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Foreword / Avant-Propos

This final number of 1990 contains four articles and notes, giving a total of twelve for Volume 24. The *Bulletin* has expanded substantially in this regard in the past few years, and it seems that interest in Canada in climate has never been higher. Please make known to myself or to CMOS your views about the direction the Society's publication efforts in the climate domain should take.

Ce dernier numéro de 1990 contient quatre articles et notes, dont il résulte un total de douze pour le volume 24. Le *Bulletin* a donc beaucoup agrandi les dernières années et il semble que l'intérêt des Canadiens pour le climat a bien augmenté. On aimerait que les abonnés expriment leurs opinions de la route que la Société devrait suivre concernant la publication dans le domaine du climat, en écrivant au rédacteur du *Bulletin* ou à la SCMO elle-même.

Alec Paul
Editor/Rédacteur en chef

Relationships Between Weather and Road Safety: Past and Future Research Directions

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and
Richard Olley[2]
[Original manuscript received 5 January 1990;
in revised form 26 June 1990]

ABSTRACT

This paper provides a state-of-the-art critique of research on relationships between weather and road safety. Available literature is summarized in two parts. In the first, a systems perspective is adopted, while the second is based on observational accident data. It was concluded that neither body of literature is able to answer basic questions about the magnitude and nature of accident risk for different weather scenarios. A direction for future research based on observational data is outlined. In particular, the advantages of using AES principal station data to assess accident risk during inclement versus normal weather are presented, and the appropriateness of these data is examined, based on a case study of Edmonton, Alberta.

RÉSUMÉ

Cet article est une critique des effets des conditions atmosphériques sur la sécurité routière. Nous résumons la littérature en deux parties. Il y a d'abord la perspective de système, et en deuxième lieu, les études analysant des données des accidents routiers et du temps. En conclusion, ni la littérature de l'approche systématique ni celle qui traite des cas spécifiques n'explique vraiment le niveau de risque d'accidents routiers reliés aux conditions atmosphériques. Nous suggérons donc de nouvelles idées en vue d'améliorer les recherches dans ce domaine, y compris l'utilisation des données des stations principales du SEA par rapport aux données policières des accidents. À cet effet nous examinons les résultats d'une étude sur le cas d'Edmonton en Alberta.

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1. INTRODUCTION

Applied climatology has developed rapidly in recent years, spurred on by the climatic anomalies of recent decades, the prospect of future climatic change, and the ensuing development of both world and national climate programs. The state of the art is summarized in such publications as the SCOPE report entitled "Climate impact assessment" (Kates, Ausubel and Berberian, 1985), and the more recent volumes by Riebsame (1988) and Maunder (1989). In reading this material, it becomes apparent that much scholarly research has been directed at establishing statistical associations between weather and a variety of impact sectors, especially agriculture, energy and water resources. In several impact sectors, however, our understanding is still in its infancy, in part because of poor data availability. The issue is most critical when the impact being investigated is sensitive to the instantaneous weather condition at a particular location and as such cannot be accurately measured by regional averages. One such impact sector is surface transportation, and more particularly road safety.

It is axiomatic that weather affects road safety; the conventional wisdom of both the professional safety community and the public at large suggests an increased accident risk associated with adverse weather, especially precipitation. Huge public expenditures on road design and surfacing, as well as on snow control, are incurred on this premise. However, little empirical information exists to provide details on the overall magnitude and minimum thresholds of elevated risk, the impacts of different storm types and intensities, and also how different driver groups and situations are affected. Such information is critical if we are to understand the nature of climate impacts on road safety, and particularly to priorize funding for accident countermeasure programs.

The purpose of this paper is twofold. First, a critical review of past research on relationships between weather and road safety is provided, including data requirements for undertaking such studies. Secondly, an empirical investigation of the usefulness of national weather service data for studying these relationships is made, based on data for Edmonton, Alberta.

2. REVIEW OF RESEARCH ON RELATIONSHIPS BETWEEN WEATHER AND ROAD SAFETY

Two approaches may be taken in studying relationships between weather and road safety. The first employs a systems perspective, where the goal is to identify and quantify changes in the highway transportation system as they occur in response to different weather scenarios, in order to predict the effect of weather on accident rates. The second approach is to depend on observational accident data and to document changes in accident rates as they vary with weather. In the first instance the emphasis is on process, but the problem is very complex conceptually and the data requirements are great. In the second, the highway transportation system is treated more as a black box. The emphasis is on accurately documenting average or aggregate impact for different weather scenarios.

The systems perspective

Road accidents result from the interplay of behavioural, technological and environmental factors. A systems perspective aims to identify the interactions in a dynamic setting among the various system components, principally the driver, the vehicle and the driving environment, which includes both the road and the broader natural and cultural setting in which driving occurs. These components are linked together by informational and mechanical interactions; the control strategists of the systems are the many drivers who, in working toward their goal of mobility, make a multitude of instantaneous driving decisions. One disutility of the system's operation is accidents. An understanding of the relationships between weather and accidents, in a systems context, requires that all weather-induced changes in the system be established and that the information be synthesized in order to predict accident rates.

The most significant changes in the operating system brought about by weather are thought to be the physical changes in road surfaces that result from precipitation. When precipitation occurs, the road surface becomes either wet or icy/snowy, with resultant changes in surface friction. Considerable experimental research on the changes brought about in tire-pavement friction by precipitation has been conducted over a span of more than two decades by the highway engineering community, especially the U.K. Transport and Road Research Laboratory, the Texas Transportation Institute, and to a lesser extent the Midwest Research Institute in Missouri, Kentucky's Department of Transportation, and the Goodyear Tire and Rubber Company. Much of the research is summarized in the Proceedings of the 2nd International Skid Prevention Conference (1977) held in Ohio. What follows is a brief summary of research results.

Most research has focussed on wet road conditions that result from rainfall. The two critical aspects of wetness are the length of time that the road is wet and the depth of water on the road surface at any given time. Until recently, the duration of rainfall was used as a proxy for wet road exposure time. However, since a period of drying following a rainstorm is necessary before road conditions return to normal, this practice significantly underestimated wet time exposure. Recently, a simple and relatively accurate method for determining the length of time when roads are wet during and following a rainfall event has been developed by Harwood *et al.* (1988), based on rainfall intensity and duration, and other meteorological variables that affect drying time. Regression-type equations are also available to estimate the depth of water on road surfaces during precipitation, based on rainfall intensity, road geometrics and road surface texture (*e.g.* Dunlap *et al.*, 1976).

Information on road wetness has in turn been related to road surface friction. Although many factors affect friction, including pavement texture, travel speed, tire tread and pressure, and ambient temperature, it is generally accepted that wet road friction is always less than that for the least skid-resistant dry road surface. Equations relating wetness/water depth and road surface friction have been established for specific road conditions in numerous studies. A more comprehensive attempt by Rose and Galloway (1977) to model road surface friction for a wide range of conditions as a function of water depths, surface textures, vehicular speeds, and tire pressures, types, and tread depths also produced impressive fit, with r-squared values of greater than 0.9. Therefore, if detailed information on the storm, road, vehicle and traffic conditions is available, it is theoretically possible to predict the effect of rainfall on road surface friction with a fair degree of accuracy. This in turn can be translated into information on stopping distances, vehicle handling and the potential for hydroplaning.

However, the next step in this logical sequence is to translate reductions in surface friction into accident risk, a much more difficult task and outside the controlled experimental setting. Several quantitative studies of this type (*e.g.* Rizenbergs *et al.*, 1976 and 1977; Proceedings of the 2nd International Skid Prevention Conference (1977); Ivey *et al.*, 1981) have achieved some success. There is consensus for an inverse statistically significant relationship between wet weather accident incidence and friction. However, the correlations show a large degree of scatter, and a recent state-of-the-art report concludes that to ". . . assume that traffic accidents, or a given subset of traffic accidents (*e.g.* accidents that result from inadequate surface friction), can be accurately predicted on the basis of one condition (such as skid number) is wishful thinking." (Herman, 1984: 41).

One reason why predicting wet weather accidents for small spatial and temporal units is so difficult lies in the large random component in accident occurrence. Of perhaps greater importance, however, is that other parts of the highway transportation system, especially in the human domain, are also affected by changes in weather. Driver visibility is affected by atmospheric conditions and it is probable also that most drivers consider weather in their decision making. Some trips are cancelled or rerouted, and driver attentiveness and control behaviour are altered as a function of weather. However, empirical information in these areas is very limited.

Research on driver visibility during rainfall has been reported in four studies (Ivey *et al.*, 1975; OECD, 1976; Morris *et al.*, 1977; Bhise *et al.*, 1981), but the combined number of observations is much too small for predictive purposes. Preliminary results indicate that driver visibility decreases with increased rainfall intensity, due mainly to the film of water on the windshield rather than to the reduction in meteorological visibility, and is accentuated by low ambient illuminance, slow wiper speed, and splash and spray from other vehicles. However, a comprehensive model to predict driver visibility under various weather scenarios is still a long way off, and there is no logical way in which this information might be translated into accident risk.

Information on driver decision-making is even more sparse. Traffic volumes in inclement weather are marginally decreased (Codling, 1974; Mende, 1982) and travel speeds are less (McBride, 1978; Jeffery and White, 1981; Yagar *et al.*, 1982). But the information is not very extensive, and there are many other possible driving adjustments which have not been systematically studied (Hanscom, 1977).

In summary, literally hundreds of studies have examined the tire-pavement interaction, such that our knowledge of the effects of rainfall on surface friction is very good. Much less is known about snowfall and very little is known about driver adjustments to either rain or snow conditions. We are therefore at a loss to predict the overall effect of inclement weather on accident rates from a systems perspective.

Observational data

An alternative means of determining the impact of adverse weather on road safety is through the direct analysis of accident data, which have been assembled at a variety of temporal and spatial scales, as depicted in Table 1. However, much of this observational information is not suitable for systematically assessing the contribution of weather to accident risk because there is no control built into the analytic framework. More particularly, data which are either site specific (top row in Table 1) or pertain to large geographic areas (bottom row in Table 1) tend to be of this nature. For example, extensive information on fatal accidents is usually collected by government-sponsored accident investigation personnel. These detailed investigations provide insight into the circumstances of an accident, including the potential contribution of weather, but the conclusions are accident specific. Additional analyses at the site level, but over longer periods of time, are provided in studies of accident-prone locations. Again the role of weather in accidents is considered, even to the point where a high incidence of skidding accidents may prompt road resurfacing. However, the information is not conducive to answering the question, "What is the relative risk of an accident occurring at this location during precipitation relative to dry conditions?".

At a larger spatial scale, the safety consequences of extreme storms are of interest. Such events usually receive coverage in major newspapers, and some have been investigated more thoroughly under the umbrella of natural hazards studies (Rooney, 1967; de Freitas, 1975). However, the results of this work tend not to be applicable to more routine weather. A fourth example is provided in provincial/national road safety reports, where the various circumstances of accidents are summarized; the message that is typically relayed is that the vast majority of accidents occur under good weather conditions. Again,

TABLE 1. Spatial-Temporal Scales for Examining Weather-Safety Relationships

	Hourly or Daily Comparisons	Monthly or Seasonal Comparisons
Individual Site	Detailed investigations of individual accidents	Analysis of accident-prone locations
City or Highway	Estimates of relative accident risk during inclement weather made	
Region	Extreme storms examined	General summary of accident characteristics

what is missing is the ability to address the question of relative risk during good versus inclement weather. In all cases, the missing ingredient is a measure of exposure, either in terms of time or travel, to act as the denominator in risk calculations. Empirical studies that explicitly incorporate an exposure measure into their analysis of accident risk are limited. They tend to focus on precipitation exclusively, and not all have been published. Those that have reached publication/ public review stage are of three genres.

The first examines the effect of different weather variables on accident rates, using multivariate statistical techniques such as regression analysis or factor analysis. Few such studies have been carried out and those which have been published have either had poor predictive capability (*e.g.* Jovanis and Delleur, 1983) or have been deficient in research design. For example, Orne and Yang (1972) conducted a stepwise linear regression analysis to predict accident rates as a function of weather, but ignored critical issues such as the assumption of normally distributed data and multicollinearity, and Roer (1974) performed factor analysis of 39 variables, in order to attribute causation between two subsets of variables.

A second and much more simplistic approach has been to examine temporally aggregated data for a given city or region. Comparisons are made of the proportion of accidents that occurred on wet roads/during precipitation with the proportion of time that the said road or weather condition prevailed at that location (*e.g.* Campbell, 1971; Clissold, 1977; Mather, Gossette and Mack, 1983). This type of assessment is fairly crude as there is no consideration of any temporal patterning in precipitation occurrence, but it does provide a first estimate of the contribution of weather to road accident risk.

The third approach, and the most successful in estimating the average effect of weather on accident rates, compares accident frequency on wet versus dry days. An ambitious literature review has turned up only eight such studies, which are summarized in Table 2. Six focussed exclusively on rainfall, by choice of either setting or season, and all were based in either North America or Britain. While there is some inter-referencing among the various studies, this is generally to acknowledge the existence of earlier work in this area, especially by Codling (1974), rather than to provide critical comment or comparison. In terms of methodology and results, however, there are several important observations to be made.

First, although all eight studies approach the problem in the same general way, varying degrees of control are built into the analytic framework (Table 2). The best framework is the matched-pair approach, as used in Codling's (1974) seminal work and in modified form by Sherretz and Farhar (1978), Bertness (1980) and Smith (1982). Under this quasi-experimental framework, each occurrence of precipitation is matched with a control time period and the data for the matched pairs are aggregated in order to determine relative risk; the convention is to choose the control as the day exactly one week prior to or following the precipitation. The advantage of this framework is that many variables which have nothing to do with the weather, but which do affect accident

TABLE 2. Empirical Research on Relationships Between Precipitation and Road Safety

Analytic Framework	Reference	Setting of Study	Sample Size Number of wet time periods	accidents	Average Increase in Accident Rate Associated With Precipitation
Comparison of accident frequency for all wet versus all dry periods	Haghigh-Talab, 1973	London, England	239	23,950	30%
	Jovanis & Delleur 1983	Indiana Tollway, U.S.A.	175	600	70%
Comparison of accident frequency for wet versus dry periods, controlling for day of week and/or season	Satterthwaite, 1976	California State Hwys, U.S.A.	72	120,000	30%
	Mende, 1982	Toronto, Canada	11	5,033	70%
Comparison of matched pairs of wet and dry periods	Codling, 1974	4 locations in England		1,258	50%[a]
	Sherretz & Farhar, 1978	St. Louis area, U.S.A.	334	957	100%
	Bertness, 1980	Chicago area U.S.A.	315	3,190	130%
	Smith, 1982	Glasgow, Scotland	202	3,615	20%[a]

[a] for injury accidents only.

frequency, are controlled rather effectively, whether their specifics are known or not. For example, if one compares accident data for the same city on two consecutive Tuesday afternoons in June, with rainfall on one but not on the other, it is reasonable to assume that the road infrastructure would be unchanged and also that the traffic characteristics would be similar, apart from any changes induced by the presence of precipitation itself.

Second, the criteria used to define precipitation-control periods vary considerably. Most studies used weather station data and defined precipitation and control periods based on the presence or absence of a minimum accumulation of precipitation over a specified time period; however, the number of nearby weather stations for which data were available ranged from one (*e.g.* Mende, 1982; Smith, 1982) to more than 300 (Bertness, 1980). Thus the spatial applicability of the weather data may be in question in some instances. As for the temporal units of analysis, in most cases the wet-dry comparisons were for 24-hour periods. As such, days on which a brief shower occurred were treated the same as days on which heavy, steady rainfall was observed. This problem of temporal averaging could be dealt with by defining precipitation events of variable length on the basis of hourly weather information, but this would be a time consuming exercise.

Third, the sample size in most of the controlled studies was modest and in some cases was not representative of all storm types (*e.g.* Mende, 1982); furthermore, statistical analysis was typically limited to a test for significant difference between precipitation and control conditions. Instead, what is needed is a reliable estimate of *how much greater* accident risk is during a given weather condition. If one were to estimate a relative risk ratio for any given weather type to within $\pm$ 0.1 at the 95% confidence level, a random sample of event-control pairs during which time several thousand accidents occurred would be necessary. Past studies, for the most part, do not meet these criteria.

Fourth, estimates of the effect of precipitation on accident rates vary widely (Table 2). With such a diverse range of methodologies and settings, it is difficult to compare these results and impossible to extrapolate the findings to other areas.

Future research

We are thus left in a position where neither the systems thinking nor past research based on observational accident data is able to address basic questions about the relationship between weather and road traffic safety. Yet rich government data bases on both weather and traffic accidents exist for most locations throughout the developed world. The time is right for improved empirical research in this area.

