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Bulletin climatologique

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La Société Canadienne de Météorologie et d'Océanographie

Information for Contributors and Subscribers

As a publication of the Canadian Meteorological and Oceanographic Society, the CLIMATOLOGICAL BULLETIN provides a medium of information on climatology. The Editorial Board gives special encouragement to the submission of manuscripts on applied climatology (e.g., agriculture, commerce, energy, environment, fisheries, forestry, health, recreation, transportation, and water resources), climatic change and variability, climate impact studies, climate model applications (including physical climatology), and regional studies (including ocean areas). It is published with the aid of a grant from the Government of Canada through the Natural Sciences and Engineering Research Council.

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Contributors should submit manuscripts to Alexander H. Paul, editor, CLIMATOLOGICAL BULLETIN, Department of Geography, University of Regina, Regina, Saskatchewan, S4S 0A2. All manuscripts should be typed double spaced on one side of good quality white paper, 28 cm x 21.5 cm, or its nearest equivalent. The abstract, list of references, tables, and a list of figure captions should be typed doubled spaced on separate sheets. Comments (including book reviews and opinions) and news items should not exceed 1 500 words. Furnish an original and three copies if possible, in the order listed below.

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Each TABLE should be numbered sequentially. Type all tables double spaced on separate sheets.

Authors should use the International System of units, but may show other units in parentheses. Authors should provide instructions in the margin for any special type required (Greek letters, capitals, bold face, etc.).

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

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

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Foreword / Avant-Propos

At the CMOS Congress at Winnipeg in June, the AGM voted to continue *Climatological Bulletin* for three more years and to review its publication again at that time. This is the support we needed to continue the journal expanding and improving. Keep those manuscripts rolling in, as well as news items and comments.

We welcome David Phillips, Richard Leduc and Stewart Cohen back to the editorial board, and thank André Hufty, Ken Drinkwater and Bonnie Magill, the retiring members, for their efforts.

Au congrès de la SCMO à Winnipeg en juin, la réunion générale annuelle a décidé de continuer le *Bulletin climatologique* trois années de plus, à laquelle date la Société évaluera encore une fois ses publications. Il faut toujours mentionner la nécessité de reçevoir de bons manuscrits si le Bulletin va consolider sa position, ce qu'il doit absolument faire suite à cette décision de la SCMO.

On accueille au Conseil de rédaction David Phillips, Richard Leduc et Stewart Cohen. Remercions André Hufty, Ken Drinkwater et Bonnie Magill qui ont complété leurs termes, pour leurs travaux.

Alec Paul
Editor/Rédacteur en chef

An Assessment of the 27-year Record of Measured Precipitation at Ocean Weather Station "P" in the Northeast Pacific Ocean

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[Original manuscript received 12 December 1990;
in revised form 7 March 1991]

ABSTRACT

Because of the almost total absence of ground-truth measurements, published charts of the precipitation climatology of the world's oceanic mid-latitudes show widely varying estimates, and nowhere is the disagreement more evident than over the North Pacific Ocean. There have been relatively recent attempts to improve the estimates, e.g. Dorman and Bourke (1979), by statistically relating present weather observations to rate of precipitation. Singularly absent in all investigations to date, however, is the use of a unique (for the high seas) 27-year record of precipitation amount at Ocean Weather Station "P" (50N 145W). This paper examines its credibility, from the point of view of instrumentation, exposure, observer expertise, and relative consistency with contemporaneous synoptic conditions. A proposal to test certain extraordinary features of the time series of annual precipitation is outlined. The paper suggests that the OWS "P" record of measured precipitation is a substantial improvement on previous estimates and that it should be given greater consideration for estimating the precipitation climatology of the northeast Pacific Ocean.

RÉSUMÉ

À cause du manque presque total des données de surface en haute mer, les cartes de précipitation des océans situés aux latitudes moyennes diffèrent beaucoup. Cela est encore plus vrai pour ce qui est de la portion nord de l'océan Pacifique. Récemment, on a tenté d'améliorer ces estimations. Par exemple, Dorman et Bourke (1979) ont analysé statistiquement les observations météorologiques courantes par rapport au taux de précipitation. Toutefois, personne n'a encore utilisé les données de la Station météorologique océanique (SMO) "P". Les données de cette station située à 50°N 145°W

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couvrent une période de 27 années d'observation. Cet article examine donc la justesse de ces données sur les plans de l'instrumentation, de l'exposition, de l'expérience des observateurs et de l'harmonie relative avec les observations synoptiques actuelles. Nous y expliquons également les méthodes utilisées afin de vérifier les anomalies présentes dans la série temporelle annuelle de précipitation. À la suite de cette analyse, nous en venons à la conclusion que les données recueillies à la SMO "P" constituent une amélioration nette par rapport aux estimations précédantes et qu'à l'avenir nous devrions accorder une plus grande importance à ces données pour l'analyse des précipitations de la portion nord-est de l'océan Pacifique.

1. INTRODUCTION

Since the turn of the century, there have been numerous published estimates of the distribution of average annual and seasonal precipitation over the Northern Hemisphere's oceans, but unfortunately there is substantial disagreement, particularly in the extratropical latitudes. The discrepancies arise because of the almost total lack of observations of measured precipitation from surface-based platforms on the high seas. Estimates must therefore be made by indirect methods, which vary from one investigation to another, and there is virtually no single point "ground-truth" against which to compare them. These discrepancies reduce

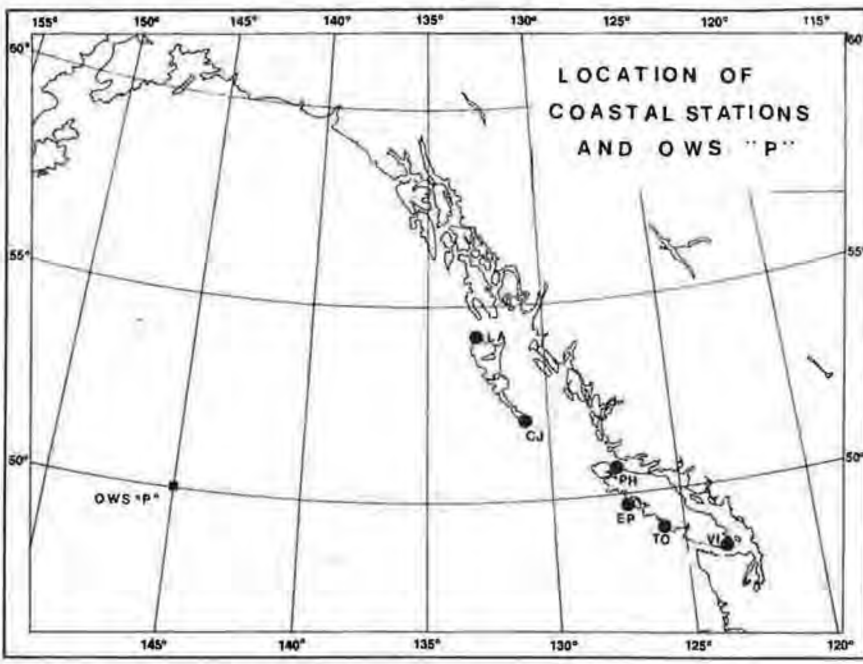

FIGURE 1. OWS "P" and coastal stations: Victoria (VI), Tofino (TO), Estevan Point (EP), Port Hardy (PH), Cape St. James (CJ) and Langara (LA).

confidence in calculations of the energy balance components of the earth-atmosphere system, and in the verification of mean seasonal and annual oceanic precipitation generated by Global Climate Models (GCMs).

The purpose of this paper, therefore, is to draw attention to a unique 27-year record of measured precipitation at Ocean Station "P" (50N 145W) in the northeast Pacific Ocean (Figure 1). It is evident from the literature that the existence of these data is not widely known, and so we shall attempt to provide background information. We shall also examine the climatological statistics of this record, and compare them with the results of other investigations which used indirect methods for measuring precipitation accumulation over the high seas.

2. A BRIEF HISTORY OF OWS "P"

An interesting history of the early days of ocean weather ship operations, and Canada's involvement in particular, will be found in Sobiski (1952). Most of the participating countries recognized the advantage, from a meteorological point of view, of strategically selected permanently fixed locations to be referred to as Ocean Weather Stations. The primary meteorological function of the ships was to provide a platform for eight surface observations (four synoptic and four 3-hourly) and two upper-air soundings per day. Usually it required two ships to operate the station, one to relieve the other, after patrols of approximately six weeks on station. Additional important functions included oceanographic and other scientific observations, search and rescue, navigational aids and communications.

Shortly after the Second World War, Canada and the United States agreed to the joint operation of Ocean Weather Station "Baker" strategically located on the North Atlantic at 56.5N 51.0W, in an area frequently traversed by intense winter storms. The Station was manned by the St. Stephen, a Canadian naval frigate, alternating with its USA counterpart, and observations began December, 1947.

Included in the Canada-USA agreement was a provision to share equally in the cost and operation of Ocean Weather Station "P" (henceforth to be referred to as OWS "P") located at 50N 145W, about 1,400km west of the outer coast of British Columbia. Manning of this station had been initiated by the USA, January 19, 1949, but it soon became obvious that, for economic reasons, each of the respective governments should operate one full station instead of two half stations. The resulting arrangement was for Canada to terminate its participation in "Baker" in June 1950 and subsequently to assume full-time operation of OWS "P" beginning December 1, 1950. The participating vessels, operated by the Canadian Coast Guard, were the St. Catharines and the Stonetown, formerly Royal Canadian Navy frigates of approximately 1,700 tonnes gross, subsequently modified and equipped for the purpose. They provided a remarkably trouble-free 16 years of operation.

In 1967 two new ships, the CCGS Vancouver (Figure 2) and its twin the CCGS Quadra, replaced the frigates. These vessels, designed specifically for

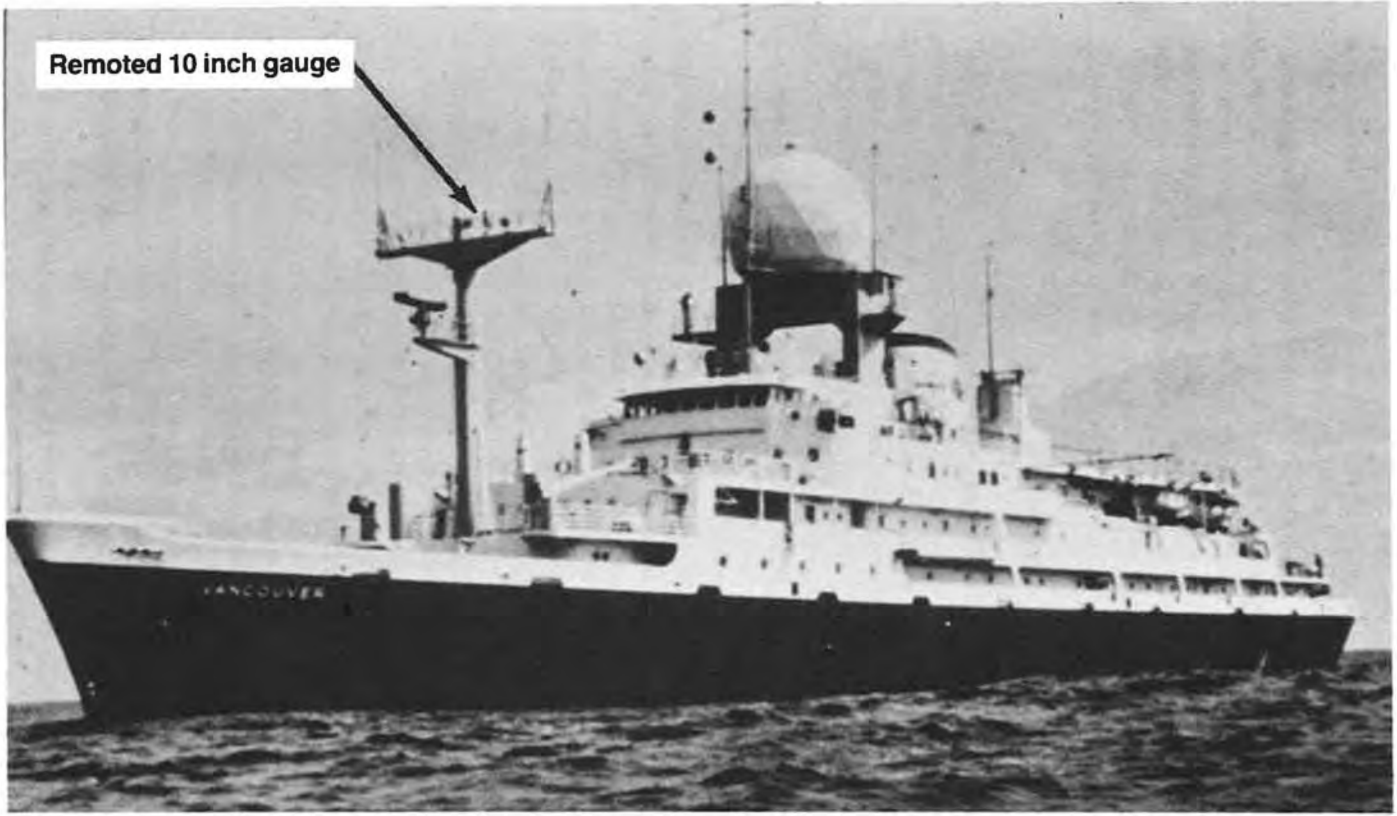

FIGURE 2. The VANCOUVER which, with its twin the QUADRA, manned OWS "P" 1967–1981. They replaced the ST. CATHARINES and the STONETOWN (1950–1967). For details concerning disposition of gauges on the new ships see text.

meteorological, oceanographic and coastguard functions, were much larger (some 6,000 tonnes gross) and provided improved amenities for the long sojourns over the often stormy waters of the northeast Pacific Ocean. Specifically, the Vancouver and Quadra began their first patrols April 7 and October 24, 1967 respectively, so that it was necessary for the frigates to continue in operation for part of that year. Thus 1968 marked the first full year during which OWS "P" was manned by the new vessels, and, except for the brief replacement of the Quadra by the Parizeau during the Garp Atlantic Tropical Experiment (GATE) program in 1974, they continued to do so until the termination of the Station June 30, 1981.

3. ESTIMATION OF PRECIPITATION OVER THE NORTHEAST PACIFIC

Because precipitation amount, with rare exceptions, has never been measured by ships on the high seas, estimates of its distribution over the oceanic mid-latitudes of the world, even to this day, vary enormously. Nowhere is this more evident than for the northeast Pacific Ocean where, for example, an interpolation from the results of Jacobs (1951) yields an annual precipitation at 50N 145W of about 1150 mm per annum, whereas the atlas of Drozdov and Berlin (1953) indicates 1900 mm per annum. Subsequent papers by Reed and Elliott (1973) and by Dorman and Bourke (1979), henceforth referred to as R-E and D-B, yield an annual mean precipitation at Station "P" of 960 mm and 1020 mm per annum respectively, a reduction of the Drozdov and Berlin estimate by nearly one-half and, for reasons to be presented later, a significant improvement.

4. PRECIPITATION MEASUREMENT AT OWS "P"

The reason for not measuring precipitation amount on the high seas was, and continues to be, a conventional wisdom that such measurements are hardly worth undertaking because of difficulties caused by factors such as ocean spray, moving platform, ship-induced turbulent eddies and so forth. In the words of Roll (1965) "this meteorological element has been treated like a stepchild of maritime [observations]". Consequently neither ships-of-opportunity nor weather ships (with very few exceptions) are, or ever have been, instrumented for measuring precipitation.

