETATIVE			
STAGE	TR	Not significant	Negative
	IVR	90% in all climatic regions	Negative
	MLDS	Not significant	Negative
	E	95% in all climatic regions	Negative
	RH	Not significant	Positive
FLOWERING	TR	95% in all climatic regions	Positive
	IVR	Not significant	Negative
	MLDS	90% in humid and moist sub-humid climate	
		95% in semi-arid and Dry sub-humid climate	Negative
	E	Not significant	Negative
	RH	Not significant	Positive
GRAIN FILLING			
STAGE	TR	90% in all climatic regions	Positive
	IVR	Not significant	Positive
	MLDS	95% in all climatic regions	Negative
	E	Not significant	Negative
	RH	Not significant	Positive
RIPENING STAGE	TR	Not significant	Negative
	IVR	Not significant	Negative
	MLDS	Not significant	Negative
	E	Not significant	Positive
	RH	95% in humid, moist and Dry sub-humid Climate	Negative
		90% in semi-arid climate	

TR = Total Rainfall E = Evaporation
IVR = Interdiurnal variability of rainfall
MLDS = Mean Length of Dry Spells RH = Relative Humidity

interdiurnal variability of rainfall is often associated with high evaporative demand and the drying out of the top soil which Olaniran (1983) emphasized as detrimental to the survival of the crop seedlings. For the same reason a higher significant negative correlation between interdiurnal variability of rainfall and maize yield during the establishment stage occurred in the arid than in the humid climatic regions of the savanna belt of Nigeria. This indicates that the drier the climate the higher the adverse effects of the interdiurnal variability of rainfall on the establishment of maize seedlings and then the ultimate yield.

Furthermore the significant negative correlation between maize yield and mean length of dry spells indicates that inadequate moisture supply due to the persistence of dry spells is detrimental to the physiological growth of maize during the establishment stage.

TABLE 2 Proportion of the Variation in Maize Yield explained by the Critical Hydrometeorological Indices during the different Phenological Stages in the different Climatic Regions of the Savanna Belt of Nigeria

Climate Station	Interdiurnal Variability of Rainfall During the Establishment Stage (%)	Evaporation During the Vegetative Stage (%)	Mean Length of Dry Spells During the Flowering Stage (%)	Total Rainfall During the Flowering Stage (%)	Mean Length of Dry Spells During the Grain Filling Stage (%)	Relative Humidity During the Ripening Stage (%)	All Elements Combined (%) R^2
HUMID							
Yandev	45.2	3.0	1.6	11.5	6.8	2.5	70.6
MOIST SUBHUMID							
Makurdi	47.1	2.4	1.8	11.0	7.2	2.0	71.5
Lokoja	45.8	4.4	3.1	12.5	7.8	2.3	75.9
Kabba	47.2	2.5	1.4	11.3	6.5	1.9	70.8
Ilorin	47.9	2.4	1.0	13.1	7.0	2.0	73.4
Badeggi	56.4	2.0	1.1	10.5	6.4	1.2	77.6
Mokwa	56.2	2.5	1.0	11.3	5.9	1.0	77.9
Minna	54.3	2.0	1.3	10.1	6.1	1.1	74.9
Jos	44.8	4.1	1.0	12.2	6.2	2.0	70.3
DRY SUBHUMID							
Yola	64.3	2.1	1.4	9.5	3.2	0.6	81.1
New Bussa	65.2	2.6	2.5	7.4	4.3	0.6	82.6
Yelwa	65.8	2.4	2.2	6.8	3.7	0.5	81.4
Bauchi	54.9	4.5	2.3	8.5	5.7	1.0	76.9
Kontagora	56.7	4.7	3.1	8.8	7.2	1.3	81.5
Kaduna	57.9	4.2	2.0	8.2	6.8	1.0	80.1
Zaria	57.4	4.4	3.1	8.6	7.1	0.9	81.5
Gusau	68.1	4.1	2.0	7.5	4.8	0.5	87.4
Potiskum	67.9	5.0	2.3	7.0	5.7	0.8	88.7
Kano	70.1	5.2	2.0	7.2	5.6	0.6	90.7
SEMI–ARID							
Maiduguri	72.3	5.3	2.2	7.4	5.2	0.4	92.8
Katsina	70.5	4.9	2.6	6.9	5.8	0.6	91.2
Sokoto	67.7	4.5	2.1	7.1	6.0	1.0	88.4

However total rainfall, evaporation and relative humidity were not found to be significantly correlated with maize yield during the establishment stage. Thus they are not considered as critical factors for the crop during this stage. For instance the non-significant influence of total rainfall can be interpreted to mean that high total rainfall resulting from 2 or 3 heavy downpours that are separated by prolonged dry spells is of no significant use to effective crop growth.

(ii) *Vegetative Stage*

From Table 1, evaporation appears to be the most critical hydrometeorological variable during the vegetative stage. The high significant negative correlation between evaporation and maize yield during this stage could be attributed to the fact that high evaporative demand and water stress are positively correlated. According to Wrigley (1969) if the high evaporative demand creates water stress in early growth, it will lead to stunted crop growth and therefore alter the process of flower formation. Furthermore the rate of grain formation will be retarded and consequently lower the ultimate grains yield.

(iii) *Flowering Stage*

Total rainfall and mean length of dry spells were found to be significantly correlated with maize yield during the flowering stage (Table 1). Total rainfall is significantly correlated with maize yield at the 95% probability levels at all locations, while mean length of dry spells is significantly correlated with maize yield at 90% probability level in the humid and moist subhumid climates and at 95% level in the dry subhumid and semi-arid climates.

The significant positive correlation between maize yield and total rainfall during the flowering stage follows from the fact that the consumptive use of water by maize would be expected to be high since the crop's canopy is fully developed by about this period. As noted by Denmead and Shaw (1959) and also Chang (1968), the ratio of evaporation from maize to open pan evaporation is at a maximum during the flowering stage, particularly at silking time when the maximum leaf area is reached. Furthermore during the flowering period, root growth is often much reduced such that soil moisture must be high enough to permit rapid water movement to the roots. Thus it could be understood why moisture stress at this period might cause the plant to wilt and therefore prevent the formation of reproductive organs due to silk drying (Salter and Goode, 1967). In view of this fact, the high significant negative correlation between maize yield and mean length of dry spells observed in the dry subhumid and semi arid climate should not be surprising. It implies that the higher the mean length of dry spells, the higher the adverse effects of moisture stress on the reproductive organs of the maize crop during the flowering stage and consequently the lower the final grains yield.

During this stage, the effects of evaporation and relative humidity on maize yield were not found to be significant at all locations.

(iv) *Grain Filling Stage*

During the grain filling stage, mean length of dry spells and total rainfall are each significantly correlated with maize yield. However mean length of dry spells was found to be significantly correlated with maize yield at the 95% probability level in all climatic regions of the study area. On the other hand total rainfall was found to be significantly correlated with maize yield at the 90% probability level. The significant negative correlation between mean length of dry spells and maize yield during this stage indicates further than inadequate moisture supply during the grain filling stage is detrimental to grain formation of maize. Thus rainfall should be uniformly distributed for effective grain formation during the grain filling stage. This agrees with the observation of Beer et al.

(1967) who noted that irregular moisture supply during the grain filling period, particularly when the kernels are in the formation process, leads to reduced yield which is evident from the reduction in grain size. With the exception of mean length of dry spells and total rainfall, no other hydrometeorological variable was found to be critical for the grain formation of maize during this stage.

(v) *Ripening Stage*

The only statistically significant hydrometeorological index for maize yield during the ripening stage turns out to be relative humidity. Relative humidity was found to be significantly correlated with maize yield at 90% probability level in the semi arid climate but at 95% level in the humid moist and dry subhumid climate.

The significant negative correlation between relative humidity and maize yield indicates that high values of relative humidity during the ripening period might reduce the final grains yield of maize. For instance Webster and Wilson (1973) noted that relative humidities above 70% during the ripening period of maize tend to favour the rapid development and spread of fungus diseases and of molds which are capable of lowering the final grain yield of maize. It should be noted that no other hydrometeorological variable was found to be significantly correlated with maize yield during the ripening stage. This could be due to the fact that the ripening stage is ultimately the closing period of the crop growth cycle and during this period, the physiological growth of the plant reproductive organs (e.g. roots, leaves and tassels) have virtually ceased. Thus moisture utilization is highly limited and therefore the pattern of moisture supply is no longer critical to growth.

From the foregoing discussions the statistically critical hydrometeorological variables (variables that are significantly correlated with maize yield at a minimum of 95% probability level in at least 2 different climatic regions) for maize growth in the savanna region are:

(i) interdiurnal variability of rainfall during the establishment stage.
(ii) evaporation during the vegetative stage.
(iii) mean length of dry spells during the flowering stage.
(iv) total rainfall during the flowering stage.
(v) mean length of dry spells during the grain filling stage, and
(vi) relative humidity during the flowering stage.

These are the variables utilized in the multiple regression analysis. The results of the multiple regression are presented in Table 2. The results show that the combination of statistically critical hydrometeorological variables accounted for between 70 and 92% of the variation in maize yield in the savanna belt of Nigeria. [i.e. R^2 varies between 70-92%]. Table 2 shows further that, of all the critical hydrometeorological parameters, interdiurnal variability of rainfall during the establishment stage accounts for the largest proportion of the variation in maize yield in the different climatic regions of the savanna belt of Nigeria.

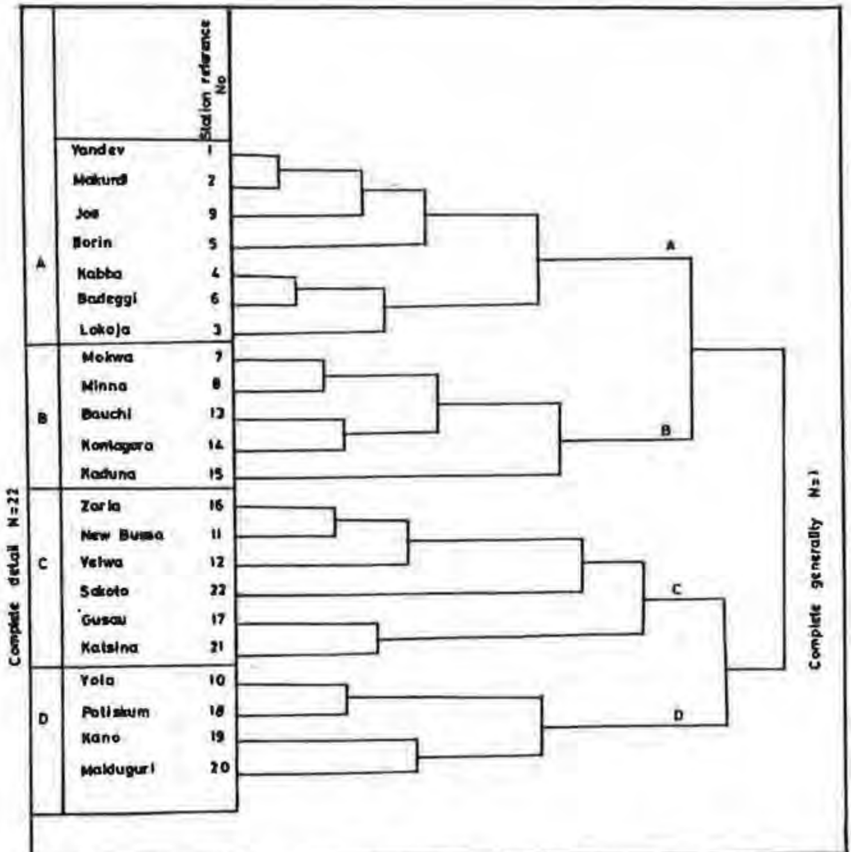

FIG 3: LINKAGE TREE (DENDROGRAM) FOR 22 AGROMETEOROLOGICAL STATIONS OF THE SAVANNAH BELT OF NIGERIA

(b) Hydrometeorological Regions for Maize Cultivation in the Savanna Belt of Nigeria

In the cluster analysis process, the critical hydrometeorological indices identified above form the distinguishing characteristics and the 22 stations from where these variables were obtained represent the objects being classified. Thus the 22 stations are otherwise referred to as the individuals. All individuals have a number of properties and the total number of individuals classified is the universe. Thus the savanna belt of Nigeria represents the universe.

Figure 3 shows the linkage tree [dendrogram] for the 22 selected stations of the savanna belt of Nigeria. The linkage tree or dendrogram illustrates the relationship between the 22 stations. The relationship is defined in terms of similarity of the effect of the distinguishing characteristics on maize yield at the

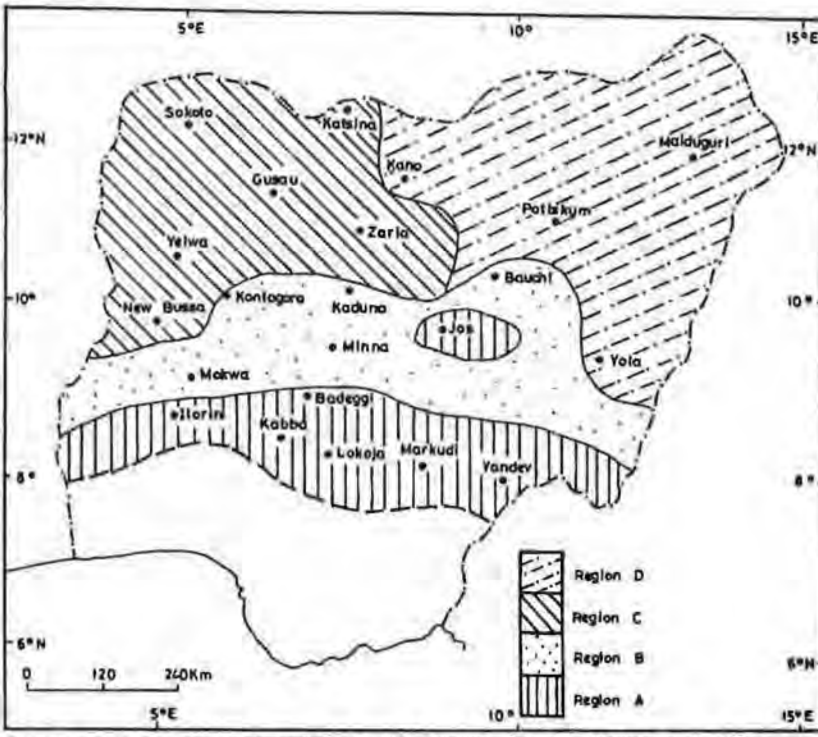

FIG 4: HYDROMETEOROLOGICAL ZONES OF THE SAVANNA BELT OF NIGERIA FOR MAIZE GROWTH.

stations. The procedure is that the most similar pair are 'collapsed' into one class, the next most similar pair are then joined and so on until a hierarchy of classes is formed as in Figure 3. It should be noted further that the similarity level and order of joining defines the regions. For instance the percentage similarity greater than 60% is categorized as high, while 50 - 60% is average, 40–50% low and less than 40% is difficult. From Figure 3, four different homogeneous regions [A - D] and elements (stations) in each group can be identified.