What is needed is a series of studies in a variety of regional and climatic settings. Each should include a large random sample of weather events for which a suitable control period can be defined. Ideally, traffic volume information from automatic counters would also be available so that risk ratios per unit of time could be translated into relative accident risk per unit of travel. The events should be defined by the beginning and ending time of the particular weather condition under investigation, to avoid unnecessary temporal averaging. Although most police records of accidents include some information on the weather at the scene, it would be difficult to use this information to define the timing and characteristics of weather events. By necessity, therefore, independent weather data must be included in the analysis. The most readily available sources are the national grids of weather observation stations. In Canada, the Atmospheric Environment Service (AES) assembles data for some 2700 sites, including more than 100 principal stations where hourly observations of selected variables are taken year-round. One question, however, that remains to be answered before embarking on this research relates to the applicability of weather station data to the weather condition at the scene of accidents.

This is a significant question; although most urban areas have an observation station nearby, the overall density of principal stations in Canada is very low. As well, precipitation, which is the condition to which accidents are thought to be most sensitive, is well documented as displaying a high degree of spatial variability, even over small areas. The World Meteorological Organization (WMO) published a number of reports relating to this question (*e.g.* Alexander, 1969; Gandin, 1970; Kagan, 1972; Rodda, 1972; WMO, 1972, but it needs further consideration in the context of the type of study outlined here. Thus the next section of this paper investigates the appropriateness of federal weather station data for assessing relationships between weather and traffic safety, by examining data for one Canadian city.

3. USING ATMOSPHERIC ENVIRONMENT SERVICE DATA TO ASSESS ACCIDENT RISK IN EDMONTON

The case study is based on data for Edmonton, Alberta for the year 1983. Edmonton offers an ideal opportunity. First, there are three principal weather stations located in the Edmonton area – one in the city proper and two outside but within close proximity of the city. Second, accident reports for the city include information on both the weather and the exact accident location. Third, this area derives a significant portion of its summer rainfall total from convective showers, which by nature are more localized than other rainfalls. Therefore, the data are conducive to answering several questions. Is the weather condition observed at a single station reasonably representative of the weather conditions across an entire city? Is there a strong distance decay effect? Can weather data from stations outside the city be used to estimate accident risk during inclement weather?

Edmonton is a city of approximately 575,000 people, covering an area of 320 square kilometres. Precipitation receipt is modest, although on average there are more than 120 days with measurable precipitation each year, of which nearly half involve snowfall (Canada AES, 1982). For 1983, the weather was warmer than normal, with mean daily January and July temperatures of −8.5 and 17.9°C respectively, as compared to the normals of −15.0 and 17.4°C. Annual precipitation totalled 430 mm, nearly 10% below normal. This was due primarily to lower snowfall than normal in both January and December (Alberta Environment, 1983).

Weather data were obtained for the three principal observation stations operated by AES, Edmonton Municipal Airport, located in the north-central part of the city, as well as Edmonton International Airport and Edmonton Namao Canadian Forces Airport, approximately 25 km south and 15 km north of the city centre respectively. Accident data are from the collision information system, compiled and administered by Alberta Transportation and based on police reports of accidents. In 1983 there were 21,835 accidents reported for the city, involving either death, injury or property damage exceeding $350.

Two separate analyses were performed. The first documented whether or not the same general weather condition was reported at the accident scene as was observed at the three airport weather stations. The second involved calculating the relative accident risk during precipitation, using data from the three different weather stations as separate starting points.

Comparisons of weather data

The first objective was to compare the weather condition identified at each accident scene with that observed at approximately the same time at the nearby airports. The comparison was made for a 10% systematic random sample of 2100 accidents, extracted from the 1983 accident data base. The sample provided relatively uniform temporal coverage throughout the year and broad spatial coverage across the city.

For each accident the weather condition recorded by the investigating police officer was compared with the weather that was observed at all three airport locations. On the accident report, the weather is indicated as having been one of the following: clear, cloudy, raining, snowing, sleet/hail/freezing rain, strong wind, dust, fog/smog/smoke, other as specified, or unknown (Alberta Transportation, 1980). For the AES data, observations were made by trained technicians at hour endings and the presence or absence of 21 specific weather elements was recorded, including 14 forms of precipitation and 7 obstructions to visibility. The comparison made here was for precipitation; the presence or absence of precipitation was noted for the accident scene and also for all three airport locations, based on observations for the two hour-endings surrounding the time of the accident. The airport data were considered to be in agreement with the accident report when either (i) both hourly observations at the airport indicated the absence of precipitation and the same was noted on the accident report, or (ii) either hourly observation at the airport indicated the presence of precipitation and the same was noted on the accident report.

In total, the weather condition observed at the accident scene was in agreement with that observed at each of the three nearby airports in 83–84 per cent of all cases, with no significant differences among the three (Table 3). This suggests that in most cases the weather information provided by accident reports is replicated by weather station data, whether the station is central to the study area or located some kilometres away.

As a second step, the accident locations were mapped in order to determine if there was any distance decay effect in the agreement with the weather station data. The individual locations of the 2100 accidents were first identified on a large-scale city map and then aggregated into thirty-four 6 km^2 grid cells covering the developed area of the city. The mean distance of each cell from each of the weather stations was calculated and the per cent agreement in weather information between the accident reports and the weather station reports was recorded for each cell and each weather station. Then correlation analysis was performed. The results provide no evidence of a distance decay effect as far as agreement is concerned (Table 3), which further suggests that weather data from any of the three nearby airports provide a reasonable indication of the presence or absence of precipitation anywhere in the city of Edmonton. Improved accuracy could be introduced by screening out storm types that display high spatial variability.

Relative accident risk during precipitation

As a complement to the above, the relative suitability of data from each of the three AES stations for documenting accident risk during inclement weather was

TABLE 3. Summary Statistics for the Edmonton Case Study

(a) Comparisons of Weather Data for Accident Reports versus Weather Station Reports

Weather Station	Agreement %	Relationship Between Distance and Per Cent Agreement (R values)
Edmonton Municipal Airport	84	−.146*
Edmonton Namao Airport	84	−.112*
Edmonton International Airport	83	+.195*

* not significant at .05

(b) Accident Risk During Precipitation as Calculated for Three Weather Stations

Weather Station	Total Number of Accidents During Events	During Controls	Relative Risk Ratios (95% confidence intervals)
Edmonton Municipal Airport	1293	823	1.6 (± .3)
Edmonton Namao Airport	1289	818	1.6 (± .3)
Edmonton International Airport	1150	728	1.6 (± .3)

examined. If the timing and intensity of precipitation are highly variable over small geographic areas, one would be intuitively most comfortable using data from the Edmonton Municipal Airport to define precipitation events, since it is fairly central in the study area. The approach taken was to estimate the risk of accident during precipitation relative to control conditions, using data from each of the three weather stations as separate starting points. The specific procedures used in deriving the matched-pairs sample are outlined below.

1. Precipitation totals were used to mark the starting and ending times of precipitation events. For rainfall, hourly totals were used. A rain event was defined as two or more hours of measurable (> .2 mm) rainfall. For snowfall and conditions of mixed rain and snow, precipitation totals were available as 6-hour totals and these were used to define snow events.
2. For each precipitation event defined, a control was sought. A control was defined as a period of time which coincided with the clock time of the precipitation event, which occurred exactly one week prior to or following the event, and for which no measurable precipitation was observed during the control and for six hours prior to the control. The latter provision ensured that the effects of any previous rainfall were minimal – only 2% of all accidents during summer control periods occurred on wet roads. The residual effect of snowfall was much greater. Approximately 40% of accidents during winter control periods occurred on wet/icy/snowy roads, but given that some residential streets are very infrequently cleared in winter, it is reasonable to suggest that normal winter driving in Edmonton

includes some roads which are not dry. All control periods were further screened to ensure that there was no evidence of severe wind or obstructions to visibility. Those events for which a suitable control could not be defined were deleted from the sample.

3. One additional check was made on all the paired events and controls in order to delete holidays from the sample. This measure was deemed necessary because of the change in traffic and accident patterns associated with holidays.

Note that, in contrast to the convention in past studies, precipitation events here are of variable length so that they coincide with the beginning and ending times of precipitation. This is an improvement in that it removes much of the temporal averaging incurred in using daily aggregated data.

Although not identical in timing and number, some 60 event-control pairs were defined for each of the three weather stations. The total numbers of accidents observed during the events and controls, along with the relative risk ratios, are presented in Table 3. Differences in absolute numbers reflect differences in the number and timing of the event-control pairs; approximately 10% fewer accidents were included in the sample set as defined by weather conditions at Edmonton International Airport, mainly because control periods could not be defined for a few of the extended rainfall events that occurred in June and were included in the other two sample sets. Interestingly, the risk ratios are virtually identical in all three cases, suggesting that weather data from either of two rural airports provide the same information about accident risk in the city as weather data from the Municipal Airport, which is located only 3 km from downtown.

4. CONCLUSIONS

Literature on weather and road safety may be divided into two schools. One documents specific changes in the road transportation system that occur in response to weather. In particular, much rigorous experimental research has been devoted to modelling the tire-pavement interface under wet conditions. However, comparatively much less is known about snowfall conditions and little is known about driver adjustments. As a result, this research has not been conducive to predicting accident rates for different weather scenarios. A second approach has been to use observational data as a means of estimating the effect of inclement weather, especially precipitation, on accident rates. A modest amount of empirical work has been conducted in this vein, but many of the studies have been either deficient in design or based on small and sometimes unrepresentative samples. The results typically indicate that precipitation is associated with a significant increase in traffic accidents, but point estimates vary widely from study to study. It is difficult to generalize from these results because of the diverse methodologies and settings on which the results are based.

An immediate opportunity exists to improve our knowledge in this area by marrying the information contained in accident files with that collected at federal weather stations. One methodological issue that must be resolved first, however, pertains to the use of data from a single such station to represent the weather condition at the scenes of accidents. The second part of this paper addressed this issue by examining empirical data for Edmonton, Alberta for the year 1983. Results indicate that in close to 85% of accidents the general weather condition observed at the scene was the same as that observed at each of three nearby weather stations. Furthermore, there was no evidence in this study of a distance decay effect in this agreement. In addition, the conclusions about the relative risk of accident during precipitation are the same, regardless of whether data from the centrally located Municipal Airport or either of two rural airports are used. Therefore, it should be possible in many instances to use weather data from a single federal climate station to approximate the weather condition for larger geographic areas, such as cities or highway segments, for the purposes of measuring the impacts of weather on road safety. As such, there is tremendous potential to use existing data to assess relationships between weather and traffic safety for a variety of settings, and to use this information as a basis for projecting the impact of possible future climatic change on road safety in Canada.

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Étude du phénomène des vagues de froid au Québec en tant que catastrophe naturelle

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RÉSUMÉ

Le présent article analyse le phénomène des vagues de froid au Québec méridional. Nos analyses statistiques et géographiques sont basées sur une double approche impliquant en premier lieu la température en utilisant un seuil de −30°C (appelées vagues de froid) et en deuxième lieu le facteur de refroidissement éolien en utilisant les valeurs de 1 900 W/m^2 (appelées vagues de froid éolien) et 2 300 W/m^2 (appelées vagues de froid intense). Nos analyses portent sur des occurrences horaires consécutives de 6, 12, 18 et 24 heures. Les résultats montrent que les vagues de froid sont rares avec une aux 30 ans, alors que la fréquence des vagues de froid associées au vent est plus élevée avec une à tous les 6 ou 7 ans. Certaines régions semblent plus affectées par cet aléa climatique comme la zone située dans le triangle entre Sept-Iles, Mont-Joli et Roberval, et qui inclut aussi Baie-Comeau et Bagotville.

ABSTRACT

This article documents the cold wave phenomenon in southern Quebec. Our statistical and geographical studies utilize a double approach to best describe this climatic hazard. The first method uses a threshold value of −30°C to identify temperature-based cold waves while the second uses values of both 1,900 and 2,300 W/m^2 for the wind-chill factor to define cold waves associated with wind. Consecutive hourly occurrences of 6, 12, 18 and 24 hours duration are considered. Our results indicate that temperature-based cold waves are rare with one in 30 years. On the other hand, cold waves associated with wind occur once in 6 or 7 years. Some areas are more prone to frequent cold waves of this sort as for example the Baie-Comeau/Sept-Iles, Mont-Joli and Roberval/Bagotville areas.

INTRODUCTION

Les vagues de temps froids hivernaux représentent, et de loin, les pires aléas du temps dans le sud du Québec. Dans le but de déterminer quelles sont l'ampleur et la fréquence de ce phénomène, en rapport avec l'homme et ses diverses activités, nous avons procédé à l'étude des vagues de froid hivernales en tant que catastrophe naturelle. Cet article constitue la première partie de nos résultats. Nous avons choisi de séparer la description et l'analyse du phénomène de ses impacts sur l'homme et de l'examen des plans de mesures d'urgence. Un deuxième article examinera ces derniers points.

DÉFINITIONS DES SEUILS DE FROID

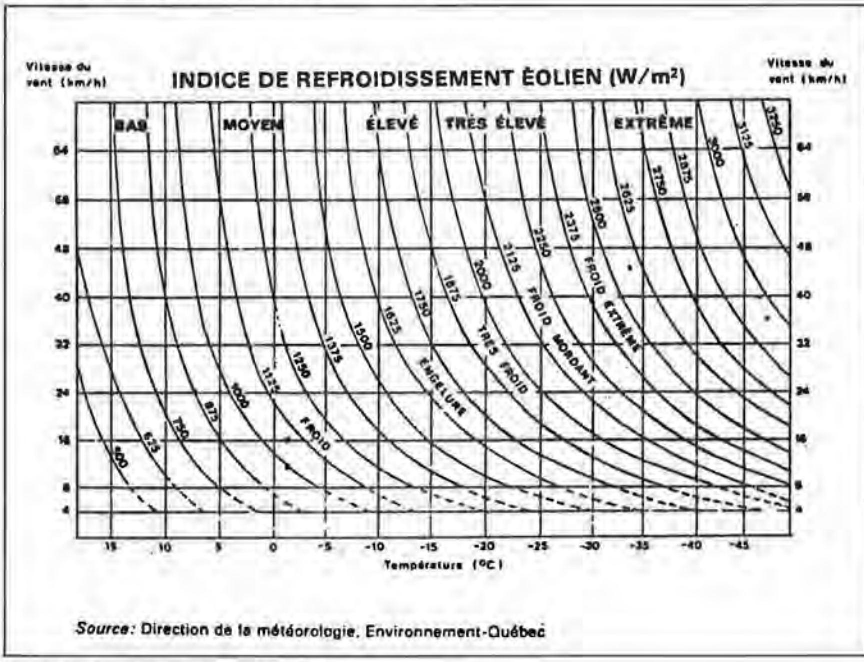
Selon Villeneuve (1974), une vague de froid est un fort refroidissement de l'air ou invasion d'air très froid, qui s'étend sur un vaste territoire. Le Service de l'Environnement Atmosphérique d'Environnement Canada (SD,a) considère, dans ses avertissements météorologiques qu'il y a *froid intense* lorsque l'action combinée du vent et de la température occasionne un facteur de refroidissement éolien supérieur à 2 000 W/m^2 soutenu durant au moins 12 heures. On retient également les conditions de *froid extrême* produit par l'effet combiné du vent et de la température qui occasionne un facteur de refroidissement éolien de 2 375 W/m^2 et plus, soutenu pendant au moins 6 heures.

Pour Ottawa, Crowe (1984) et pour Montréal, le Service de l'Environnement Atmosphérique (1987) s'attardent aux vagues hivernales de temps froid en utilisant la température minimale atteinte en 24 heures. Deux seuils sont utilisés dans l'étude du climat de Montréal, soit −25°C et −20°C alors que la valeur de −15°C est considérée dans celle du climat d'Ottawa. On s'intéresse à la température minimale atteinte mais aussi à la durée en jours pendant laquelle le thermomètre s'est maintenu en-dessous d'un seuil choisi.

Il peut s'avérer hasardeux, sur une région aussi vaste que le Québec, de déterminer un seuil où l'on peut parler de "vague de froid". La notion de froid est relative pour les diverses populations de la province d'où la difficulté d'appliquer un seuil fixe de température minimale en-dessous duquel on considère qu'une vague de froid a effectivement lieu. Considérant que les températures minimales moyennes au sud de la province sont de l'ordre de −10,0 à −15,0°C et, vers le nord, de l'ordre de −20,0 à −25,0°C (Proulx *et al.*, 1987), la valeur de −30°C nous a semblé appropriée comme seuil critique.

Une meilleure façon de définir le facteur froid est le calcul bien connu de l'indice de refroidissement éolien. La figure 1 donne les courbes de calcul de cet indice, ainsi que des remarques sur les différents niveaux prévisibles. A partir de ces courbes, calculées par le Service de l'Environnement Atmosphérique d'Environnement Canada (SD, b), il a été déterminé que les seuils critiques à retenir pour la santé humaine sont de 1 900 et 2 300 W/m^2. A titre indicatif, mentionnons que la peau exposée commence à geler lorsque le taux atteint une valeur égale à 1 625 W/m^2 et qu'elle gèle en moins d'une minute à 2 300 W/m^2.