One of the exceptions was Ocean Weather Station "P" where, starting April 1953, 6-hourly precipitation amount was measured, recorded, and usually entered in the Meteorological Log as part of the concurrent synoptic observation. Thus, a record of 27 complete years (1954 to 1980) was acquired, and the original hand-entered data are still accessible from the archives of the Canadian Climate Centre. Considerable effort was expended to optimize the exposures, and, in the case of the replacement weather ships (the Vancouver and Quadra) to deploy the precipitation gauges in accordance with recommendations by the World Meteorological Organization (WMO, 1981). Moreover, OWS "P", during its entire history, was staffed by experienced meteorological technicians of the Atmospheric Environment Service (AES) and it should be accepted that observations were as accurate as possible given the difficult environmental factors.

Unfortunately, all files relating to the meteorological operation of OWS "P" appear to have been purged from the archives at AES Headquarters, Downsview, Ontario, and also from those at the AES Pacific Region, Vancouver, B.C. These included the "Voyage Reports" (submitted by the Meteorological Officer-in-charge at the end of each patrol) and the Port Met. Officer's "Inspection Reports". For this reason the author interviewed a number of meteorological technicians, meteorologists, and oceanographers, still active or retired, who at some time during their career were involved, directly or otherwise, with precipitation measurements at OWS "P". Much of what follows pertaining to instrumentation is based on these interviews.

5. EXPOSURE OF THE PRECIPITATION GAUGES

Before examining the record we should be aware of differences between gauge exposures on the frigates, from 1954 to 1966, and on the replacement vessels, from 1969 to 1981. The years 1967 and 1968 were transition years, 1967 because all four ships participated in operating Station "P", and 1968 because the intended gauge configuration for the new ships did not become operative until the following year. First it should be noted that detailed documentation and analysis of the measurement of precipitation on the Stonetown and St. Catharines from 1953 to 1962 is provided by Allen (1963) and we have no reason to believe that there were any substantive changes through to the year of their withdrawal in 1967. On these frigates, it was not possible to mount the gauges higher than 12 metres above the sea, and so in heavy seas and strong winds there was always the possibility of the gauge catch being augmented by sea spray. There were three standard 3-inch gauges located on each frigate, and of these, Allen chose fixed gauge "B" on the St. Catharines and "F" on the Stonetown (noting the similarity of their mounting and exposure) to provide a continuous record of precipitation amount. He remarked that "in the stormier months, October through April, the catch from these gauges is probably too high due to tilting in high winds and the addition of sea spray".

It would seem that by measuring the salinity in precipitation catches it would have been possible to approximately determine the error caused by sea spray, and indeed 200 samples were analyzed in the oceanographic laboratory aboard the Vancouver during cruises in 1967 and 1968. These were the transition years when, for reasons indicated later, precipitation gauges, even on the new ships, continued to be subject to sea spray contamination. Unfortunately, the salinity analysis documentation appears to have been a victim of the aforementioned archive purges. However, we are informed by the oceanographers that a systematic correction would have been difficult to implement because the salinity in a precipitation sample would not necessarily be attributable entirely to spray. Wind-blown salt crystals from accretions on the ship's superstructure and deposited into the gauge could make significant contributions, a view that was confirmed by the findings of Skaar (1955). For this reason, it was learned from the interviews, correction for possible sea spray contamination was never introduced.

The gauges on the Vancouver and Quadra were located as high as possible to avoid the problem of sea spray and to be well removed from turbulent eddies from the ship's structure. They were initially 3-inch standard gauges placed rigidly on the catwalk atop the foremast, some 30 metres above the sea, thereby virtually eliminating the spray problem; but it was soon found that in heavy seas they were not only difficult, but dangerous to access. During the first complete year of operation, 1968, it was necessary to position accessible gauges (a) above the wheel-house on the Quadra, and (b) aft of the funnel on the Vancouver in order to measure 6-hourly amounts. In January 1969, fixed 10-inch diameter gauges were installed on the foremast catwalk (Figure 2) and these in turn were connected by a non-wetting teflon-coated tube to a graduated container below deck. The 3-inch gauges were retained for comparison. The remoted system became operational and remained in place through to June 1981, except for the period April to August, 1974, when the Quadra was taken off station for the GATE project, and the oceanographic vessel, the Parizeau, took its place.

Intuitively one might conjecture that a reduction-of-catch error would be introduced by the increase in sway of the platform occasioned by the higher location. It turns out that, theoretically at least, this would not be the case. Skaar (1955) came to the conclusion that during periods of strong winds, an overcatch would be more likely. His mathematical analyses took into account the pitch and roll of the gauges, wind speed and direction, and the ship's speed and heading. The overcatch would be minimised (to about 10%) by manoeuvres typically carried out during stormy weather. This theoretical result appeared to have some support from the results of Allen (1963) who compared observed precipitation catches with wind speed (5-knot class intervals) on the older vessels. He showed that the mean catch was "considerably greater for high wind speeds than for intermediate or low speeds" but added that it was impossible to determine the extent to which the increased catch was attributable to high winds because it was precisely during those events that accretion by sea spray was likely. Since this was not a problem with the new ships, it is recommended that the comparison be repeated for the period 1969 to 1980.

It could also be argued that some attenuation of the catch might have occurred due to evaporation as the water descended through the final length of the tube into the ship's warmer environment below. To determine if this might have caused significant loss, the procedures were as follows: (1) On the Quadra, the standard 3-inch gauge remained mounted on the foremast catwalk and was used for comparison. Every 24 hours, weather permitting, the mast was climbed, and the accumulated precipitation manually measured and recorded in the Weather Log synoptic. (2) On the Vancouver, the 3-inch gauge on the platform aft of the funnel (facetiously referred to as "monkey's island") was used in a similar way. Comparison of the respective results indicated no evidence of significant undercatch by the operational system. Moreover, none of those AES interviewees who had served on station appeared to have the impression that there was an undercatch occasioned by the change in gauge exposure on the new weatherships.

6. RESULTS AND DISCUSSION

A time series of the annual precipitation amount measured at Ocean Station "P" from 1954 to 1980 is presented in Figure 3. The mean for the 27-year period is 590 mm, which is about 30% less than the aforementioned estimates of R-E and D-B. There is also a suggestion of two regimes, the first from 1954 to 1968, approximately stationary, with fluctuations about a mean of 650 mm, and the second from 1969 to 1980 showing a decidely upward trend but a much reduced mean of 530 mm. The two regimes appear to be separated by a striking change from 1968 to 1969, when there was a decrease of 255 mm. The precipitous decline "bottoms out" in 1970 and 1971 and then there is a steady increase to a value of 764 mm in 1980, the largest annual catch during the 27 years of record! It is clear

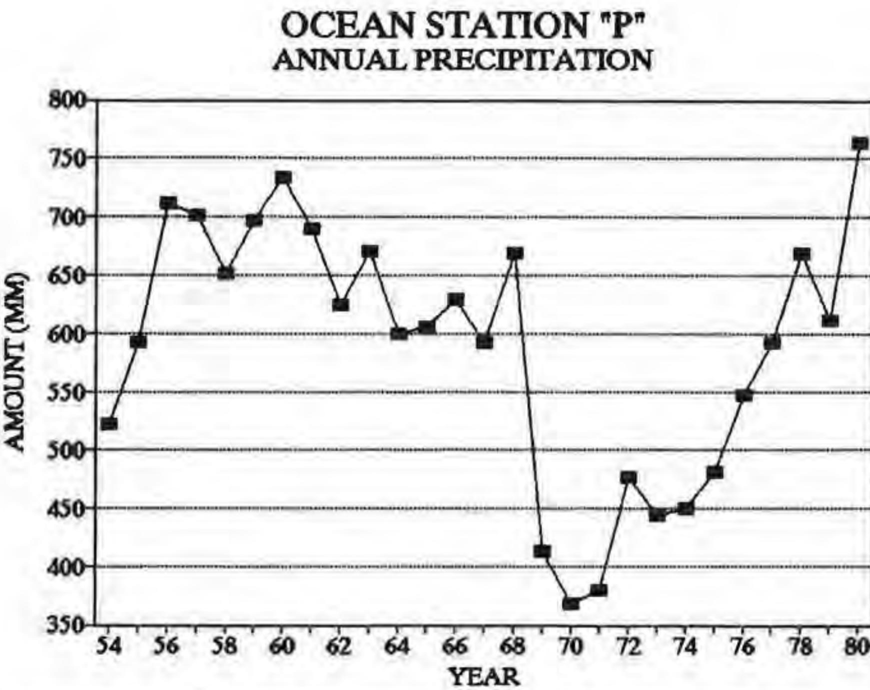

FIGURE 3. Time series of total annual precipitation measured at Ocean Weather Station "P" 1954 to 1980.

(Figure 4) that the primary contributors to the main features of the annual time series are fall and winter, the combined precipitation from which is displayed as "COLD SEASON".

Our initial reaction was to attribute the two apparently different precipitation regimes to changes in the precipitation gauge exposures described above, and, had the second regime been stationary about its mean, we would have been hard-pressed for an alternative explanation. However, the second regime was far from stationary, and clearly gauges with foremast exposure (unchanged from 1969 to 1980) were capable of measuring the largest annual catch. It is therefore possible that a contributing factor to the difference between precipitation regimes is short-period variation of the Pacific Ocean climate. Shabbar *et al*. (1990) presented strong evidence of decadal-scale change during the period 1946 to 1985 by demonstrating substantial tropospheric cooling over a vast east-west reach of the Pacific Ocean mid-latitudes (their Figure 5). Since precipitation amount is temperature-related it would not be inconsistent for the second regime to have a lower annual mean than the first.

During 1969, there were a few months when precipitation-inhibiting circulations appeared to occur with unusual frequency. The most striking case was

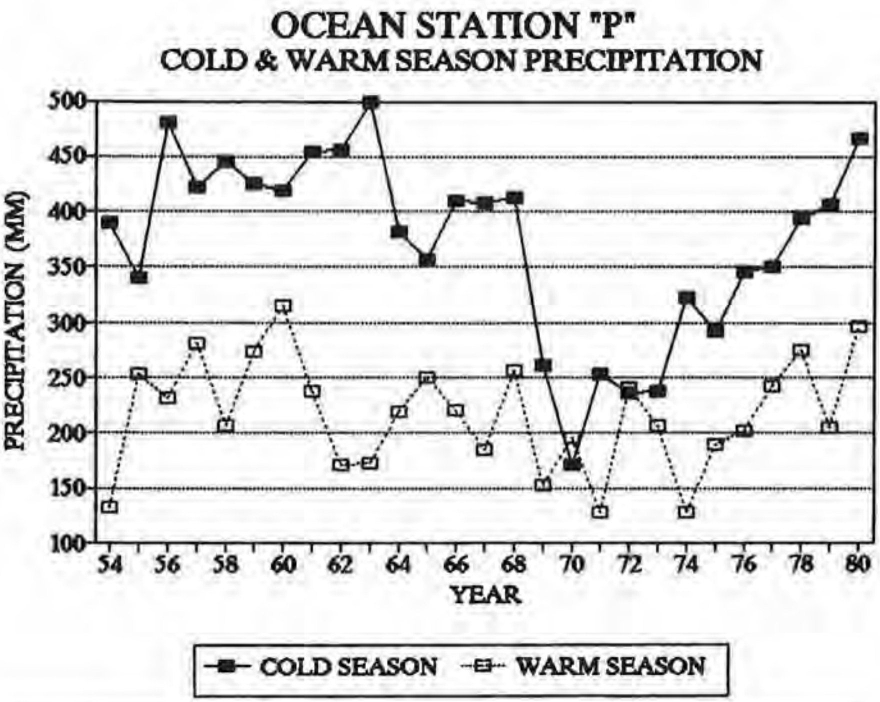

FIGURE 4. Time series of Station "P" precipitation: (a) COLD SEASON (Winter + Fall) and (b) WARM SEASON (Spring + Summer).

January 1969, when a strong blocking 70kPa ridge at 180W moved eastward to near 145W as the month drew to a close. The Weather Log shows that what little precipitation did accumulate at OWS "P" derived from brief showers of rain or snow, most of which occurred during the first half of the month. The total measured January precipitation was only 5.5 mm, or 9% of normal, the lowest during the 27-year record. An examination of the composited mean brightness photographs from the ESSA-7 satellite (Wagner, 1969) reinforces the evidence for a dry month over the Station "P" area.

It is of interest to note that circulation regimes giving rise to above-normal annual precipitation at OWS "P" in 1968, and below-normal in 1969 and 1970, appeared to influence the coast of British Columbia in a similar way. Victoria (Gonzales Heights), for example (Figure 5), experienced an above-normal year in 1968 (114%) while 1969 and 1970 (68.6% and 68.9%) were the second and third lowest precipitation years of the 1954–1980 period. Langara and Cape St. James, located respectively on the northern and southern extremities of the Queen Charlotte Islands, and Port Hardy, on the northern tip of Vancouver Island (Figure 1), all showed a similar annual precipitation sequence. However, it should also be noted that the below-normal annual precipitation at OWS "P" for

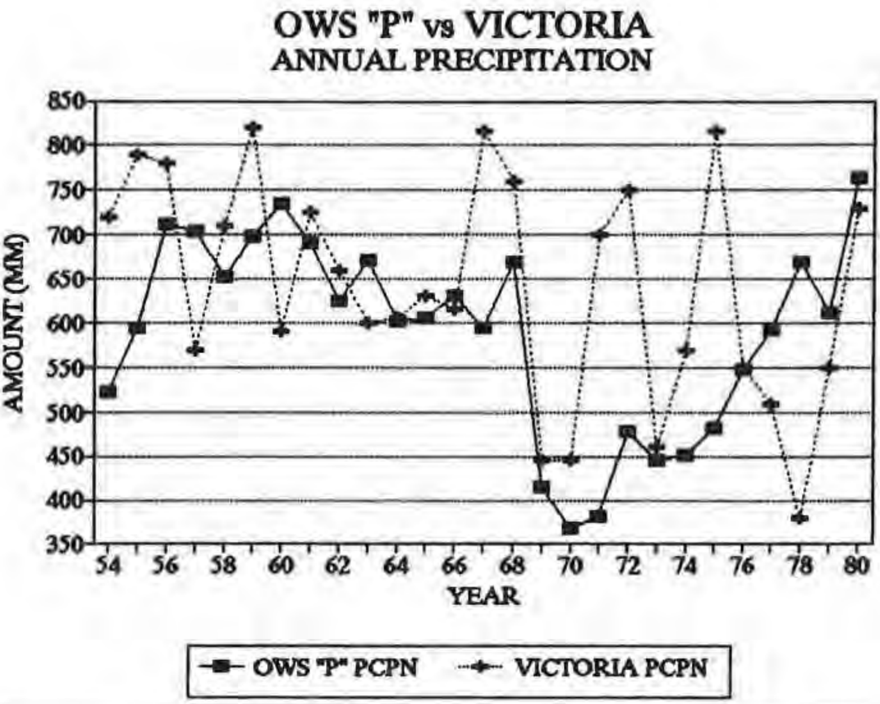

FIGURE 5. Comparison between annual measured precipitation at OWS "P" and Victoria (Gonzales Heights), B.C.

the period 1972–1975 did not persist at the above stations. During that time, they averaged near their long-term normals, and Victoria in particular (Figure 5) showed large fluctuations.