Using the information on Figure 3, the spatial pattern of the different homogeneous regions for maize cultivation has been prepared (Fig. 4). From Figure 4, areas covered by Region A represent high potential hydrometeorological zones for maize cultivation. Region B is classified as average potential zone and Regions C and D are low and difficult zones respectively.

With the exception of Jos Plateau area, the potential hydrometeorological zones for maize cultivation reflect variation with latitude up to the Kontagora-Bauchi axis, that is about 10° N. However beyond this axis the division into regions follows lines of longitude in such a way that a west-east orientation is more apparent. Thus beyond latitude 10° N the moisture potential for maize growth in the savanna belt of Nigeria decreases north-eastwards.

TABLE 3 Relating the Potential Hydrometeorological Regions for Maize Cultivation to the Present Land Use Under Maize in the Savanna Belt of Nigeria

Regions	Potential for Maize Cultivation	Present Land Use Under Maize (%)	Remark (Level of Utilization)
A	High	20 - 30	Underutilized
B	Average	10 - 19	Underutilized
C	Low	Below 9	Satisfactory
D	Difficult	Below 9	Satisfactory

IMPLICATIONS FOR AGRICULTURAL LAND USE PLANNING IN THE SAVANNA BELT OF NIGERIA

A superimposition of Fig. 4 on Fig. 2 shows that the hydrometeorological regions for maize cultivation (Fig. 4) do not correspond perfectly with the moisture adequacy climatic regions (Fig. 2). For instance, Region A (Fig. 4) is not limited to the humid climate (Fig. 2) but extends to the southern parts of the moist sub-humid climate. Region A is also found localized around Jos area, reflecting the microclimatic effect of the physiography of Jos area. Also, unlike the moisture adequacy regions (Fig. 2) the spatial variation in the hydrometeorological regions for maize cultivation (Fig. 4) in areas beyond 10°N cannot be explained in terms of latitude. Thus in view of the changing nature of climate, the results of Fig. 4 appear to be more useful for the planning of crop land under maize.

Relating the potential meteorological regions A - D to the present land use under maize (Table 3), it is evident that the area with high potential for maize cultivation is yet to be fully utilized, particularly when examined in terms of the percentage of crop land devoted to maize. For instance in Region A where conditions are optimum for maize growth (Fig. 4), less than 30 percent of the crop land is devoted to maize cultivation. Thus land use devoted to maize cultivation can be increased in the southern parts of the savanna belt of Nigeria particularly in areas stretching from the south-western corner around Ilorin and eastwards through Kabba and Lokoja to Makurdi and beyond Yandev around the south-eastern part of the savanna belt of Nigeria. Also Jos area belongs to Region A, thus land use for maize cultivation can be intensified in this area. Generally in Region A, intercropping maize with groundnut/sorghum is a worthwhile attempt at increasing the acreage under maize. It should be noted that intercropping of maize with groundnut/sorghum has been successfully practised, but on a micro scale, in the area (Agboola, 1979). Thus such intercropping can be popularised in the whole of region A.

In Region B where conditions can be described as adequate, about 10-19 percent of the crop land is devoted to maize growth. Therefore in Region B (Fig. 4) an appropriate increase in the crop land devoted to maize can be effected from the northeastern part of Yandev to the southern parts of Yola and further westwards up to the north-western part of Ilorin.

In Regions C and D where conditions are low and difficult respectively for maize growth, about 9 percent of the crop land is put to maize growth, suggesting that the proportion of land use under maize appears to be compatible with the moisture resource base of these areas for maize cultivation.

However considering some management factors such as moisture conservation through mulching or supplemental water supply from irrigation, most parts of Region C and the southern locations of region D might be suitable for the growth of varieties which can be harvested within less than 130 days after planting. Examples are the early and extra early maturing cultivars. In particular extensive parts of Region C can be cultivated to early maturing genotypes of both the white and yellow maize. Generally, the extra early maturing cultivars would have a very good advantage in Region D.

CONCLUSION

In conclusion, the results of the correlation analyses show that the moisture-based agrometeorological indices (hydrometeorological variables) are critical for effective growth of maize from the time of planting to maturity. For instance there is no location in the different climatic regions of the savanna belt of Nigeria where the combination of the critical hydrometeorological indices accounted for less than 60 percent of the variation in maize yield. However each phenological stage has been found to be more sensitive to a particular or certain combination of hydrometeorological variables than others. Furthermore an hydrometeorological variable found to be critical for effective growth of maize at a given developmental stage may not necessarily be critical to another stage. Therefore studying crop-climate relationships with respect to the phenological stages is a useful guide to synchronizing the climatic requirements of a crop with the climatic regime of the plant environment. For instance the interdiurnal variability of rainfall was found to be critical for physiological growth of maize. Therefore in areas characterized by frequent moisture stress due to high interdiurnal variability of rainfall and prolonged dry spells, the practice of mulching where practicable and supplemental water supply from irrigation could be adopted.

Regarding the zoning of the area for maize cultivation, using the critical climatic requirements at the different phenological stages as the criteria for classification is quite appropriate. For instance, the spatial distribution of the existing moisture adequacy climatic regions of the area (Fig. 2) differs from the hydrometeorological regions of the area for maize cultivation (Fig. 4). Therefore, although maize is generally sensitive to moisture, the moisture adequacy regions

(Fig. 2) are not essentially synonymous to potential moisture regions for maize cultivation.

Finally, it is generally understood that the savanna belt of Nigeria is the major food crop producing ecological zone of the country. Thus as an additional means by which we can check the seasonal fluctuations in food supply and ultimately the perennial food shortage in the country, it will be necessary to extend this study to other major food crops grown in the savanna belt of Nigeria. In particular, because crop-climate relationships might vary spatially and according to crop cultivars and stages of growth, it is suggested that this type of study should be extended to different cultivars of various food crops grown in the area. It is evident from this study that the need to adjust land use to ensure optimal climatic condition for the cultivation of the high-yielding late maturing maize cultivar in the savanna belt of Nigeria cannot be over-emphasized.

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Temperature Trends at Coastal Stations in Eastern Canada

M.R. Morgan[1]
K.F. Drinkwater[2]
and
R. Pocklington[2]

ABSTRACT

Trends in the annual mean air temperature records at coastal stations in eastern Canada (since 1900) are compared to the Canadian average trend, and to trends of stations in Greenland and around the periphery of the North Atlantic.

Results obtained by least squares fits are compared to those of climate normals. The latter show that a curvilinear trend is of higher statistical significance than the corresponding best-fit linear.

In contrast to the recent warming documented over much of continental Canada, air temperatures have continued to decline in the Maritime Provinces, in Newfoundland, along the Labrador Coast, and on Baffin Island from maxima that occurred in the 1940s and 1950s. The rate of cooling is shown to increase northward and to be part of a general decrease in air temperatures at coastal stations around the periphery of the northern North Atlantic, with the greatest decrease centred over Greenland. The decline in air temperature corresponds to similar declines in sea surface temperature throughout much of the North Atlantic. On the continental shelf off the Labrador Coast and northern Newfoundland, the recent years of low air temperatures have been accompanied by the presence of anomalously cold seawater and more extensive and more persistent ice-cover.

RÉSUMÉ

On a analysé les tendances annuelles et saisonnières des températures moyennes de l'air aux stations côtières du Canada de l'est (depuis 1900), et on a fait une comparaison avec la tendance nationale et les tendances dans des stations en Groenland et autour de la périphérie de l'Atlantique du Nord. On a comparé les résultats qu'on a obtenus par régression des carrés moyens avec les tendances des normales de température. Ces dernières indiquent qu'une courbe parabolique conforme mieux aux tendances et possède une signifiance statistique plus haute que les tendances lineaires correspondantes.

[1] CLIMARCON, 32 Rocklin Drive, Dartmouth, Nova Scotia B2X 2S1
[2] Department of Fisheries and Oceans, Physical and Chemical Sciences, Bedford Institute of Oceanography, PO Box 1006, Dartmouth, Nova Scotia B2Y 4A2

La chaleur qu'on trouve partout au Canada continental n'est pas en évidence aux stations dans les provinces Maritimes, en Terre-Neuve, le long de la côte du Labrador, et dans l'île Baffin. Au contraire, un refroidissement général est en train et augmente au nord. Des déclins semblables de la température de la surface de la mer sont en évidence partout dans l'Atlantique du Nord. Sur la plate-forme continentale de Labrador et de Terre-Neuve du nord, les années récentes froides ont été accompagnées de la présence de l'eau de mer froide, et de la glace plus persistante.

1. INTRODUCTION

In recent years there have been many publications examining hemispherical and/ or global temperature trends, using data mainly from land-based stations (Hansen and Lebedeff, 1987; Jones *et al.*, 1986). These have shown that an irregular gradual warming has been taking place over the past 100 years, which some (e.g. Kellogg, 1991) see as support for the "greenhouse warming" hypothesis (most recently summarized by Houghton *et al.*, 1992) according to which warming is predicted to be greater at higher latitudes. Such large-scale analyses performed over a long time-interval may mask important details of the temporal and spatial variability in regional climates. It seemed appropriate, therefore, to analyze local data sets in order to identify regional trends and to determine the degree of similarity (or dissimilarity) with the global and hemispherical trends. Important climatic effects may be found which may impact differently upon the socioeconomic fabric of one region as compared to another.

A recent national review (Gullett and Skinner, 1992; referred to as G&S, 1992; also Skinner and Gullett, 1993) of temperature change in Canada during the past century (1895-1991) shows that a general warming trend from the late 1800s to the mid-1940s was followed by cooling over the next 30 years throughout the country. Since the mid 1970s, warming has re-occurred, resulting in the 1980-89 decade being the warmest on record, not just in Canada, but in the Northern Hemisphere as a whole (Houghton *et al.*, 1992).

According to G&S (1992), the amplitude of the warming trend in Canada was greatest in the interior - from the Yukon/North BC region to the southern Prairie region - and weakest on the Pacific and Atlantic coasts, and in the eastern Arctic region. Temperatures in the Atlantic region (Nova Scotia, New Brunswick, P.E.I., and Newfoundland) have deviated from the national trend, especially during the last 40 years (Morgan, 1991). The warmest conditions in this region did not occur until the 1950s. Rapid cooling thereafter to uniformly cold temperatures in the early 1970s was followed by a warming trend which culminated in three warm years in 1981, 1983 and 1984. However, colder temperatures in the latter half of that decade resulted in the two most recent decadal means being close to the 1900-90 long-term mean. In the coastal regions of Labrador and southern Baffin Island (where reliable records only exist for the past 50 years), the air temperature trend has also been negative (but not statistically significant according to G&S, 1992).

These notable cooling trends in the early 1970s, and again in the late 1980s, have been accompanied by unusually extensive and persistent seasonal ice coverage (Chapman and Walsh, 1993; Drinkwater, 1993) and the presence of greater volumes of polar ice-melt water in the Labrador Current (Bunker, 1979; Dickson *et al.*, 1988).

As temperature trends at coastal stations in eastern Canada are somewhat contrary to those of continental Canada, an explanation has been sought by analyzing time-series of air temperatures at over 20 locations around the periphery of the North Atlantic, from Nova Scotia northeastward to Greenland and Spitsbergen (77° N, 15° E), then south to the coasts of Norway, Scotland and Ireland. Our intent is to determine to what extent temperature changes in eastern Canada are related to changes taking place in other coastal regions around the periphery of the North Atlantic.

2. DATA AND METHODS

2.1 *Data-bases*

Long-term annual and monthly mean surface air temperature datasets were obtained for a network of stations around the periphery of the North Atlantic Ocean. The stations and the lengths of record are listed in Table 1, and station locations are shown in Figure 1. Few stations have had continuous records from the same location for 100 years or more. Most stations having long records have changed sites and reporting procedures, some have periods of missing data, and records in major cities have been subject to increasing "heat island" effects due to population and industrial/commercial growth. This has made it necessary for national weather services to rigorously process climate records for errors and omissions, and to make estimates of other possible man-induced components.

All temperature data used herein have been obtained from the respective national weather services or from World Meteorological Organization (WMO)-recognized data centres, in Canada, the USA, Norway and the United Kingdom. We have accepted the processing that has been carried out by these organizations as providing the best authoritative records available. In the case of missing data, we have used proxy data derived by linear regression with nearby stations. For example, by using data for Godthab plus the short record for Resolution Island (N.W.T.) for the period 1929 to 1961, correlated proxy data for Iqaluit was obtained and was included in calculating the trends.

TABLE 1 List of stations.

Place name	Lat. Long. (degrees/minutes)	Height (m)	Record (years)
	MARITIMES		
YARMOUTH, N.S.	43 52 N 66 06 W	9	1941-1992
SABLE ISLAND, N.S.	43 56 N 60 01 W	4	1898-1992
SYDNEY, N.S.	46 10 N 60 03 W	62	1880-1992
CHARLOTTETOWN, P.E.I.	46 17 N 63 08 W	54	1880-1992
ST.JOHN'S, NFLD.	47 37 N 52 44 W	140	1880-1992
	LABRADOR/BAFFIN IS.		
CARTWRIGHT, NFLD.	53 42 N 57 02 W	14	1938-1992
KUUJJUAQ, QUE.	58 06 N 68 25 W	37	1950-1992
RESOLUTION IS., N.W.T.	61 18 N 64 53 W		1929-1961
IQALUIT, N.W.T.	63 45 N 68 32 W	34	1947-1992
	GREENLAND		
AKOBSHAVN	69 15 N 51 04 W	31	1880-1970*
GODTHAB	64 12 N 51 41 W	70	1880-1992
ANGMAGSSALIK	65 36 N 37 38 W	52	1895-1992
UPERNAVIK	72 47 N 56 10 W	63	1880-1992
	ICELAND		
STYKKISHOLMUR	65 05 N 22 44 W	8	1880-1992
AKUREYRI	65 41 N 18 05 W	27	1921-1992
	NORWAY		
JAN MAYEN	70 56 N 08 40 W	9	1926-1992*
ISFJORD	78 04 N 13 38 E	9	1912-1975*
BJORNOYA	74 31 N 19 01 E	18	1920-1992
OWS MIKE	66 00 N 02 00 E	0	1949-1992
TROMSO	69 42 N 19 00 E	10	1920-1992
BODO	67 16 N 14 22 E	13	1868-1992
BERGEN	60 23 N 05 20 E	36	1861-1992
	FAEROES		
THORSHAVN	62 01 N 06 46 W	55	1880-1992*
	UK AND EIRE		
LERWICK	60 08 N 01 11 W	84	1931-1992
PLYMOUTH	50 21 N 04 07 W	10	1931-1990
STORNOWAY	58 13 N 06 19 W	13	1931-1992
VALENTIA	51 56 N 10 15 W	14	1880-1992
	ACORES		
PONTA DELGADA	37 44 N 25 42 W	72	1894-1990*

*Record incomplete

2.2 *Data presentation*

Air and sea temperatures are presented as time-series plots of annual or seasonal means. Smoothing of the annual means was carried out using a 5-year running-mean filter and trends were investigated by both linear regressions and by examining climate normals (as defined by WMO, see below). Correlations were calculated using a standard statistical software package.