FIGURE 1. Abaque de l'indice de refroidissement éolien.



tiré de Leduc & Gervais (1985, p.219)

DESCRIPTION SYNOPTIQUE

La présence de vagues de temps froid dans le sud du Québec s'explique, selon Hare et Thomas (1974) et Blair et Fite (1965) de deux façons différentes, selon leur durée. Ainsi, les vagues de froid de courte durée résultent de tourbillons anticycloniques superficiels d'air froid Arctique, qui se déplacent vers le sud-est à partir du nord-ouest canadien. Ces zones de hautes pressions amènent un temps clair et un froid rigoureux associé, dans l'est du Canada et au Québec, à des conditions venteuses. Dans le cas des vagues froides de longue durée, qui s'installent pour plus de deux à trois jours, on assiste généralement à la présence d'un fort anticyclone stationnaire qui maintient un flot d'air Arctique froid, clair et très sec à travers l'est du Canada et au Québec. Ces hautes pressions persistantes peuvent être centrées au-dessus de la Baie d'Hudson ou au-dessus de la partie centrale ouest du Québec. Elles se déplacent très lentement du nord, nord-ouest, vers le sud, sud-est. Ces systèmes très larges vont, occasionnellement, se former directement au travers de la route normale des vents d'ouest et les bloquer. On aura alors, à l'est et au sud des centres de ces systèmes, un flot d'air très froid qui peut souffler sans interruption à travers tout l'est du Canada et ceci pour des périodes pouvant atteindre une semaine.

Pour cette recherche, seules les stations au sud du 50^e parallèle nord ont été considérées, à l'exception de Sept-Iles (50° 13′ N) qui, malgré sa position plus nordique, représente une zone avec une certaine densité de population et une architecture urbaine développée. Ces stations, au nombre de 17, sont notées au tableau 1. Pour ce qui est des régions nordiques, au-delà du 50^e parallèle, une première visualisation des données nous a démontré que ces zones subissent, de façon soutenue, des températures et/ou des valeurs de refroidissement éolien supérieurs aux seuils établis. Il nous a donc paru superflu d'analyser, pour ces régions, les périodes de temps froid intensif hivernaux, puisque celles-ci sont coutumières. Il n'en demeure pas moins que les conclusions de cette recherche s'appliquent, et à plus fortes raisons, à ces zones.

Pour les 17 stations étudiées, nous avons considéré des valeurs horaires de températures et de refroidissement éolien pour des périodes variant entre 10 et 30 ans (tableau 1). Pour chacune de ces stations nous avons élaboré les fichiers, tableaux et graphiques suivants:

1) Analyse de fréquence, par mois, des observations horaires de *temps froid* (−30°C) et de *refroidissement éolien* supérieur à1 900 et à 2 300 W/m^2 (tableaux 2 à 4).

2a) Calcul d'occurrences des *vagues de froid* (≤ -30°C) et des *vagues de froid associées au vent* (refroidissement éolien supérieur à 1 900 W/m^2). Par "vague" nous entendons des périodes de froid persistant au moins: (i) 6, (ii) 12, (iii) 18 heures consécutives.

2b) Calcul d'occurrences des *vagues de froid intense* où le refroidissement éolien est égal ou supérieur à 2 300 W/m^2, ceci pour des périodes de froid persistant au moins: (i) 6, (ii) 12, (iii) 18 heures consécutives.

3) A partir des tableaux élaborés pour les calculs de 2a et 2b, qui représentent des valeurs d'occurrence sur des périodes variant entre 10 et 30 ans, nous avons construit des tableaux équivalents pour des valeurs *estimées sur un an*. Ceci nous permet de comparer les stations entre-elles. Ces tableaux sont numérotés de 5 à 7 et ce sont eux que nous utiliserons pour l'analyse des résultats.

   Les estimations des fréquences d'occurrence *annuelles* d'observations horaires de froid et des périodes de vagues de froid ont été calculées suivant l'hypothèse que les données disponibles à chacun des sites étaient représentatives de la période de 30 ans retenue. Cette méthode permet de procéder à une cartographie de la récurrence probable de valeurs élevées pour le Québec afin de mieux documenter la problématique de l'estimation de la vulnérabilité municipale à ce risque.

4) Pour toutes les stations ayant dénoté des vagues de froid de 12, 18 et 24 heures, des vagues de refroidissement éolien supérieur à 1 900 W/m^2 de 18 et 24 heures, et des vagues de froid intense

TABLEAU NO. 1. Stations météorologiques

stations	numéro d'identification	nombre d'années	latitude °N	longitude °W	type de climat
Bagotville	7060400	30	48,20	71,00	semi-continental
Baie-Comeau	7040440	23	49,12	68,16	maritime côtier
Chibougamau (2)	7091401	16	49,49	75,25	continental
Gaspé	7052605	10	48,46	64,29	maritime côtier
Mont-Joli	7055120	30	48,36	68,13	maritime côtier
Mtl/Dorval	7025250	30	45,28	73,45	continental
Mtl/Mirabel	7035290	12	45,41	74,02	continental
Ottawa	6106000	30	45,19	75,40	continental
Québec	7016294	30	46,48	71,28	semi-continental
Rivière-du-Loup	7056615	15	47,48	69,33	maritime côtier
Roberval	7066685	30	48,31	72,16	semi-continental
Rouyn	7086720	13	48,13	78,50	continental
Sept-Iles	7047910	30	50,13	66,16	maritime côtier
Sherbrooke	7028124	25	45,26	71,41	continental
St-Hubert	7027320	30	45,31	73,25	continental
Ste-Agathe-des-Monts	7036762	21	46,03	74,17	continental
Val-d'Or	7098600	30	48,04	77,47	continental

(refroidissement éolien supérieur à 2 300 W/m^2) de 6, 12 et 18 heures, nous avons construit des *fichiers-dates* (jour-mois-année) d'occurrence de ces vagues. Ces fichiers permettent de vérifier si les différentes vagues de froid sont locales ou provinciales et si elles ont une certaine cyclicité ou répétitivité.

RÉSULTATS

Observations horaires de froid

Toutes les stations du Québec présentent, en hiver, des occurrences horaires ou la température atteint ou descend sous le seuil de -30°C (tableau 2). C'est la région de Chibougamau qui est la plus froide, avec plus de 197 heures par hiver (décembre à mars), suivie par celles de Rouyn et Val-d'Or. Ce sont les régions continentales qui, à latitude égale, subissent les températures les plus froides. Les régions côtières ont des températures plus douces, tempérées par la proximité de grandes surfaces d'eau libre de l'estuaire maritime et du golfe du Saint-Laurent. Par contre, il est à noter que la rivière du Saguenay et le lac Saint-Jean sont, en hiver, recouverts de glace en grande partie, d'où une influence modératrice moindre.

Les observations horaires de froid arrivent principalement en janvier (56,5% du temps en moyenne), suivi par février (moyenne de 25,2%). Elles sont beaucoup moins fréquentes en décembre, 13% en moyenne, sauf dans les stations de Chibougamau, Mont-Joli et Mtl/Mirabel, où elles sont aussi nombreuses qu'en février. Le mois de mars en présente, en moyenne, moins de 1% du temps et seulement dans 8 des 17 stations. Encore là, c'est Chibougamau qui est la station la plus froide.

Observations horaires de refroidissement éolien

Les fréquences d'occurrence des observations horaires de froid reliées au facteur de refroidissement éolien (1 900 W/m^2) sont, en général, nettement supérieures à celles strictement rattachées aux températures (tableau 3). Ceci est particulièrement vrai pour toutes les stations le long de l'axe du Saint-Laurent où les vents jouent un rôle important. Ainsi, dans le cas de ces stations on note que les fréquences d'occurrences horaires de froid éolien sont de 6 à 18 fois supérieures à celles du froid sans vent et même 136 fois dans le cas de Mont-Joli (tableau 8). En ce sens, Mont-Joli et Rivière-du-Loup sont vraiment dans une classe à part (tableau 3). Pour les stations que nous avons appelées semi-continentales, soit celles de Bagotville et Roberval, ainsi que les stations Laurentidiennes, il y a trois fois plus d'observations horaires de froid avec vent que sans vent. L'effet du vent dans ces régions se fait donc sentir, sans être toutefois aussi important que pour les stations le long de l'axe du Saint-Laurent. Pour ce qui est des stations continentales, on remarque que les fréquences des valeurs critiques de

TABLEAU NO. 2. Occurrences annuelles des observations horaires de froid (−30°C)

Nom de la station	janvier	février	mars	décembre	total-hiver	% mensuel des occurrences annuelles: janvier	février	mars	décembre
Bagotville	26,9	14,7	0,2	7	48,9	55	30,1	0,5	14,4
Baie-Comeau	11	6	0,6	2,1	19,7	55,9	30,4	2,9	10,8
Chibougamau (2)	90,8	50	10,1	46,4	197,3	46	25,3	5,1	23,5
Gaspé	3,4	0,9	0	0	4,3	79,1	20,9	0	0
Mont-Joli	0,7	0,1	0	0,1	1	73,7	13,1	0	13,1
Mtl/Dorval	1,9	0,6	0	0,2	2,7	68,5	23,1	0	8,4
Mtl/Mirabel	8	1,4	0	1,8	11,3	71,1	12,6	0	16,3
Ottawa	1,9	0,8	0	0,2	2,9	65,9	26,3	0	7,8
Québec	4,2	2	0	0,5	6,7	62,4	30,2	0	7,4
Rivière-du-Loup	0	0,6	0	0	0,6	0	100	0	0
Roberval	26,8	13,8	0	8,1	48,8	55	28,3	0,1	16,7
Rouyn	76,9	38,2	1,7	29,4	146,1	52,6	26,1	1,2	20,1
Sept-Iles	9,5	4,5	0,1	2	16,1	59	28	0,4	12,6
Sherbrooke	16,7	8,4	0,6	4,6	30,2	55,2	27,6	2,1	15,1
St-Hubert	1,4	0,6	0	0,2	2,1	64,9	27	0	8,1
Ste-Agathe-des-Monts	25,2	12	0	6,6	43,7	57,6	27,4	0	15
Val-d'Or	47,4	27	1,9	17,9	94,2	50,3	28,7	2	19

Nom de la station	0–6 hr	6–12 hr	12–18 hr	18–24 hr	% des heures totales: 0–6 hr	6–12 hr	12–18 hr	18–24 hr
Bagotville	20,4	18,5	0,9	9,1	41,7	37,9	1,8	18,6
Baie-Comeau	8,9	7,3	0,4	3,2	45,1	37,2	1,8	16
Chibougamau (2)	81,4	75	6,1	34,8	38,7	35,6	2,9	16,6
Gaspé	1,6	2,1	0	0,6	37,2	48,8	0	14
Mont-Joli	0,5	0,3	0	0,2	53	27	0	20
Mtl/Dorval	0,8	1,6	0,2	0,2	28,2	58,6	6,2	7,3
Mtl/Mirabel	4,4	5,3	0,8	0,8	39,3	47,4	6,7	6,7
Ottawa	1	1,7	0,1	0,2	34,1	57	3,4	5,8
Québec	2,5	3,1	0,5	0,7	36,7	46,1	7,4	10
Rivière-du-Loup	0	0,5	0,1	0	0	78,3	21,7	0
Roberval	18,4	17,7	2,4	10,3	37,7	36,3	4,9	21,1
Rouyn	40,7	77,7	5,7	22	27,8	53,2	3,9	15,1
Sept-Iles	7,6	6,8	0,2	1,6	47	42,1	1,2	9,8
Sherbrooke	14,9	11,5	0,3	3,6	49,2	38	1,1	11,8
St-Hubert	0,7	1,3	0,1	0	33,3	61,9	3,3	1,4
Ste-Agathe-des-Monts	16,6	21,6	2,3	3,2	38,1	49,5	5,2	7,3
Val-d'Or	37,1	39,7	2,5	15	39,3	42,1	2,7	15,9

TABLEAU NO. 3. Occurrences annuelles des observations horaires de froid associé au vent (1 900 W/m²)

Nom de la station	total hiver	janvier	février	mars	décembre	% mensuel des occurrences annuelles			
						janvier	février	mars	décembre
Bagotville	169,1	72,6	54,4	15	27,1	42,9	32,2	8,9	16
Baie-Comeau	119,9	57,2	35	4,8	22,8	47,7	29,2	4	19
Chibougamau (2)	110,3	47,8	30,6	10,3	21,7	43,3	27,7	9,3	19,7
Gaspé	58,1	23,5	21,9	1,3	11,4	40,4	37,7	2,2	19,6
Mont-Joli	135,9	62,1	47,5	4,5	21,8	45,7	34,9	3,3	16,1
Mtl/Dorval	40,1	23,7	8,9	0,5	7,1	59,1	22,1	1,2	17,6
Mtl/Mirabel	35	24	2,5	0,6	7,9	68,6	7,1	1,7	22,6
Ottawa	37,9	19,9	10,7	0,9	6,4	52,5	28,2	2,3	17
Québec	99,2	50,2	27,1	1,3	20,6	50,6	27,3	1,3	20,7
Rivière-du-Loup	47,5	20,1	20,9	0,9	5,7	42,2	43,9	2	11,9
Roberval	147	59,8	47,3	7,1	32,7	40,7	32,2	4,8	22,3
Rouyn	98,5	50,3	28,1	4,3	15,9	51	28,5	4,4	16,1
Sept-Iles	133,6	58,7	44,1	5,3	25,5	44	33	4	19,1
Sherbrooke	25,2	13,3	6,2	0,6	5	52,9	24,6	2,5	19,9
St-Hubert	38	22,5	7,4	0,6	7,4	59,3	19,5	1,7	19,6
Ste-Agathe-des-Monts	104,7	48,9	28,6	4,6	22,6	46,7	27,3	4,4	21,5
Val-d'Or	87,6	37,5	29,4	7	13,6	42,9	33,6	8	15,5

Nom de la station	0–6 hr	6–12 hr	12–18 hr	18–24 hr	% des heures totales			
					0–6 hr	6–12 hr	12–18 hr	18–24 hr
Bagotville	48,5	54,9	33,4	32,3	28,7	32,5	19,8	19,1
Baie-Comeau	33,7	41,8	19,1	25,4	28,1	34,9	16	21,1
Chibougamau (2)	27,6	37	25,3	20,4	25,1	33,6	22,9	18,5
Gaspé	13,1	18,2	15,5	11,3	22,5	31,3	26,7	19,4
Mont-Joli	38,2	41,5	25,2	31,1	28,1	30,5	18,5	22,9
Mtl/Dorval	8	14,8	11,1	6,2	19,9	36,9	27,7	15,5
Mtl/Mirabel	6,6	11,8	9,9	6,7	18,8	33,8	28,3	19,1
Ottawa	9,9	15,9	6,7	5,5	26	41,8	17,7	14,4
Québec	27,6	33,8	20,7	17,1	27,8	34,1	20,8	17,2
Rivière-du-Loup	15	13,5	8,1	11	31,6	28,3	17	23,1
Roberval	48,9	53,1	17,6	27,4	33,3	36,1	12	18,7
Rouyn	13,8	42	30,7	12	14	42,6	31,2	12,2
Sept-Iles	39,7	40,8	23,6	29,6	29,7	30,5	17,6	22,2
Sherbrooke	6,1	8,4	7,4	3,3	24,3	33,4	29,3	13
St-Hubert	8	12,9	9,8	7,3	21,1	34	25,8	19,2
Ste-Agathe-des-Monts	26,7	35	20,6	22,4	25,5	33,4	19,6	21,4
Val-d'Or	24,5	32,3	16,1	14,6	28	36,9	18,4	16,7

refroidissement éolien sont, en moyenne, 25% inférieures à celles des températures froides. Ce sont les seules régions où le facteur de refroidissement éolien est moins important que les seules températures froides, et aussi les régions qui sont les plus éloignées des grandes masses d'eau.

Cest le mois de janvier qui présente le plus de risque au niveau du refroidissement éolien (tableau 3), suivi du mois de février. Les seules exceptions à cette règle sont les stations de Gaspé et Rivière-du-Loup où les mois de janvier et février sont aussi froids et les stations de Mtl/Mirabel et St-Hubert où le mois de décembre est plus froid que février. Contrairement aux basses températures, les froids éoliens touchent toutes les stations en mars, bien qu'à des degrés divers. Ce sont les régions de Bagotville, Chibougamau et Val-d'Or qui sont les plus affectées (8–9% des occurrences), alors que les régions de Montréal, des Laurentides, de Québec et de Rivière-du-Loup sont à peine effleurées (moins de 2%).