7. INDIRECT ESTIMATION OF PRECIPITATION AMOUNT

Because of the great paucity of precipitation measurements on the high seas, investigators have focused much attention on frequency of occurrence in attempts to derive climatological estimates of amount. To explore the relationship at OWS "P", we compared the frequency of occurrence of precipitation during a given month with the corresponding accumulation. The frequency count was made on the basis of whether or not precipitation was actually occurring at the time of the 3-hourly observation. Figure 6 shows the relationship, by month, between amount and frequency during the 27-year period, and it is noted that the correlations for February, May, July and December are particularly low. Clearly, estimating monthly accumulation of precipitation exclusively from frequency of occurrence is not likely to provide an accurate climatology, nor should we have expected otherwise. The interviewees often commented upon the high frequency of fast-

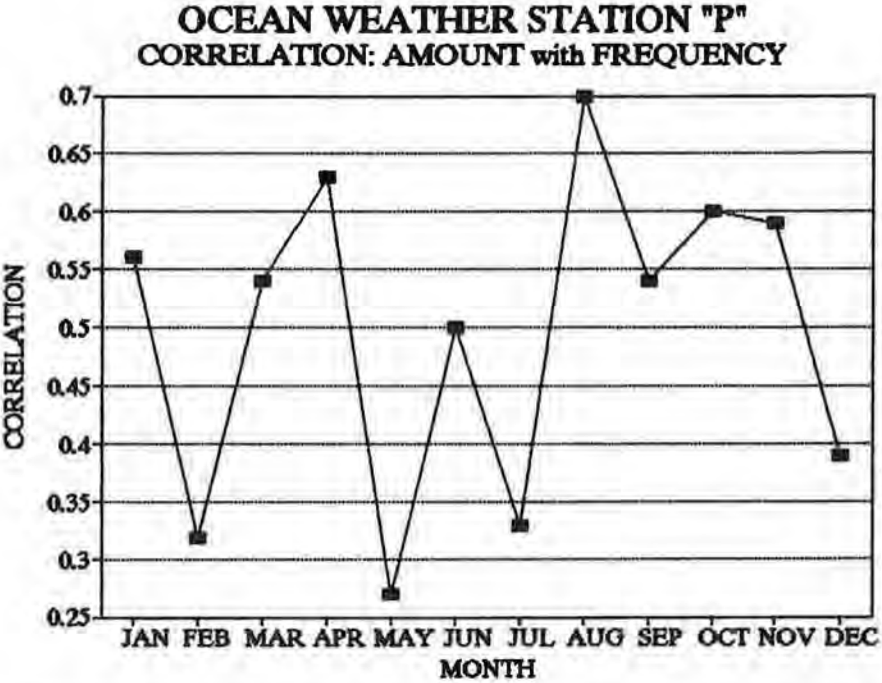

FIGURE 6. Coefficient of correlation between mean monthly measured OWS "P" precipitation and mean monthly frequency of occurrence.

moving light showers of snow or rain in cold-season circulations of unstable air to the rear of Gulf of Alaska cyclones. Because of their brief duration, accumulation was small, often unmeasurable, and therefore reported as a trace of precipitation. The high incidence of brief periods of light drizzle, particularly during the warmer months, added to the number of trace entries. Traces occurred on average 254 times per year, but because they individually are unmeasurable, their totality contributes zero to the annual accumulation. The annual total of these small amounts is probably significant, and to this extent the measured total falls short of the actual. Since the definition of a trace is an accumulation of 0.01 in, or < 0.254 mm, it might be reasonable to assume that, on average, the maximum possible error caused by not counting traces at OWS "P" is 65 mm per annum (254×0.254 mm) or about 10% of the normal.

Tucker (1961) developed a method of indirectly estimating Atlantic Ocean precipitation by taking into account not only frequency of occurrence but also its nature and intensity as described by the "present-weather" group of the synoptic report. For brevity, we shall henceforth refer to "present-weather" as "ww". (A brief outline of the Tucker technique is presented in Appendix I).

R-E applied the Tucker technique without modification to estimate

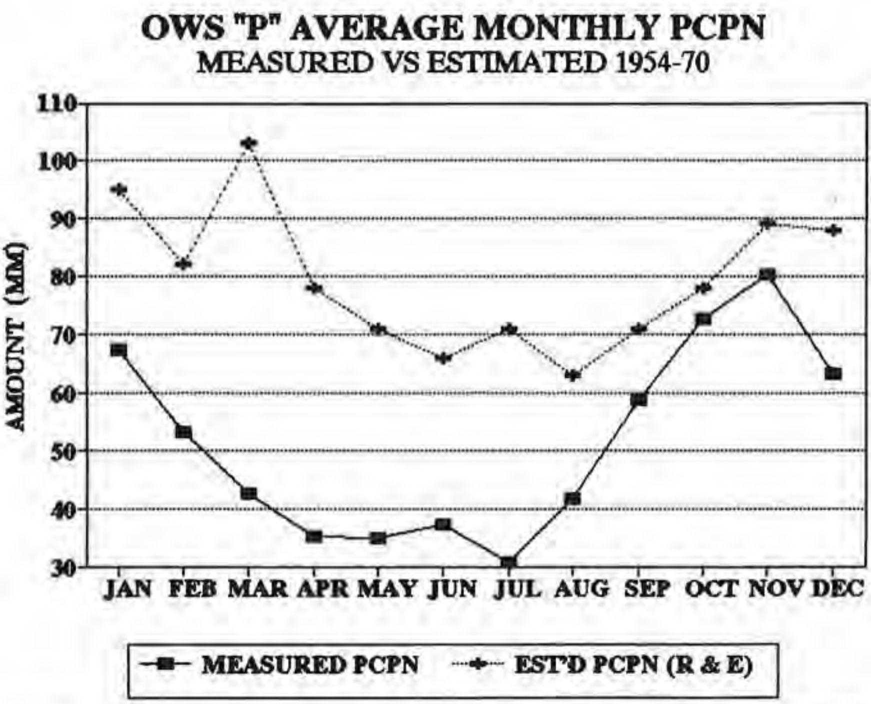

FIGURE 7. Comparison between the mean monthly measured precipitation at OWS "P" and R-E estimates for the period 1954–1970 (Reed and Elliott, 1973).

average monthly and annual precipitation at seven Pacific Ocean Weather Stations. One of these was OWS "P", from which, at the time of their study, there were available 17 years of 3-hourly synoptic data. A comparison between R-E estimates of the mean monthly precipitation at OWS "P" and those calculated from actual measurements for the period 1954–1970 is displayed in Figure 7. Except for approximate agreement in September, October, and November, R-E monthly estimates range from 20 to 60 mm greater than the measurements.

D-B questioned the universality of the Tucker parameters and found that when they were applied to stations in warmer latitudes, and particularly the tropics, there were large negative errors in precipitation estimates. Accordingly the Tucker technique was modified for air temperature and then applied to 23 years of synoptics from ships-of-opportunity. In this way they estimated rainfall distribution over the Pacific Ocean from 60N to 30S. Their result for the OWS "P" area was an annual average of 1020 mm. It came as a surprise to this author that the record of actual measurements of 6-hourly precipitation amount at OWS "P" received only passing comment from R-E, and none whatsoever from D-B.

One should be aware of the exposure of the land observing stations which Tucker chose to obtain the data required to calculate the parameters (i.e. the X, Y, Z rainfall rates shown in Table A of the Appendix). It is entirely conceivable that, for a given "ww", precipitation duration at several of his six stations located on the west coast of the United Kingdom was increased by coastal topographic effects. These, as shown by Bergeron (1949), can be substantial and in many cases identified separately from enhancement occasioned by inland orographic lifting. It is possible therefore that the R-E and D-B results may have a significant positive bias in the OWS "P" area. Nevertheless, their estimates, and also Tucker's for the North Atlantic, are probably a substantial improvement on the Drozdov and Berlin Atlas.

8. COASTAL GRADIENT OF ANNUAL PRECIPITATION AMOUNT

The coastal topographic effect which Bergeron demonstrated for Scandinavia has its counterpart along the coast of British Columbia. There is a striking difference between the annual mean measured precipitation at Station "P", 590 mm, and values typical of the west coast of Vancouver Island near 50N such as Tofino Airport, 3288 mm, and Estevan Point, 3120 mm (Figure 1). It should be noted that both Tofino (elevation 24 m) and Estevan Point (elevation 7 m) are near Mean Sea Level, and this raises an interesting question:– How far out from the coast does the precipitation gradient occasioned by land-sea forcing mechanisms such as topographic convergence extend? Some light is shed on this question by the results of Elliott and Reed (1973), who compared precipitation amount at the Marine Science Center, Newport, Oregon with measurments from the buoy "Totem" tethered 55 km off the coast. They found the catch at "Totem" was from ½ to ⅓ of the Newport catch, during the fall, winter, and spring months. These ratios were supported by comparisons between lightship estimates and measured precipitation at nearby land-based stations, northward along the coast of the Olympic Peninsula. In view of the similarities in topography and synoptic climatology, there is good reason to believe that the gradient leading to the threefold enhancement of precipitation along the west coast of Vancouver Island relative to estimates for the OWS "P" area is confined to a similarly narrow strip of coastal waters. Linear interpolation of mean annual precipitation amount from coastal data to OWS "P" would result in an erroneous distribution over the northeast Pacifc Ocean. Moreover, in applying the Tucker statistical method to OWS "P" 3-hourly "ww"s, it would not be advisable to use parameters developed from observations taken at Canadian or USA west-coast stations.

9. PROPOSAL

As indicated earlier, our examination of cold-season monthly mean circulation anomalies tended to support low annual precipitation amounts in 1969, 1970 and 1971, but it did not account for the persistently below-normal values during the immediately subsequent years. This does not necessarily mean that low totals for years such as 1972, 1973, and 1974 are wrong, for one should be highly circumspect in drawing inferences regarding precipitation from monthly mean 70kPa or 50kPa analyses. Nevertheless, further investigation is clearly in order.

In a subsequent companion paper, we propose to compare the respective time series of annual, cold-season, and warm-season measured precipitation, 1954 to 1980 (Figures 3 and 4) with the corresponding series of estimated precipitation statistically derived from observations of 3-hourly "ww". We shall apply the Tucker technique to a representative window (about 5 years of data) in the stationary portion of the OWS "P" time series, 1954–1966, to determine the most likely hourly rate associated with a given "ww". These rates will then be applied to the 3-hourly "ww"s for the entire record, 1954–1980, to generate for each year the estimated total cold-season and annual precipitation. Hopefully these two time series will replicate, at least in a relative sense, the salient features of Figures 3 and 4.

10. CONCLUDING COMMENT

Our conclusion is that the unique and hard-won 27-year record of 6-hourly precipitation amounts measured at OWS "P" deserves more attention than it has heretofore received. The climatology derived from these data is probably closer to the truth than estimates for that location derived from published atlases or from statistical analyses. Credibility will be reinforced if the two regimes of Figure 3 are confirmed by the results of our proposed investigation.

APPENDIX I

Indirect Precipitation Estimation at Atlantic Ocean Weather Stations: Tucker (1961)

Using "present weather" and associated 6-hourly precipitation from two years of data at six first-order U.K. coastal observing stations, Tucker developed hourly precipitation rate parameters X, Y, and Z which, used in conjunction with Table A, provided the "most likely" precipitation rate for each "ww", codes 50 to 99. He then applied these relationships to five years of 3-hourly "ww" observations taken at nine Atlantic Ocean Weather Stations to obtain estimates of mean seasonal and annual precipitation amount. For a given station, he estimated the r.m.s. error for a 5-year average of monthly, seasonal, and annual precipitation calculated by this methods to be 13%, 8%, and 4% respectively. For a single specified month he estimated an r.m.s. error of 30%.

It is important to recognize that the coefficients of X, Y, and Z in Table A were selected *a priori* by Tucker and, though reasonable, are subjective. Another investigator using this method might choose to modify the coefficients. However, the subsequent statistical procedure was completely objective. The parameters X, Y, and Z were determined by a least-square solution of a series of equations of the type:

$$a_i X + b_i Y + c_i Z = d_i$$

where a, b, and c are the total coefficients of X, Y, and Z "rainfall" reported during a month, and d is the measured precipitation. The index i is the serial number of the month and varies from 1 to 105 for Tucker's data set.

TABLE A: Estimated Present-Weather Precipitation Rates corresponding to "ww" codes 50 to 99.

	0	1	2	3	4	5	6	7	8	9
5	0	X/2	X/2	X	X	2X	X/2	Y/2	X/2	Y/2
6	X/2	X	Y/2	Y	Z/2	Z	X	(Y+Z)/2	X	(Y+Z)/2
7	X/2	X	Y/2	Y	Z/2	Z	0	0	0	0
8	X/2	Y/2	Z/2	X/2	(Y+Z)/4	X/2	(Y+Z)/4	X/2	(Y+Z)/2	X/2
9	(Y+Z)/2	X	(Y+Z)/2	X	(Y+Z)/2	(X+Y)/2	(X+Y)/2	Z	0	Z

Where: X = 1.85, Y = 5.66, Z = 8.13, mm/hr

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Greenland Sea Ice and Salinity Anomalies and Interdecadal Climate Variability

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ABSTRACT

Large positive sea-ice and negative salinity anomalies observed in the Greenland Sea during the late 1960s were preceded by above-average runoffs from North America into the western Arctic during the mid 1960s. Such strong freshets produced large positive sea-ice anomalies in the latter region. This large buildup of sea ice, it is argued, then drifted out of the Arctic into the Greenland Sea via the Beaufort Gyre and Transpolar Drift Stream about three to four years later. During the melt season such ice anomalies would have contributed to the production of an extensive layer of cool, relatively fresh surface water in the Greenland Sea which suppressed convective overturning during winter. This stably stratified oceanic situation appears to have subsequently reduced high-latitude cyclonic activity and precipitation over northern Canada. This sequence of hydrological, sea-ice, oceanic and atmospheric events can be described in terms of a negative feedback loop which suggests the existence of self-sustained climatic oscillations in the Arctic with a period of about 15–20 years. Remarkably, during the late 1980s another large positive sea-ice anomaly occurred in the Greenland Sea, in agreement with the proposed interdecadal climate cycle.

RÉSUMÉ

D'importantes anomalies aux plans de l'accroissement des glaces flottantes et de la diminution de la salinité furent observées dans la mer du Groenland à la fin des années 60. Ces anomalies furent précédées par un écoulement de surface supérieur à la normale en provenance de l'Amérique du Nord vers la portion ouest de l'océan Arctique au milieu des années 60. Cet écoulement maximum serait responsable de l'accroissement des glaces flottantes dans cette région. On a également estimé que cette même accumulation de glaces se retrouverait dans la mer du Groenland trois ou quatre années plus tard via le Remous de Beaufort et le Courant de dérive transpolaire. De plus, durant la saison de fonte, une telle

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accumulation de glace formerait une couche d'eau froide relativement douce dans la mer du Groënland ce qui empêcherait le renversement couvectif durant l'hiver. Ce phénomène océanique stratifié et stable semblerait réduire l'activité cyclonique aux latitudes plus au nord et par le fait même le montant des précipitations dans le nord canadien. Cette séquence d'événements hydrologiques, des glaces flottantes, océaniques et atmosphériques peut donc être décrite en termes de phénomène cyclique négatif lequel laisse présager l'existence d'une oscillation climatique unique à l'Arctique avec une récurrence de 15 à 20 ans. Tel que proposé par ce cycle interdécennal, nous avons observé un accroissement anormal des glaces flottantes dans la mer du Groënland à la fin des années 80.

1. INTRODUCTION

The North Atlantic "Great Salinity Anomaly" (hereafter referred to as the GSA) consisted of a cool, relatively fresh water mass that was first observed north of Iceland during the late 1960s and was then traced cyclonically around the subpolar gyre during 1968–82 (Dickson *et al.*, 1988). It was accompanied by large positive sea-ice anomalies in the Greenland and Labrador Seas (Malmberg, 1969; Mysak and Manak, 1989) and led to the suppression of deep convection in different parts of the northwest Atlantic (Malmberg, 1969; Lazier, 1980). Since deep convection in this region drives the ocean thermohaline circulation, which transports heat poleward, anomalies such as the GSA could have a noticeable effect on climate in the vicinity of the North Atlantic (Broecker *et al.*, 1985; Bryan, 1986; Aagaard and Carmack, 1989). Also, since sea ice is continuously exported from the Arctic Ocean through Fram Strait, Greenland Sea ice anomalies could signify the occurrence of preceding ice anomalies in the Arctic. Clearly such natural variability should be taken into account as baseline information when searching for "evidence" of greenhouse warming in long-term records of sea-ice thickness and areal extent (Wadhams, 1990; McLaren *et al.*, 1990).