FIGURE 1 The study area (North Atlantic) with the locations of climatological stations that were used in this analysis.

2.3 *Temperature Normals*

Climate normals (30-year averages) were established by the International Meteorological Organization in 1935 as the standard for climate data exchange and comparison. Averages over this time interval were considered representative of the "population" from which they were derived. In 1967, it was agreed that a 30-year mean should be retained, updated every decade (WMO, 1967).

In G&S (1992), the use of climate normals as the standard for reliable comparison of climate data is acknowledged, yet temperature changes shown therein were discussed only in terms of best-fit linear trend of annual means. Since climate fluctuations are seldom linear, long-term changes may show up as illusory linear trends depending on the point of entry of the data set and the length of record (WMO, 1967). For example, the linear trend for the Maritimes region from 1900-90 is clearly positive, yet the trend from 1950-90 is negative (Figure 2B). The question arises "Is the recent cooling in the Maritimes just a reversal of a long-term warming trend or a significant independent cooling trend?".

To attempt to answer this question, we analyzed the linear trend for each station (or region) over the entire record, plus the trends to and from the point of maximum warming. These we compared to the trend of the climate normals. As the latest normal comprises data for the three decades since 1961 (the period during which dramatic cooling took place regionally in the early 1970s and warming in the early 1980s; G&S, 1992), we also calculated decadal mean trends for the 1951-90 period.

Seasonal data were also examined, with particular emphasis on the winter (consecutive months of December, January and February; most General Circulation Models postulate greatest CO_2-induced warming at this season; e.g. Houghton *et al.*, 1992), to determine the extent of the contribution of each season to the annual trend.

3. RESULTS

3.1 *Maritimes Region*

Annual air temperature anomalies (relative to the 1900-90 mean) for a composite record derived from the average of the annual means of data from Charlottetown (P.E.I.), Sydney and Sable Island (N.S), are shown in Figure 2A. Data from the three stations were similar with correlation coefficients (r) between any two sites exceeding 0.85 ($p<.01$).

A cooling trend from 1900 to 1923 was followed by a rapid rise of about 1.0°C by 1930. Some cooling again in the 1930s preceded a further strong increase from 1942 to maximum warming in the early 1950s. This was followed by a decrease to a minimum in the mid-1960s, after which the air temperatures have oscillated fairly evenly about the long-term mean. In the last decade, three warm years (1981, 1983 and 1984) were followed by five cold years (1985-89) with the result that the decadal average remains close to the 1901-90 mean (Figure 2D). The warmest decade for the Maritimes region was 1951-60; this differs markedly from most other regions of Canada (G&S, 1992) and the Northern Hemisphere (Houghton *et al.*, 1992).

The linear trend (Figure 2B) over the entire record is positive (+0.05°C decade^{-1}) for a net regional warming of +0.45°C during this century, but a positive linear trend from 1900 to 1952, and a negative trend from 1952 onwards, clearly fit the data more closely. These trends with slopes of +0.11°C and -0.18°C decade^{-1}, respectively, have higher significance than the single trend over the whole period. The plot of the normals shows (Figure 2C) that a curvilinear function would be a better fit to the data.

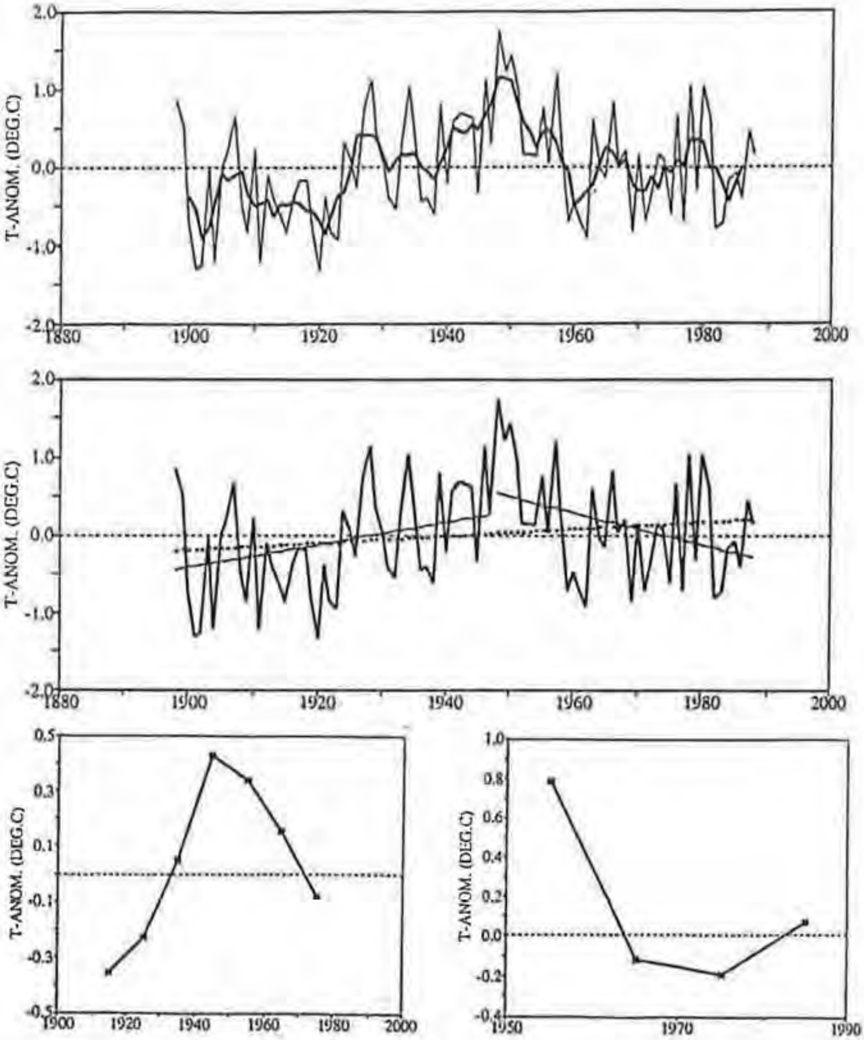

FIGURE 2 Maritimes Composite.

A. Annual air temperature anomalies (departures from 1901-1990 mean, solid; smoothed 5-year running mean, heavy solid).

B. Regressions of annual air temperature anomalies for 1901-1990 (dotted), 1901-1950 and 1951-1990 (solid).

C. Air temperature normals for 1901-1990.

D. Decadal means of air temperature for 1951-1990.

3.2 *Newfoundland and Labrador/Baffin Island Region*

Air temperature records for St. John's, Newfoundland, are available from 1880 onwards, whereas most stations along the Labrador Coast and on Baffin Island only commenced operations during, or after, World War II. Air temperatures at St. John's (Figure 3A) show a similar pattern to those in the Maritimes, with a general rise during the first half of the century, a peak near 1950, followed by a general decline with periodic maxima (late 1960s, 1980) thereafter. Along the Labrador coast, the maximum temperatures occurred earlier (around 1940) and the subsequent cooling trend has been more pronounced than in the Maritimes or at St. John's (Figure 3B).

The trend of air temperature normals for St. John's and that estimated for Iqaluit show a similar curvilinear distribution (Figure 3C) as for Maritime stations (Figure 2C). The decadal trends (Figure 3D) suggest that the cooling cycle may now have been arrested at St. John's but not yet at Iqaluit nor at Labrador stations such as Kuujjuaq and Cartwright which have experienced similar cooling.

3.3 *Greenland*

Data from a total of six stations in Greenland were examined and two (Godthab and Angmagssalik) were taken as representative of conditions on the west and east coasts, respectively.

In Greenland, a dramatic rise in air temperature during the 1920s led to a maximum (in the filtered data) before 1930. The trend at both stations has been persistently negative since that time (Figures 4A & 4B), although there were two warmer years during the 1940s at Godthab.

For the period 1901-90 at Godthab and at Angmagssalik, there is virtually no slope to the linear fit of temperature data. However, the trends of normals for both stations are curvilinear, with the latest normals at, or close to, their lowest values this century (Figure 4C). The most-recent decadal trend suggests that this cooling phase is continuing (Figure 4D). Since 1930, climate normals in Greenland have fallen on the order of 0.8°C on the southwest coast and over 1.0°C on the east and northwest coasts.

The normal indicates the characteristics of the curve and is, therefore, more representative and more significant (Table 2) than a linear trend. Figures 4A and 4B demonstrate the limitations of linear regressions in temperature data analyses compared to using the trends of normals.

3.4 *Other data sets*

Data for coastal and island stations in Iceland, the Greenland and Norwegian Seas, the Faeroes, Scotland and Ireland (Table 1) have also been examined.

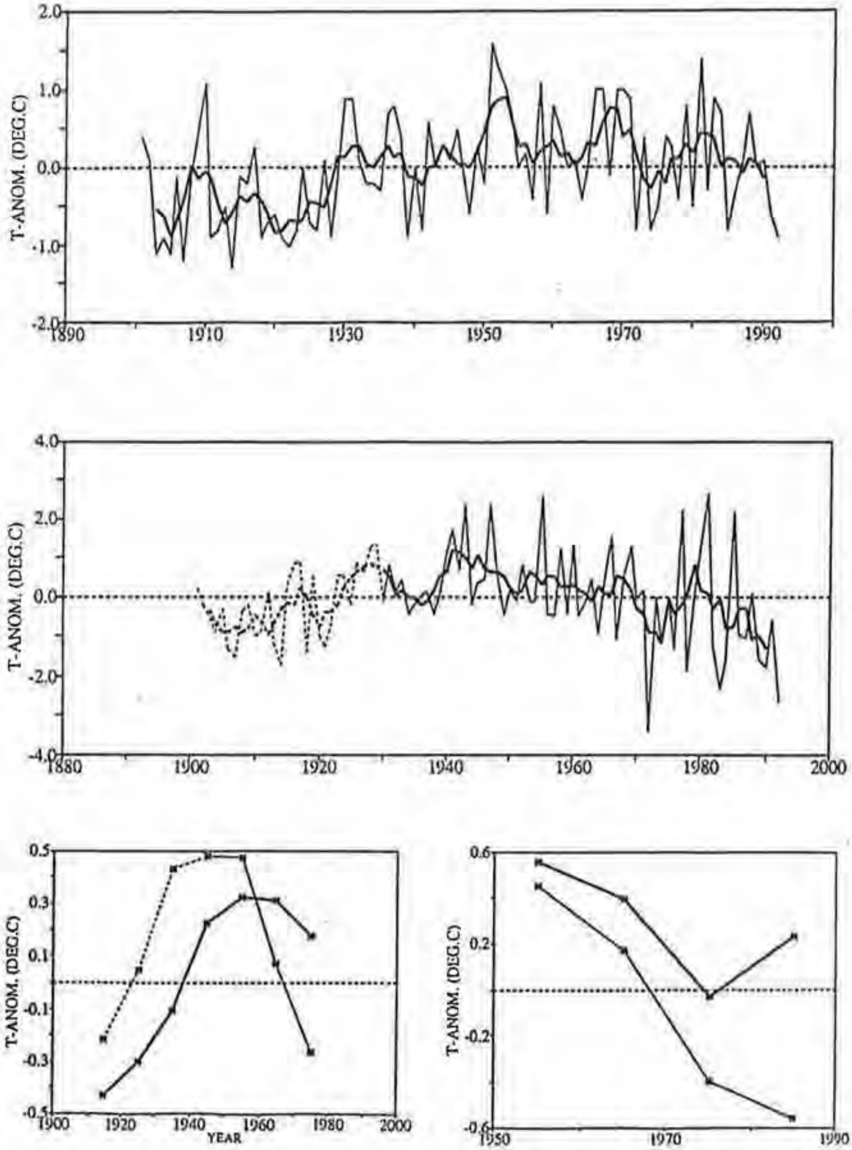

FIGURE 3 Annual air temperature anomalies.

A. St. John's, Newfoundland (mean, solid; smoothed 5-year running mean, heavy solid).

B. Iqaluit, NWT 1930-1990 (mean, solid; smoothed 5-year running mean, heavy solid): [estimated 1901-1930 (mean, dashed; smoothed, heavy dashed)].

C. Air temperature normals for 1901-1990. St. John's (heavy solid); Iqaluit (dashed then solid).

D. Decadal air temperature means for 1951-1990. St. John's (heavy solid); Iqaluit (solid).

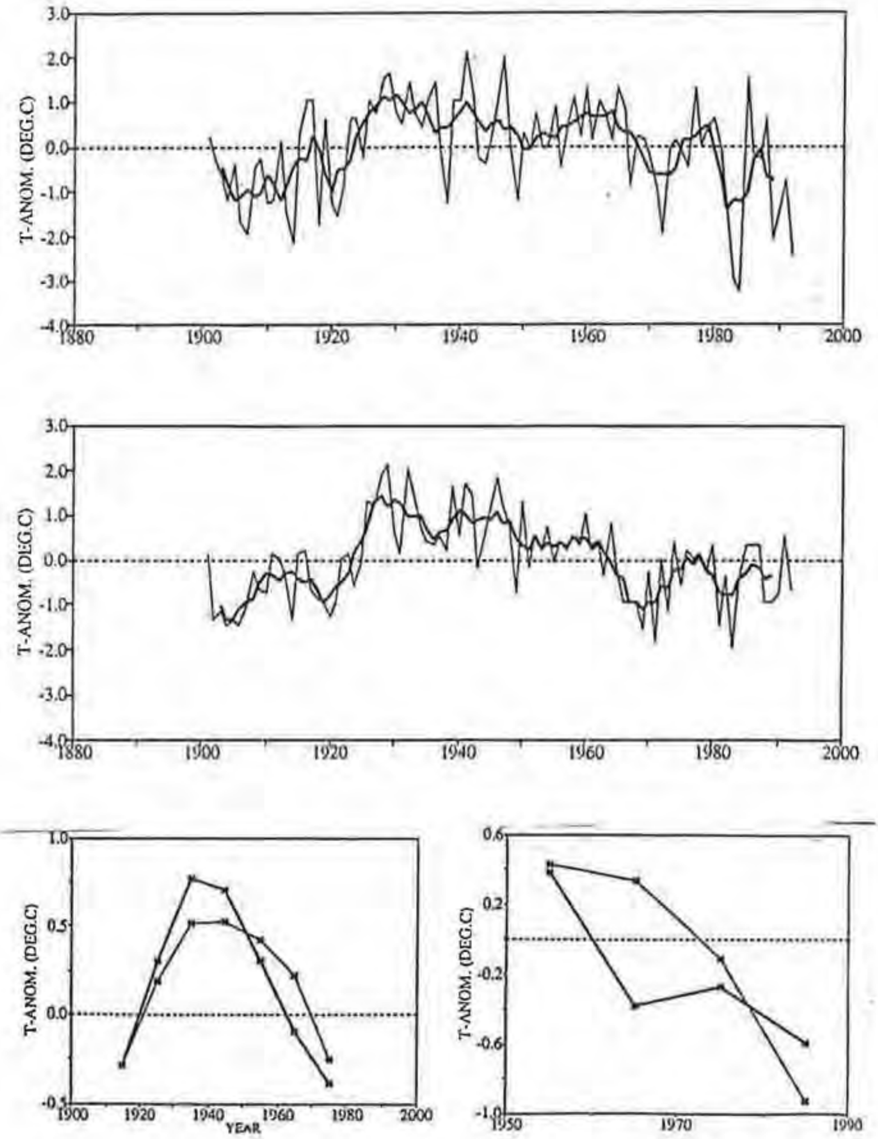

FIGURE 4 Greenland: annual air temperature anomalies.
A. Godthab (mean, solid; smoothed 5-year running mean, heavy solid).
B. Angmagssalik (coded as A).
C. Trend of air temperature normals for 1901-1990. Godthab (solid); Angmagssalik (heavy solid).
D. Decadal air temperature trends for 1951-1990 (coded as C).