Observations horaires de refroidissement éolien intense

Les observations horaires de froid intense soit celles où le facteur de refroidissement éolien est égal ou supérieur à 2 300 W/m^2 touchent, à des degrés divers, les 17 stations considérées. La fréquence annuelle des périodes horaires varie de 0,08 à Sherbrooke à 8,0 à Bagotville (tableau 4). Le patron tant qu'à la distribution de ces fréquences est assez erratique bien qu'on puisse faire certains rapprochements entre les stations. Ainsi, les stations les plus au sud de la province (sous le 46^e parallèle) ont toutes des fréquences d'occurrences annuelles égales ou inférieures à 1. Dans cette classe s'ajoutent les stations de Gaspé, Mont-Joli et Rivière-du-Loup qui, malgré leur caractère côtier et leurs latitudes autour des 47° et 48° N, sont peu touchées par des refroidissements éoliens intenses. Rouyn et Val-d'Or (Abitibi) constituent une classe avec des valeurs légèrement supérieures à une occurrence annuelle (1,23 et 1,30). Baie-Comeau, Chibougamau et Sept-Iles, qui sont les stations les plus nordiques de cette étude, ont des valeurs qui oscillent autour de 4 et 5 ce qui, à l'exception de Bagotville avec 8, représentent les fréquences d'occurrences les plus élevées. Bagotville, avec ses 8 occurrences annuelles, est vraiment dans une classe à part et seules des analyses plus approfondies des vents hivernaux en fonction de la situation géographique de cette station (fond d'une cuvette) pourraient sans doute nous éclairer sur ce point. Ceci est d'autant plus surprenant que Roberval, qui est aussi le long de l'axe Saguenay/Lac-St-Jean, est beaucoup plus ouvert aux vents que Bagotville et, pourtant, n'est touché par des froids intenses que 2 à 3 fois par hiver, tout comme Québec et Ste-Agathe-des-Monts.

Pour toutes les stations, les périodes de froid intense se produisent principalement en janvier, dans une proportion variant entre 50 et 100% avec une moyenne de 71% et en février (tableau 4). Elles se produisent à tout moment de la journée avec une dominance, sauf pour Ste-Agathe-des-Monts, entre 6 et 12 heures.

TABLEAU NO. 4. Occurrences annuelles des observations horaires de froid intense (2 300 W/m²)

Nom de la station	total hiver	janvier	février	mars	décembre	% mensuel des occurrences annuelles — janvier	février	mars	décembre
Bagotville	8	5	2	0	1	62,5	25,4	0	12,1
Baie-Comeau	3,9	2,7	1,2	0	0	68,2	30,8	0	1
Chibougamau (2)	4,6	3,8	0,4	0	0,4	83,5	8,3	0	8,3
Gaspé	0,6	0,4	0,2	0	0	66,7	33,3	0	0
Mont-Joli	3,1	1,8	1,3	0	0	57,2	41,6	0	0,9
Mtl/Dorval	0,9	0,7	0,2	0	0	78,5	21,5	0	0
Mtl/Mirabel	0,6	0,5	0,1	0	0	86,2	13,8	0	0
Ottawa	0,3	0,2	0,1	0	0	60,6	39,4	0	0
Québec	2,1	1,6	0,4	0	0,1	76,5	17,4	0	6,1
Rivière-du-Loup	0,4	0,4	0	0	0	100	0	0	0
Roberval	2,6	1,5	0,8	0	0,3	57,7	31,9	0	10,4
Rouyn	1,2	0,8	0,4	0	0	69,1	30,9	0	0
Sept-Iles	4,9	2,8	1,9	0,1	0,1	58,3	39	1,4	1,4
Sherbrooke	0	0	0	0	0	50	50	0	0
St-Hubert	0,9	0,7	0,2	0	0	80,5	19,5	0	0
Ste-Agathe-des-Monts	2,8	2	0,5	0	0,3	70,9	19,5	0	9,6
Val-d'Or	1,3	1	0,3	0	0	76,9	23,1	0	0

Nom de la station	0–6 hr	6–12 hr	12–18 hr	18–24 hr	% des heures totales — 0–6 hr	6–12 hr	12–18 hr	18–24 hr
Bagotville	2,4	3,3	1,2	1,2	29,6	41,3	14,6	14,6
Baie-Comeau	1	1,2	1	0,8	24,6	30	25,6	21,3
Chibougamau (2)	1,1	1,9	0,7	0,9	23,2	42,5	15,1	19,3
Gaspé	0,2	0,3	0	0,1	33,3	50	0	16,7
Mont-Joli	1	1,1	0,5	0,6	33,2	34,5	17,1	18,4
Mtl/Dorval	0,2	0,4	0,2	0,1	24,7	43	24,7	7,5
Mtl/Mirabel	0	0,4	0,2	0	0	71,2	28,8	0
Ottawa	0,1	0,1	0	0,1	39,4	39,4	0	21,2
Québec	0,5	1,2	0,4	0	24,9	56,3	17,4	1,4
Rivière-du-Loup	0,1	0,2	0,1	0	32,5	50	17,5	0
Roberval	0,8	1	0,5	0,3	30,8	38,5	19,2	11,5
Rouyn	0	0,8	0,2	0,2	0	62,6	18,7	18,7
Sept-Iles	1,5	1,7	0,7	0,9	30	35,3	14,9	17,8
Sherbrooke	0	0	0	0	0	0	0	0
St-Hubert	0,2	0,4	0,2	0,1	23	49,4	19,5	8
Ste-Agathe-des-Monts	1,2	1,1	0,5	0,1	41,8	38,7	16	3,2
Val-d'Or	0,2	0,6	0,3	0,2	15,4	43,8	25,4	15,4

Les vagues de froid

a) vagues de 12 heures
Les données du tableau 5 montrent que, sur une période d'un an, la région de Chibougamau est celle qui, de loin, peut s'attendre au plus grand nombre de vagues de froid ($\leq -30°C$) par hiver, soit environ 5. Elle est suivie par les stations de Rouyn et Val-d'Or avec près de 2 vagues, et de Bagotville et Roberval avec une (1) vague de froid. Ceci concorde avec le fait que ce sont ces stations, de type continental, qui, en ordre, présentent le plus grand nombre de périodes horaires de froid par hiver. Mirabel peut s'attendre à une telle vague à tous les 3 ans; les stations de Baie-Comeau, Sherbrooke et Ste-Agathe-des-Monts à une aux 6 ans; et les stations de Dorval, Ottawa, St-Hubert, Québec et Sept-Iles à une aux 14 ans. Les trois stations côtières sur la rive sud du Saint-Laurent n'ont connu aucune vague de froid pendant la période de données disponibles.

Ces vagues de froid ont lieu principalement ou en totalité (% variant entre 52 et 100) au mois de janvier. Les six stations les plus froides peuvent en attendre en février et décembre, bien que deux à trois fois moins qu'en janvier, alors que seule la station de Chibougamau a de rares possibilités d'en subir une en mars, soit à tous les 17 ans.

b) vagues de 18 heures
Les vagues de froid d'au moins 18 heures affectent 10 des 17 stations considérées (tableau 5). Si on excepte Chibougamau, qui peut en accuser 2 par 3 hivers, les autres stations ont des fréquences d'occurrence beaucoup plus faibles. Ainsi on peut dénombrer une occurrence à tous les 2 ans à Rouyn et Val-d'Or, une à tous les 4 à 5 ans à Roberval, une à tous les 7 ans à Ste-Agathe-des-Monts et Bagotville, une à tous les 14 ans à Mirabel, Québec et Sept-Iles et à peine une par 25 ans à St-Hubert.

Ces occurrences se produisent principalement en janvier avec, pour les stations les plus froides, des occurrences secondaires en décembre (février pour Bagotville et Roberval). La possibilité de ces vagues en février est faible et ne touche que 4 des 10 stations, alors qu'elle est inexistante en mars.

c) vagues de 24 heures
Ces vagues de froid persistantes n'affectent que 5 des 17 stations, soit Chibougamau, Rouyn, Val-d'Or, Roberval et Ste-Agathe-des-Monts. Les fréquences d'occurrence sont faibles (tableau 5) et toutes ces vagues surviennent en janvier, quoique Chibougamau puisse en accuser une sur six en décembre.

d) les fichiers-dates
Lorsqu'on analyse les fichiers-dates des vagues de froid on note que:

i) des vagues de froid généralisées à travers la province sont rares, soit une aux 30 ans, la dernière datant des 3 et 4 janvier 1981;
ii) des vagues de froid générales de 12 heures consécutives se produisent

TABLEAU NO. 5. Occurrences mensuelles des vagues de froid (−30°C) sur un an

	vagues de 12 heures					vagues de 18 heures					vagues de 24 heures				
Nom de la station	jan	fév	mar	déc	total	jan	fév	mar	déc	total	jan	fév	mar	déc	total
Bagotville	0,63	0,13	0,00	0,07	0,83	0,07	0,07	0,00	0,00	0,13	0,00	0,00	0,00	0,00	0,00
Baie-Comeau	0,17	0,00	0,00	0,00	0,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Chibougamau (2)	2,56	1,06	0,06	1,19	4,88	0,88	0,13	0,00	0,56	1,56	0,31	0,00	0,00	0,06	0,38
Gaspé	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mont-Joli	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mtl/Dorval	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mtl/Mirabel	0,17	0,00	0,00	0,00	0,17	0,08	0,00	0,00	0,00	0,08	0,00	0,00	0,00	0,00	0,00
Ottawa	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Québec	0,07	0,00	0,00	0,00	0,07	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00
Rivière-du-Loup	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Roberval	0,80	0,17	0,00	0,20	1,17	0,17	0,07	0,00	0,03	0,27	0,03	0,00	0,00	0,00	0,03
Rouyn	1,15	0,38	0,00	0,38	1,92	0,38	0,00	0,00	0,15	0,54	0,15	0,00	0,00	0,00	0,15
Sept-Iles	0,07	0,00	0,00	0,00	0,07	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00
Sherbrooke	0,20	0,00	0,00	0,07	0,27	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00
St-Hubert	0,03	0,00	0,00	0,00	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ste-Agathe-des-Monts	0,24	0,05	0,00	0,05	0,33	0,14	0,00	0,00	0,00	0,14	0,10	0,00	0,00	0,00	0,10
Val-d'Or	1,07	0,40	0,00	0,20	1,67	0,33	0,03	0,00	0,07	0,43	0,10	0,00	0,00	0,00	0,10

pendant 2 à 3 jours, à tous les deux ou trois ans, mais seulement sur les régions au nord du 48e parallèle;

iii) les stations de Chibougamau, Rouyn et Val-d'Or, soit les régions de l'Abitibi et du centre nord-ouest du Québec, subissent une vague régionale de froid de 12 heures, parfois deux, à tous les ans et pour des périodes variant entre 1 et 3 jours;

iv) seule la station de Chibougamau présente une vague de froid de 18 heures à presque toutes les années;

v) les stations subissent, en moyenne, trois fois plus de vagues de froid (12 heures) d'une journée que de vagues de froid de deux jours et plus. Seules les stations de Chibougamau, Rouyn et Val-d'Or ont des vagues de froid de trois jours, soit environ une occurrence sur vingt (20). Chibougamau est l'unique station à subir des vagues de froid continues pour plus de trois jours soit, en 11 ans, une occurrence de 5 jours et une 8 jours;

vi) la nature des vagues de froid locales et à l'échelle régionale est erratique. L'analyse des données semble plutôt démontrer que les vagues de froid arrivent par groupes d'années. Ainsi, les hivers 1967–1968 furent froids alors que les années 1969 à 1975 semblent avoir été plus tempérées sauf l'hiver 1975 qui fut froid pour l'Abitibi et le centre nord-ouest du Québec. Les années 1976 à 1980 furent aussi supportables alors que 1981 et 1982 ont été particulièrement froides à l'échelle de la province. Depuis 1983 les températures demeurent plus tempérées.

Vagues de froid associées au vent (1 900 W/m²)

a) vagues de 12 heures

Les vagues de froid qui impliquent un refroidissement éolien égal ou supérieur à 1 900 W/m^2, pour des périodes de 12 heures et plus, ont été observées dans nos 17 stations et se produisent, sauf à Chibougamau et Rouyn, beaucoup plus fréquemment que les vagues de froid strictement associées aux températures égales ou inférieures à $-30°C$ (tableaux 6 et 7). Ainsi, bien que Chibougamau et Rouyn subissent environ 30% moins de vagues de froid associées au vent que de vagues de froid associées aux seules températures, les autres stations en accusent 1,5 à 58 fois plus.

Pour les vagues de froid associées au vent, ce sont les stations de Bagotville, Mont-Joli et Sept-Iles qui, en ordre, ont les plus grandes fréquences d'occurrences annuelles, entre 4 et 5,8 par hiver. Suivent les stations de Chibougamau, Roberval, Baie-Comeau et Québec avec 3 à 4 occurrences; Val-d'Or avec 2,4; Ste-Agathe-des-Monts, Dorval, Rouyn, St-Hubert, Gaspé et Mirabel avec un peu plus d'une occurrence et, finalement, Rivière-du-Loup, Ottawa et Sherbrooke avec un peu moins d'une occurrence par hiver. Pour ce type de vague de froid, ce sont les stations près des côtes (sauf Gaspé et Rivière-du-

TABLEAU NO. 6. Occurrences mensuelles des vagues de froid associées au vent (1 900 W/m²), sur un an

	vagues de 12 heures					vagues de 18 heures					vagues de 24 heures				
Nom de la station	jan	fév	mar	déc	total	jan	fév	mar	déc	total	jan	fév	mar	déc	total
Bagotville	2,50	1,87	0,43	0,77	5,57	1,33	1,00	0,10	0,40	2,83	0,43	0,30	0,00	0,13	0,87
Baie-Comeau	1,83	0,87	0,04	0,57	3,30	0,48	0,52	0,00	0,13	1,13	0,17	0,22	0,00	0,00	0,39
Chibougamau (2)	1,75	1,19	0,00	0,81	3,75	0,44	0,31	0,00	0,25	1,00	0,25	0,06	0,00	0,00	0,31
Gaspé	0,30	0,60	0,00	0,20	1,10	0,10	0,30	0,00	0,10	0,50	0,00	0,20	0,00	0,00	0,20
Mont-Joli	2,40	1,77	0,03	0,70	4,90	1,20	1,07	0,00	0,30	2,57	0,30	0,43	0,00	0,00	0,73
Mtl/Dorval	0,80	0,27	0,00	0,27	1,33	0,23	0,03	0,00	0,10	0,37	0,10	0,00	0,00	0,00	0,10
Mtl/Mirabel	0,83	0,08	0,00	0,17	1,08	0,33	0,00	0,00	0,08	0,42	0,08	0,00	0,00	0,00	0,08
Ottawa	0,57	0,23	0,00	0,10	0,90	0,13	0,03	0,00	0,03	0,20	0,00	0,00	0,00	0,00	0,00
Québec	1,73	0,77	0,03	0,73	3,27	0,83	0,27	0,00	0,30	1,40	0,17	0,07	0,00	0,10	0,34
Rivière-du-Loup	0,47	0,40	0,00	0,07	0,93	0,13	0,27	0,00	0,00	0,40	0,07	0,07	0,00	0,00	0,13
Roberval	1,63	1,33	0,03	0,73	3,73	0,53	0,47	0,00	0,17	1,17	0,17	0,23	0,00	0,03	0,43
Rouyn	1,08	0,08	0,00	0,15	1,31	0,23	0,08	0,00	0,00	0,31	0,00	0,00	0,00	0,00	0,00
Sept-Iles	1,87	1,40	0,03	0,80	4,10	0,80	0,67	0,00	0,23	1,70	0,17	0,10	0,00	0,00	0,27
Sherbrooke	0,76	0,20	0,00	0,20	1,16	0,20	0,07	0,00	0,00	0,27	0,00	0,00	0,00	0,00	0,00
St-Hubert	0,73	0,17	0,03	0,20	1,13	0,33	0,03	0,00	0,07	0,43	0,07	0,00	0,00	0,00	0,07
Ste-Agathe-des-Monts	0,76	0,38	0,00	0,24	1,38	0,33	0,05	0,00	0,10	0,48	0,10	0,00	0,00	0,00	0,10
Val-d'Or	1,10	0,87	0,13	0,30	2,40	0,37	0,23	0,00	0,10	0,70	0,07	0,03	0,00	0,00	0,10

TABLEAU NO. 7. Rapport des fréquences des observations horaires annuelles de froid éolien versus le froid associé aux températures égales ou inférieures à −30°C.

Nom de la station	hres froid −30°C A	hres froid 1 900 W/m² B	B/A
Bagotville	48,87	169,23	3,46
Baie-Comeau	19,78	119,91	6,06
Chibougamau (2)	197,3	110,25	0,56
Gaspé	4,3	59,1	13,74
Mont-Joli	1	135,9	135,9
Mtl/Dorval	2,73	40,23	14,74
Mtl/Mirabel	11,25	35	3,11
Ottawa	2,93	37,93	12,95
Québec	6,73	99,17	14,74
Rivière-du-Loup	0,6	47,53	79,22
Roberval	48,77	147	3,01
Rouyn	146,15	98,31	0,67
Sept-Iles	16,1	133,63	8,3
Sherbrooke	30,24	25,16	0,83
St-Hubert	2,1	38,07	18,13
Ste-Agathe-des-Monts	43,73	104,64	2,39
Val-d'Or	94,2	87,57	0,93

Note: toutes les valeurs sont calculées sur une période d'un hiver, soit entre décembre et mars (inclusivement).