In this contribution we first show that the Koch ice-severity index, which is a proxy variable for ice cover in the Greenland Sea (Kelly *et al.*, 1987), is significantly correlated with runoff into the western Arctic Ocean from North America. Changes in the latter could, in turn, be caused by anomalous ocean-to-atmosphere heat fluxes which generate atmospheric circulation anomalies. Next we give a brief overview of a recently proposed (Mysak *et al.*, 1990) interdecadal Arctic climate cycle which links together the aforementioned hydrological, sea-ice, oceanic and atmospheric data. Lastly, we present some recently analyzed sea-ice concentration data which show a large positive sea-ice anomaly in the Greenland Sea during the winters of 1987 and 1988. Such an anomaly was predicted in Mysak *et al.* (1990) and serves as further evidence for the existence of an interdecadal climate cycle.

2. ORIGIN OF THE GREAT SALINITY ANOMALY AND ITS RECURRENCE

Two open questions concerning the GSA are its origin and its frequency of occurrence. It is suggested here that the GSA may in part originate from preceding large runoffs from North America into the western Arctic, and that such low-salinity events may be cyclic with a recurrence time of about 15–20 years. The concept of a remote origin for part of the GSA contrasts with earlier hypotheses which suggest that the GSA may be due to mainly local effects such as northerly wind anomalies over the Greenland Sea which drove more polar water there (Dickson *et al.*, 1975), the excess of precipitation over evaporation (Pollard and Pu, 1985), and fluctuations in sea-level atmospheric pressure difference between Greenland and the northern Asian coast which resulted in enhanced export of sea ice (fresh water) from the central Arctic (Walsh and Chapman, 1990a).

Figure 1a shows the Koch ice severity index for the period 1900–75. The high values of the index in the late 1960s (with a peak in 1968) are indicative of the GSA and the accompanying positive sea-ice anomalies. This index suggests that another GSA-like event occurred during the first two decades of this century. In support of this, we note that large positive sea-ice anomalies have been observed during 1909–1919 in Danish Meteorological Institute ice-limit charts (Mysak *et al.*, 1990). Figure 1b, which shows the total North American runoff into the western Arctic during 1930–67, clearly indicates that large freshets (about two

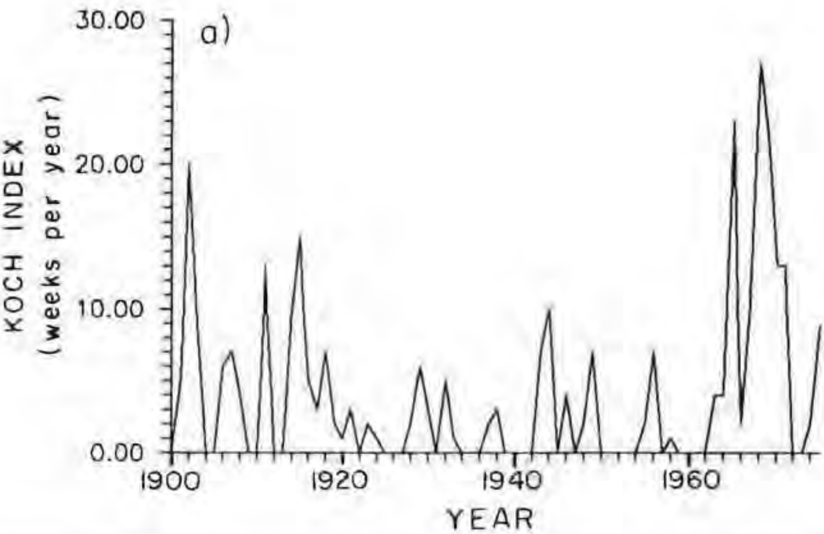

FIGURE 1a. The Koch sea-ice severity index, which is the number of weeks per year when ice affected the coast of Iceland (Kelly *et al.*, 1987).

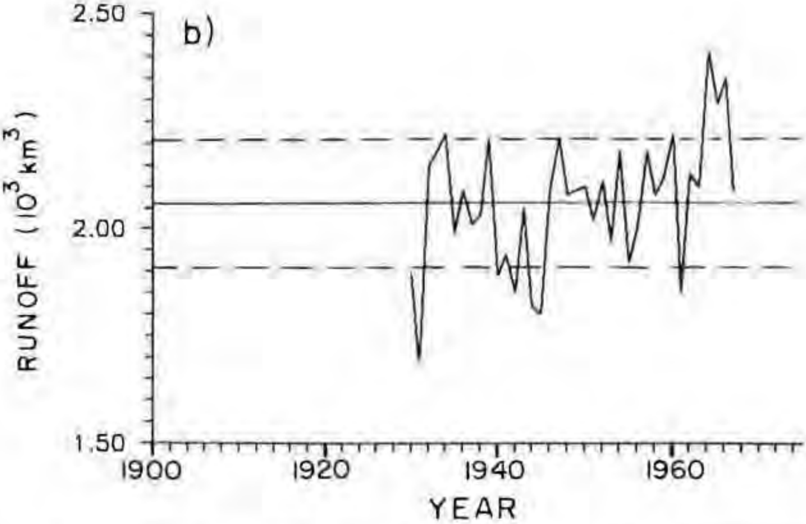

FIGURE 1b. Annual runoff from the North American continent into the Arctic Basin (data derived from UNESCO (1978), courtesy of R. Lawford). The solid line indicates the mean (2.06) and the dashed lines are located one standard deviation (0.15) from the mean.

standard deviations above the mean) during 1964–66 preceded the GSA. High runoff also took place in the early 1930s and late 1940s, and low runoff occurred in the early 1940s and during 1961. On the basis of these variations, it is conjectured that there may be a cycle of approximately 15–20 years in peak runoffs. However, it should be noted that the runoff record is relatively short and that efforts are being made to construct reasonable proxy data for the runoff in order to extend the record further back. An alternating sequence of relatively high and low (or zero) values is also seen in the ice index, but there is a delay in the "signal" of several years. For example, the large runoffs in 1939 and 1964 are followed by relatively large ice indices in 1944 and 1968. This lagged relationship is confirmed by a simple cross-correlation analysis which shows that the fluctuations in Figures 1a and 1b are significantly correlated (Figure 1c), with runoff leading the ice index by several years (maximum correlation at a 5-year lead). The 99% significance level shown in Figure 1c was obtained using a 2-tailed test of normally distributed data (Pearson and Hartley, 1966). We note in passing that Figure 1c also indicates that the runoff leads the Koch ice index by 11 years (at about the 95% significance level). Our current interest, however, centres on the climatic processes associated with the shorter 5-year lead.

There are two (sequential) mechanisms which are believed to account for the above maximum correlation at the 5-year lead. Firstly, fluctuations of

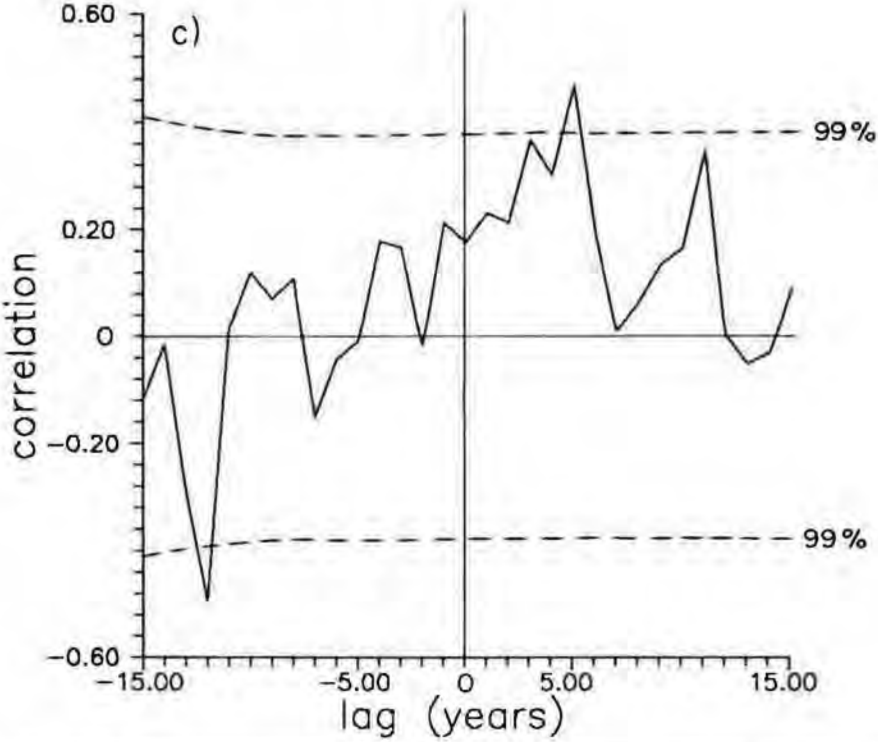

FIGURE 1c. The lagged cross-correlation between runoff (Figure 1b) and the Koch index for the period 1915–75 (Figure 1a). A positive lag means runoff leads the sea-ice index. This runoff leads the sea-ice by 3 to 5 years, with the 5 year peak being above the 99% significance level. The highly significant negative correlation at − 12 years (i.e., large ice extent leads low runoff by 12 years) is consistent with the significant positive correlation at five years if the two signals in Figures 1a and 1b are cyclic with a period of about 16–18 years.

Mackenzie River discharge tend to produce sea-ice anomalies of similar sign in the Beaufort and Chukchi Seas region about one year later (Manak and Mysak, 1989). This is mainly due to the fact that a larger (lower) than normal runoff in spring produces fresher (saltier) surface water in the western part of the Arctic Ocean. Hence the stability of the water column is increased (decreased) so that during the following winter and early spring ice formation is enhanced (hindered). Secondly, since the general pattern of ice drift in the Arctic consists of the Beaufort Gyre and the Transpolar Drift Stream (TDS) (Figure 2) which supplies ice to the East Greenland Current, it is conceivable that a large buildup of sea ice to the northwest of Alaska would be exported out of the Arctic via the TDS into the Greenland Sea about three to four years later (Mysak *et al.*, 1990).

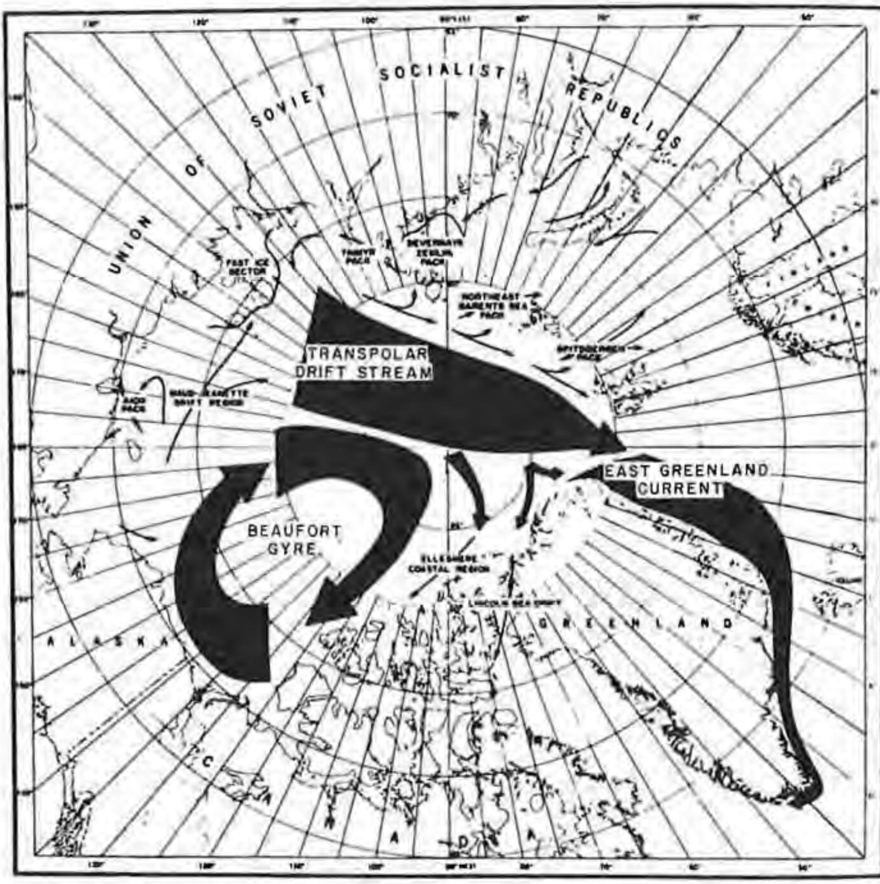

FIGURE 2. Early schematic of the major drift patterns of sea-ice in the Arctic (Dunbar and Wittman, 1963). The general features are consistent with more recent data (see Colony and Thorndike (1984), for example).

3. RELATED ATMOSPHERIC CHANGES

The origin of the three large runoffs seen in Figure 1b (peaks at around 1932–34, 1947 and 1964–66) may be traced to 'climatic jumps' in the Arctic tropospheric circulation which occurred just prior to the runoff peaks (Knox *et al.*, 1988; Shabbar *et al.*, 1990; Walsh and Chapman, 1990b). For example, just after the abrupt change in sign of the zonally averaged 50 kPa height anomalies around 1962–63 (Knox *et al.*, 1988), negative height anomalies occurred to the north of both Greenland and Hudson Bay (Mysak *et al.*, 1990). This was accompanied by an increase in precipitation in the Canadian high Arctic (Bradley and England, 1978), which presumably led to the large 1964–66 runoffs (Figure 1b).