Derived composite normal trends (Figure 5) have maximum to minimum ranges of 0.5° to 0.9° C. Normals for Icelandic and the north Norwegian Sea stations

TABLE 2 Significance of fit of trends to data.

Place name	Years used in analysis	Linear regression r values	Parabola r values
SABLE ISLAND	1900-1990	0.04519	0.23952
SYDNEY, N.S.	1900-1990	0.31891	0.42538
ST.JOHN'S	1900-1990	0.36235	0.40098
CHARLOTTETOWN	1900-1990	0.14252	0.42008
GODTHAB	1900-1990	0.01774	0.46013
ANGMAGSSALIK	1900-1990	0.00349	0.56086
STYKKISHOLMUR	1900-1990	0.10254	0.47607
JAN MAYEN	1926-1990	0.43608	0.45263
BJORNOYA	1920-1990	0.12757	0.12788
TROMSO	1920-1990	0.21613	0.23246
THORSHAVN	1900-1990	0.12599	0.37641
VALENTIA	1900-1990	0.04753	0.33062

are currently at, or near, their lowest values this century and the decadal trend shows little, if any, recent warming. However, from the Faeroes southwards to stations in Scotland and Ireland, the trend over the last decade has been positive with mean temperatures approaching the 1900-90 average.

The coastal regions around the North Atlantic generally experienced rising temperatures from the 1920s to the 1940s, or early 1950s. Since then, temperatures have fallen. The spatial variability in the amount of cooling is shown in Figure 6. It shows a centre of cooling over Greenland and outward extent of this influence to the coasts of Canada and northwest Europe. These results are consistent with the findings of Chapman and Walsh (1993).

4. SEASONAL TRENDS

To determine which (if any) season dominates the annual signal, seasonal temperature anomalies have been analyzed for Sydney, N.S., and Iqaluit as being representative of stations in the Maritimes and Labrador/Baffin Island, respectively (Figures 7 & 8).

Spring, summer and autumn, at both stations, show lower amplitude variability than winter. Temperature differences between successive winters often exceed 4°C at Sydney and 6°C at Iqaluit. Winter temperatures at both stations (since the 1950s) dominate the annual pattern.

Examination of seasonal data from Greenland and stations in and around the Norwegian Sea shows similar results, except that the spring variability increases at stations within the Arctic Circle due to wintry conditions extending into spring months at high latitudes. Stations around the UK and at Valentia (Ireland) show far less seasonal variability with more moderate amplitudes — rarely is there a differential of $>$ 2°C between successive years in any season. However, all seasons have shown a negative trend since 1950 until the last decade when there has been a return to temperatures near the long-term mean.

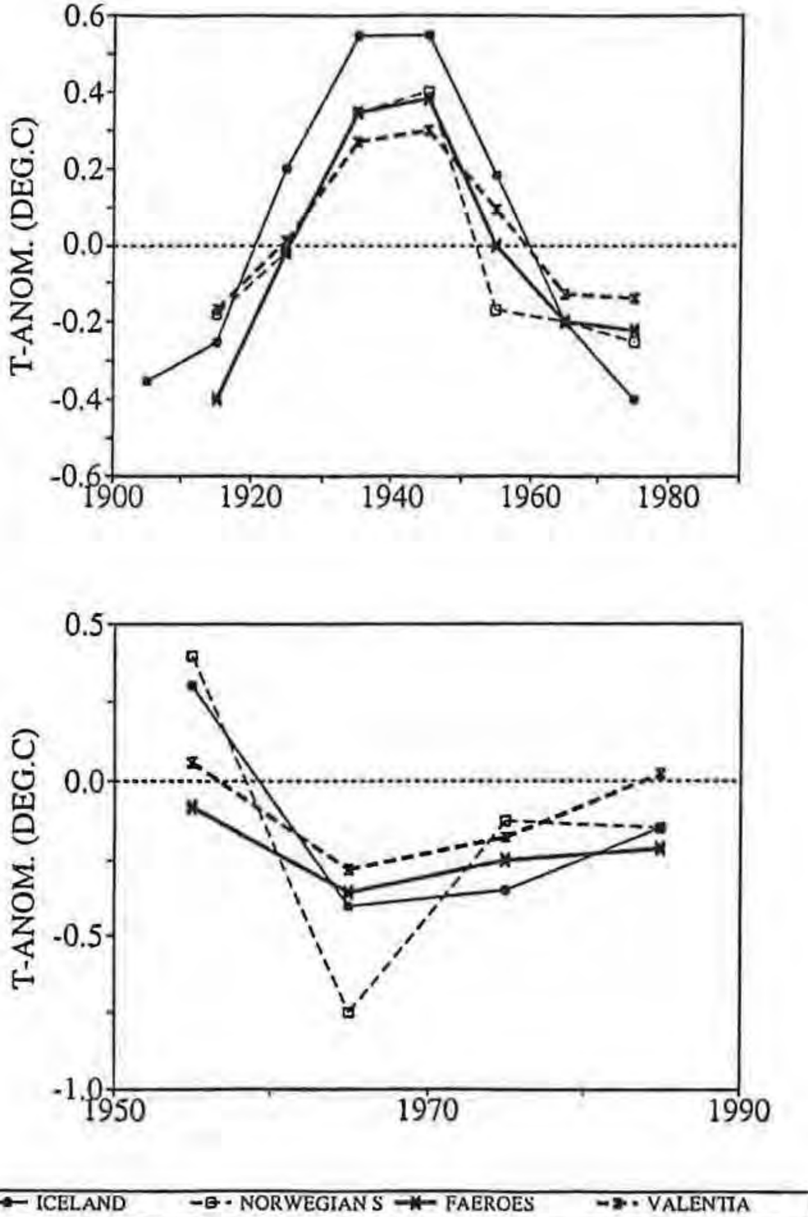

FIGURE 5 Trends of composite temperature normals and decadal means as anomalies from the long-term mean for regions.

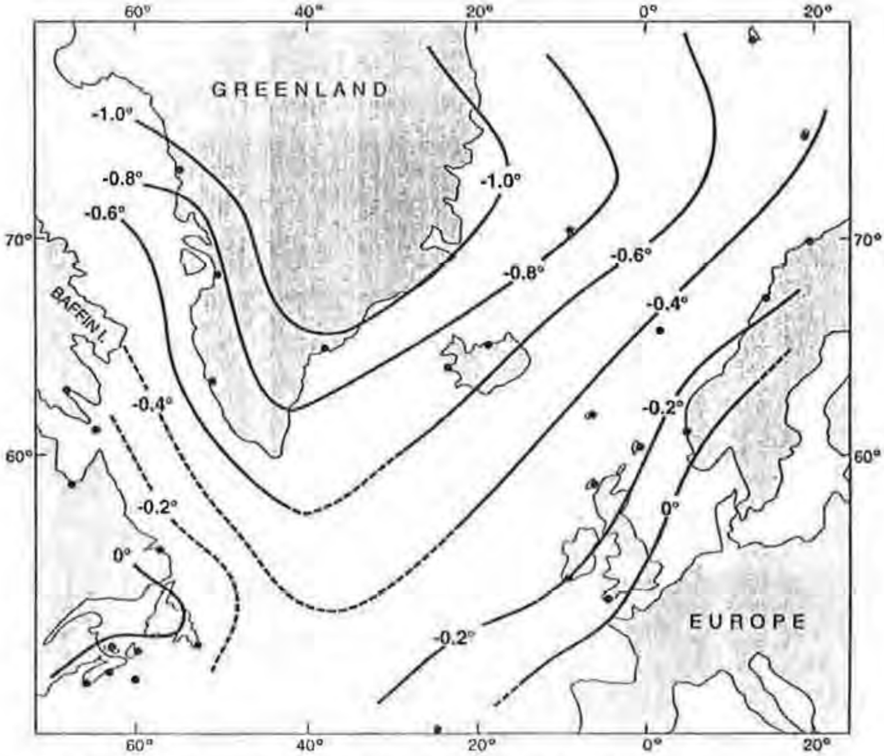

FIGURE 6 Mean temperatures for 1921-1945 minus those for 1946-1990.

5. OCEANOGRAPHIC CHANGES

5.1 *Sea Temperature and Salinity*

Sea surface temperature (SST) anomalies averaged within an area bounded by 55-60° N and 10-15° W in the eastern North Atlantic (Rockall area) for the period 1920 to the late 1980s are shown in Figure 9. There is a remarkable similarity with regional air temperature trends, i.e. a sharp increase during the 1920s, above average values between 1930 and 1960, followed by a cooling up to the present. A maximum occurred during the late 1950s which was slightly later than the maximum in air temperature.

This pattern of SST variability and its similarity with air temperature trends has also been observed throughout most of the northern North Atlantic (Smed et al., 1982; Folland and Parker, 1990; Rodlonov and Krovnln, 1992; Deser and Blackmon, 1993) although some differences are observed between regions. While there is similarity between the air and sea

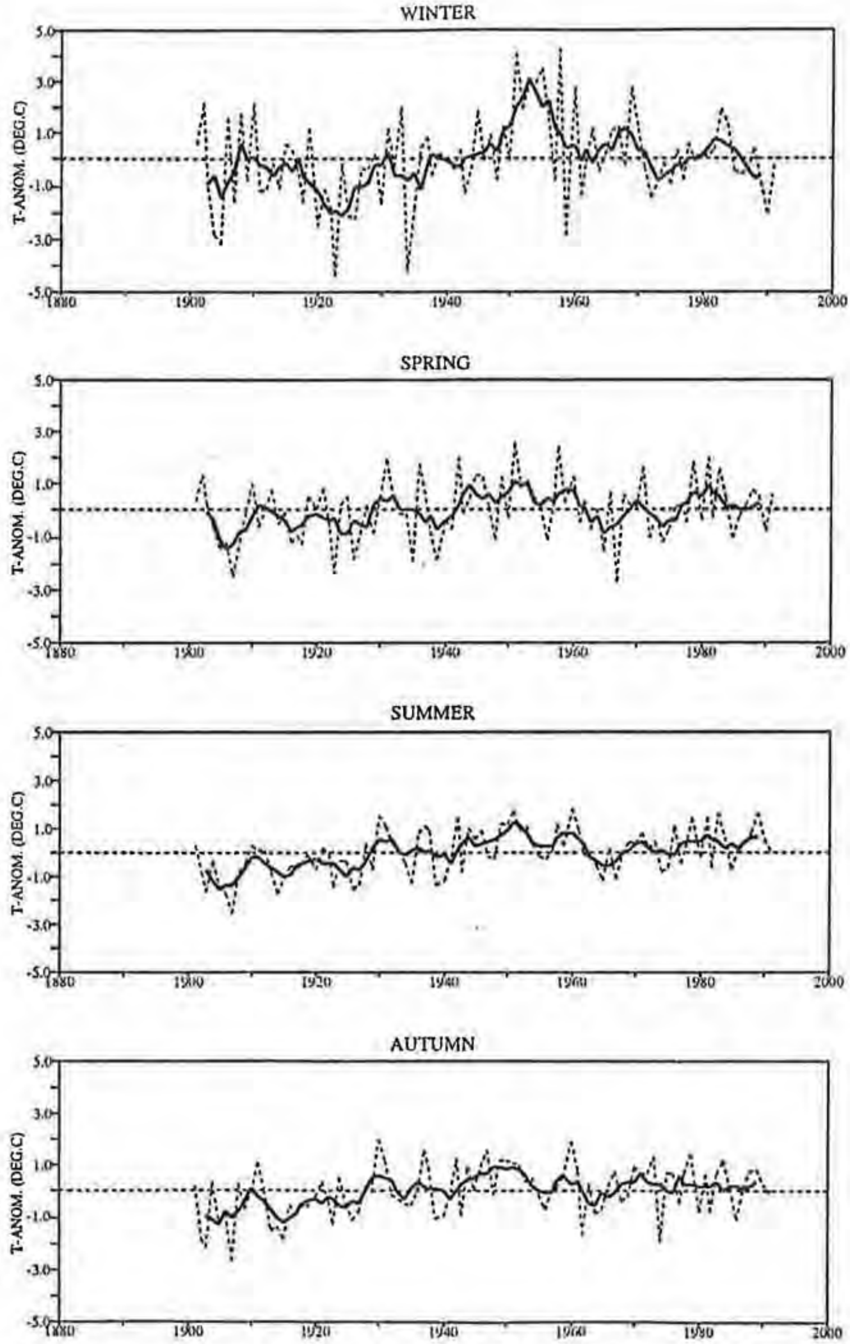

FIGURE 7 Annual seasonal temperature anomalies for Sydney (dashed; smoothed, solid).