Loup) qui ont les plus fortes occurrences, et on peut y voir l'importance de la vallée du Saint-Laurent sur l'effet soutenu des vents. Les stations les plus méridionales ont des fréquences d'occurrence plus faibles, mais tout de même nettement supérieures (en moyenne 10 fois plus) aux vagues de froid associées aux seules températures.

Les vagues de froid associées au vent se produisent avant tout en janvier (sauf à Gaspé où février est plus froid) suivi généralement de février puis décembre, sauf dans les cas de Mirabel, Rouyn et St-Hubert où le contraire se produit. Seulement 8 des 17 stations présentent des occurrences au mois de mars et elles sont rares (tableau 6).

b) vagues de 18 heures

Les 17 stations analysées sont aussi sujettes aux vagues de froid de 18 heures et plus, quoique les fréquences d'occurrence soient nettement plus faibles que pour les vagues de 12 heures. Bagotville et Mont-Joli dénotent 3 vagues par hiver; Sept-Iles, Québec, Roberval, Baie-Comeau et Chibougamau entre 1 et 2 et les autres stations moins de une.

Ces vagues de froid se produisent surtout en janvier, suivi du mois de février (sauf Baie-Comeau et Rivière-du-Loup où le contraire est observé). Les occurrences en décembre représentent environ 10% des occurrences totales. Le mois de mars est exempt de ce type de vague, sauf à Bagotville qui peut en accuser une à tous les dix ans.

c) vagues de 24 heures

Un total de 14 stations sur 17 accuse des vagues de froid associées au vent d'au moins 24 heures consécutives. Les fréquences d'occurrence sont faibles. On en note environ une par hiver à Bagotville et Mont-Joli, qui sont les deux stations les plus affectées par les vents, une aux trois ans à Baie-Comeau, Chibougamau, Québec, Roberval et Sept-Iles, et une aux dix ans dans toutes les autres stations, sauf Ottawa, Sherbrooke et Rouyn qui n'en subissent pas. A noter que ces trois stations sont de type continental, donc moins sujettes aux vents soutenus qui parcourent la vallée du Saint-Laurent.

Ces vagues de froid arrivent deux fois sur trois en janvier, sauf pour les stations côtières et semi-continentales de Baie-Comeau, Gaspé, Mont-Joli et Roberval où février est légèrement plus froid. Les occurrences en décembre sont rares et ne frappent que Bagotville, Roberval et Québec, toutes des stations de type semi-continental. Aucune de ces longues périodes de froid ne se produit en mars.

d) les fichiers-dates

A noter que:

i) des vagues de froid associées au vent, à l'échelle provinciale, de 18 heures et plus, se produisent à tous les six ou sept ans;

ii) si on excepte la zone au sud du 46^{e} parallèle, ces vagues de froid qui persistent pour 18 heures et plus peuvent se produire, en moyenne, à tous les trois ans, ceci pour des périodes de un ou deux jours;

iii) seules les régions de Mont-Joli, Bagotville et Sept-Iles peuvent s'attendre à une telle vague de froid à toutes les années et même, surtout dans le cas de Mont-Joli, à deux ou trois vagues par hiver durant les années froides;

iv) tout comme pour les vagues de froid strictement associées aux basses températures, les vagues de froid associées au vent ne sont pas vraiment cycliques. Les années 1959–1961, 1967–1968, 1975 et 1979 à 1982 ont eu des hivers particulièrement froids alors que les années 1963–1966, 1969–1971 et 1977–1978 furent beaucoup plus tempérées sur la majorité des régions de la province. Depuis 1983 les temps très froids sont relativement rares, à l'exception de vagues de froid locales ou régionales dans la région du bas du fleuve, en aval du Saguenay;

v) la majorité des stations subissent des vagues de froid associées au vent qui, dans 80% des occurrences, ne se prolongent pas au-delà d'une journée. Cependant, dans le cas des stations côtières et semi-continentales les vagues de deux et trois jours représentent, en moyenne, 25% des occurrences totales. Seule la zone située dans le triangle entre Sept-Iles, Mont-Joli et Roberval et qui inclut aussi Baie-Comeau et Bagotville, subit de ces vagues de froid pour une durée supérieure à trois jours. Ces dernières vagues peuvent se prolonger jusqu'à neuf jours, mais ne représentent, pour les stations concernées, que 5 à 6% des vagues au total.

Vagues de froid intense (2 300 W/m²)

a) vagues de 6 heures
Ces périodes de refroidissement éolien très élevé sont dangereuses pour l'homme mais peu fréquentes. Sur les 17 stations étudiées, 12 en sont affectées, Gaspé, Mirabel, Ottawa, Rivière-du-Loup et Sherbrooke en étant exemptées (tableau 8). Bagotville et Chibougamau, les stations les plus propices à ce type d'événement, n'en subissent qu'environ une aux deux ans. Sept-Iles suit avec une occurrence aux trois ans, Baie-Comeau avec une aux quatre ans, Mont-Joli avec une aux cinq ans et Roberval avec une aux six ans. Québec, Ste-Agathe-des-Monts et Val-d'Or peuvent en attendre une par dix ans, Dorval et Rouyn une aux quatorze ans et finalement St-Hubert une aux trente ans. La distribution des vagues de froid intense ne suit aucun schéma géographique particulier, si ce n'est que les stations les plus au sud sont généralement celles qui sont le moins affectées. A latitude égale, ce sont les stations côtières qui sont les plus touchées, à l'exception de Gaspé et Rivière-du-Loup qui semblent être relativement protégées des vents très froids.

Toutes les vagues de froid intense se produisent en janvier et février et, en moyenne, janvier dénote trois fois plus d'occurrences que février. Aucun cas ne s'est présenté en décembre ou en mars. La période de la journée la plus touchée par ces vagues est le matin, entre 6 et 12 heures, alors que les occurrences sont quasi-inexistantes entre 18 et 24 heures.

b) vagues de 12 heures
Sur les 17 stations étudiées, 9 peuvent subir, à des degrés divers, des vagues de froid intensif pour des périodes de 12 heures consécutives. Bagotville est encore la station la plus affectée avec la possibilité d'une telle vague à tous les trois ou quatre ans. Baie-Comeau et Chibougamau présentent des risques une fois à tous les six ans. Mont-Joli, Québec et Sept-Iles peuvent s'y attendre aux quatorze ans alors que Dorval, Roberval et Val-d'Or en essuyeront une aux trente ans.

Ces vagues sont particulièrement présentes en janvier avec, toutes proportions gardées, deux fois plus d'occurrences qu'en février. Elles débutent surtout au milieu de la nuit pour se poursuivre jusqu'en début d'après-midi le lendemain.

c) vagues de 18 heures
De telles vagues de froid n'atteignent que Bagotville, Baie-Comeau, Chibougamau et Mont-Joli, toutes des stations sises entre le 48^{e} et le 50^{e} parallèle Nord. Ces stations ont d'ailleurs démontré, tout au long de nos résultats, qu'elles constituent les zones les plus froides du Québec au sud du 50^{e} parallèle. Bagotville avec la possibilité d'une telle vague aux dix ans est la station la plus touchée.

Ces vagues se manifestent en janvier à Bagotville et Chibougamau, deux stations plutôt continentales, alors qu'elles se présentent en février dans les deux stations côtières de Baie-Comeau et Mont-Joli. Elles affectent toujours les

TABLEAU NO. 8. Occurrences mensuelles des vagues de froid intense (2 300 W/m²), sur un an

Nom de la station	total des hres de froid	vagues de 6 heures					vagues de 12 heures					vagues de 18 heures				
		jan	fév	mar	déc	total	jan	fév	mar	déc	total	jan	fév	mar	déc	total
Bagotville	8.00	0,37	0,10	0,00	0,03	0,50	0,17	0,07	0,00	0,03	0,27	0,10	0,00	0,00	0,00	0,10
Baie-Comeau	3.95	0,22	0,04	0,00	0,00	0,26	0,09	0,04	0,00	0,00	0,13	0,00	0,04	0,00	0,00	0,04
Chibougamau (2)	4.56	0,38	0,06	0,00	0,00	0,44	0,13	0,00	0,00	0,00	0,13	0,06	0,00	0,00	0,00	0,06
Gaspé	0.60	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mont-Joli	3.20	0,13	0,07	0,00	0,00	0,20	0,03	0,03	0,00	0,00	0,07	0,00	0,03	0,00	0,00	0,03
Mtl/Dorval	0.93	0,07	0,00	0,00	0,00	0,07	0,03	0,00	0,00	0,00	0,03	0,00	0,00	0,00	0,00	0,00
Mtl/Mirabel	0.58	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ottawa	0.33	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Québec	2.13	0,07	0,03	0,00	0,00	0,10	0,07	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00
Rivière-du-Loup	0.40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Roberval	2.60	0,10	0,03	0,00	0,00	0,13	0,03	0,00	0,00	0,00	0,03	0,00	0,00	0,00	0,00	0,00
Rouyn	1,23	0,08	0,00	0,00	0,00	0,08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Sept-Iles	4.80	0,20	0,13	0,00	0,00	0,33	0,03	0,03	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00
Sherbrooke	0.08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
St-Hubert	0.87	0,03	0,00	0,00	0,00	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ste-Agathe-des-Monts	2.82	0,05	0,05	0,00	0,00	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Val-d'Or	1.30	0,07	0,03	0,00	0,00	0,10	0,03	0,00	0,00	0,00	0,03	0,00	0,00	0,00	0,00	0,00

stations entre 18 heures et 12 heures de la journée suivante. On peut souligner que Bagotville et Mont-Joli sont les seules stations à subir des vagues de froid intensif qui persistent pour au moins 24 heures. Une telle vague ne revient, dans les deux cas, qu'à tous les 30 ans.

d) les fichiers-dates

L'analyse permet de constater que:

i) à l'exception des stations au sud du 46ᵉ parallèle qui ne sont pas affectées, un tel phénomène météorologique peut frapper simultanément la majorité de la province une fois tous les 15 ans;

ii) des vagues plus régionales affectent les régions à l'est du 68ᵉ méridien environ aux 5 ans, autant sur la rive nord que sur la rive sud du Saint-Laurent;

iii) la majorité des stations semblent surtout affectées par des vagues locales dont la distribution temporelle ne dénote aucune périodicité. Encore une fois, il semble qu'on assiste plutôt à une alternance non cyclique de séries d'années chaudes et d'années froides.

CONCLUSION

Le phénomène vague de froid est omniprésent sur tout le territoire méridional du Québec pour les mois de janvier et février et, dans une moindre mesure, en décembre et mars pour les stations les plus au nord. Des vagues de froid généralisées à travers la province sont rares, soit environ une aux 30 ans, la dernière datant des 3 et 4 janvier 1981. Pour les régions au nord du 48ᵉ parallèle, des vagues de froid générales de 12 heures consécutives se produisent pendant 2 à 3 jours, à tous les deux ou trois ans. Les régions de l'Abitibi et du centre nord-ouest du Québec subissent une vague régionale de froid de 12 heures, parfois deux, à tous les ans et pour des durées variant entre 1 et 3 jours.

A l'échelle de la province, les vagues de froid associées au vent, qui se maintiennent pour 18 et 24 heures consécutives, se produisent à tous les 6 ou 7 ans. La majorité des stations subissent des vagues de froid associées au vent qui, dans 80% des occurrences, ne se prolongent pas au-delà d'une journée. Seul le triangle entre Sept-Iles, Mont-Joli et Roberval, et qui inclut aussi Baie-Comeau et Bagotville, connaît de telles vagues d'une durée supérieure à trois jours.

En ce qui a trait aux vagues de froid intense, elles peuvent frapper les stations au nord du 46ᵉ parallèle une fois tous les 15 ans. Nous avons également remarqué que des vagues plus régionales affectent la région à l'est du 68ᵉ méridien environ à tous les 5 ans et ceci autant sur la rive nord que sur la rive sud du Saint-Laurent.

Cet article ouvre la porte vers d'autres études géographiques et climatologiques. Ainsi, dans une prochaine étape, il serait approprié d'analyser le risque pour les stations nordiques. Maintenant que l'on dispose d'une source de renseignements précise sur le risque réel en régions méridonales, nous sommes en mesure de procéder à l'examen et à la validation des plans de mesures d'urgence des municipalités du Québec qui doivent estimer le risque vague de froid sur leur territoire.

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Precipitation Trends at Victoria, British Columbia

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ABSTRACT

Trends in precipitation at Victoria Gonzales Heights over a 74-year period (1914–1987) are described. Eleven-year moving averages of both annual total and maximum one-day precipitation had maxima in the 1930s and 1950s and a minimum in the 1940s. Growing-season precipitation reached a maximum in the 1930s but otherwise has been very consistent. Decreasing winter precipitation is mainly responsible for a decline in the annual total since the early 1950s. The year-to-year variability of annual total precipitation has been greater in the second half of the record. Trends at Victoria are not necessarily replicated in other areas of British Columbia.

RÉSUMÉ

Cette note présente les tendances des précipitations à Victoria Gonzales Heights durant la période 1914–1987 (74 années). La moyenne mobile d'onze ans révèle que la hauteur annuelle et la valeur journalière maximale de précipitations ont enregistré des maxima durant les décennies 1930 et 1950 et un minimum durant les années 1940. La précipitation de la saison de croissance a atteint un maximum pendant les années 1930 mais autrement n'a pas beaucoup changé. Une réduction des précipitations hivernales est la cause principale de la diminution du total annuel depuis le début des années 1950. La variabilité d'une année à l'autre du total annuel des précipitations a augmenté dans la deuxième moitié de la période d'étude. Les tendances à Victoria ne représentent pas nécessairement les autres régions de la Colombie Britannique.

1. INTRODUCTION

The annual means of observed climatic parameters vary from year to year and often show increasing or decreasing trends over time. Information on these variations and trends not only adds an interesting and important dimension to the climatic description of a region but is also useful in many areas of applied climatology.

The purpose of this note is to describe recent trends and variations in measured precipitation at Victoria, British Columbia. Precipitation influences many important segments of the local economy including agriculture, forestry, and tourism and year-to-year variations are important in a relatively dry area such as Victoria. Discussion of Victoria's precipitation trends is not new. Crowe (1963) and Powell (1965) presented the trends in annual total precipitation at Victoria Gonzales Heights through the year 1960. Powell (1965) included several other British Columbia stations and seasonal precipitation as well. Thomas (1975), utilizing 1940–1974 data, indicated trends for regions of Canada including southern British Columbia. The study presented here extends the time period to 1987 and expands the coverage to include maximum one-day precipitation.

2. METHODS

Victoria lies in the rain shadow of the Olympic Mountains and Vancouver Island (Kerr, 1951, and Figure 1) and has a relatively low annual total precipitation

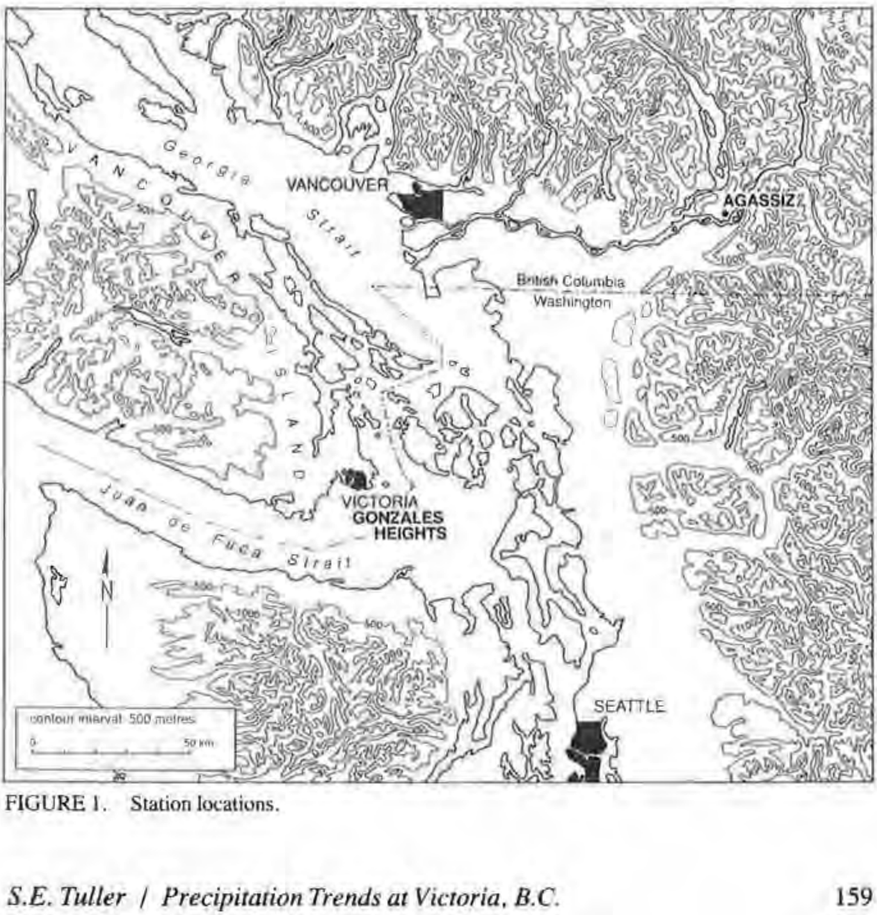

FIGURE 1. Station locations.