We hypothesize that the aforementioned climatic jumps, on the other hand, were partly caused by prolonged periods of increased cyclonic activity north of Greenland (Mysak *et al.*, 1990), which in turn were due to an increased inflow into the Arctic of warm West Spitsbergen Current water from the Greenland Sea. The latter would result in an increased ocean-to-atmosphere heat transfer north of Greenland and hence greater cyclonic activity in the Arctic, especially during winter. Conversely, should the inflowing water be colder than normal due to reduced convective overturning (and more extensive sea ice) in the Greenland Sea, then Arctic cyclonic activity would be reduced, as would precipitation over the Canadian high Arctic. The latter is expected because the upper troposphere cyclonic polar vortex acts as a waveguide for disturbances that are generated

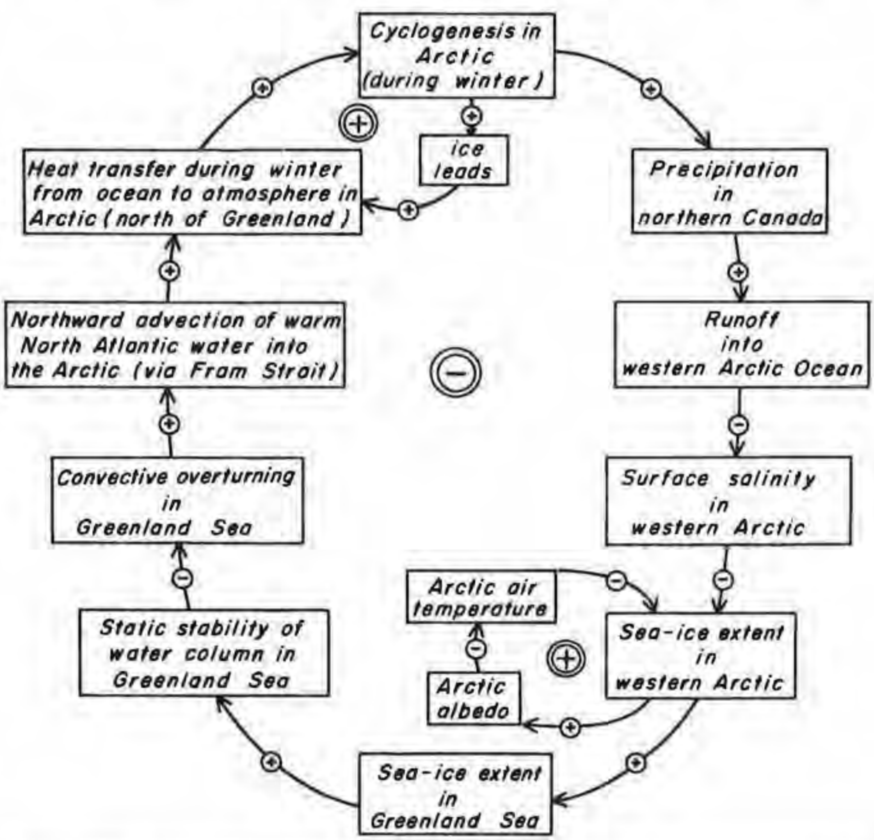

FIGURE 3. Possible negative feedback loop linking Arctic cyclonic activity, precipitation, runoff, salinity, sea-ice extent, oceanic stability, convective overturning, poleward oceanic heat transport and heat flux into the atmosphere (Mysak *et al.*, 1990). The lower small positive feedback loop involving Arctic air temperature is the familiar ice-albedo feedback mechanism which could assist in the cooling of the troposphere if ice extent increases. The upper small feedback loop involving ice leads results in the intensification of cyclonic activity if the area of ice leads increases (Maslanik and Barry, 1989).

elsewhere and transmitted to this region (Lamb, 1982, for example). Hence North American runoff and sea-ice formation in the western Arctic might be reduced. The quantification of the impact that air-sea flux anomalies in this and adjacent regions have upon precipitation over the Mackenzie basin is the subject of ongoing research.

4. INTERDECADAL CLIMATE CYCLE

It has been suggested (Mysak *et al.*, 1990) that the above sequence of atmospheric, hydrological, oceanic and sea-ice events can be linked by a multi-component feedback loop which results in interdecadal climate oscillations. Figure 3 shows the ten components of the feedback loop. A plus (minus) sign between two boxes A and B, say, means that an increase in A would cause an increase (decrease) in B. Since the number of minus signs in the main loop is odd, it represents a reversing or negative feedback loop (Kellogg, 1983). Therefore, in the absence of other strongly damping factors, a perturbation transferred from any one component to the next can theoretically result in a reversal of the sign of the initial perturbation.

It is estimated (Mysak *et al.*, 1990) that the period of the proposed climate cycle (which is twice the loop circuit time) is about 20 years. Thus because of the GSA in the late 1960s and the occurrence of previous Greenland Sea ice anomalies during the 1910s, 1930s and early 1950s (Mysak *et al.*, 1990, Figure 15), it has been predicted (Mysak *et al.*, 1990) that during the late 1980s, the sea-ice extent in the Greenland Sea should show large positive anomalies, the salinity should be relatively low and convective overturning should be reduced. Remarkably, a large ice anomaly in the Greenland Sea has been detected in the winters of both 1987 and 1988 (Figure 4) from recent updates of the sea-ice concentration data analized by Walsh and Johnson (1979). The December 1988 data (latest available) also suggest that the Greenland Sea ice anomaly persisted into winter 1989 as well (the 9/10 concentration contour for December 1988 has a large bulge similar to that seen for February 1987). During the period of this recent ice anomaly in the Greenland Sea, convection was reduced during winter 1988 (Rudels *et al.*, 1989) and low-salinity water was observed in February and March, 1989 (GSP Group, 1990). Because of the interesting evolution of the 1960s GSA and its role in interdecadal variability, it will be most worthwhile to trace the development of the present Greenland Sea ice and salinity anomalies into the 1990s. For example, it is conceivable that these anomalies will move into the Labrador Sea by the early 1990s (Dickson *et al.*, 1988; Mysak and Manak, 1989; Mysak *et al.*, 1990). Work on this fascinating topic as well as on the origin of the GSA is now under way.

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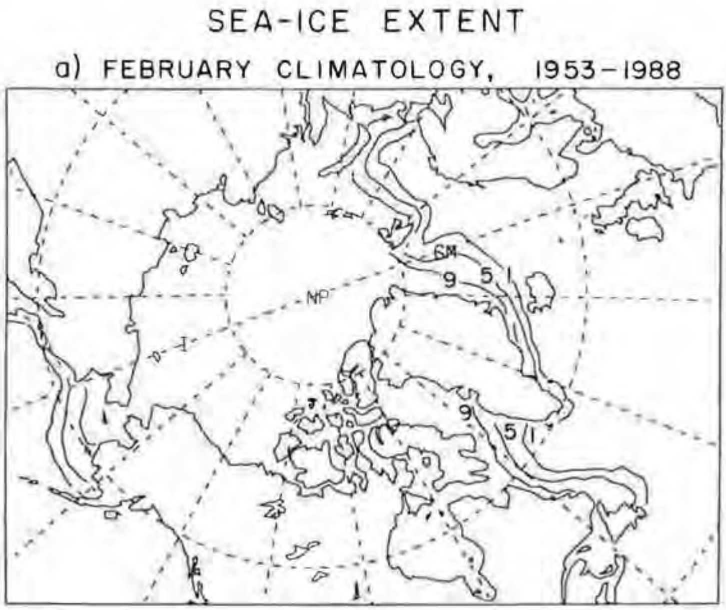

FIGURE 4a. February climatology of sea-ice extent in the Arctic for the period 1953–88. The ice concentration contours are labelled in tenths (1 = 1/10, etc.). In general the sea-ice extent in the Greenland Sea is greatest during February (Mysak and Manak, 1989).

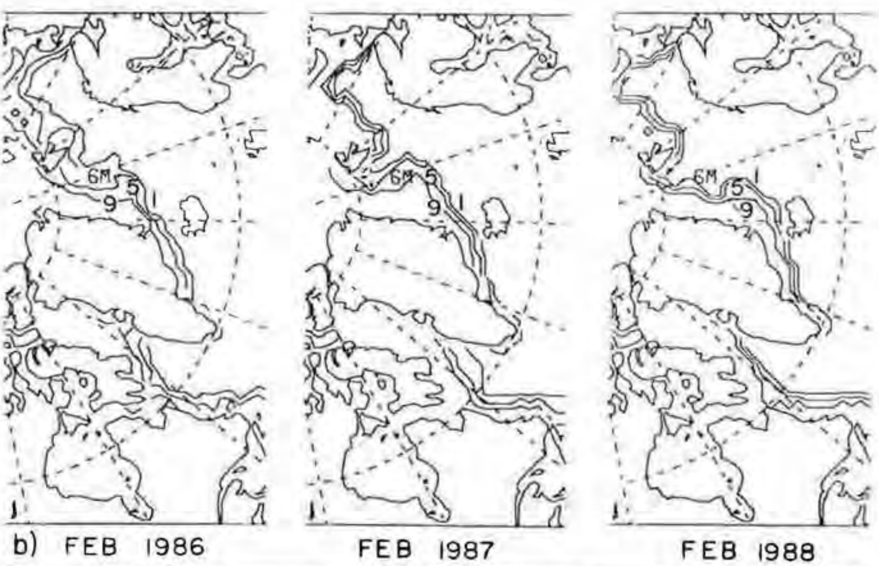

FIGURE 4b. Monthly mean sea-ice extent in the Greenland Sea for February 1986, 1987, and 1988. While the 9/10 contour off the east Greenland coast is near its climatological position for February 1986 (see Figure 4a), during 1987 and 1988 this contour extends well out into the Greenland Sea.

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Étude du phénomène de vents violents au Québec en tant que catastrophe naturelle

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RÉSUMÉ

Les vents violents et les vents en rafales dont la vitesse atteint ou dépasse 90 km/h sont des phénomènes fréquents dans toutes les régions du Québec, particulièrement le long de l'axe du Saint-Laurent et sur les côtes du golfe et de l'estuaire du Saint-Laurent. Ils se produisent à l'année longue, spécialement en hiver. Les dommages matériels associés peuvent être considérables et les cas de blessures ou de mortalités humaines, bien que peu fréquents, ne sont pas à minimiser. Au Québec, trois municipalités ont retenu le risque de vents violents dans leur estimé de vulnérabilité municipale. Une valeur-seuil de trois (3) rafales par année a été choisie pour définir quelles municipalités du Québec (265 en total) devraient retenir ce risque dans leur estimé de vulnérabilité et leur plan de mesures d'urgence municipales.

ABSTRACT

High winds and gusts with a speed of 90 km/h and more are a frequent phenomenon in all regions of the province of Quebec, especially along the river section, the gulf and the estuary of the St Lawrence. They may occur at any time of year, but are most frequent in winter. Associated damages can be extensive and injuries or deaths, while infrequent, must not be disregarded. In the province, however, only three municipalities have included extreme winds as a potential hazard in their vulnerability evaluation. A threshold value of three (3) wind gusts per year is used here to determine which municipalities (265 in all) should include this hazard in their vulnerability evaluation and emergency-measures plans.

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1. INTRODUCTION

Dans le cadre d'une recherche sur la vulnérabilité municipale face aux catastrophes météorologiques, nous avons étudié les vents violents et les rafales de vents dont les vitesses atteignent et/ou dépassent 90 km/h sont des phénomènes météorologiques fréquents dans toutes les régions du Québec et particulièrement le long de l'axe du Saint-Laurent et de toutes les régions côtières. En été ils peuvent être prévisibles, si associés à des cellules orageuses régionales engendrées par de forts mouvements convectifs. A cette échelle, les stations radar d'Environnement Canada peuvent détecter les cellules orageuses et en suivre l'évolution. A une échelle plus locale, cependant, la détection peut s'avérer plus aléatoire et les données obtenues sont beaucoup plus incomplètes. En hiver on retrouve des vents violents et des rafales souvent associés à de violentes tempêtes de neige et parfois de verglas, ce qui accentue leurs méfaits face aux différents moyens de transport. Bien que la majorité des gens ne s'en préoccupent guère, sauf lorsqu'ils doivent en subir les désagréments, les vents violents provoquent, à l'échelle annuelle, autant de dommages, sinon plus, que les phénomènes convectifs de type ouragans ou tornades.

Le Service d'Environnement Atmosphérique (S.E.A.) d'Environnement Canada considère qu'un vent est violent lorsque des rafales atteignent 90 km/h. Il faut cependant noter qu'une distinction importante doit être faite entre la notion de "vent violent" et celle de "rafale". Ainsi, pour qu'un vent soit considéré violent, il doit souffler sans discontinuer pendant au moins 1 minute. C'est la période minimale requise pour que l'observateur météorologique puisse établir une vitesse et une direction moyenne. La donnée ainsi obtenue est extrapolée sur une période horaire, pour une direction prise sur une rosette en 16 points. La rafale, quant à elle, est considérée comme une variation rapide et brève de la vitesse du vent, d'au moins 20 km/h entre les pointes et le niveau moyen (Leduc et Gervais, 1985). La différence principale entre ces deux fluctuations est donc la durée de l'événement.

2. MÉTHODOLOGIE

Pour les analyses statistiques, 23 stations avec des données portant sur 10 à 30 ans ont été utilisées (tableau 1). Pour ces stations nous avons considéré les valeurs horaires de vents ainsi que toutes les occurrences de rafales de vents dont la vitesse était égale ou supérieure à 90 km/h. Le tableau 2 donne, pour les stations touchées, une synthèse des fréquences d'occurrences horaires des vents violents indiquant les mois où le phénomène s'est produit ainsi que la direction et la vitesse des vents.

Pour l'ensemble des stations étudiées les fréquences d'occurrences mensuelles des rafales ont aussi été calculées, ceci pour une période d'un an (tableau 3). Les calculs des rafales mensuelles et du nombre total de rafales sur un an ont été faits à partir de toutes les données de chaque station (10 à 30 ans de données selon les stations), suivant l'hypothèse que les données disponibles à

nom de la station	identification	à la fig. 1	nombre d'années	période	latitude	longitude
Bagotville	7060400	BAG	30	01.58-12.87	48.20	71.00
Baie-Comeau	7040440	BAI	23	01.65-12.87	49.12	68.16
Chibougamau	7091401	CHI	16	09.71-12.87	49.49	75.25
Gaspé	7052605	GAS	20	01.68-12.87	48.46	64.29
Grande-Rivière 1	7093715	GRA	11	10.76-12.87	53.38	77.42
Inukjuak	7103282	INU	30	01.58-12.87	58.46	78.04
Kuujjuaq	7113534	KUJ	30	01.58-12.87	58.06	68.25
Kuujjuarapik	7103536	KUP	30	01.58-12.87	55.17	77.46
Mont-Joli	7055120	MON	30	01.58-12.87	48.36	68.13
Mtl/Dorval	7025250	DOR	30	01.58-12.87	45.28	73.45
Mtl/Mirabel	7035290	MIR	12	10.75-12.87	45.41	74.02
Nitchequon/La Grande	7095480	NIT/LAG	29	10.58-12.87	53.12	70.54
Ottawa	6106000	OTT	30	01.58-12.87	45.19	75.40
Québec	7016294	QUE	30	01.58-12.87	46.48	71.28
Rivière-du-Loup	7056615	RIV	15	06.65-04.80	47.48	69.33
Roberval	7066685	ROB	30	01.58-12.87	48.31	72.16
Schefferville	7117825	SCH	30	01.58-12.87	54.48	66.49
Sept-Iles	7047910	SEP	30	01.58-12.87	50.13	66.16
Sherbrooke	7028124	SHE	16	12.71-12.87	45.26	71.41
Saint-Hubert	7027320	STH	30	01.58-12.87	45.31	73.25
Sainte-Agathe-des-Monts	7036762	STE	21	04.66-12.87	46.03	74.17
Val-d'Or	7098600	VAL	30	01.58-12.97	48.04	77.47
Wabush	8504175	WAB	27	11.60-12.87	52.56	66.52

chaque site étaient représentatives de la période de 30 ans retenue et pouvaient être ramenées sur une période d'un an. Pour chaque station, nous avons établi les fréquences, en pourcentage, des directions de vents associés aux rafales (tableau 4). Les directions des vents furent établies suivant 8 quadrants géographiques de 45 degrés chacun, du nord au nord-ouest.

3. RÉSULTATS

3.1 Les vents violents

Seulement 5 des 23 stations étudiées présentent des épisodes horaires de vents violents (tableau 2). Ce sont les stations de Baie-Comeau, Mont-Joli, Mtl/Dorval, Saint-Hubert et Sept-Iles et on peut noter qu'elles se retrouvent toutes le long de l'axe du Saint-Laurent. Pour ces stations, les vents violents ont des vitesses qui varient entre 90 et 103 km/h et ils proviennent toujours, sauf pour Sept-Iles, de l'ouest-sud-ouest au sud-sud-ouest. Dans le cas de Sept-Iles, les vents proviennent, dans 11 occurrences sur 13, de l'est, ce qui peut s'expliquer par la position de cette station (aéroport) le long de la rive nord du golfe du Saint-Laurent. En effet, la station est relativement protégée des vents d'ouest, alors qu'elle est ouverte aux vents qui proviennent des autres directions. Sept-Iles se

TABLEAU 2. Occurrences de vents violents, vitesse et direction

station	occurrences horaires	vitesse km/h	direction en degrés	mois d'occurrence
Baie-Comeau	2	100 à 103	220	février
Mont-Joli	1	97	250	novembre
Mtl/Dorval	1	90	230	janvier
Saint-Hubert	2	93	240	février et avril
Sept-Iles	13	90 à 101	80 à 100 (11), 200(1), 320(1)	jan(5), fév(1), avril(1), déc(6)

démarque aussi des autres stations par le nombre d'occurrences de tels événements, soit 13 en 30 ans, comparativement à 1 ou 2 pour les autres. C'est Baie-Comeau qui, avec 2 occurrences en 23 ans, est la deuxième station la plus affectée.