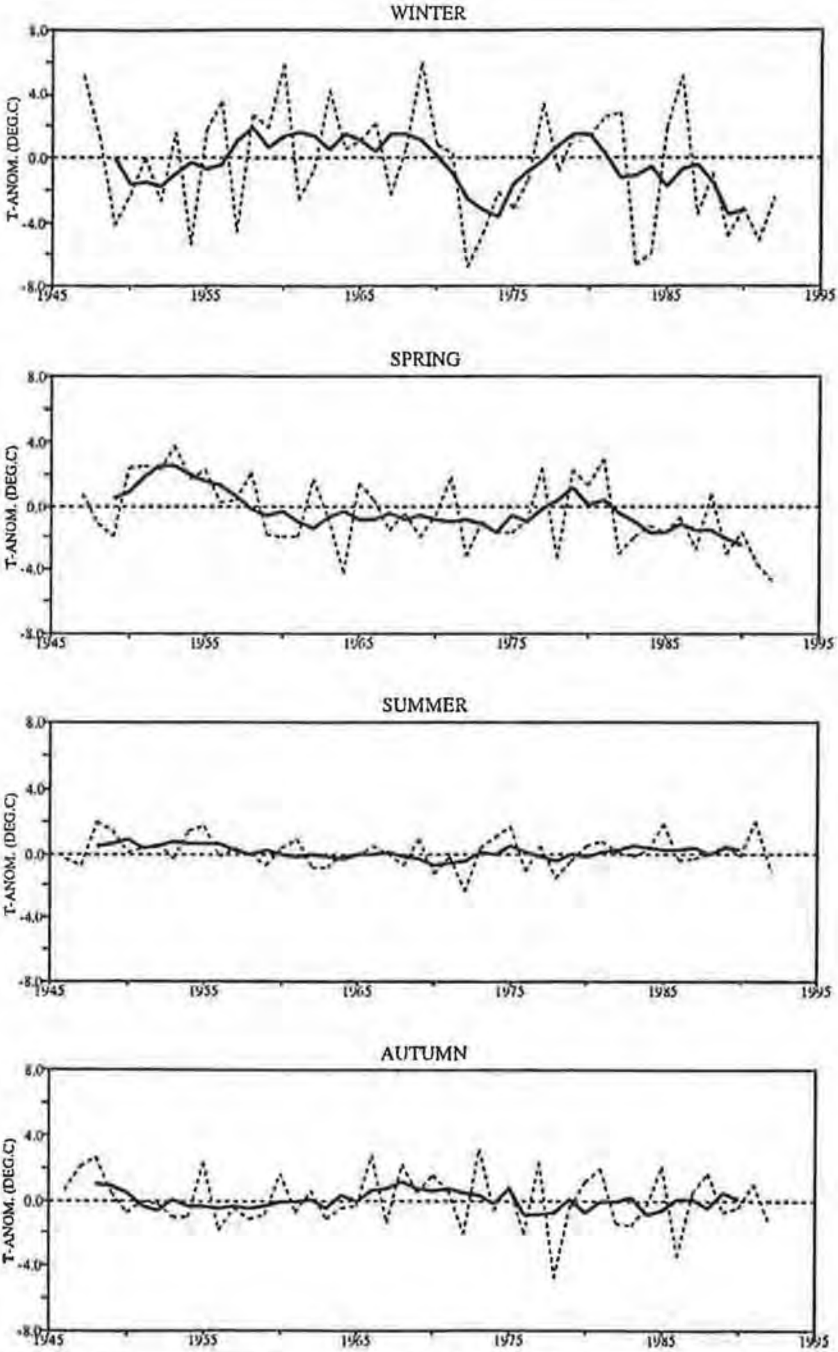

FIGURE 8 Annual seasonal temperature trends at Iqaluit (dashed; smoothed, solid).

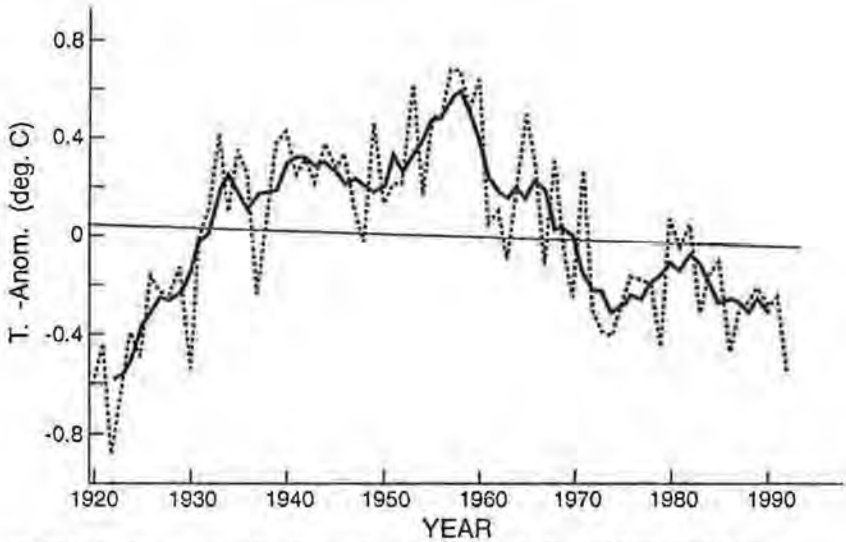

FIGURE 9 Annual sea surface temperature anomalies in the North Atlantic Drift Current — Rockall area (dashed; smoothed, solid).

surface temperatures over the North Atlantic, it has not been firmly established which is the cause and which is the effect.

Over the continental shelves off southern Labrador and northern Newfoundland, ocean temperatures have also varied in concert with the air temperature trends (Petrie *et al.*, 1988) with the clearest pattern evident in the deeper waters on the shelf (Drinkwater, 1993). Atmospheric cooling along the northeast coast of Canada in the early 1970s was contemporaneous with the presence of cold water of low salinity in the Labrador Sea (Lazier, 1979). Dickson *et al.* (1988) traced the source of this low-salinity water from the Greenland Sea (in 1968) eventually to the Labrador Current, arriving off Newfoundland in 1972. Known as the "Great Salinity Anomaly" this cold, low-salinity water mass is believed to have circumnavigated the North Atlantic reaching the vicinity of OWS India in 1975 and being detected at OWS Mike in 1977.

5.2 *Ice and Icebergs*

In winter, ice covers the northern Labrador Sea and the shelf off Labrador and northern Newfoundland. In addition, icebergs from Greenland and Baffin Island drift southwards in the Labrador Current towards the Grand Banks.

During relatively mild years (from 1945-1969), few icebergs reached the Grand Banks (except in 1957 and 1959; Ebbesmeyer *et al.*, 1980) and there was lesser extent of sea-ice. In cold years (1972-1974, 1983-85 and 1991-1992), iceberg counts in the southern regions climbed dramatically (Ebbesmeyer et al., 1980; Drinkwater and Trites, 1991) and the sea-ice spread further south and persisted for longer than usual (Prinsenberg, pers. com.). With the general decline in winter temperatures during the last 20 years, there has been a trend towards earlier ice formation and an increase in the ice extent during the early months of the winter (Drinkwater, 1993).

6. CONCLUSION

Analysis of annual mean air temperature records in eastern Canada over the last century shows that a warming trend from the early 1900s to the middle of this century was followed by cooling. This cooling was particularly noticeable over Baffin Island and along the coast of Labrador. Comparison with coastal stations around the periphery of the North Atlantic indicates that this cooling is part of a general northern North Atlantic temperature response with the greatest decrease occurring over Greenland. Thirty-year temperature normals and decadal trends at Greenland stations are at, or close to, their lowest values this century. Analysis of seasonal means confirms that annual trends are primarily determined by the characteristics of the winter season.

The use of least squares linear regressions to determine temperature trends has been found far from satisfactory. When used for data sets in eastern Canada and coastal stations throughout the northern North Atlantic having 90 years duration or more, positive trends dominate, whereas for stations with records of 50 years or less, negative trends prevail. This demonstrates the problem of deriving trends from linear regressions since results are dependent upon the length of the data base and the selected points of entry and departure. By using climate normals for temperature change comparisons, it has been found that linear regressions mask the fact that temperature trends at coastal stations around the periphery of the North Atlantic, in general, have conformed to a curvilinear distribution that fits the data more closely and correlates with higher statistical significance than the corresponding linear fit.

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Driver Adjustments to Wet Weather Hazards

Sean T. Doherty,
Jean C. Andrey,
and
Jeffrey C. Marquis
Department of Geography, Faculty of Environmental Studies,
University of Waterloo,
Waterloo, Ontario N2L 3G1
[Original manuscript received 6 October 1993;
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ABSTRACT

The importance of human adjustment to risky situations is well recognized in both the natural hazards and traffic safety research fields. This study explores the range and magnitude of driver adjustments to wet weather using a combination of traffic volume and driver survey data. The results show that substantial adjustments are made, but they are insufficient to fully counteract the added risk associated with rainfall. Explanatory variables and policy implications are discussed.

RÉSUMÉ

Les recherches concernant la securité routière en présence de risques et de dangers naturels démontrent clairement l'importance de l'adaptation de la conduite des automobilistes aux situations hazardeuses. Cette étude explore l'étendue et l'importance de l'adaptation des conducteurs par temps pluvieux, par la comparaison de données sur le volume de circulation routière et les résultats d'une enquête menée auprès des automobilistes. Les résultats de cette étude démontrent que des adaptations appréciables sont effectuées, cependant, celles-ci sont insuffisantes pour contrecarrer complètement les risques associés à la présence de précipitations. La discussion porte sur l'analyse des résultats ainsi que sur les différentes implications concernant les lignes de conduite à suivre.

1. INTRODUCTION

Canadians experience wide variations in day to day weather, and drivers learn to operate in less than optimal conditions. But how well do drivers cope? What factors are significant in the process of choice? Are there differences across the various driver groups? Perhaps more importantly, how do we find answers to these questions and what implications do findings have for safety policy? This paper discusses conceptual and methodological issues related to the problem of weather-related accidents and reports on two pilot studies carried out to investigate driver adjustments to the precipitation hazard in Southern Ontario.

Study Approach: A Hazards Perspective

Geographers have long been interested in the interactions between human activities and the natural environment. Out of this tradition grew the natural hazards research paradigm, which originated with the work of Gilbert White (1942) on flood losses in the United States. White found that damage from floods actually increased despite increased levels of government expenditure on preventative measures, which led him to pose the question: "How does man adjust to risk and uncertainty in natural systems, and what does understanding of that process imply for public safety?" (White 1973, 194). This question provided a central theme for research that emanated from the collaborative hazards program at the Universities of Chicago, Clark, and Toronto (White 1974; Burton et al. 1993).

The classical hazards approach identified the importance of perceptions in understanding hazard response, but it has not been without its critics, both on theoretical and methodological grounds (e.g., Torry 1979; Hewitt 1983). One major criticism is the focus on extreme geophysical events as the starting point for analysis; a second is the rather simplistic attempt at explaining the widespread irrationality of exposure and response to environmental hazards; and a third is on the validity of responses from traditional survey techniques. This paper attempts to address these three criticisms by focusing on a "common killer" that emerges out of routine activity, and one in which the constraints to adjustment are embedded in the way that life and space are organized. The focus is on measuring, understanding and improving driver adjustments to wet weather hazards.

Wet Weather Hazards and Traffic Safety

Despite significant improvements in highway safety over the past century, traffic crashes continue to be a major global health problem. Over the past two decades, more than 100,000 Canadians have been killed in traffic crashes and more than 50 times as many injured. The road safety community has responded to the safety problem with a range of accident countermeasures aimed at educating drivers, enforcing driving laws, and improving the design of both vehicles and roadways. Little attention has been given to the ambient environment, however, including the built and natural arena in which driving takes place.

One important aspect of the natural environment is weather, and it is widely acknowledged that inclement weather, especially in the form of

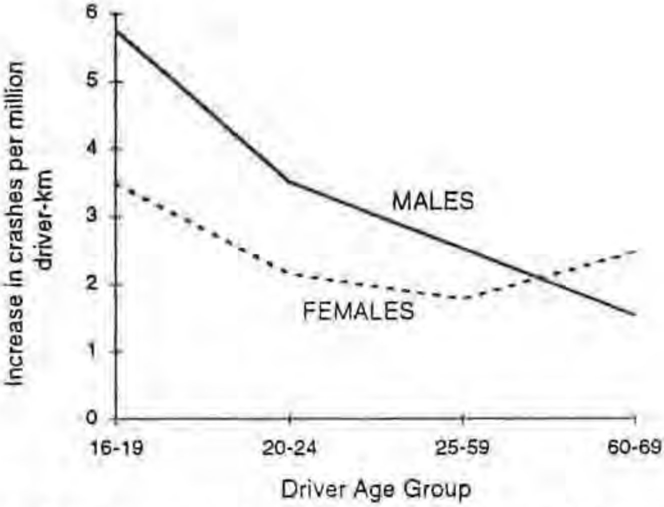

FIGURE 1 Increased Crash Risk Due to Rainfall (crashes per million driver-km)
Source: Data from Chipman et al. (1991) and Andrey (1989)

precipitation, increases accident risk by reducing both friction and visibility. In fact, recent Canadian studies by Mende (1982) and Andrey (1989) found that the relative risk of a collision increased by approximately 50% for all drivers, regardless of age or gender. Despite this, the effects of weather hazards on absolute risk are not the same for all driver groups, since different groups have different accident rates to start with. Combining data on accident rates by age and gender with information on the relative risk of accident during rainfall, as depicted in figure 1, reveals that rainfall represents a much greater accident risk for young drivers, especially young males. Thus the human component, particularly the effects of age and gender, appears crucial to approaching and understanding the adjustment process.

There is a substantial amount of research into the human factors that affect driving behaviour in general, and their subsequent relationship to traffic safety; however, very little of it focuses specifically on weather hazards. In particular, the links between driver perceptions and adjustments to weather have not been fully explored. There have been a few studies on traffic volumes as an indicator of trip cancellation (Codling 1974; Wilde 1977; Mende 1982; Yagar et al. 1982), and some survey research that deals with self-reported driving changes (Andrey and Knapper 1993). Because of limited empirical data, however, it is generally unclear whether personal factors, including perceptions, significantly affect driver adjustments to weather hazards and what implications this has for road safety.

2. METHODOLOGY

This study is based on data for the twin cities of Kitchener-Waterloo, located in Southern Ontario, with a total population of 240,000. Travel in these cities is almost exclusively auto-based, due to the relatively low population density and the dominance of suburban-style residential areas. The internal road system of the city basically follows a linear pattern around the main street. A multi-lane divided expressway system spans the city forming a semi-circle on the south and east sides of the built-up area. The modified continental climate of the Kitchener-Waterloo area is heavily influenced by its central position in the Great Lakes Basin. It receives approximately 900 mm of precipitation per year, of which approximately 85 per cent falls as rain. Typically, precipitation occurs on one day in three.

Techniques

Two complementary approaches were taken in this study to gain a fuller understanding of the range and magnitude of adjustments made during wet weather. One is based on direct observations of traffic volume and the second on self-reported adjustments.

In order to compare traffic volumes for rainfall versus dry conditions, a matched pair approach was used, where traffic volumes for given locations were compared for matched time periods. More specifically, each period of time during which traffic was exposed to rainfall was paired with a control time period when precipitation did not occur. The event and control were spaced just one week apart, and they matched in terms of clock time and weekday. Precipitation events and controls were defined as in Andrey and Olley (1990), using hourly weather data from the Waterloo-Wellington Airport weather station located eight kilometres east of the city and operated by the Atmospheric Environment Service of Environment Canada. Traffic volume data for five major intersections in Waterloo and six in Kitchener were obtained from the Traffic and Transportation Division of the Regional Municipality of Waterloo. The data covered the two calendar years, 1990 and 1991, for which 52 paired observation periods were defined.

In addition to traffic volumes, an innovative diary approach was used to probe drivers' wet weather behaviour. To assist with survey design, preliminary focus group discussions were held with 18 drivers to explore the range of driver attitudes to various aspects of wet weather hazards. Based on careful analysis of the focus group transcripts, a trip diary was designed to collect adjustment information during two types of events defined by the following scenarios:

- Heavy to moderate rainfall associated with a notable reduction in visibility. Windshield wiper blades on high or medium speed throughout.