TABLE 1. Stations and their precipitation regimes (1914–1987).

	Victoria Gonzales Heights	Agassiz
Latitude (North)	48° 25′	49° 15′
Longitude (West)	123° 19′	121° 46′
Elevation (m)	69	15
Mean annual total precipitation (mm)	655	1647
Percentage falling November–February	61	50
Percentage falling May–September	16	23

(Table 1) compared with other stations on the British Columbia coast. The Victoria Gonzales Heights weather station has a long precipitation record for Canada's west coast (1914–1987). Although changes in the surroundings of the gauge cannot be discounted, the station remained at one site for 74 years. Most other west coast stations with a similar record length have experienced some shift in gauge location during this period (Atmospheric Environment Service, 1981). The station was situated on a small hill near the shore of the Strait of Juan de Fuca in the southeastern portion of the Victoria metropolitan area. Downtown Victoria is located about 3 km to the WNW of the station. Surface winds during most precipitation events come from the Strait of Juan de Fuca limiting the effect of urban influences on precipitation trends.

Although the focus of this study is Victoria, it is of interest to compare the trends at Victoria with those of another location. Agassiz, located in the Fraser River Valley about 100 km east of Vancouver, has a precipitation record dating back to 1890. Nearby mountains create orographic uplift and Agassiz has a higher annual total precipitation than Victoria (Figure 1, Table 1). Both stations have a winter precipitation maximum but the influence of the sub-tropical high pressure cell and the stabilizing effect of nearby ocean surfaces are a greater limitation for summer precipitation at Victoria. Therefore, Victoria's seasonal precipitation variation is more pronounced (Table 1).

Three precipitation parameters are emphasized. Annual total precipitation indicates the overall supply of moisture to the area over the year. May–September precipitation falls during the bulk of the growing season and the peak of tourist activity. Tuller (1987) found that maximum one-day precipitation was a good indicator of major precipitation events. The maximum one-day precipitation recorded in each year, therefore, is used to represent the amount of precipitation brought by the most intense storm of the year. The precipitation recorded in one climatological day is used. Although the amount over a 24-hour period would be preferable because heavy precipitation can straddle the time of observation separating two climatological days, the length of the recording rain gauge record was too short for use in this study. The trends of maximum two-day precipitation are the same as those of one-day, indicating that the parameter presented here should be a representative measure.

Annual values and unweighted eleven-year moving averages are plotted. The eleven-year period is long enough to smooth out very short period variations, yet short enough to indicate important cycles within the 74-year record. It is between the five- and thirty-year moving averages given by Powell (1965) and does not repeat his analysis but provides additional information and a gradient in smoothing when used in conjunction with his study.

3. RESULTS

Annual Total Precipitation

Annual total precipitation at Victoria was above the long-term mean and the eleven-year moving average had maxima at three times: 1) the late teens, early 1920s; 2) the 1930s; and 3) the late 1940s through the early 1960s (Figure 2). Powell (1965) shows additional maxima in the Victoria record centered on about 1895 and 1910. The movement of the station in the pre-1914 period contaminates the record, however, and some of these early fluctuations could result from differing station location (for a record and description of early location changes see Atmospheric Environment Service, 1981; Victoria Weather Office, 1975).

Precipitation was below average during: 1) the late 1920s, and 2) the early 1940s. The eleven-year moving average has declined since the peak in the early 1950s and year-to-year fluctuations have increased.

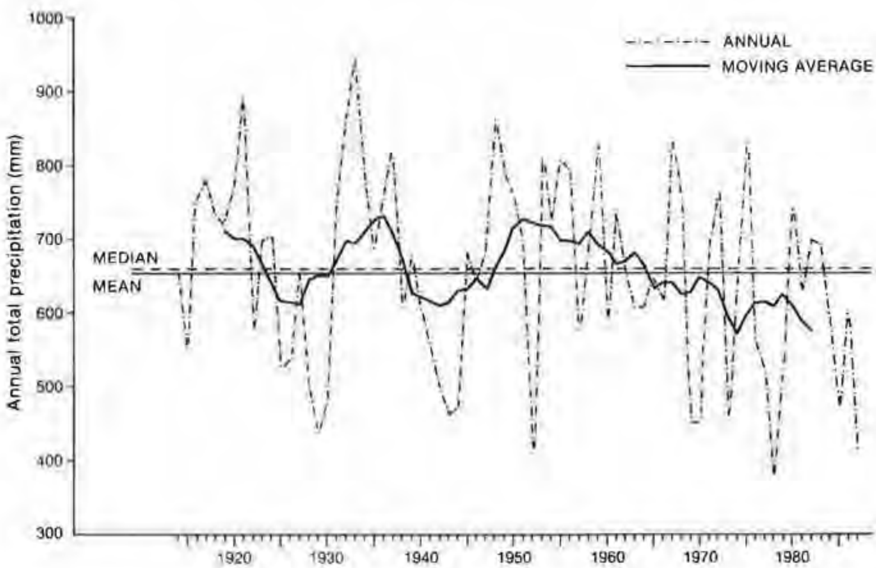

FIGURE 2. Yearly total and eleven-year moving average of annual total precipitation, Victoria Gonzales Heights (mm), 1914–1987.

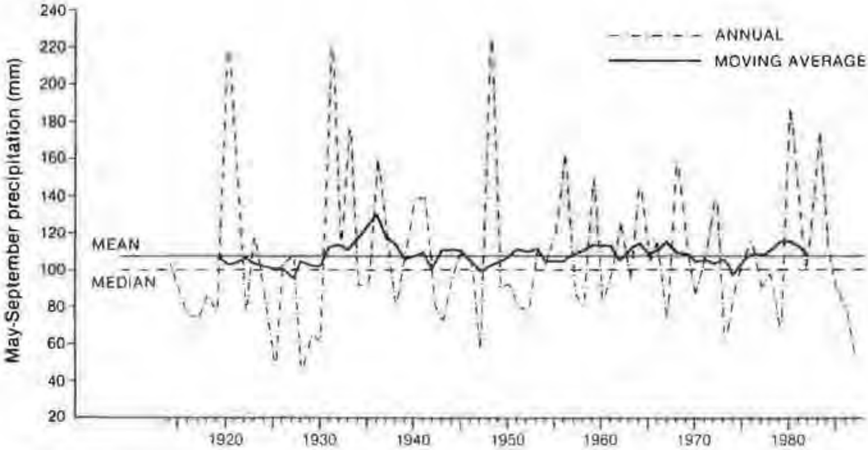

FIGURE 3. Yearly total and eleven-year moving average of May–September precipitation, Victoria Gonzales Heights (mm), 1914–1987.

Growing-Season (May–September) Precipitation

Victoria's growing-season precipitation displays a great deal of year-to-year fluctuation but except for a maximum centered on 1936 there has been little change in the eleven-year moving average (Figure 3). This is consistent with Powell (1965) who noted more uniform trends in summer precipitation than in annual or other-season precipitation at several B.C. stations.

The latest position of the eleven-year moving average is within 0.7 mm of the long-term mean. The recent decline in annual precipitation has not been seen in growing-season precipitation. One of the driest but also two of the wettest growing seasons on record occurred during the 1980s.

Maximum One-Day Precipitation

The eleven-year moving average of maximum one-day precipitation at Victoria shows three maxima: 1) the mid-1930s, 2) the 1950s, and 3) the late 1970s, early 1980s (Figure 4). Minima occurred in: 1) the 1940s, and 2) the 1960s through early 1970s.

With the exception of the lack of the 1920s maximum, the trends in one-day precipitation are similar to those of annual precipitation until the late 1960s. After this time the moving average of annual precipitation continued downward, whereas that of one-day precipitation moved upward to a new peak in 1980.

4. DISCUSSION

The trend in the eleven-year moving average of annual total precipitation at Victoria Gonzales Heights has been downward for the last 35 years (Figure 2).

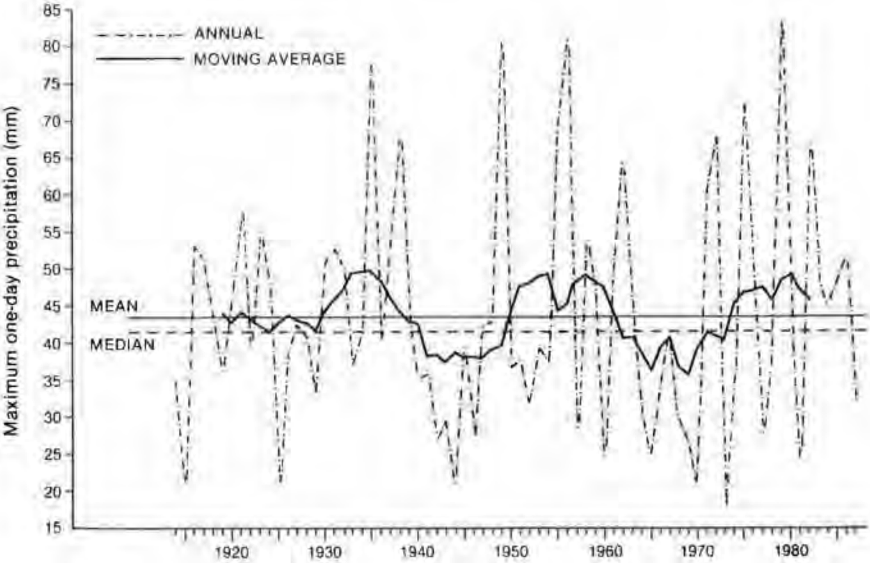

FIGURE 4. Yearly total and eleven-year moving average of annual maximum one-day precipitation, Victoria Gonzales Heights (mm), 1914–1987.

This is not reflected in growing-season or maximum one-day precipitation, however, which are both at or above the long-term mean (Figures 3 and 4). This indicates that the trend in one precipitation parameter is not always the same as that of another. It also suggests that the recent decline in annual precipitation is mainly a result of a decline in winter precipitation from storms of low to moderate intensity. This supposition is supported by the trends in winter (November–February) precipitation which closely follow those of annual precipitation (Figure 5).

The year-to-year variability of all precipitation parameters is quite high. The autocorrelation coefficients between precipitation in adjacent years are: annual, +.34; winter, +.25; May–September, −.05 and maximum one-day, +.05. The growing-season or one-day precipitation received in one year has virtually no relation with that recorded the previous year. The autocorrelation coefficient of winter precipitation at Victoria, however, is somewhat greater than those reported for 20 California stations (Granger, 1979).

The year-to-year variation of annual precipitation has increased since the early 1950s (Figure 2). The one-year lag autocorrelation coefficient for the first half of the record (1914–1950) is +.56. That for the second half is only +.08. The probability of a year with annual total precipitation greater or less than the long-term median being followed by a similarly wet or dry year was .70 during the 1914–1950 period. The probability declined to .54 in the second half of the record.

Although a detailed analysis of regional precipitation trends and

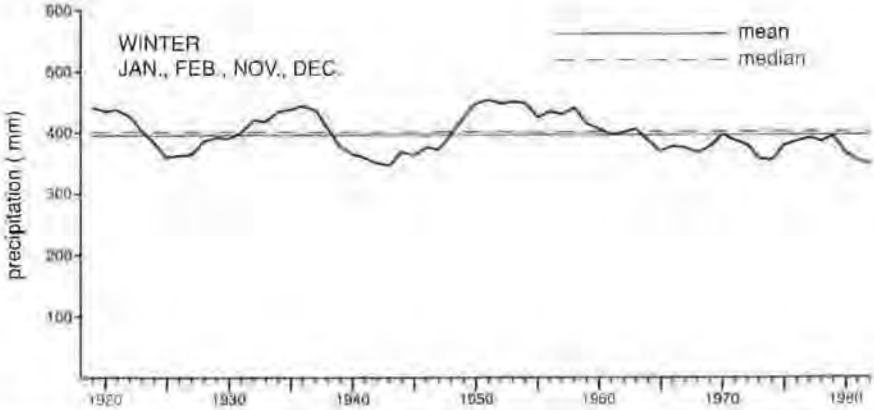

FIGURE 5. Eleven-year moving average of winter (November–February) precipitation, Victoria Gonzales Heights (mm).

variability is beyond the scope of this study, it is of some interest to compare the patterns at Victoria Gonzales Heights with those in other areas. Thomas (1975) presented ten-year moving averages of annual total precipitation for various regions of Canada utilizing data from 1940 through 1974. Ten- and eleven-year moving averages give similar results allowing direct comparison.

The moving average for Gonzales Heights over the 1940–1974 period most closely resembles those of Thomas's two Prairies regions even though Gonzales Heights was one of the three stations used to determine the pattern for his Pacific region.

This similarity does not extend back to the 1930s, however. The Prairie provinces (especially Saskatchewan) and the central United States experienced drought during the 1930s (Hare and Thomas, 1974). This was a relatively wet period in much of British Columbia, however (Crowe, 1963; Powell, 1965). In Victoria, the moving averages of precipitation were well above the long-term means (Figures 2, 3, 4 and 5). The highest annual total precipitation on record at Gonzales Heights (945 mm) occurred in 1933, and all annual totals were above the mean from 1931 through 1937.

A more localized and detailed comparison can be made with Agassiz which has a record length comparable with that of Gonzales Heights. The eleven-year moving average of annual total precipitation at Agassiz follows the same pattern as that of Victoria Gonzales Heights up to the 1950s (Figures 2 and 6). The relative magnitudes differ, however. The Agassiz moving average was lower relative to the long-term mean from the late 1920s through the mid-1940s. This same difference is seen in growing-season and maximum one-day precipitation (Figures 3, 4 and 6).

The year-to-year variability of annual total precipitation at Agassiz, like that at Victoria, has been greater since 1950 (one-year lag autocorrelation coefficients: 1914–1950, +.52; 1951–1987, −.21). Agassiz, however, lacks the steady decline in the eleven-year moving average of annual total precipitation during the second half of the record. The only pronounced recent change was a rapid decline in the eleven-year moving average in the early 1970s. Winter

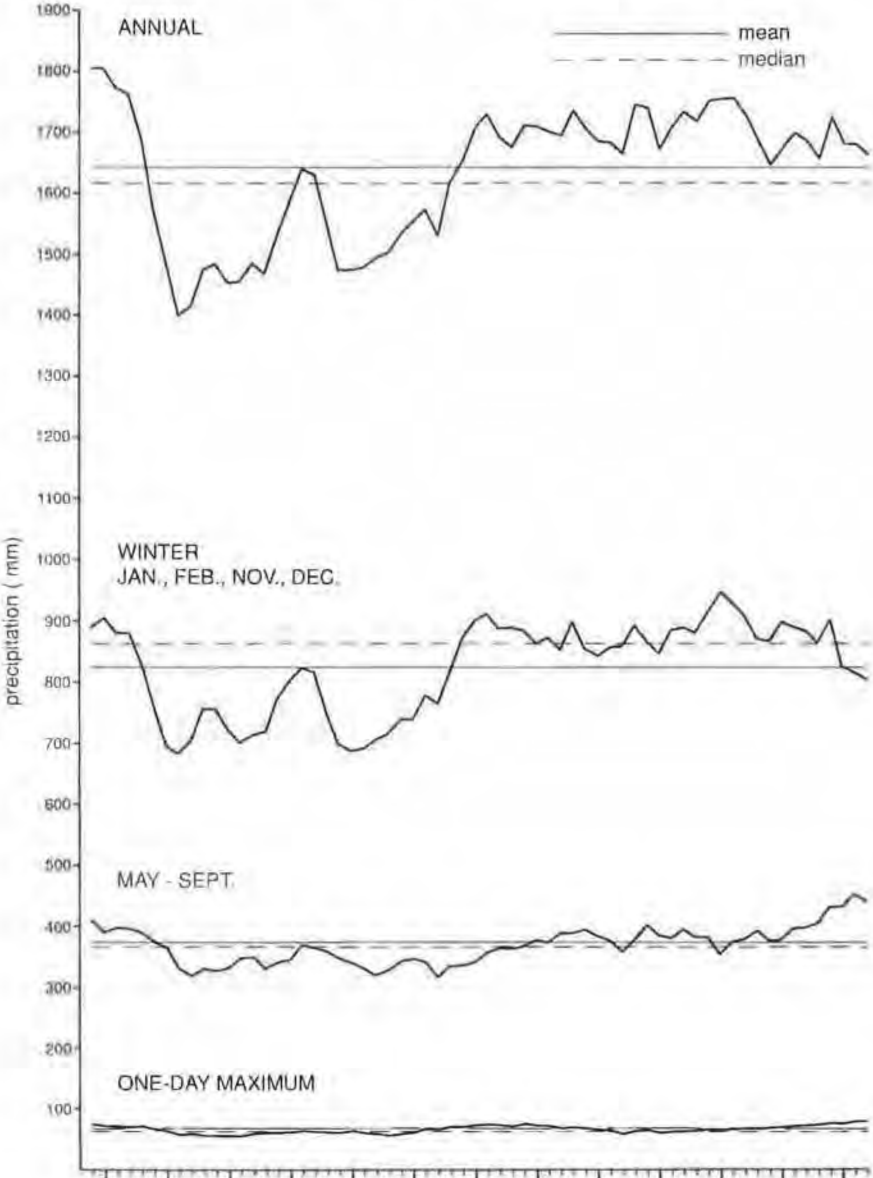

FIGURE 6. Eleven-year moving averages of different precipitation parameters at Agassiz, B.C.

precipitation is now lower than it was in the early 1950s. This decrease has been matched, however, by an increase in growing-season precipitation which, although it dates from the late 1940s, has been especially rapid since the early 1970s (Figure 6). Victoria experienced a decline in winter precipitation equal to that at Agassiz but no compensating increase in summer precipitation.