3.2 Les rafales violentes

Toutes les 23 stations étudiées présentent des occurrences de rafales violentes. La direction et la fréquence des rafales varient beaucoup d'une région à l'autre du Québec. Divers facteurs, en particulier la topographie et la proximité de grands plans d'eau, vont contribuer à inhiber ou à canaliser les déplacements d'air. C'est pourquoi, dans le cadre de cette analyse, nous avons divisé le Québec en 5 régions physiographiques (figure 1) y compris la région du Saint-Laurent, elle-même subdivisée en 3 sous-régions, soit le haut Saint-Laurent (HSL), le bas Saint-Laurent (BSL) et le golfe du Saint-Laurent (GSL).

Dans la sous-région du Haut Saint-Laurent (HSL), la station de St-Hubert est la plus touchée par les rafales, avec une moyenne de trois (3) par année (tableau 3). Ce résultat concorde avec ceux de Bruce et Johnstone (1951). Cette fréquence d'occurrence atteint une valeur minimale de 0,8 à Ottawa. Sur une période annuelle, les vents sont dominants de l'ouest et/ou sud-ouest dans une proportion de 75 à 85%, ceci en toutes saisons. Le Bas Saint-Laurent (BSL) présente des occurrences de rafales qui varient de 0,9 à Rivière-du-Loup à 3,6 à Mont-Joli. Seule la station de Québec présente des rafales à longueur d'année. Sur une période annuelle, les vents dominants ont des directions variables selon la saison et/ou la position topographique (rive sud par rapport à la rive nord du fleuve), quoique les vents d'ouest soient plus fréquents. Dans le Golfe du Saint-Laurent (GSL) Sept-Iles présente presque dix fois plus d'occurrences annuelles de rafales que Gaspé, soit 6,7 contre 0,75. Sept-Iles est d'ailleurs, sur les 23 stations étudiées, celle qui est la plus touchée par les rafales. Sur une base annuelle, les rafales proviennent principalement de l'est et du nord à Sept-Iles, alors que Gaspé présente des vents dont les directions privilégiées sont du sud et de l'ouest. Dans toutes les sous-régions du Saint-Laurent, l'hiver est la saison la plus affectée par les rafales violentes, l'été la plus calme.

Les stations du Saguenay/Lac-Saint-Jean (SAL) et du sud du Québec

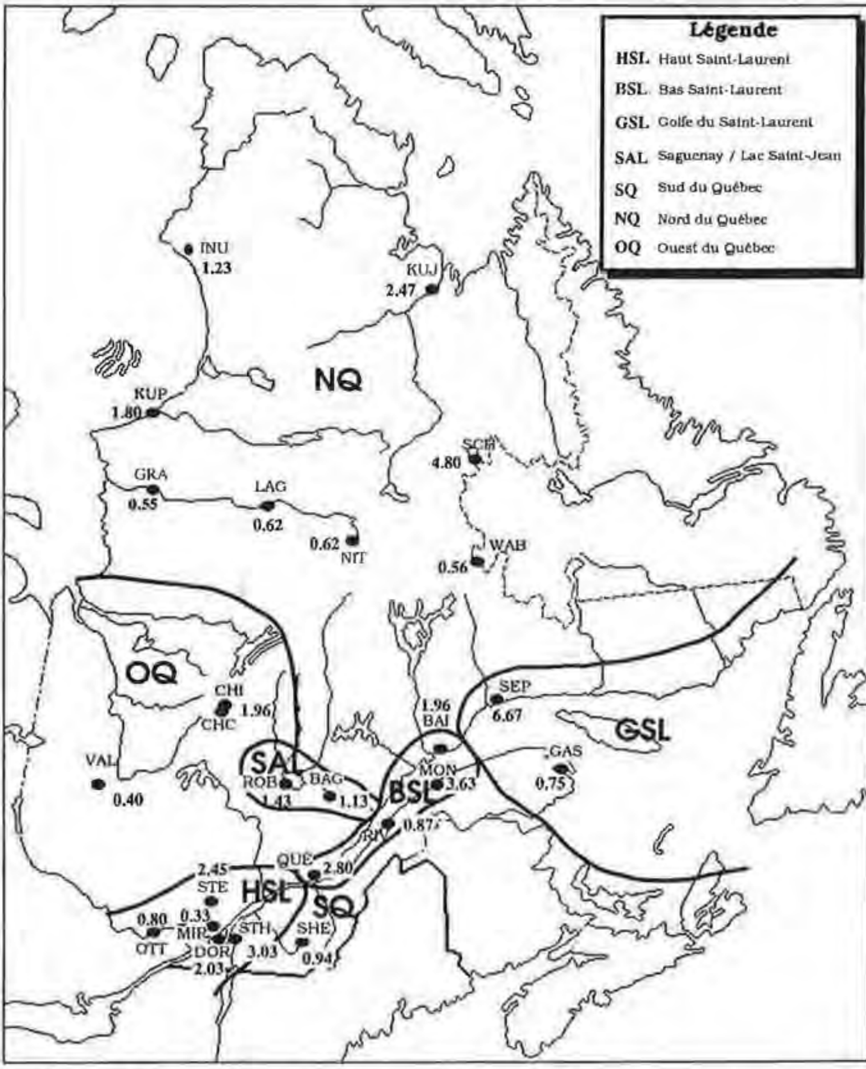

FIGURE 1: Fréquence annuelle des rafales aux 23 stations étudiées et délimitation des régions et sous-régions d'analyse.

(SQ) présentent autour d'une occurrence de rafales par année. Les rafales se produisent surtout en automne et en hiver alors que le printemps et l'été sont les plus calmes. Sur une base annuelle, les vents proviennent principalement des directions sud-ouest à nord-ouest. La région de l'ouest du Québec (OQ), avec des valeurs entre 0,2 et 0,4 présente les plus faibles occurrences de rafales annuelles de la province. Les vents associés, sur une base annuelle, dominent des directions ouest à sud-ouest.

TABLEAU 3. Fréquence d'occurrence des rafales par mois, pour un an.

station	position 1–23	janvier	février	mars	avril	mai	juin	juillet	aout	sept.	oct.	nov.	déc.	total	rafale max.
Bagotville A	13	0.23	0.07	0.13	0.20	0.03	0.03	0.07	0.03	0.07	0.07	0.17	0.03	1.13	113 (2)
Baie-Comeau A	9	0.43	0.13	0.22	0.22	0.09	0.00	0.00	0.04	0.00	0.13	0.35	0.35	1.96	131
Chibougamau (2)	23	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.06	0.00	0.00	0.00	0.06	0.25	103
Gaspé A	17	0.30	0.15	0.05	0.05	0.00	0.05	0.00	0.00	0.05	0.00	0.05	0.05	0.75	115 (2)
Grande-Rivière	19	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.09	0.00	0.18	0.00	0.00	0.55	122
Inukjuak	12	0.03	0.03	0.10	0.13	0.00	0.00	0.07	0.10	0.23	0.17	0.20	0.17	1.23	117
Kuujjuak	6	0.33	0.33	0.40	0.10	0.00	0.00	0.13	0.17	0.17	0.27	0.20	0.37	2.47	161
Kuujjuarapik	10	0.13	0.10	0.07	0.07	0.00	0.03	0.07	0.13	0.33	0.30	0.33	0.23	1.80	111
Mont-Joli	3	0.70	0.57	0.40	0.10	0.00	0.13	0.10	0.03	0.13	0.27	0.43	0.77	3.63	137
Mtl/Dorval A	8	0.40	0.30	0.17	0.20	0.07	0.13	0.07	0.10	0.00	0.10	0.30	0.20	2.03	161
Mtl/Mirabel A	22	0.08	0.08	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.33	97
Nitchequon-La Grande IV	18	0.00	0.07	0.00	0.03	0.03	0.07	0.00	0.03	0.10	0.17	0.07	0.03	0.62	122
Ottawa Int'l A	16	0.10	0.00	0.13	0.13	0.13	0.00	0.07	0.07	0.00	0.07	0.07	0.03	0.80	135
Québec	5	0.40	0.33	0.17	0.17	0.17	0.17	0.23	0.17	0.07	0.17	0.37	0.40	2.80	177
Rivière-du-Loup	15	0.27	0.07	0.07	0.13	0.00	0.00	0.07	0.00	0.00	0.13	0.07	0.07	0.87	135
Roberval A	11	0.13	0.10	0.17	0.07	0.03	0.13	0.13	0.07	0.07	0.17	0.23	0.13	1.43	121 (4)
Schefferville	2	0.70	0.47	0.20	0.30	0.20	0.30	0.20	0.20	0.57	0.33	0.57	0.77	4.80	153
Sept-Iles A	1	1.17	0.73	0.83	0.63	0.43	0.23	0.07	0.13	0.20	0.53	0.73	0.97	6.67	161
Sherbrooke A	14	0.25	0.06	0.06	0.06	0.06	0.06	0.00	0.00	0.06	0.00	0.06	0.25	0.94	117
St-Hubert A	4	0.43	0.43	0.37	0.20	0.17	0.20	0.10	0.13	0.10	0.30	0.40	0.20	3.03	130
Ste-Agathe-des-Monts	7	0.64	0.09	0.09	0.36	0.00	0.18	0.09	0.09	0.18	0.00	0.27	0.45	2.45	113
Val-d'Or	21	0.03	0.00	0.03	0.00	0.00	0.13	0.07	0.00	0.03	0.03	0.00	0.07	0.40	119
Wabush Lake	20	0.15	0.07	0.00	0.00	0.00	0.00	0.11	0.00	0.04	0.07	0.11	0.00	0.56	113

TABLEAU 4. Fréquence (%) des directions des vents associés aux rafales.

DIRECTION EN DEGRÉS Quadrant géographique	337–22 Nord	23–67 Nord-Est	68–112 Est	113–157 Sud-Est	158–202 Sud	203–247 Sud-Ouest	248–292 Ouest	293–336 Nord-Ouest	NBRE RAFALES 1 AN
STATION									
Bagotville A	0.00	0.00	11.76	0.00	5.88	5.88	58.82	17.65	1.13
Baie-Comeau A	0.00	17.78	51.11	0.00	0.00	11.11	17.78	2.22	1.96
Chibougamau (2)	25.00	0.00	0.00	0.00	0.00	50.00	25.00	0.00	0.25
Gaspé A	0.00	0.00	13.33	13.33	40.00	13.33	20.00	0.00	0.75
Grande-Rivière	0.00	0.00	0.00	0.00	16.67	33.33	50.00	0.00	0.55
Inukjuak	5.41	2.70	29.73	0.00	13.51	5.41	29.73	13.51	1.23
Kuujjuak	31.08	8.11	2.70	0.00	1.35	4.05	45.95	6.76	2.47
Kuujjuarapik	3.70	0.00	1.85	16.67	22.22	14.81	35.19	5.56	1.80
Mont-Joli A	5.50	17.43	8.26	2.75	20.18	17.43	26.61	1.83	3.63
Mtl/Dorval	0.00	13.11	1.64	0.00	4.92	31.15	47.54	1.64	2.03
Mtl/Mirabel A	0.00	50.00	0.00	0.00	0.00	0.00	50.00	0.00	0.33
Nitchequon et La Grande	0.00	0.00	0.00	5.56	22.22	11.11	44.44	16.67	0.62
Ottawa Int'l A	4.17	0.00	12.50	0.00	4.17	20.83	54.17	4.17	0.80
Québec	3.57	8.33	27.38	0.00	2.38	16.67	35.71	5.95	2.80
Rivière-du-Loup	0.00	0.00	7.69	7.69	38.46	30.77	0.00	15.38	0.87
Roberval A	4.65	0.00	0.00	0.00	16.28	27.91	34.88	16.28	1.43
Schefferville	10.42	0.00	2.78	0.00	8.33	12.50	57.64	8.33	4.80
Sept-Iles A	26.50	1.50	48.00	0.00	0.50	2.50	10.50	10.50	6.67
Sherbrooke A	0.00	0.00	0.00	0.00	0.00	0.00	86.67	13.33	0.94
St-Hubert	2.20	4.40	0.00	1.10	10.99	17.58	60.44	3.30	3.03
Ste-Agathe-des-Monts	0.00	0.00	0.00	0.00	0.00	11.11	74.07	14.81	2.45
Val-d'Or	0.00	8.33	0.00	0.00	16.67	33.33	33.33	8.33	0.40
Wabush Lake	13.33	6.67	0.00	0.00	6.67	13.33	60.00	0.00	0.56

Pour le nord du Québec (NQ) l'analyse des fréquences de rafales nous montre une forte variabilité, avec des valeurs qui varient de moins d'une occurrence par année dans trois stations à 4,8 à Schefferville (deuxième station la plus touchée au Québec). L'automne ou l'hiver, selon les stations, sont les saisons de plus fréquentes rafales violentes, sauf dans le cas de Grande-Rivière où c'est l'été. La saison la moins affectée est, dans tous les cas, le printemps. Au niveau des directions moyennes annuelles des vents dominants on note que ceux-ci proviennent, pour l'ensemble des stations, entre l'ouest et le sud-ouest, bien que des vents d'est à Inukjuak et du nord à Kuujjuak soient aussi très fréquents.

3.3 Cartographie climatologique

La figure 1 représente la cartographie des fréquences annuelles de rafales violentes pour les 23 stations considérées dans cette étude. Considérant l'éparpillement des stations, leurs emplacements et l'effet majeur de la topographie sur les données de vents en rafales, la cartographie ne peut représenter que des valeurs ponctuelles. On peut tout de même suggérer deux axes de vents, un le long de l'estuaire maritime et de la partie nord du Golfe du Saint-Laurent et un autre le long de l'estuaire supérieur du Saint-Laurent et dans le prolongement des Grands Lacs. On suggère aussi une zone moins affectée par les rafales dans le centre de la province.

4. ANALYSE DE VULNÉRABILITÉ MUNICIPALE

Dans le cadre de la loi sur la protection des gens et des biens en cas de sinistre (1984), chaque municipalité du Québec est tenue de préparer un plan de mesures d'urgence. C'est ainsi que chaque municipalité doit évaluer quels sont les risques naturels et technologiques qui pourraient éventuellement menacer la vie de ses concitoyens et les biens matériels privés ou publics. D'après une liste de 39 risques fournie par le Bureau de la Protection Civile du Québec, chaque municipalité décide quels sont les risques qu'elle retient. Le risque de vents violents ne figure pas parmi ces risques naturels. Malgré cela, trois municipalités ont retenu le risque vents violents dans leur évaluation de vulnérabilité municipale, soit: Port-Cartier, Sept-Iles et Notre-Dame-des-Prairies. Il faut bien comprendre ici que les données analysées reposent sur 1100 municipalités sur un total de 1580 puisqu'il y a encore 400 municipalités au Québec qui n'ont pas adopté leur plan de mesures d'urgence.