- Wet roads following a rainfall or associated with light rainfall only. Windshield wiper blades off or used only intermittently.

Drivers were instructed to complete the indicated diary section immediately following the designated event, so that actual behaviour changes could be accurately recorded. The diary contained questions that prompted drivers to indicate how they changed their behaviour compared to dry, clear conditions. Most of the questions were closed-ended and included responses that were either nominal or ordinal level data. The diary booklet was supplemented by standard survey questions regarding demographics, driver experiences and risk perceptions. Experience measures included driver training, amount of driving, accident history and violations. Risk perception information was obtained using a procedure similar to that used by Matthews and Moran (1986), asking a respondent to rate the likelihood of an accident for him/herself and for other driver groups given the two weather scenarios.

The trip diary was completed by volunteers recruited through bulletin board announcements at two places of employment and one institute of higher learning in the Kitchener-Waterloo area. Those who responded were mailed the 14-page survey package, along with a covering letter, instructions and envelopes for their return. In total, 47 surveys were completed during the summer of 1992, with roughly equal numbers in four comparison groups defined by older (25-59) and younger (18-24) male and female drivers.

3. SUMMARY OF DRIVER ADJUSTMENTS

Burton et al.'s (1978) use of a choice tree has become a classical model for depicting adjustments to hazards. In terms of driver adjustments to wet weather hazards, this choice tree can be depicted as in Figure 2. Potential adjustments made prior to driving include the purchase of auto insurance (share potential loss) or improvements in technology, such as anti-lock brakes (prevent effects); background preparation such as skid training (prevent effects); or changes in the nature of a trip, including the mode, timing, or destination (change location or activity). Potential adjustments made while driving focus on preventing or reducing the effects of the weather hazard.

The present study deals entirely with trip cancellation (change activity) and behind-the-wheel adjustments (prevent or reduce the effects). Table 1 summarizes the range and frequency of these types of adjustments. The most radical trade-off between mobility and safety is to refrain from exposure altogether by cancelling, delaying or rescheduling a desired trip, in exchange for a total elimination of the added risk associated with wet weather. The traffic

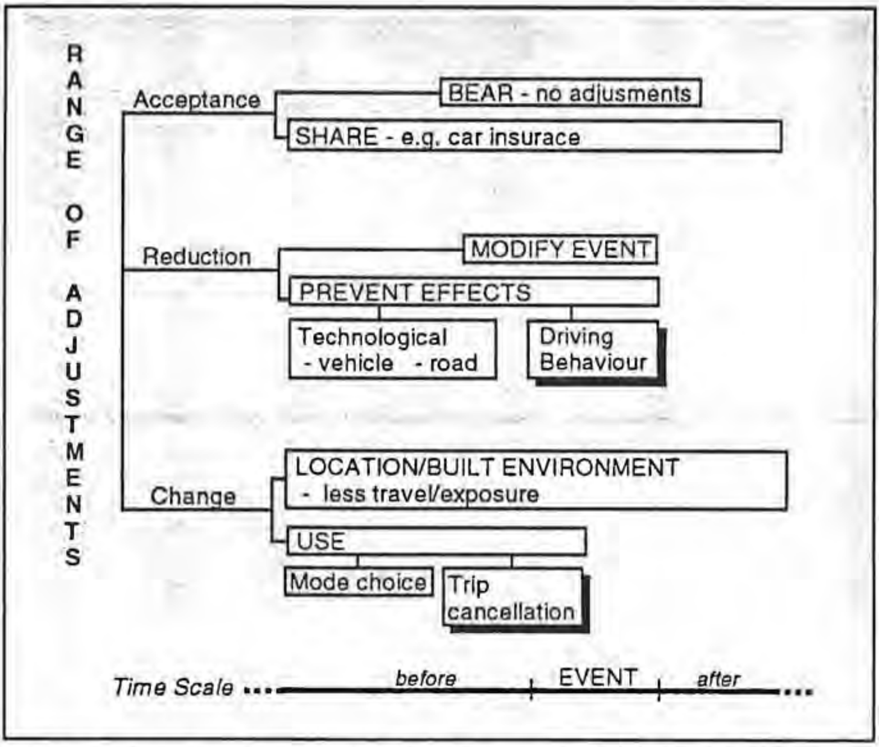

FIGURE 2 Choice Tree of Adjustments to Wet Weather Hazards Depicting the Role of Driver Behaviour
Source: Adapted after Burton et al. (1993)

count data indicate that, on average, volumes dropped by two per cent, which is similar to the findings from research conducted in the United Kingdom (Codling 1974). The diaries detailed the in-transit adjustments that were made. Increased concentration and alertness were the most common adjustments, with drivers more often motivated by concern for the unsafe actions of other drivers rather than their own. Changes in driving speeds, braking distances, following distances and manoeuvring around corners and bends were also frequently cited. Changes in travel plans occurred only rarely and usually involved leaving a little extra time for the trip, rather than a change in the mode or destination.

In addition to adjustment frequencies, information on the magnitude of speed reduction was also collected. Results indicate that, on average, drivers made greater speed reductions during rainfall than during wet road conditions, and on highways versus city streets, ranging from as high as 15 kilometres per hour (kph) for highway driving during rainfall events to as low as three kph for driving on city streets under wet road conditions. Previous

TABLE 1 Summary of Driver Adjustments

Wet Weather Driver Adjustment	Estimated Frequency	
	Rainfall	**Wet Roads**
Mobility Impacted Adjustments		
Highway speed reductions	very high	moderate
City speed reductions	high	moderate
Trip cancellation	very low	very low
Plan changes (before/during trip)	moderate	low
Driver Behavioural Adjustments		
Increased following distance	high	moderate
Increased braking distance	very high	high
Increased care around corners and bends	high	moderate
Increased concentration/alertness	very high	high

Note: Very High >90% of drivers, High 70-90%, Moderate 30-70%, Low 10-30%, Very Low <10% of drivers.

estimates have ranged from one to three kph during rainfall (Wilde and Ackersviller 1982) and eight kph in drizzle (Yagar et al. 1982). The fact that virtually all drivers change their behaviour during wet weather and make speed reductions is encouraging, but reduced speeds still tended to be higher than posted speed limits on both highways and city streets, especially for the wet road scenario.

4. ADJUSTMENT PROCESS: TOWARDS AN UNDERSTANDING

Hazards theory suggests that response is related to perceptions of risk and to the awareness of opportunities to make adjustments. It has long been recognized that this rather simplistic process needs to be expanded to include a wide range of other potential explanatory variables related to social, economic, cultural and political constraints. This is clearly the case in the road environment, where driver decision-making and behaviour is the product of a multitude of highly interactive factors. The design of this study allows for an examination of various factors that affect the process and choice of adjustment, which are loosely categorized as personal, geophysical, and societal.

Personal Factors

Perceived risk in hazardous situations has long been considered as a major determinant of personal response. Data from this study indicate that drivers perceive lower risks for themselves during wet weather than for other drivers. This type of driver optimism is common among most accident risk perception studies (e.g., Matthews and Moran 1986). Drivers also perceived significantly ($p<.05$) higher risk levels for rainfall versus wet roads (average 57% higher), with no significant differences between age or gender groups.

Perceptions of risk do little to explain adjustments to hazards unless they can be shown to influence actual adjustments once on the road. To test this relationship, Pearson's correlation coefficients were tabulated between the measures of "self perceived risk" and those of "driver speeds", but associations were low ($r<.30$) and statistically insignificant. This demonstrates that perceived risk plays a rather minor role, and lends support to the search for alternate explanations for the choice of adjustments. This appears particularly true for young drivers, in that their perceptions differed very little from older drivers, but their frequencies of adjustment were considerably lower. Groeger and Brown (1989) provide one explanation, finding that once on the road, young drivers have a lower ability to detect hazards than older drivers. Improving hazard detection, as opposed to increased hazard awareness, may be a crucial objective for safety programs aimed at youth.

Further analysis by age and gender groups revealed that young males exhibited significantly lower ($p<.05$) adjustment frequencies compared to their older counterparts on all but a few categories, whereas younger female adjustment frequencies were not significantly different than their older counterparts. In terms of speed adjustments, young drivers reduced their speeds by similar amounts to older drivers; however, the resulting actual speed levels of young males were well above those of other drivers (significant at $p<.05$). These findings concur with previous research which identified the risky behaviour of young drivers in the form of higher speeds (Wasielewski 1984), shorter headways (Evans and Wasielewski 1983), shorter gap acceptance (Bottom and Ashworth 1978), and underestimation of stopping distances (Quimby and Watts 1982). The added riskiness of young male driver behaviours exhibited here helps to explain their high susceptibility to crashes in wet weather as displayed earlier in Figure 1.

Other researchers have suggested that past experience plays a more significant role in differentiating driver behaviours and adjustments. To test this relationship, two measures of experience — exposure (years driving x average km driven/week) and accident history (number of accidents in last three years) — were correlated with speed reductions. The common problem with such analysis is that exposure and accident frequency are also correlated with age, confounding the results. The analysis did, however, reveal that speed reductions correlated positively with exposure ($p<.05$) and negatively with accident frequency ($p>.05$).

Geophysical Perspective

Adjustment patterns were affected by the nature of the geophysical event. Reductions in trip volumes were three times greater during thunderstorm events than other rain events. The most apparent reason is the heightening of the visibility hazard caused by intense falling rain, which would affect both trip cancellation/delay and travel speed, the latter of which potentially affects traffic counts by reducing road capacity. The diary information also revealed higher frequencies for every type of adjustment strategy during rainfall events versus wet road conditions, as displayed in Table 1.

As for their relationship to accident frequency, previous work suggests that precipitation events of different types and intensities are associated with a hierarchy of accident risk (Andrey 1989), and that rainfall is more problematic than wet road conditions on their own (Andrey and Yagar 1993). This would suggest that, although more intense weather hazards do invoke greater adjustments, these adjustments are insufficient to offset the increased risks on the road.

Societal Role

An alternate approach is to focus on the role of the social constructs that govern mobility in Canadian society. This approach is consistent with the argument put forth by critics of the natural hazards research paradigm and is gaining acceptance within the road safety community as well (e.g., Friedland et al. 1990). At the highest level, the nature of development governs the need for mobility, and is thus the primary cause of exposure to hazards in the road environment. It might therefore be argued that the underlying 'need' for mobility sometimes compels drivers to accept risks against their better judgement. The trip cancellation data confirm the importance of social factors, in that the lowest level of trip cancellation/delay occurred during peak journey-to-work hours and the highest occurred on weekends when travel activities are more discretionary.

Cultural influences, although less obvious, also provide insight into the low adjustment levels and supposedly 'irrational' behaviour of young male drivers during wet weather. Past research has suggested that young drivers are under more social pressure to commit violations (Matthews and Moran 1986) and endorse the positive aspects of speeding and dangerous overtaking more strongly than older drivers (Parker et al. 1992). Unfortunately, safety officials have tended to prefer a focus on the individual driver as a means of improving safety, at the expense of examining the much larger, and perhaps more critical role of society itself.

5. CONCLUSIONS AND POLICY IMPLICATIONS

This study provides new information on the types and magnitudes of driver responses to wet weather, and explores some of the underlying processes and factors that influence these responses. The results have implications for safety programs and/or priorities.

The findings of this study suggests that drivers need little convincing of the hazardousness of wet weather events, and they recognize a broad range of possible adjustments that might be taken to reduce their risk of accident. Thus, there seems to be little need to provide general education to the public about the perils of driving during inclement weather. By contrast, the safety community needs to be encouraged to give greater consideration to weather-related risks. Their position, which is that most accidents occur in clear conditions and on dry roads, does not do justice to the magnitude of the problem and does nothing to encourage creative solutions.

Despite general awareness, however, drivers continue to exhibit adjustment levels that are insufficient to counteract all the added risk. Increased skills training can clearly play a role here, and it is also possible that technological improvements, such as intelligent vehicle systems, will help to reduce weather-related traffic accidents. The danger of these approaches, however, is articulated in both the catastrophe hypothesis as described in Burton et al. (1993, 256), and the risk homeostasis theory described by Wilde (1982): the impact on safety will not necessarily be positive if such measures encourage over-confidence and lead to increased risk exposure.

A more radical approach to driving hazards is to reduce exposure to unsafe situations altogether. Possibilities include graduated licensing programs that restrict novice drivers from driving during inclement weather, and differential speed limits that legislate speed reductions on wet pavement. The major drawbacks to such measures are political acceptability and their implications for enforcement. Unfortunately, the most effective and long term method of reducing exposure to driving risks lies beyond the present mandate of the road safety community, and that is to change land use planning so as to encourage less auto dependence, and thus reap the benefits of a safer and more sustainable transport system, regardless of the weather.

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Western Canada Noctilucent Cloud Incidence Map

Mark Zalcik[1]
Edmonton, Alberta
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ABSTRACT

A map of western Canada shows lines of equal average number of noctilucent cloud (NLC) sightings per year for the years 1988–1992 according to observations by the surveillance network NLC CAN AM. Incidence appears to be highest in the central prairies in the latitude range 52–57°N and longitude range 105–115°W. Average incidence decreases north and south from this area due to understood NLC climatological behaviour, and east and west due to summer tropospheric weather patterns.

RÉSUMÉ

Une carte de l'ouest du Canada montre des lignes d'un nombre moyen égal d'observations annuelles de nuages noctulescents (NNL) pour les années 1988 à 1992, selon les observations du réseau de surveillance NLC CAN AM. La plus haute fréquence semble se trouver aux prairies centrales dans les latitudes Nord de 52° à 57° et dans les longitudes Ouest de 105° à 115°. À partir de cette région, la fréquence moyenne décroît au Nord et au Sud en raison du comportement climatique connu et elle décroît à l'Est et à l'Ouest en raison des tendances météorologiques de la troposphère en été.

Noctilucent clouds (NLC) are a phenomenon of the summertime high latitude upper mesosphere. They probably consist of water ice crystals, the nuclei of which are meteoric dust and large cluster ions (Thomas, 1991). They occur in a kilometres thin layer about 82 km above sea level, making them the highest clouds known. Their great height and insignificant optical thickness enable them to be seen only in twilight, specifically, when the sun is between six and sixteen degrees below the local horizon; when present the clouds then appear as silvery cirrus-like clouds within the arch of twilight.

Mesospheric temperatures and water vapour concentrations govern NLC evolution (Theon et al., 1967). Temperatures in the high latitude mesosphere reach their coldest values in the early summer. These values, as low as 130 K, are the coldest in any part of the atmosphere at any time of the year.

1 Mark Zalcik, 9022–132A Avenue, Edmonton, Alberta T5E 1B3

TABLE 1 Number of seasonal noctilucent cloud sightings at selected NLC CAN AM sites, listed in order of increasing longitude, during the period 1988-92. A (—) symbol indicates that no observing was conducted, or that data for that year were not used in the analysis.