Victoria International Airport also has experienced a decline in annual total precipitation since the early 1950s although of lesser magnitude than that at Gonzales Heights. Thus, the decline is not confined to a single station in the Victoria region but its severity does vary throughout the local area.

Comparisons with both Thomas' (1975) regional patterns and the Agassiz data suggest that the precipitation trends at Victoria are not necessarily representative of other regions of British Columbia. Regional variation is to be expected throughout B.C. because of the complex interaction of the effects of latitude, local and regional relief and surface-type differences on precipitation trends.

SUMMARY

Annual total and winter precipitation at Victoria have decreased and variability has increased in recent years. No decline in growing-season or maximum one-day precipitation has occurred, however. A detailed analysis of the causes of the fluctuations in Victoria precipitation is beyond the scope of this paper. The results, however, suggest that one possible contributing factor is the frequency and/or duration of winter storms. Winters with the sub-tropical high pressure cell located well to the south of B.C. and a zonal flow in the upper-air westerlies have a steady series of mid-latitude cyclonic storms. Persistent upper-air ridges and a northward extension of the sub-tropical high pressure cell over the west coast divert storms to the north and limit winter rainfall (Namias, 1978; Pittock, 1977). More recent studies have further highlighted the importance of the adjacent air pressure pattern and position of the storm track for winter precipitation on the west coast. Relations with central North Pacific air pressure anomalies and teleconnections with other parts of the Pacific have also been suggested (Cayan and Peterson, 1989; Yarnal and Diaz, 1986).

Unfortunately, precipitation observations ceased at Gonzales Heights in mid-1988 breaking the continuity of record and hindering analysis of continuing precipitation trends at Victoria.

ACKNOWLEDGEMENT

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Change in Frost Season Characteristics in Winnipeg, 1872–1988

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ABSTRACT

Temporal aspects of Winnipeg's frost-free season are examined for 0°C, −2.2°C and −4.4°C thresholds, using the daily record of minimum temperatures from 1872 to 1988. No change was found in the average date of last spring frost but a statistically significant increase in the average date of first fall frost is shown to have begun in the decade after 1910, producing a correspondingly longer average frost-free season from 1911 to 1988. For the 0°C threshold, the average first fall frost has occurred 10 days later after 1910 and the frost-free season has been 12 days longer. Frequency analysis indicates that from 1872 to 1910 early fall frosts were more common, and the relatively short return periods of August frosts make references to such exceptionally early events in documents from the nineteenth century more understandable.

RÉSUMÉ

On examine ici les aspects temporaux de la période sans gel à Winnipeg, en utilisant les seuils de 0°C, −2,2°C et de −4,4°C et les données des températures minimales quotidiennes de 1872 à 1988. L'analyse ne révèle aucun changement de la date moyenne du dernier gel de printemps, mais dès les années 1910 il y a eu un délai statistiquement significatif de celle du premier gel d'automne. Il en résulte que la durée moyenne de la période sans gel a augmenté de 1911 à 1988; pour le seuil de 0°C, le premier gel d'automne est arrivé en moyenne 10 jours plus tardif et la période sans gel a connu une augmentation de durée d'une moyenne de 12 jours. Les données nous montrent que la période 1872–1910 voyait plus fréquemment des gels au début de l'automne et même assez souvent des gels du mois d'août. On peut donc mieux comprendre les rapports de tels événements catastrophiques contenus dans certains manuscrits du dix-neuvième siècle.

1. INTRODUCTION

Winnipeg's location near the geographical centre of North America, its unmoderated continental climate, and its relatively long instrumental record (1872 to the present) make it an important site in western Canada for assessing climate change. In a study of frost-free seasons in thirteen cities across Canada, Nkemdirim and Venkatesan (1985a) found Winnipeg to be among a minority group of four cities whose mass curves of cumulative frost-free season length from 1881 to 1970 plotted as a straight line, and consequently they concluded that Winnipeg's average season length has not changed since 1881. This conclusion, which was restated in another paper by the same authors (Nkemdirim and Venkatesan, 1985b), is at variance with other evidence that Winnipeg has experienced a warming in this century, and in fact is not supported by the decadal averages for Winnipeg reported in their papers. A mass curve of their Winnipeg data drawn by this writer (Figure 1) indicates a distinct break in the slope of the line after 1910, such that the average annual frost-free season length changed from 114 days in the period 1881–1910 to 126 days from 1911 to 1970, an increase of 12 days or 10.5%. The mass curves of eight other cities in Nkemdirim and Venkatesan's 1985a study exhibited increases in slope (indicating increased season length) after about 1940. For all eight cities, the increases were determined to be statistically significant, but only Edmonton had a larger percentage increase (23.8%) than Winnipeg's post-1910 increase, and the absolute increase of 12 days for Winnipeg was exceeded by only three of the eight cities. Thus Winnipeg's post-1910 increase was greater in both relative and absolute terms than those in the majority of the cities found to have experienced a statistically significant increase after 1940, and Nkemdirim and Venkatesan's assertion that Winnipeg's frost-free season length has not changed from 1881 to 1970 seems questionable.

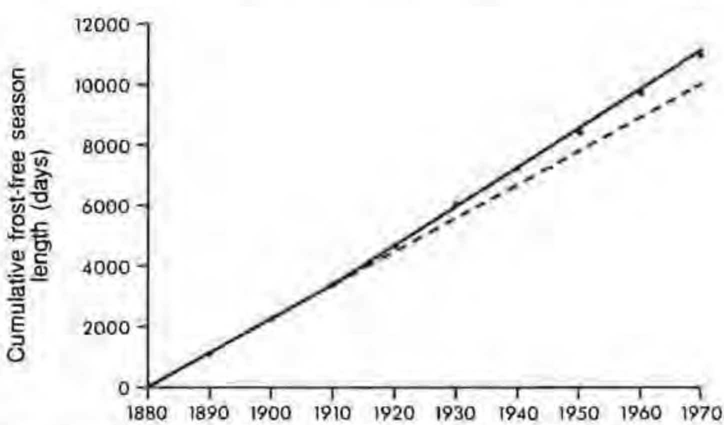

FIGURE 1. Mass curve of decadal average of frost-free season length (0°C minimum temperature) from data in Nkemdirim and Venkatesan (1985a).

This paper reexamines Winnipeg's frost season characteristics using the record of daily temperature minima from 1872 to 1988, a data set nearly 30% longer than that used by Nkemdirim and Venkatesan. Frost is normally defined by the occurrence of minimum temperatures equal to or less than a specific threshold, most commonly 0°C, −2.2°C or −4.4°C; each of these will be examined in this paper, although emphasis is placed on the 0°C minimum threshold used by Nkemdirim and Venkatesan.[1] Thus frost is defined here as the occurrence of a minimum temperature equal to or less than the stated threshold (0°C, −2.2°C, −4.4°C) and the frost-free season is the number of days between the last occurrence in the spring and the first occurrence in the fall of minimum temperatures equal to or less than the threshold.

[1] The threshold of 0°C *mean daily temperature* reported by Nkemdirim and Venkatesan in their 1985a paper should have read 0°C *minimum temperature* (Nkemdirim, personal communication).

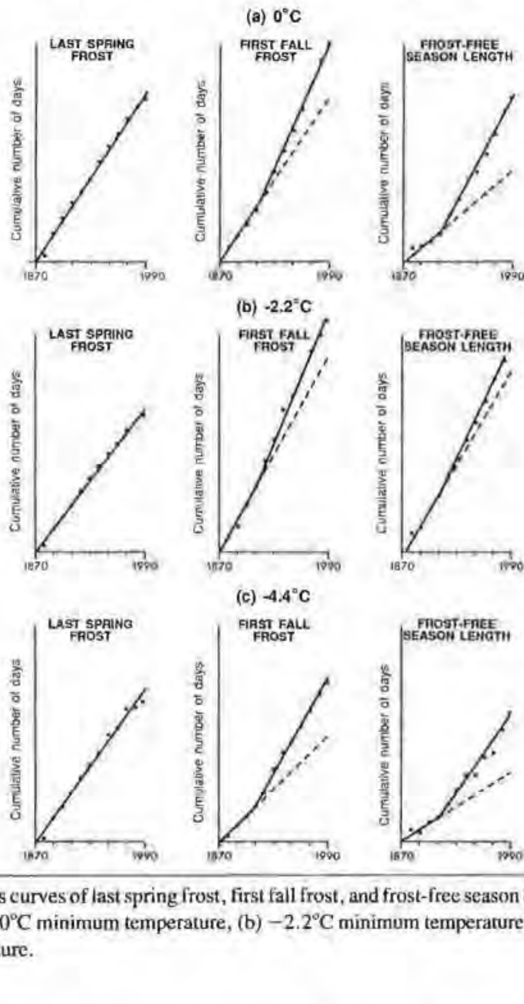

FIGURE 2. Mass curves of last spring frost, first fall frost, and frost-free season length in Winnipeg, 1872–1988 for (a) 0°C minimum temperature, (b) −2.2°C minimum temperature, and (c) −4.4°C minimum temperature.

2. ANALYSIS OF INSTRUMENTAL RECORD FOR WINNIPEG, 1872–1988

The mass curve is a useful graphical means of detecting non-homogeneity in climatological and other data. As used in this paper, the mass curve was prepared by accumulating the annual values of the variable in question (*i.e.* length of frost-free season) and plotting the cumulative annual total (Y value) against the year (X value). Homogeneous data yield a straight line through the origin ($Y = mX$), the slope m of which is equal to the average annual value of the variable. A change in slope which persists for a sufficient time indicates a change in the average annual value of the variable and the point of intersection of the two segments indicates the year in which the change occurred.

Mass curves of the last spring frost (LSF), first fall frost (FFF), and frost-free season length (FFSL) from 1872 to 1988 for all thresholds are given in Figure 2. The original data for all curves were compiled with annual LSF and FFF expressed as days after January 1 (including leap year days) and FFSL as the difference, in days. In order to make any change in slope relatively more apparent at publication scale, however, the annual values were reduced by a convenient constant number of days per year before drafting the curves in Figure 2. This treatment did not affect the absolute magnitude of any change which may have occurred. For all curves which displayed a change in slope, differences in mean values of the original data before and after the change were tested for significance by one-way analysis of variance. The results of this analysis are summarized in Table 1.

For the 0°C threshold, the mass curves of FFF and FFSL (Figure 2a) show distinct, persistent changes in slope beginning in the decade after 1910 such that average FFF occurred about 10 days later and average FFSL increased by 12 days (Table 1); both differences are significant at $p = 0.01$. The mass curve for LSF shows no persistent change in slope during the entire period and the difference in mean date of 2 days before and after 1910 is not statistically significant. Thus, virtually the entire change in FFSL after 1910 was caused by the later occurrence of fall frosts.

The −2.2°C and −4.4°C thresholds show similar patterns (Figures 2b and 2c). The mass curves for each indicate distinct but smaller changes in FFF and FFSL after 1910 but no change in the average date of LSF. Each indicates that later average post-1910 FFF accounted for virtually all of the increase in FFSL. Although the FFSL difference for the −2.2°C threshold was only 5 days and significant only at $p = 0.10$, the increase in FFF (5 days) was significant at $p = 0.05$ and both differences are accepted as real.

Mass curves of decadal mean minimum temperatures are given in Figure 3 for May, June, August, September and October. For all months except June, the mass curves indicate an increase in average minima after 1910 (or approximately 1895 for October). The differences between the pre- and post-1910 mean monthly minima are summarized in Table 1. The magnitudes of the increases

TABLE 1 Summary of Changes in Winnipeg Frost-Free Season after 1910

	Period I 1872–1910	Period II 1911–1988	Period II –Period I Difference	Significance of Difference
0°C Threshold				
Last spring frost (mean date)	May 27	May 25	−2 days	—
First fall frost (mean date)	Sept. 11	Sept. 21	+10 days	.01
Frost-free season length (days)	108	120	+12 days	.01
−2.2°C Threshold				
Last spring frost (mean date)	May 13	May 13	0 days	—
First fall frost (mean date)	Sept. 26	Oct. 1	+5 days	.05
Frost-free season length (days)	136	141	+5 days	.10
−4.4°C Threshold				
Last spring frost (mean date)	May 4	May 3	−1 day	—
First fall frost (mean date)	Oct. 7	Oct. 15	+8 days	.01
Frost-free season length (days)	156	165	+9 days	.01
Mean Minimum Temperature (°C)				
May	3.7	4.7	+1.0°	.05
June	10.0	10.4	+0.4°	—
August	10.5	12.0	+1.5°	.01
September	5.3	6.6	+1.3°	.01
October	−1.0	+0.7	+1.7°	.01

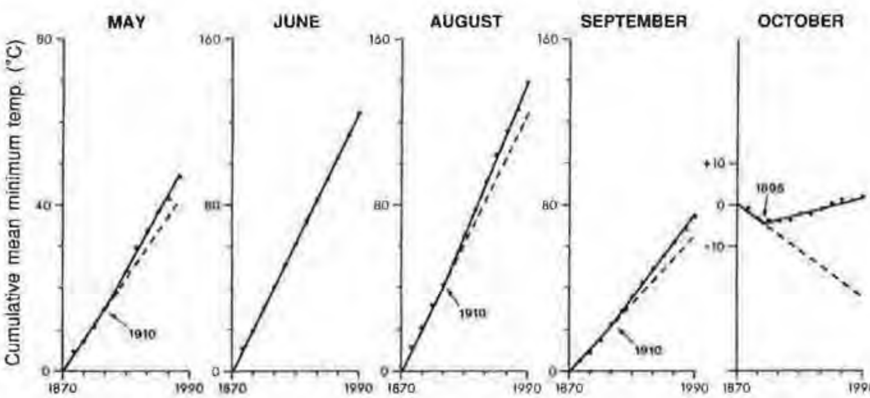

FIGURE 3. Mass curves of mean minimum temperature in Winnipeg, 1872–1988, for May, June, August, September, and October.

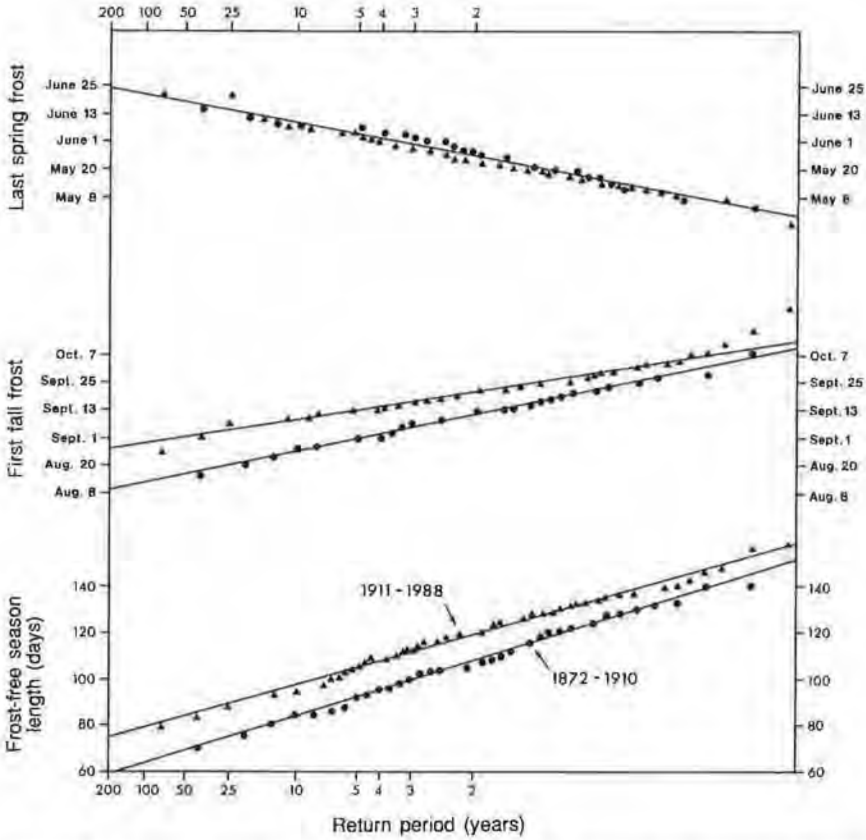

FIGURE 4. Frequency curves for last spring frost, first fall frost and frost-free season length (0°C minimum temperature) in Winnipeg, 1872–1910 (dots) and 1911–1988 (triangles).