L'examen de la situation générale des vents et la cartographie des occurrences annuelles moyennes de rafales supérieures à 90 km/h montre que cette liste de municipalités est très faible par rapport au risque réel et que le risque de dommages a donc été considérablement sous-évalué au Québec. Ceci s'explique en premier lieu par le fait que le risque de vents violents ne figure pas dans la liste fournie aux municipalités par le Bureau de la Protection Civile. Ainsi, certaines municipalités ont tout simplement choisi les risques qui leur semblaient pertinents parmi une liste et n'ont pas cherché à ajouter d'autres risques à cette liste alors que d'autres comme Port-Cartier, Sept-Iles et Notre-Dame-des-Prairies ont estimé que ce risque pouvait les menacer. La terminologie utilisée par ces trois municipalités est d'ailleurs significative car différente; l'une a utilisé le terme vents excessifs, une autre tempête de vent et la dernière vents violents.

En deuxième lieu, il est probable mais difficilement vérifiable que certaines municipalités aient choisi un risque similaire pour exprimer leur crainte, soit vraisemblablement tornade/ouragan. A ce sujet, il est regrettable que la Bureau de la Protection Civile ait choisi d'agglomérer certains risques forts différents ensemble. Pour l'est de l'Amérique du Nord l'ouragan est une forte tempête de provenance tropicale qui prend naissance dans les Caraïbes et les Antilles et qui remonte à l'intérieur des terres du sud des Etats-Unis. Le Québec n'est touché qu'exceptionnellement par les "queues" d'ouragans. Le phénomène de tornade est, quant à lui, un tourbillon de vent puissant associé à des orages violents. Ainsi, même si l'on observe des effets secondaires en matière de vents violents, les trois phénomènes d'ouragan, de tornade et de rafales sont bien différents et devraient être considérés comme tels dans la liste fournie par le Ministère.

Il est utile de mentionner ici que les comités municipaux chargés de la préparation des plans de mesures d'urgence ne sont pas à même de distinguer de façon précise les différences entre ces trois risques et accordent plus d'importance aux effets de ces temps violents sur leur territoire. En première hypothèse, nous présumons que les municipalités, de par l'expérience cumulée de leurs résidents, sont en mesure d'estimer correctement les risques qui les menacent, en se basant sur les événements qui ont secoué la municipalité dans le passé. Notre analyse a révélé que si cela s'est avéré exact dans certains cas, nous avons noté que les comités sous-estiment la violence de certains phénomènes météorologiques.

Le choix d'une valeur-seuil est relativement difficile car elle suscite un jugement basé sur des critères qui peuvent être considérés comme prudents ou imprudents. Ainsi, si l'on retient une valeur-seuil de 4 rafales par année, on confirme le choix de Port-Cartier et de Sept-Iles et on réfute le choix de Notre-Dame-des-Prairies (région de Joliette). Une valeur de 6 pourrait être considérée comme élevée et par conséquent imprudente alors qu'une valeur de 2 pourrait être considérée comme trop basse et par conséquent trop prudente. Il faut cependant garder en mémoire que la problématique doit être centrée autour des risques pour la santé humaine d'abord et envers les dommages aux biens privés et publics en second lieu. Il va sans dire qu'une seule rafale de 90 km/heure peut causer des dommages importants à un territoire municipal et qu'il y a très peu de territoires au Québec qui ne connaissent pas ce phénomène au moins une fois par année. A la lumière de ce que nous avons analysé et basé également sur la figure 1, nous suggérons que les municipalités connaissant au moins 3 rafales violentes par année modifient leur plan de mesures d'urgence et leur estimé de vulnérabilité municipale pour inclure ce risque. Ainsi, en fixant une valeur-seuil de 3 rafales par an, on obtient une liste de plus de 265 municipalités qui auraient dû retenir ce risque dans leur estimé de vulnérabilité. La distribution régionale donne:

Région administrative	Région physiographique correspondante	Nombre
Bas Saint-Laurent	estuaire du fleuve Saint-Laurent	27
Québec	vallée du Saint-Laurent	12
Chaudière-Appalaches	vallée du Saint-Laurent	12
Mauricie-Bois-Francs	vallée du Saint-Laurent	88
Montérégie	vallée du Saint-Laurent	81
Lanaudière	vallée du Saint-Laurent	22
Côte-Nord	golfe du Saint-Laurent	23
		total: 265 municipalités menacées

On peut constater que toutes ces municipalités se retrouvent le long de l'axe fluvio-maritime du Saint-Laurent qui, selon nos résultats d'analyse, présente les plus hauts risques de rafales et/ou de vents violents.

5. CONCLUSION

Il existe deux types de situations climatiques qui peuvent engendrer des rafales supérieures à 90 km/h, soit les vents d'est qui balaient le golfe et une partie de l'estuaire du Saint-Laurent, et l'engouffrement des vents d'Ouest dans la vallée du Saint-Laurent, encadrée par les Laurentides au nord et les Appalaches au sud. Les occurrences annuelles de vents violents varient de presque 0 dans la partie centrale du Nord du Québec et près de la frontière américaine à 7 sur la Côte-Nord. Nous suggérons une valeur-seuil de 3 rafales par an pour déterminer quelles municipalités devraient ou non retenir le risque de vents violents dans leur plan de mesures d'urgence. Ce seuil peut être considéré comme un compromis acceptable en termes de prudence et de prévention.

En matière de protection civile, 265 municipalités devraient ainsi inclure dans leur estimé de vulnérabilité le risque de vents violents, et ceci sans tenir compte des risques supplémentaires d'ouragans et de tornades qui sont des phénomènes météorologiques différents et qui doivent être évalués dans une prochaine étape. Au Québec, seulement trois municipalités ont déjà retenu avec justesse le risque de vents violents. Notre étude aura ainsi démontré que ce risque a été grandement sous-évalué au Québec.

REMERCIEMENTS

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The Sensitivity of Soil Moisture Reserves to Precipitation Amount and Frequency Under Current and Future Climates

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ABSTRACT

Climate-change impact studies in the domain of agriculture require consideration of changes in precipitation frequency as well as in precipitation amount. In the current study, a similar relationship was found to exist between the number of days with precipitation in a month (Y) and the monthly total precipitation (P), in both a spatial and a temporal sense, in Canada. The best fit to this relationship was found by relating Y to the squared natural log of P. Because of the consistency of the relationship through time, it was concluded that the expected frequency of days with precipitation in a future changed climate can be estimated from the values of P projected for that climate.

An assessment of the sensitivity of weather-based computer simulations of soil moisture reserves to changes in Y and P was performed. It suggests that an appreciable amount of the response of soil moisture levels to changes in precipitation is due solely to changes in the frequency of days with precipitation.

RÉSUMÉ

Les effets du changement climatique sur l'agriculture exigent une étude plus approfondie de la variation de la fréquence et de la quantité des précipitations reçues. Nous démontrons, dans cet article, qu'il existe un lien, sur les plans spatial et temporel, entre le nombre de jours de précipitation durant un mois (Y) et la quantité de précipitation reçue durant ce mois (P), au Canada. La courbe correspondant le mieux à ce lien indique que Y varie selon le logarithme naturel au carré de P. Puisque nous avons remarqué une certaine harmonie avec les années, nous concluons que le nombre de jours de précipitation (Y) dans un mois peut être déterminé à partir d'une projection des valeurs de P, et que ce lien restera inchangé advenant un changement climatique.

Lors de cette étude, nous avons de plus vérifié, à l'aide de données climatiques simulées par ordinateur, la sensibilité des réserves d'eau du sol en fonction de P et Y. D'après

cette simulation, une bonne proportion de la variation de ces réserves due à des changements de précipitations dépend seulement du changement de la fréquence de jours de précipitation.

INTRODUCTION

The aim of this paper is to improve our ability to analyze the impact of changes in precipitation on crop growing conditions, specifically soil moisture reserves. Such changes are anticipated under possible global climate modification due to the greenhouse effect. The improvement envisaged here relates to the incorporation of changes in frequency of days with precipitation which will likely accompany changes in precipitation amount. The study involved two basic steps. The first was to establish the relationship between monthly total precipitation and the frequency of days with precipitation. The second was to evaluate the sensitivity of soil moisture simulations to changes in precipitation sequences that are related to changes in monthly precipitation totals.

BACKGROUND

Many recent studies have attempted to evaluate potential CO_2-induced changes in global climate (Harrington, 1987) and their impacts on Canadian agriculture (Savdie, 1989; Stewart and Muma, 1990; Stewart, 1986; Arthur, 1987; Bootsma *et al.*, 1984; Singh and Stewart 1990; Smit *et al.*, 1987; and Williams *et al.*, 1987). Global circulation models (GCM's) from several research groups (Manabe and Wetherald, 1980, 1986; Hansen *et al.*, 1981, 1983, 1986; Mitchell, 1983; Parry *et al.*, 1988) have generated quantitative regional estimates of temperature increases throughout the world. Their models have also estimated possible scenarios for changes in the global hydrological cycle, although with lower precision than for temperature.

The actual time steps used in the GCM computations have not been used in most follow-up impact studies. The GCM output is generally analyzed only on a monthly basis, even though the agricultural production models, such as used by Stewart (1986) and Savdie (1989), rely on daily computations to adequately reflect crop moisture stress. However, a shift to daily rather than monthly output from the GCM's is unlikely since it would mean 30 times as many computations each year.

One approach to the analysis of agricultural impact of increased or decreased precipitation has been to use an existing sequence of daily precipitation data and to increase or decrease the amounts on days with precipitation in direct proportion to proposed changes in monthly totals (Savdie 1989). This approach assumes no changes in the number of precipitation days in the month. To what extent this simplification is affecting climate-change impact analysis for agriculture can only be determined by first understanding the relationship between monthly total precipitation and the frequency of days with precipitation. This is a primary concern of the current article.

The first analysis conducted here was of 1951–80 normals (Atmospheric Environment Service, 1982), of total precipitation (P) and number of days with precipitation (Y), for each month from April to September at 140 synoptic weather stations across Canada. The P-Y pairings for all stations for each month-grouping (e.g., all Aprils) were then subjected to simple linear regression analysis. Six regressions, each of 140 data points, were performed.

To determine whether the same form of relationship also held in a temporal sense, a second analysis of a historical type was carried out. Long-period daily weather records (generally 60 years) were examined on a monthly basis at 13 selected sites across southern Canada (Table 1). This entailed summing the precipitation (P) and counting the days with precipitation (Y) for each month of every year to produce a pair of 60-year time series for April through to September at each site. For all 78 cases a regression of Y against P was performed.

Although ten of the sites in Table 1 are included among the 140 stations used in the first analysis, of the 1951–80 normals, the time period used for the second analysis at five of them has very little overlap with 1951–80. They thus function essentially as independent data sets. Although the other five sites do have a 50% overlap, their historical relations between Y and P all were broadly similar to those of the first eight sites. The form of the relationships found in this historical analysis was similar to that obtained in the spatial analysis of the 1951–80 normals at 140 synoptic stations. This gives confidence that such a relationship can be expected in a future climate.

Various combinations of power and logarithm functions were then tested as numerical transforms for monthly precipitation totals (P) that linearize the relationship between Y and P. The best fitting simple transformation was found by relating Y to the squared natural log of P. The form of the relationship was first determined using the 1951–80 climate normals at 140 stations, and then confirmed by the historical investigations at each of the 13 selected sites.

A sensitivity analysis of simulated mid-summer (July 31) soil moisture was done to demonstrate the impact of possible future changes in both Y and P. The analysis of sensitivity to changes in P was based on plus or minus 20% of the 1951–80 normal monthly total. The response of soil moisture was

TABLE 1. The thirteen selected sites across Canada and the periods of record used for the historical analysis.

Prince George, B.C.	1931–87	Lethbridge, Alta.	1909–68
Medicine Hat, Alta.	1921–80	Swift Current, Sask.	1900–59
Brandon, Man.	1900–59	Kapuskasing, Ont.	1918–77
London, Ont	1940–87	Ottawa, Ont.	1900–59
Montreal, Que.	1901–60	Lennoxville, Que.	1921–80
Fredericton, N.B.	1921–80	Kentville, N.S.	1913–72
Charlottetown, P.E.I.	1931–87		

represented by computer simulations for perennial grass on July 31 using the Versatile Soil Moisture Budget (Baier and Robertson, 1966) as revised by Dyer and Mack (1984) who renamed the model the "Versatile Budget – version three" (VB3). These simulations were initiated on June 1 of the previous year in order to reflect antecedent weather conditions (Dyer, 1985).

The VB3 requires daily weather data as input, whereas the data for the sensitivity analysis must come from monthly climate parameters. Dyer (1989) developed a procedure called PROXDAYS for generating sequences of daily precipitation data suitable as input to the VB3, using only monthly climate normals. As a first approximation precipitation days were distributed according to the ratio of the number of days in the month to the mean number of precipitation days, but PROXDAYS goes further. It defines the effective periodicity, the average time between precipitation days, as being double the period suggested by this ratio. This is because days with precipitation very frequently come in pairs, and there are also many days with very small amounts of precipitation ineffective, for soil moisture recharge.

In the current study, three years of data generated by PROXDAYS were input to the VB3 for each of the 140 stations. The assigned days with precipitation were then staggered from year to year to minimize random errors introduced by the arbitrary scheduling procedure. To illustrate, after scheduling precipitation for year two, days with precipitation in year one would be assigned a few days earlier than year two and the days with precipitation in year three would be a few days later. The estimated soil moisture on any given date is the average estimate for that date over the three years.

RESULTS

Figure 1 shows the point scatter for the relationship for July between Y and P at 140 synoptic stations across Canada, using the 1951 to 1980 normals. Table 2 shows the results of regression analysis for the same 140 sites for each month (April to September) and the average values for all months. The relationship is in the form of:

$$Y_i = b_i (\log_e P_i)^2 + a_i \qquad \text{eq. 1}$$

where Y_i = number of days with precipitation per month i

P_i = monthly precipitation total in mm per month i

The coefficient of determination (R^2) for all six of the monthly relationships is significant at the 0.01 level. The averages of the six slopes and Y-intercepts were rounded to one digit ($b = .6$; $a = 2$) and used to generate the best-fit curve shown in Figure 2 for all six months combined, for the 140 synoptic stations. The form of the relationship is now:

$$Y_i = .6 (\log_e P_i)^2 + 2 \qquad \text{eq. 2}$$

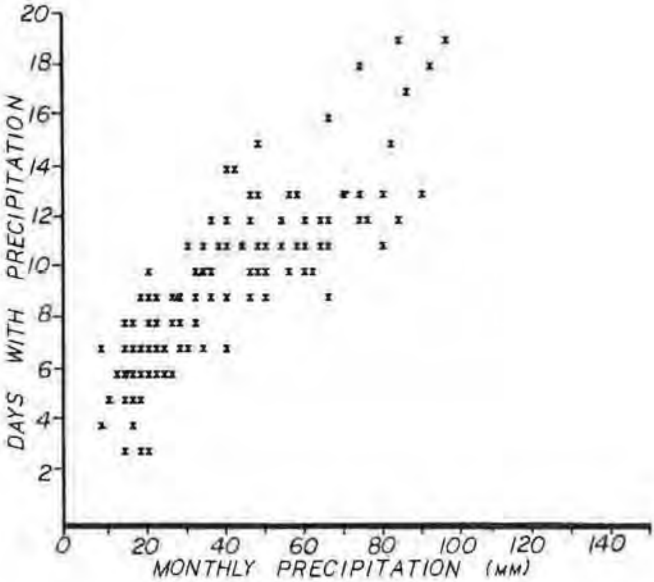

FIGURE 1. Scatter diagram of the 1951–80 normals for number of days with precipitation during July (Y-axis) and total amount of precipitation during July (X-axis) at 140 synoptic stations across Canada.