Site	Latitude (°N)	Longitude (°W)	1988	1989	1990	1991	1992	$\bar{x}$
Winnipeg	49.9	97.2	—	2	1	1	0	1.0
The Pas	54.0	101.1	1	8	3	3	—	3.8
Broadview	50.4	102.7	2	3	1	0	0	1.2
Estevan	49.2	103.0	—	—	2	0	1	1.0
Wynyard	51.8	104.2	6	8	—	—	—	7.0
La Ronge	55.2	105.3	—		10	9	7	8.7
Swift Current	50.3	107.7	1	2	—	—	—	1.5
Ft. Reliance	62.7	109.2	1	9	2	—	—	4.0
Lethbridge	49.6	112.8	7	3	0	1	0	2.2
Edmonton	53.7	113.5	12	8	8	12	3	8.6
Slave Lake	55.3	114.8	7	8	5	1	—	5.3
Vancouver	49.2	123.2	—	—	1	0	0	0.3
Watson Lake	60.1	128.8	4	6	5	4	—	4.8
Cape St. James	51.9	131.0	—	—	—	2	0	1.0

Consequently, NLC occur in the late spring and summer, from mid May to mid August (and December through February in the southern hemisphere). NLC are thought to be the equatorward fringes of a larger mantle of mesospheric cloud which caps each of the poles during their respective summers. This cloud mass, termed polar mesospheric clouds (PMC), was discovered by satellite (Thomas, 1991). During several nights over the above three month period mesospheric conditions in the subarctic foster evolution of noctilucent clouds, leading to sightings of NLC at lower latitudes.

Reported latitude of maximum boreal NLC incidence has varied from 55°N (Paton, 1964) to 60°N (Fogle, 1966). Even though the clouds actually form at latitudes down to about the 60th parallel (Fogle, 1966), visibility of NLC north of the 55-60°N zone is not necessarily favoured because at NLC peak season in late June and July twilight conditions in this region are too bright to permit observation of the clouds. When viewing conditions improve in August, NLC are already on their downward leg of evolution. Conversely, as one travels further south from the highest incidence zone NLC are eventually out of range.

Latitudinal limits of boreal NLC sightings have been 76.3°N (Fogle, 1966) and 43.3°N (Lohvinenko and Zalcik, 1991), though with respect to the southerly limit, there have been positive reports from perhaps further south in the state of New York (McConnell, 1987).

Since 1988 the surveillance network NLC CAN AM, which consists of both amateur observers and personnel observing voluntarily at several Canadian weather and flight service stations, has monitored the summer skies for noctilucent clouds. Participants are listed in Appendix 1. Climatological data from the network has permitted incidence analyses. Table 1 lists numbers of seasonal sightings, that is, nights through which NLC were seen during at least one check of the local sky, from fourteen selected sites in the years 1988–1992.

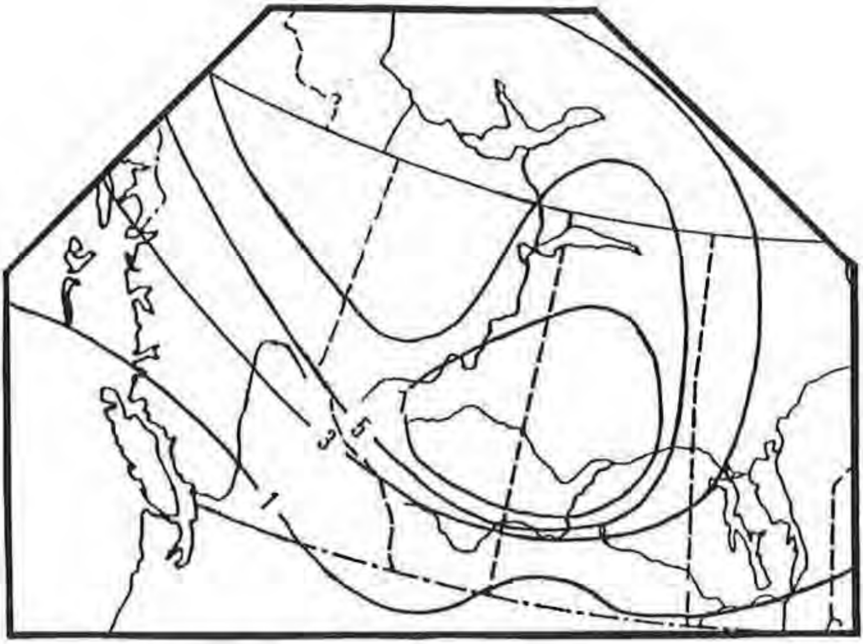

FIGURE 1. Map of western Canada showing lines of equal average seasonal incidence of noctilucent clouds. Data are derived from observations of the NLC CAN AM surveillance network over a five year period, from the years 1988–92.

Selection was made on the bases of completeness of reports, observing through all or most of the NLC season, and observations for at least two years during the five year period. Generally, activity over the five years was fairly consistent, with the exception of 1992, when incidence dropped markedly at several locations.

These data are incorporated into Figure 1, a map showing lines of equal average annual NLC incidence from 1988–1992. Activity appears to be highest over the central prairies between the latitudes of 52–57° N and the longitudes of 105–115° W. Here, NLC may be seen during as many as nearly ten nights per season. Both north and south of this zone, incidence decreases as explained previously. Variations within some individual provinces are great. For example, in southern Saskatchewan near the U.S. border, perhaps only one NLC display per year may be seen. Residing some 500 km north in the central part of the province allows this number to increase eightfold, but observing in the Lake Athabasca region, only fivefold.

Summertime weather appears to be another critical factor affecting incidence. Tropospheric climate may be the reason behind the decrease in sightings both east and west of the central prairies. Cloudier conditions both on the west coast and toward Hudson Bay, as illustrated, for example, by Yorke and Kendall (1972) may preclude observation of displays which would be visible otherwise. The cloudy conditions may hence be truncating the highest incidence zone into a rounded configuration rather than a more streamlined one spanning a greater portion of the 55th parallel. Actual longitudinal variations in NLC activity are possible, but in one study by Lohvinenko and Zalcik (1991), none were found.

From the data gathered by the NLC CAN AM network, it may be concluded that ground-based North American NLC research could perhaps best be conducted, in order to study the greatest number of noctilucent cloud displays per season, from locations within the central Canadian prairies.

The upper limit of actual NLC sightings may be in the high teens or low twenties. A search by a team of observers stationed at Grande Prairie, Alberta (lat. 55°) in 1965 yielded 19 active nights (Fogle, 1966). During a three-year study from 1957–59 one Soviet site at approximately 60°N and 35°E reported an average of 24 sightings per year (Bronshten and Grishin, 1976). Site choice, time spent checking the sky, degree of nocturnal clarity, and the ability to descry noctilucent clouds despite varying amounts of interference from tropospheric clouds probably all influence the number of NLC displays seen each season.

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Appendix 1. *NLC CAN AM participants during the years 1988–92.*

Amateur observers: Michael Boschat, Halifax, NS; Peter Brown, Sheila Callan, Helen Hawes, Robert Howell, Brian Tkachyk, Ft. McMurray, AB; Gaetan Chevalier, Ste.-Foy, PQ; David Dawson, Broad Brook, CT; Bob Fearn, West Vancouver, BC; Bob Fischer, Fairbanks, AK; Susan French, Scotia, NY; L. Geelan, Lucian Kemble, Cochrane, AB; Dale Johnson, Muskegon, MI; Frank Kosalla, Germany; Glen Ledrew, Cape Parry, NT; Alister Ling, Don Thacker, Mark Zalcik, Edmonton, AB; Todd and Stan Lohvinenko, Winnipeg, MB; Wayne Madea, Mapleton, ME; Cheryl Matsugi, Raymond, AB; Steve McKinnon, Oakville, ON; Adrienne Morris, Buffalo, NY; Dave Parkhurst, Anchorage, AK; John Rousom, Arva, ON; Art and Joan Seabury, Jr., Norris Point, NF; Chris Spratt, Victoria, BC; Ron Thompson, Wynyard, SK; Oscar Van Dongen, Vermilion, AB; Karren Webb, Freeport, MI.

Atmospheric Environment Service Stations: Alert, NT; Broadview, SK; Cambridge Bay, NY; Cape Parry, NT; Cape St. James, BC; Cree Lake, SK; Edson, AB; Estevan, SK; Ft. Reliance, NT; Gander, NF; Lethbridge, AB; Meadow Lake, SK; Moosonee, ON; Red Lake, ON; Pickle Lake, ON; Slave Lake, AB; Vancouver, BC; Wynyard, SK.

Transport Canada Flight Service Stations: Ft. Simpson, NT; La Ronge, SK; Peace River, AB; Schefferville, PQ; Sept-Iles, PQ; Sioux Lookout, ON; Swift Current, SK; The Pas, MB; Thompson, MB; Wabush, NF; Watson Lake, YT; Whitecourt, AB.

U.S. weather station: Fairbanks, AK.

The Thunderstorms of 8 July 1989 in the Northern Great Plains

Alexander H. Paul and *Dan E. Blair*
Department of Geography
University of Regina
Regina, Sask. S4S 0A2

Department of Geography
University of Winnipeg
Winnipeg, Man. R3B 2E9

SUMMARY

This paper analyzes in detail an outbreak of severe thunderstorms in southeastern Saskatchewan, southwestern Manitoba and North Dakota. Unexpectedly severe wind damage, extensive crop-hail losses and very rapid translatory motion characterized these storms. Data and information have been derived from official meteorological sources such as weather stations, cooperative observers and regular publications including the Monthly Record and Storm Data; and from unofficial sources such as local newspapers, crop-hail insurance records and private individuals. Multi-million-dollar damages were incurred even in this largely rural region, and the nature of the devastation at some localities was suggestive of tornado occurrences. Despite the advent of weather radar, an effective weather-watcher network throughout the study area, and an adequate job of forecasting on both sides of the Canada-U.S. border, many local residents were unaware of the significant threat which they faced. The paper concludes with some observations on the problems at the general public's end of the weather warning issuance-dissemination-receipt-protection sequence.

INTRODUCTION

Drought conditions in 1989 over the eastern Canadian prairies and North Dakota were eased in some localities by rainfall from scattered thunderstorms on July 7-8. The severe storms of July 8, however, also did a great deal of crop and property damage as they produced large hail and strong winds. Despite much-improved forecasting of severe thunderstorms in the region in the 1980s these storms still caught many people by surprise, and it is instructive to look at this particular outbreak in more detail.

Figure 1 shows aspects of five separate named severe thunderstorms in eastern Saskatchewan, western Manitoba and northern North Dakota on Saturday, 8 July 1989 plus several other short-lived cells. The map is based on a variety of official and unofficial information: AES and NOAA precipitation records; crop-hail insurance data from Manitoba Crop Insurance Corporation (MCIC), Co-operative Hail Insurance Company and Saskatchewan Municipal Hail Insurance Association (SMHIA); reports from NOAA co-

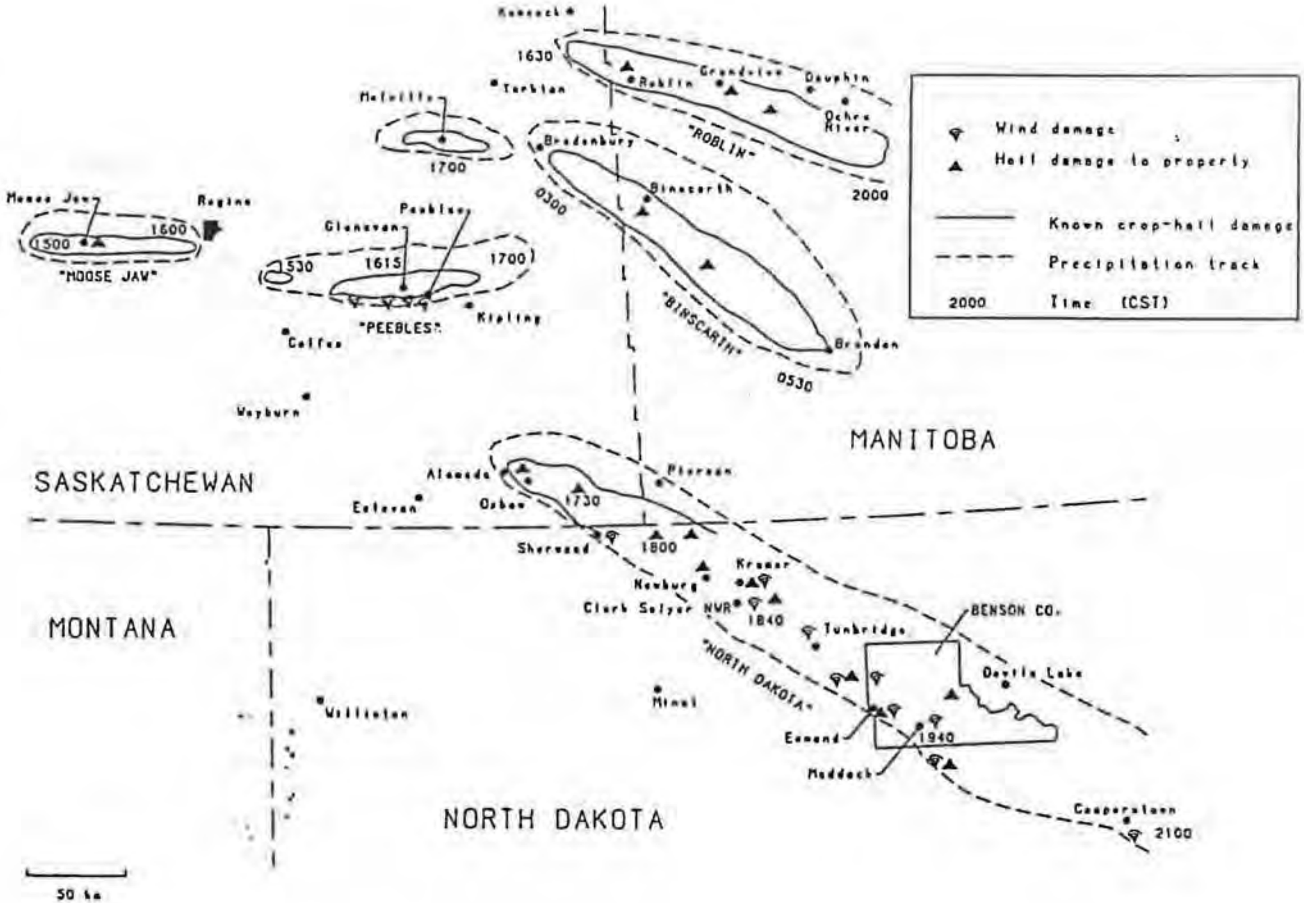

FIGURE 1 Principal Thunderstorms, 8 July 1989

operative observers in North Dakota; coverage in daily and weekly newspapers consulted at the Manitoba and Saskatchewan Provincial Archives; and other miscellaneous sources.