TABLE 2 Comparison of 0°C First Fall Frost Dates at Selected Frequencies Before and After 1910

Return Period (years)	1872–1910[1]	1911–1988[1]	1951–1980[2]
100	August 13	August 29	—
50	August 16	September 1	—
25	August 20	September 4	—
10	August 26	September 9	September 8
4	September 2	September 14	September 17
3	September 6	September 16	September 18
2	September 11	September 21	September 21

[1] Figure 4, this paper.
[2] Current frost normals (Environment Canada, 1982).

were greatest in the late-summer and fall months. Both the mass curves and statistical tests indicate no significant change in average June minima and the increase in average May minima was apparently insufficient to significantly advance the average date of last spring frost at any threshold.

Frequency curves for LSF, FFF and FFSL at the 0°C threshold are given in Figure 4 for the pre- and post-1910 periods; all data are normally distributed. As would be expected from the mass curve analysis, the LSF data follow a single distribution from 1872 to 1988 but major differences exist between the pre- and post-1910 frequency curves of FFF and FFSL. For a given frequency, FFF dates were earlier prior to 1910 and the FFSL was shorter or, stated in reverse, relatively early FFF and short FFSL occurred more frequently prior to 1910. A comparison of FFF dates at selected return periods derived from the frequency curves in Figure 4 and from published current (1951–1980) frost normals for Winnipeg is given in Table 2.

3. DISCUSSION

This analysis directly contradicts Nkemdirim and Venkatesan's conclusion that Winnipeg has experienced no statistically significant trend in frost-free season length. The discrepancy arises from the fact that Nkemdirim and Venkatesan's mass curve for Winnipeg did not depict the change in slope after 1910, and consequently they only tested for a difference in average FFSL after 1940, the year when the majority of stations in their sample exhibited a change in mass curve slope.

The increases in the slopes of the mass curves after 1910 do not appear to be related to relocation of the Winnipeg station. Since the beginning of records in 1871, the station has been in four locations (Environment Canada, 1975): near what is now the centre of downtown Winnipeg (1871–1875), at St. John's College about 3 km to the north (1875–1932), at the Manitoba Agricultural College (now University of Manitoba) 8 km to the south (1932–1938), and at the Winnipeg Airport 7 km to the west (1938–present) The changes in FFF and temperature minima began within the period of stable location at St. John's College and the average slopes of the mass curves are consistent from the first decade of the change through the relocations in 1932 and 1938 to the present.

The effects of urbanization as a possible cause of the change are more difficult to assess. The change in FFF dates and temperature minima began during a period of exceptional urban growth in Winnipeg which saw its population increase from c. 44 000 in 1901, to 144 000 in 1911, 229 000 in 1921, and 295 000 in 1931. Much of this expansion occurred toward and beyond the St. John's College site, and the coincidence in the timing of the apparent climatic change and the growth in population might suggest that the change was primarily an "urban effect." Detailed examination of this question is beyond the scope of this paper but the absence of significant changes in spring frost dates is difficult to account for under an urban effect hypothesis. The relocations to the Manitoba

Agricultural College in 1932 and to the airport in 1938, both of which were essentially non-urban in character for several decades after, should have removed the urban influence and caused a shift in FFF back toward the earlier pre-urban dates. While FFF dates after these changes were somewhat earlier than during the period 1911–1930, the average dates at the 0°C threshold after the airport relocation were still 12 days later than those prior to 1900 before the major period of urban expansion occurred.

In a survey of climatic change on the Prairies, Longley (1977) noted a general tendency for increased summer minimum temperatures and longer frost-free seasons during this century. Curves of 10-year running means of average growing season (May–September) temperatures presented by Longley show that the variations at Winnipeg have been very similar to those of other stations in Manitoba and Saskatchewan; the similarity to the patterns at Morden, Russell and Indian Head is particularly noteworthy since these stations are closest to Winnipeg and none has experienced significant urbanization. For most of the stations in Longley's study, 10-year mean growing season temperatures were lowest near the beginning of record in the 10-year period ending just before or after 1910 and have fluctuated upward since. Nkemdirim and Venkatesan's data also provide evidence that other cities in western Canada experienced relatively shorter frost-free seasons prior to 1910. Although the major change in season length in Calgary and Edmonton occurred after 1930, the decadal averages reported for Calgary between 1881 and 1910 were the shortest in the entire period of record and Edmonton experienced very short average seasons in the decades 1881–1890 and 1901–1910. Data for Saskatoon are reported by Nkemdirim and Venkatesan only from 1901 onward but the average FFSL from 1901 to 1910 was 17 days shorter than the 1911–1970 average.

Independent phenological evidence in favour of a climatic change hypothesis is provided by the discontinuity in freezeup/breakup dates of the Red River in Winnipeg (Rannie, 1983). On average, the river has frozen 12 days later and cleared of ice 10 days earlier in the twentieth than in the nineteenth century, resulting in an average ice-free season which has been about three weeks longer. The breakup and freezeup dates suggest that March–April and October–November mean temperatures have been about 2.5°C warmer in the twentieth century. Rannie concluded

> While the period 1861–1880 appears to have been particularly severe, breakup and freezeup data provide no indication of significantly milder temperatures, averaged over a period of a decade or more, during the entire century. The change in the fall and spring climate at Winnipeg appears to have occurred relatively rapidly in the last years of the 19th Century and become most pronounced by the 1920's. (Rannie, 1983, p. 295)

While the earlier ice clearing date is not relected in average last spring frosts (perhaps because ice clearing is more related to maximum temperatures and river discharge), the later freezeup date is a direct function of minimum temperatures and is consistent with the sense of change implied by the fall frost and mean minimum temperatures described above.

Documents from the nineteenth century contain numerous references to frosts in August which are difficult to reconcile with climatic normals established from twentieth century data but which are not unusual when viewed in the context of pre-1910 frost conditions. Reverend William Cochran, an Anglican clergyman and agriculturalist in the Red River Settlement, reported that on August 19, 1832,

> This morning the air was excessively cold, a thick hoar frost covered the ground and the stagnant waters of the swamps were frozen . . . The potatoe tops are blasted. (Cochran, 1832.)

In 1836, again on August 19, Reverend David Jones observed

> we were visited by a most destructive frost which destroyed the reward of the farmer . . . in wheat; it was truly a gloomy morning the whole of the vegetable world drooped and blackened as the sun grew warm, and (the) air was filled with a most unpleasant odour . . . All garden seeds have been destroyed. (Jones, 1836.)

Although the minimum temperatures during these events are unknown, the references to hoar frost, frozen swamps and destruction of vegetation suggest that the 0°C threshold, at least, was reached. From the 1911–1988 frequency curve (Figure 4), a 0°C frost on August 19 would have a scarcely-credible return period in excess of 1000 years whereas the 1872–1910 frequency curve indicates a return period of only about 30 years. Many other frosts were reported later in August in the nineteenth century. For example, on August 24, 1863, Dr. W. Cowan wrote in his diary ". . . frost last night ground white this morning" and on August 27, 1853, he observed "Frost during night, rime seen . . ." (Cowan, 1871). If these events represented 0°C frosts, their return periods would have been 500 and 200 years respectively based on the 1911–1988 frequency curve but only 13 and 9 years based on the 1872–1910 curve. Thus, recognition that the distribution of first fall frost dates was different prior to 1910 makes nineteenth century references to August frosts more comprehensible, and, conversely, the number of such references lends support to the contention that a change in fall frost regime has occurred.

4. CONCLUSIONS

Mass curves of first fall frost occurrence for 0.0°C, −2.2°C, and −4.4°C thresholds in Winnipeg indicate that the average date of first fall frost from 1911–1988 was significantly later than from 1872–1910. At the 0.0°C threshold, the 1911–1988 average first fall frost was 10 days later than in the 1872–1910 period; in contrast, no statistically significant change has occurred in the average date of last spring frost during the entire 1872–1988 period of record. The later average first fall frosts after 1910 caused the frost-free season to lengthen correspondingly. Frequency curves of 0°C first fall frost for the periods before and after 1910 indicate that, prior to 1910, relatively early fall frosts occurred more frequently (*i.e.* had shorter return periods) and, thus, that the date of a frost with a specific return period was earlier. The changes in fall frost dates and consequently of frost-free season length do not appear to be related to changes in station location, and while urban expansion may have had some effect, the results are in general agreement with other evidence for a climatic change on the eastern Prairies around the turn of the century.

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News and Comments
Nouvelles et commentaires

1990 CANADA/UNITED STATES SYMPOSIUM ON THE IMPACTS OF CLIMATIC CHANGE AND VARIABILITY ON THE GREAT PLAINS, CALGARY, ALBERTA, September 11–13, 1990.

Report by E. Wheaton, Saskatchewan Research Council and R. Lawford, National Hydrology Research Centre, Saskatoon

The Great Plains region, including the three Canadian prairie provinces, is vulnerable to climatic variability and change. A symposium sponsored primarily by the Canadian Climate Centre, the Inland Waters Directorate and the National Climate Program Office of the U.S. National Oceanic and Atmospheric Administration was convened in Calgary to consider this issue. This symposium examined this sensitivity through plenary sessions and six working group sessions. The working group sessions were on agriculture, water resources, forestry, wetlands, wildlife, energy, recreation and rangelands. Plenary papers dealt with climatic variability and change, global climate models, climate change scenarios, impacts of climate variability, demographic responses to past climates, and response strategies. The working groups were tasked with indicating the state of knowledge, gaps in understanding and providing recommendations and research initiatives. The results of the working groups were presented, summarized and briefly discussed during the final day. Aspects and challenges unique to the Great Plains region were emphasized. This symposium will provide the basis for further integration of work on the impacts of climatic change and variability on the Great Plains. The proceedings will be available early in 1991. Another United States/ Canada Symposium on the Implications of Climatic Change and Variability for Pacific North West Forest Management will be held in Seattle in 1991. The conference statement follows.

CONFERENCE STATEMENT
Climatic Change Unites U.S./Canadian Plains

The impact of climate change in the Great Plains of North America was the theme of a recent symposium organized by Canadian and U.S. scientists. Impacts of Climatic Change and Variability on the Great Plains was held September 11–13, 1990, at the Westin Hotel in Calgary, Alberta, Canada.

More than 120 scientists, decision makers, and planners came to exchange information on potential impacts and management issues relevant to the resources of the region. Representatives from agricultural, water resources, forestry, rangeland, wetland, wildlife, energy and recreational agencies and groups addressed the vulnerability of resources in the region. They drew attention to the unique character of the Great Plains and the sensitivity of the region to climatic variation. Conference participants endorsed the development of a joint U.S./Canadian proposal for a combined effort to use climate information to strengthen the management of resources and to improve the effectiveness of social and economic structures of the Great Plains.

The symposium was designed to inform decision makers and managers of the latest climate research findings and to identify areas that would be most affected by future climatic variations, such as climate change due to increasing concentrations of greenhouse gases in the atmosphere. Specific recommendations to improve climatic research activities on the Great Plains included development of compatible resource data bases and improved monitoring of various resources; studies of soils, plants and water; enhancement and integration of computer tools from various resource areas; and increased emphasis on translating research findings to policy and everyday activities.

The symposium was sponsored by the Canadian Climate Centre and the Inland Waters Directorate (both of Environment Canada), the U.S. National Climate Program Office (National Oceanic and Atmospheric Administration), and the High Plains Climate Center (University of Nebraska).

CENTRE FOR CLIMATIC AND GLOBAL CHANGE RESEARCH

The Centre for Climate and Global Change Research, established in March 1990, at McGill University in Montreal is an outgrowth of the Climate Research Group (CRG), which was established in 1987 in cooperation with the Natural Sciences and Engineering Research Council and the Atmospheric Environment Service of Environment Canada. A major grant was awarded by these agencies to support the climate group at McGill, including two new faculty positions in the Department of Meteorology as Industrial Research Chairs in Climate Research.

The activities of the Centre have expanded from the original CRG focus of atmosphere-ocean climate modelling and data analysis to include studies pertinent to the recently established International Geosphere-Biosphere Program: A Study of Global Change (IGBP).

The two main objectives of the Centre are:

1. To promote research on the interactive physical, biological, chemical and socioeconomic processess that regulate our global environment, including the climate.
2. To provide a stimulating academic environment for graduate students and postdoctoral fellows in the emerging transdisciplinary field of "earth system science" and on the impacts of climate and global change on the environment and the economy.

To achieve these objectives, thirteen faculty members from the Departments of Meteorology, Geography, Renewable Resources and Economics have been brought together in the Centre's formation (March 1990). The research strengths of the Centre members are wide ranging and include: atmospheric and oceanic circulation; air-sea, air-land, and air-ice-sea interactions; climate cycles; cloud effects on climate; boundary layer meteorology; remote sensing; urban climatology; permafrost, soils and their relation to the environment; hydrology, biophysical interactions in the oceans, marine ecosystems, and fish-climate interactions; polynyas and sea-ice; and economic processes and climate change.

To tackle the fundamental problems of climate and global change in a focussed manner, the Centre faculty members have been grouped together into four teams as follows:

- Global climate modelling
- Biogeochemical and hydrological cycles
- Small scale and surface processes and their parameterization
- Impacts of climate and global change.

Associated with the Centre faculty are 38 graduate students (17 Ph.D., 21 M.Sc.) and 4 postdoctoral fellows.

Other activities of the Centre include the publication of a quarterly

Newsletter and a technical report series, and the sponsorship of Colloquium Series on climate and global change. The latter is designed to (i) bring in internationally renowned researchers to speak and interact with the graduate students and (ii) provide an opportunity for the Centre members to give overview seminars on their research work.

Gradaute student members of the Centre are registered in one of the four departments listed above. Potential new students are encouraged to contact the departmental chairpersons to obtain details about the graduate programs.

Dr. L.A. Mysak, Director
Centre for Climate and Global Change Research
McGill University

CLIMATOLOGY IN THE U.S. FOREST SERVICE

Some readers of *Climatological Bulletin* will be well aware of the diverse activities of the U.S. Department of Agriculture Forest Service Experiment Stations in terms of research in weather and climate and climate impacts. Others may not be. The purpose of this brief comment is to draw attention to the variety of climate-related work that is conducted at these Stations. Mentions of only a few projects and publications are possible here but they will serve as a useful introduction for readers who are not familiar with this source.

The nine Stations are distributed on a regional basis. The Southeastern Experiment Station, for example, covers Virginia and South Carolina, Georgia and Florida and is headquartered in Asheville, North Carolina. Each station publishes series of Research Notes, Research Papers and General Technical Reports, and puts out quarterly a list of publications. The various series cover a vast range of topics relevant to forest and range management.

Climate-related research reported includes forest microclimate, wind modelling over mountainous terrain, forest-fire meteorology, climate change, acid deposition, instrumentation, droughts, flood and storm events, and a host of other areas. A few examples of recent publications are listed below by title and source to indicate this diversity:

Verifying Eddy Correlation Measurements of Dry Deposition: A Study of the Energy Balance Components of the Pawnee Grasslands. Research Paper RM-288, Rocky Mountain Station, Fort Collins, Colorado, February 1990, 14 pp.

Critical Temperature: A Quantitative Method of Assessing Cold Tolerance. General Technical Report NE-134, Northeastern Station, Broomall, Penna., December 1989, 6 pp.

Firefamily 1988. General Technical Report NC-138, North Central Station, St. Paul, Minnesota, March 1990, 35 pp.

Estimating Lake Susceptibility to Acidification due to Acid Deposition. Research Paper NC-289, North Central Station, St. Paul, Minnesota, February 1990, 25 pp.

Sulfur Accumulation and Atmospherically Deposited Sulfate in the Lake States. Research Paper NC-290, North Central Station, St. Paul, Minnesota, December 1989, 7 pp.

Climate Change and America's Forests. General Technical Report RM-187, Rocky Mountain Station, Fort Collins, Colorado, February 1990, 12 pp.

MTCLIM: A Mountain Microclimate Simulation Model. Research Paper INT-414, Intermountain Station, Ogden, Utah, November 1989, 52 pp.

Variation in Damage from Growing-Season Frosts Among Open-Pollinated Families of Red Alder. Research Note PNW-RN-464, Pacific Northwest Station, Portland, Oregon, July 1987, 8pp.

Illustrating Harvest Effects on Site Microclimate in a High-Elevation Forest Stand. Research Note PNW-RN-466, Pacific Northwest Station, Portland, Oregon, August 1987, 10 pp.

Readers should be able to obtain addresses of the publication-dissemination centres for the various Stations from their local libraries. In most cases the publications are made available free of charge upon request, and the Station will put you on its mailing list for its publication announcements.

Alec Paul
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CLIMATE/AGRICULTURE SYMPOSIUM

A Symposium/Workshop focussing on: "Changing Climate in Relation to Sustainable Agriculture" will be held on 29–30 July 1991 at the University of New Brunswick, Fredericton, N.B. For further information, please contact the Symposium Chairman, Peter Dzikowski, in Edmonton:

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