The storms produced costly wind and hail damages at some locations. Trailer homes were smashed in the Montmartre-Glenavon-Peebles area of Saskatchewan; MCIC paid out more than 2.6 million dollars for hail damage; according to NOAA's *Storm Data*, in North Dakota numerous buildings lost roofs, and millions of dollars of crop-hail damage was done. Fortunately there were only a few injuries and no fatalities. The troubling thing about the whole episode is that the storms were more than adequately forecast and yet many people still found themselves in dangerous situations. Perhaps this was because over much of the region conditions were sunny, warm and dry as they had been for much of the previous several weeks. The storms "seemed to come out of nowhere", as a woman from the Roblin area of Manitoba put it; she was caught outside in heavy hail and received "several hardball-sized bruises to show for it" (Roblin Review, 11 July 1989).

Unexpectedly severe wind damage, extensive crop-hail losses and very rapid translatory motion characterized these storms. Multi-million dollar damages were incurred even in this largely rural region, and the nature of the devastation at some places was suggestive of tornado occurrences.

THE INDIVIDUAL STORMS

Figure 1 shows the precipitation areas produced by the five principal storms of July 8. Comparison with Figure 2, the map of daily rainfall listed for July 8 at AES observing stations, is most instructive. The Moose Jaw storm is absolutely invisible on Figure 2, a point which illustrates the well-known problem of attempting to study thunderstorm precipitation from official records alone. The Binscarth storm occurred in the early morning hours of July 8, and thus it would show up only on the map of precipitation for the climatological day of July 7 (most co-operative observing stations take their daily reading of precipitation amount at 0800 local time).

The *Binscarth* storm appears to have originated around Bredenbury, Saskatchewan about 0300 CST and to have travelled southeast at 70-80 km/h at least as far as Brandon, Manitoba where the AES reported hail at 0530 CST. It produced walnut-sized hail southwest of Binscarth and in numerous other localities, and substantial crop losses on both sides of the provincial boundary, although no significant property damage appears to have resulted.

Ten hours later around 1500-1530 CST the *Moose Jaw* and *Peebles* storms broke out. The former hit Moose Jaw city and agricultural areas eastwards towards Regina with golfball-sized hail and heavy damage, but fortunately just missed CFB Moose Jaw where the annual air show was taking

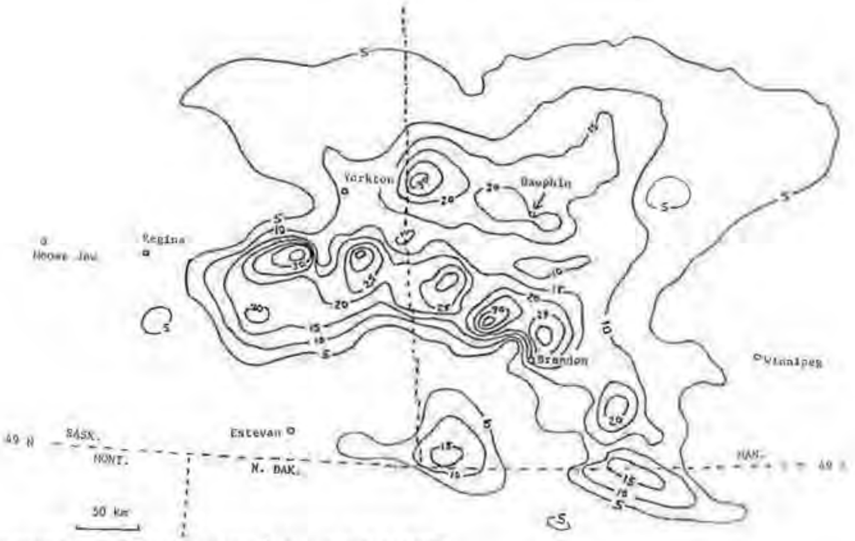

FIGURE 2 Daily Precipitation (mm), 8 July 1989

place. The Peebles storm did the most damage to property, with manyfarmsteads and the entire village of Peebles being "mangled", according to the Regina *Leader-Post*. Trailer homes were rolled and shattered but miraculously only a few minor injuries resulted. The word "twister" was mentioned by several eyewitnesses and there were two descriptions of a funnel cloud. The spatial distribution of the wind damage leads us to believe that the occurrence of three F1 or F2 tornadoes would be needed to explain the situation. In our view the occurrence of one F2 tornado plus downburst or "microburst" winds (Fujita 1981) is the most likely explanation. Both these storms moved almost due east at 80 km/h and both died out after only an hour or so.

About 1600-1630 CST, as the Moose Jaw and Peebles storms faded away, the *Roblin* storm (Figure 1) developed south of Kamsack, Saskatchewan. Most of its crop damage was done in Manitoba and it battered buildings and cars in Roblin with hailstones up to 4 cm across. It continued east-southeast at 70 km/h and disappeared southeast of Ochre River around 2000 CST. At about 1630-1700 some short-lived but intense cells produced crop-hail losses southeast of Regina and near Melville, and apparent downburst wind damage in and around the village of Colfax, Saskatchewan (Figure 1).

The final major storm of July 8, the *North Dakota* storm, was also the largest and longest-lived. It was more or less contemporary with the Roblin storm, tracking in the same direction at the same speed, but 240 km to the south. It developed in the vicinity of Alameda, Saskatchewan, laid a swath of damaging hail at least 20 km wide in the extreme southeast of the province and caught the

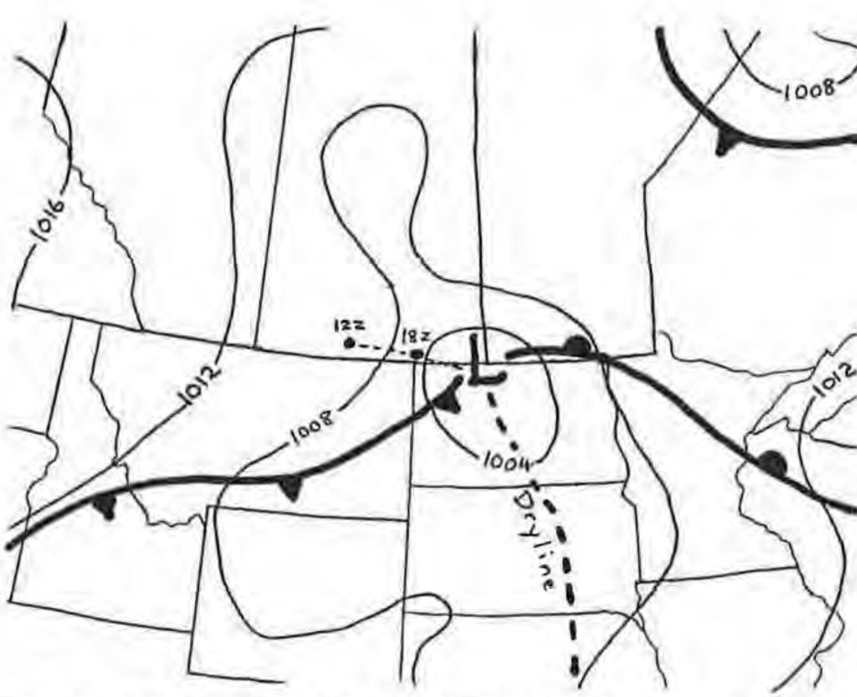

FIGURE 3 Surface weather analysis, 0000Z 9 July 1989 (18 CST 8 July) courtesy AES

very southwest corner of Manitoba from Pierson south. Wind damage along the southern edge of the hailswath in North Dakota was spectacular. *Storm Data* reported a tornado at Sherwood, North Dakota where the roof was ripped off a school gymnasium. NOAA co-operative observers reported many trees downed in the Clark Salyer National Wildlife Refuge and severe damage in the town of Maddock. Kramer, Esmond and Tunbridge had much wind damage to solidly built houses and 20,000 acres of crops were reported destroyed in Benson County. Hailstones 2.5 inches (6.3 cm) in diameter fell in Newburg and Kramer (Figure 1). The North Dakota storm persisted for at least 4 hours and had a path length of more than 300 km.

THE WEATHER SITUATION

At the synoptic scale, a weak surface low-pressure centre moved across southern Saskatchewan on July 8 (Figure 3). On the evening of July 7 and through the night, strong thunderstorms developed in the over-running warm moist air over southwestern Manitoba, with some just extending into southeastern Saskatchewan. Satellite imagery indicates at least one mesoscale convective complex (Maddox, 1980) with high-level cold anvil clouds coalescing for a distance of about 300 km over southwestern Manitoba in the early hours of July 8. A westsouthwest 500 mb flow with a core of maximum speed over western Montana curved anticyclonically to flow about due west to east over southeastern Saskatchewan at 0600 CST.

Surface winds during morning and afternoon of July 8 over the region were light to moderate southeasterly; thus thunderstorms would develop in a strongly sheared environment. Dewpoints were high in the eastern portion of the warm sector close to the warm front, hitting 18-19°C at many stations by noon local time (Regina had its highest dewpoint of the year, 20.4°C, at 1700 CST). Convective instability was present and some thunderstorms were experienced northeast of the warm front, for instance at Brandon and Dauphin during the morning. Severe weather watches and warnings were in effect in southwestern Manitoba at this time. Satellite imagery shows that conditions were essentially clear, however, over the regions that were affected later in the day. Even the photos for 1401 CST show virtually no convection in the warm sector of the surface low.

The 1431 CST satellite photo shows an isolated narrow band of towering cumulus aligned WSW-ENE, centered over Regina and about 100 km long and 10-15 km wide. The "cold cloud shield" (Maddox 1980) from this line of convection is clearly visible on the 1501 CST photo and the line has moved ESE. Between 1400 and 1500 CST at Regina the surface wind shifted from E19 to NNE30, dewpoint rose from 17.8°C to 18.8°C and dry-bulb temperature remained at 29°C. The beginnings of the Moose Jaw storm were now visible from the satellite along the southern edge of an area of broken clouds marking the cold front. On the 1531 CST photo the Moose Jaw storm is easily identifiable as a separate entity from the much larger cloud shield which has developed from the Peebles storm, but by 1601 CST it appeared to be merging with this cloud shield which now covered a larger portion of southeastern Saskatchewan. An extension towards the southeast of this cloud shield indicates that the North Dakota storm has now reached severe stage; on the 1701 CST photo a strong new cell was developing right along the 49th Parallel and the cloud shield over southeastern Saskatchewan and southwestern Manitoba has the dimensions of a mesoscale convective complex.

Within the warm sector there had been a marked dryline all through the day, and at 1800 CST the surface analysis suggests that the dryline met the centre of the surface low in the vicinity of the intersection of the Manitoba-Saskatchewan-N. Dakota borders. At this time the North Dakota storm was located right at this same position. The satellite photos suggest that the Peebles storm had also developed along this dryline; the precise origin of the Moose Jaw storm is more questionable.

A better meteorological understanding of storms of this type has emerged in recent years, but this case study of 8 July 1989 strongly suggests that such understanding is not being transmitted to the public. In Saskatchewan the local and regional newspapers almost all described the wind damage as being due to tornadoes. At Maddock, North Dakota, however, the damage was of the same intensity as at Sherwood where *Storm Data* reported a tornado. At Maddock a wind gauge hit 78-82 mph (130 km/h) but no one described the damage as being due to anything more than very strong winds. This observed windspeed of 130 km/h, with a speed of storm translation of 75 km/h, could be caused by a downburst producing an outflow at the surface of 55 km/h relative to the storm.

A photograph of the gust front of the North Dakota storm taken with a telephoto lens just prior to the storm's arrival at Maddock at about 1940 CST was provided to us by Mr. Fred Rehling, the local co-operative observer for NOAA. The gust front has given rise to a spectacular roll cloud where the warm air ahead of the storm is lifted above the outflowing downdraught. Although there is some indication of rotating motion in the roll cloud, this cloud appears to have a horizontal extent of several kilometres; at least at this stage of the storm's life there is no tornado funnel in the picture. Yet the storm "took two grain elevators [and] roofs off many homes, etc." in the town. It appears to be a microburst situation.

AES personnel on the prairies tend to be conservative in using the word "tornado" in post-storm damage evaluations where no very definite observations of funnel clouds touching ground were made. With the severe weather watch program and extended weather radar coverage in the 1980s, there is greater awareness by prairie meteorologists of the frequency of severe thunderstorm events and forecasters also have been rather more prepared to issue tornado watches since the Edmonton disaster of 31 July 1987. However, the problem of getting the message across to the public about damaging thunderstorm winds still remains. The storms of 8 July 1989 occurred during a severe thunderstorm watch but this watch was not upgraded to a tornado watch. The result seems to have been that the public was not aware of the threat which they faced on this date. One might speculate that the public feels that if tornadoes or severe wind damages are going to occur, then a tornado watch will always be issued. They do not realize that microbursts can be just as damaging as — and more widespread than — an F1 or even an F2 tornado. The usual terminology of "damaging wind gusts" and the "possibility of tornadoes" accompanying severe thunderstorms seems to be inadequate to convey to the public the real potential for injuries and even fatalities which these storms carry even when they do not generate true tornadoes.

There are certainly some misconceptions in many people's minds about damage potential from thunderstorm winds. An excellent example of this is furnished by the coverage in the *Weyburn Review* newspaper of the windstorms on 8 July 1989. The damage in and near Colfax was quite well reported, but the comment was then made that the "twister" was not experienced in the villages of Fillmore, Osage and Lang, 40 km, 30 km and 30 km respectively in various directions from Colfax. We are not blessed with clairvoyance but this does seem to us to suggest that if the reporter visualized a "twister" as being a small tornado, then he/she had little understanding of the characteristics of the dimensions and paths of tornadoes.

A further comment in this same newspaper article is very revealing. On 8 July 1989 there was some wind damage in the city of Weyburn itself. A large tree was uprooted, a sure indication of gusts exceeding 70 km/h, and shingles blown off a number of roofs. The reporter commented that winds at Weyburn that afternoon averaged only 40 km/h, a "mild breeze" compared to the winds at Peebles, but that this "mild breeze" had still been enough to dislodge shingles and uproot the large tree and some "shrubbery". The reporting seems to indicate a lack of awareness that (a) damaging winds in one part of the city may not affect the location of the weather station 1 or 2 km away; (b) reported average windspeeds say nothing of short-period maximum gusts that may have occurred; and (c) the average of 40 km/h is insufficient to explain the damage done.

In conclusion, we believe that despite all the excellent initiatives that have been taken by the AES in the forecasting and warning of severe thunderstorm weather in the prairie region, a communications problem with the general public still exists. This case study of 8 July 1989 indicates that while many people reacted very competently to the storm situation, there were many others in the region who were unaware that they faced a significant threat, who have little awareness of the nature of thunderstorm wind damages, and who are thus unable to interpret the true meaning of forecasts and watches even if they hear them. Whether the AES with its limited resources can do much more in this context is questionable. Perhaps the real need is for the provinces, municipalities and emergency-preparedness organizations to undertake at the local level a program of raising awareness of the thunderstorm wind hazard on the prairies.

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