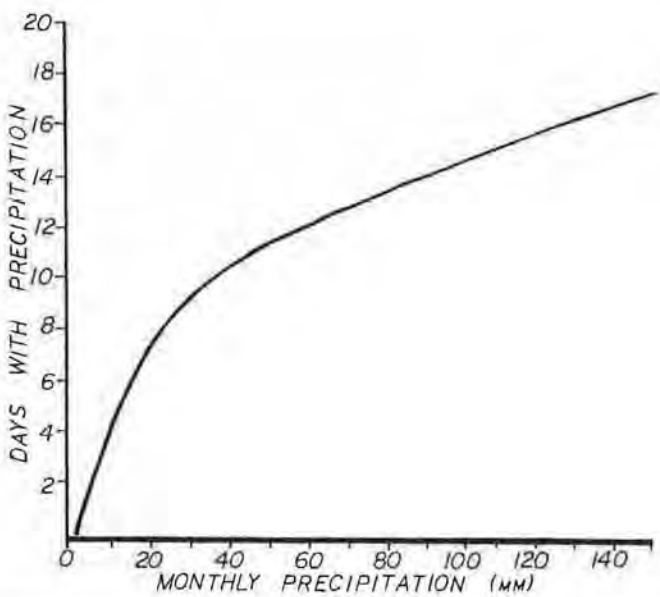

FIGURE 2. Best-fit curve of the number of days with precipitation regressed on the total amount of precipitation for all six month-groupings analyzed.

TABLE 2. Regression results for the normal (1951–80) number of days with precipitation (Y) with the normal monthly total precipitation (P) at 140 synoptic stations across Canada.

	R-squared	Slope	Y-intercept	D-index
April	0.751	0.630	1.270	0.924
May	0.494	0.537	2.467	0.808
June	0.388	0.498	3.030	0.736
July	0.631	0.718	−1.178	0.877
August	0.503	0.639	0.166	0.816
September	0.484	0.537	1.257	0.803
Average		0.59	1.56	

For values of P up to 200 mm, the values of Y estimated by eq. 2 would range from about 5 to 20. The relationship in eq. 2 was also used in the sensitivity analysis for soil moisture. The D-index, a curve fitting test described by Wilmott (1982), shows that the squared log transformation of monthly precipitation gives a reliable fit. The slopes and Y-intercepts in Table 2 are reasonably similar over all six months.

Table 3 shows a summary of the historical regression analysis. The thirteen analyses for each month-grouping have been averaged. Although lower than those for the analysis of the 1951–80 normals (Table 2), the R^2 values in Table 3 are still significant at the 0.05 level.

For April, July and August, the average slopes found in the historical analysis fell just below the 95% confidence intervals (Table 3) of slopes for the corresponding months found in the analysis of 1951–80 normals. The Y-intercepts

TABLE 3. Historical regression analysis of the number of days with precipitation (Y) with the square root of the natural log of monthly total precipitation (P) for each month-grouping over all thirteen selected sites.

				* 95% Confidence Intervals		
	R-squared	Slope(b)	Y-intercept(a)	b (lower)	a (lower)	a (lower)
April	0.427	0.528	2.487	.568	−2.128	4.668
May	0.499	0.535	2.654	.446	−1.033	5.968
June	0.374	0.476	3.312	.393	0.017	6.044
July	0.373	0.459	3.060	.625	−4.679	2.323
August	0.378	0.434	2.926	.532	−3.709	4.041
September	0.377	0.446	2.991	.444	−1.896	6.558
Over all months and sites:						
Average	0.405	0.480	2.905			
S.D.	0.124	0.117	1.557			

* Confidence intervals based on analysis of climate normals from 140 weather stations from Table 1.

for all months except July also fell within the 95% confidence limits from the first analysis. Because of the higher R^2 values, the regression coefficients a = 2 and b = .6 derived from the first analysis, of 1951–80 normals at 140 synoptic stations, were chosen for the sensitivity analysis of soil moisture reserves. The VB3 simulations are also based on recent climate normals, as would be most climate-change impact studies.

The summary in Table 3 of the thirteen site-specific time series gives confidence that a similar relationship between Y and P exists historically as well as for the 1951–80 normals. Probably it will still apply in a changed climate. However, it must be cautioned that the results in Table 3 represent an average.

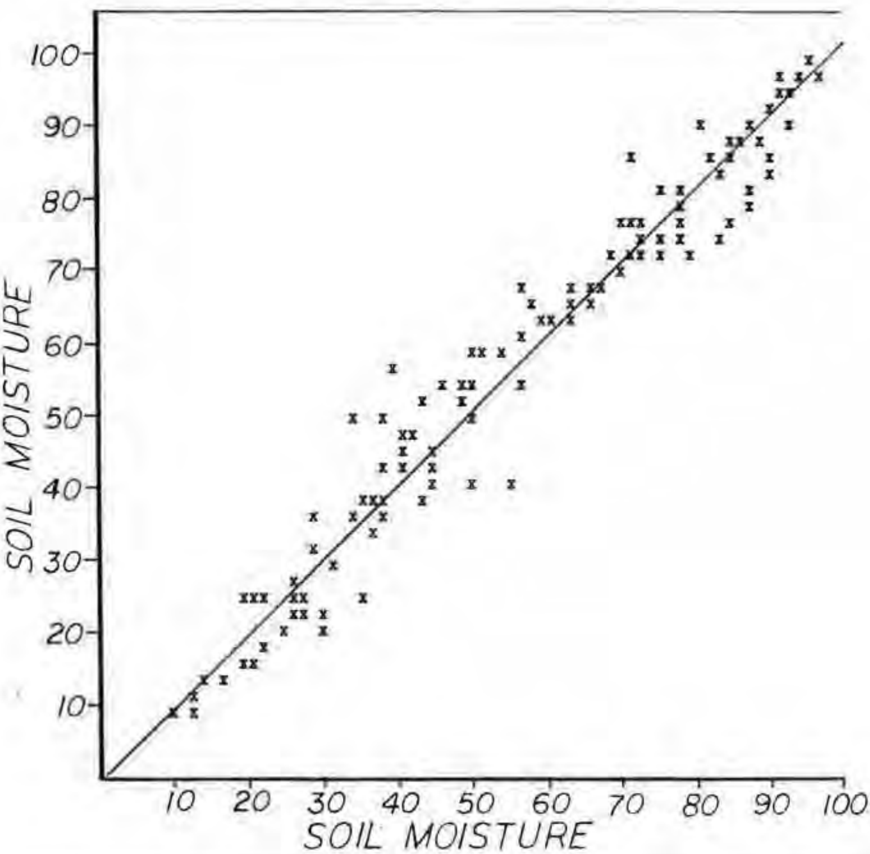

FIGURE 3. Comparison of soil moisture simulations, expressed as % of field capacity, where the number(s) of days with precipitation have been estimated from the squared natural log of the monthly total precipitation amount (Y-axis), with soil moisture simulations based on 1951–80 normals for precipitation amount and number(s) of days with precipitation (X-axis) at 140 synoptic stations across Canada.

They do not guarantee that a relationship over time at an individual site will be close to that described in eq. 2.

Figure 3 compares soil moisture reserves simulated by the VB3 using eq. 2 (Y-axis) with those obtained using the number of precipitation days from 1951–80 normals (X-axis) at the 140 synoptic stations. In both cases PROXDAYS was used to select the days of each month on which to distribute 1951–80 normal monthly precipitation. Although some scatter is evident in Figure 3, the points are distributed evenly about the one-to-one line. The simulated soil moisture based on eq. 2 is thus not a biased estimate.

The results of the soil moisture sensitivity analysis are shown as national averages in Table 4. For testing sensitivity to plus or minus 20% of 1951–80 normal precipitation, Y is computed from eq. 2, rather than by using the normals. This decision was based on the results shown in Figure 3. The tests were applied separately to Y and P.

Line 2 in Table 4 reflects only a 20% increase in P with no change in Y. Line 3 reflects the effect that a 20% increase in Y would have without a corresponding increase in P. Line 1 shows the combined effect of 20% increases in both Y and P. Line 4 gives the simulation result for an unchanged climate, i.e., when Y and P are drawn from 1951–80 normals. Lines 5, 6 and 7 correspond to lines 3, 2 and 1 respectively for the various 20% decreases. The sensitivity is illustrated by the difference between each average value of simulated soil moisture levels and the value in line 4 for the no-change situation.

The greatest impact on soil moisture comes from the increase and decrease in P. However, approximately one third of the combined response to simultaneous increases in both P and Y (compare the difference between lines 3 and 4 with that between lines 1 and 4) and one quarter in the case of decreases (compare difference between lines 5 and 4 with that between lines 7 and 4) can be

TABLE 4. Average sensitivity of soil moisture simulations at 140 synoptic weather stations across Canada to a 20% change in monthly precipitation totals and in the corresponding number of days with precipitation.†

Line number	Number of days with precipitation*	Monthly total precipitation**	Soil moisture on July 31***
1	1.2 × Normal	1.2 × Normal	70.3
2	Normal	1.2 × Normal	67.4
3	1.2 × Normal	Normal	61.4
4	Normal	Normal	57.7
5	.8 × Normal	Normal	54.2
6	Normal	.8 × Normal	45.6
7	.8 × Normal	.8 × Normal	43.0

* Based on squared natural log of monthly total precipitation.

** Normal from each of 140 weather stations.

*** Average % of field capacity over all 140 weather stations.

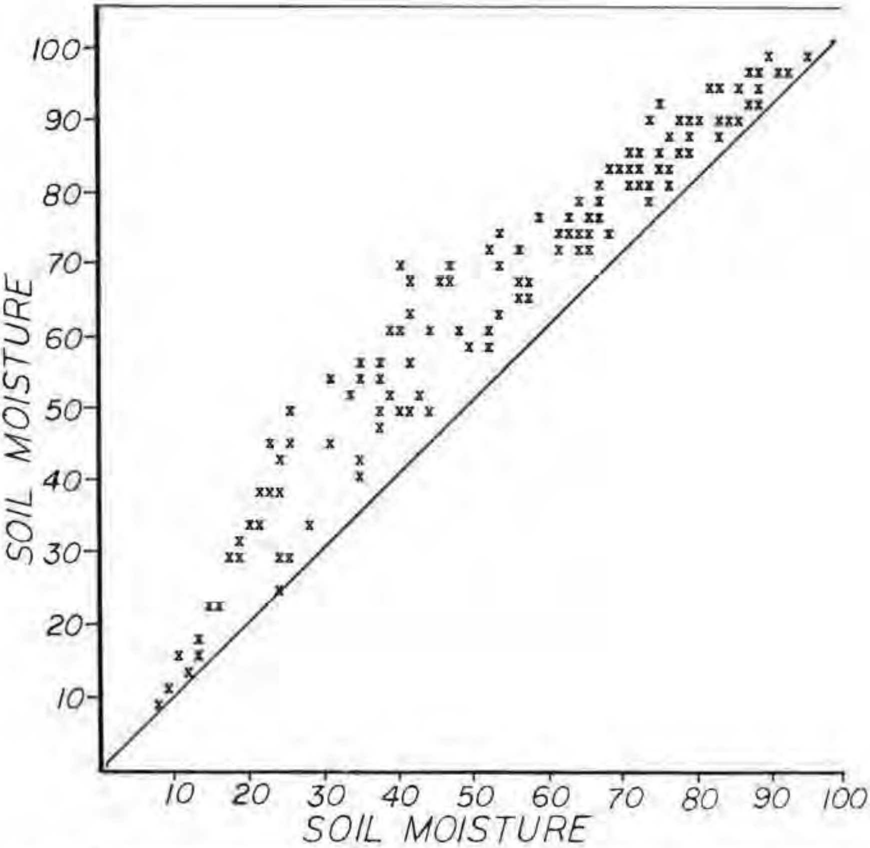

FIGURE 4. Comparison of soil moisture simulations, expressed as % of field capacity, where the actual precipitation amounts have been increased by 20% without a corresponding increase in the number(s) of days with precipitation (Y-axis) with soil moisture simulations based on 1951–80 normal precipitation (X-axis) at 140 synoptic stations across Canada.

attributed to the changes in Y. Looked at another way, the sensitivity to the increase in Y is half as much as to the increase in P while the sensitivity to the decrease in Y is about one quarter as much as to the decrease in P.

The relative contributions of Y and P are illustrated in the scatter diagrams in Figures 4 to 7. These show the impacts on soil moisture at the individual synoptic stations, in contrast to the averages shown in Table 4. Response to a 20% increase in P is shown in Figure 4, and to the same increase in Y in Figure 5.

The increase in P alone (Figure 4) has the most impact at those stations with mid-range values of soil moisture reserves. The extremes, close either to field capacity or to the permanent wilting point, are affected very little. The increase in

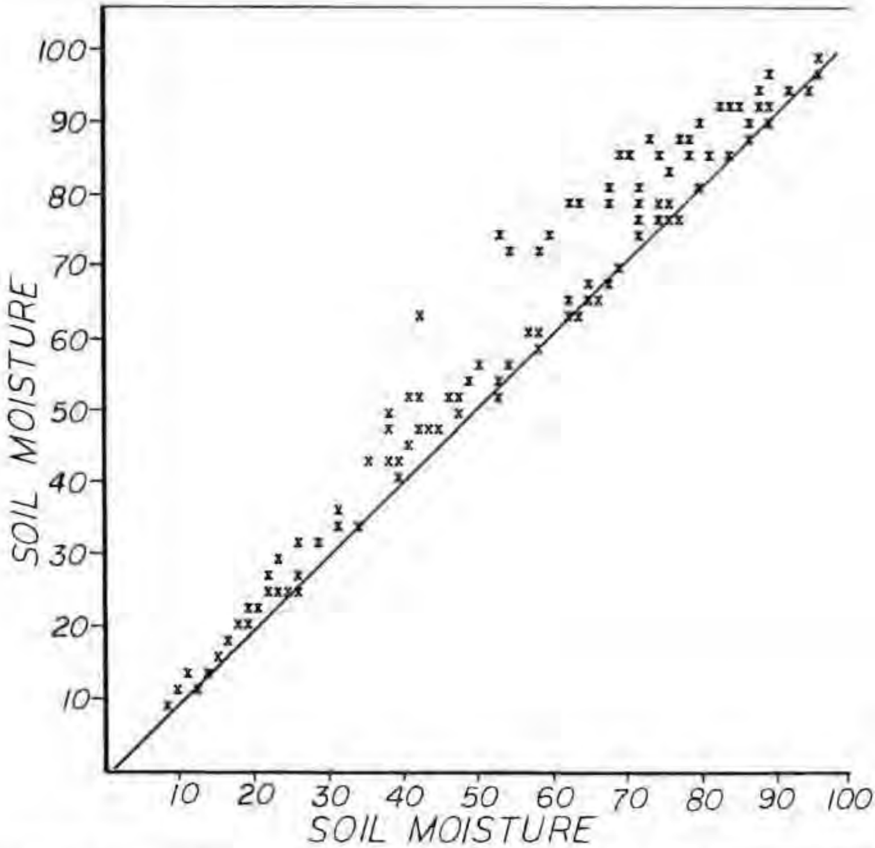

FIGURE 5. Comparison of soil moisture simulations, expressed as % of field capacity, where the number(s) of days with precipitation have been increased by 20% and rescheduled according to PROXDAYS without a corresponding increase in the actual precipitation amount (Y-axis) with soil moisture simulations based on 1951–80 normal precipitation (X-axis) at 140 synoptic stations across Canada.

Y alone (Figure 5) shows approximately half the overall response seen in Figure 4, with a few stations showing about the same sensitivity. Figure 5 also shows the greatest impact to be in the mid-range values of soil moisture.

Figure 6 shows response to a 20% decrease in Y alone and Figure 7 that to the corresponding decrease in P alone. The impact on soil moisture level in Figure 6 is almost half that evident in Figure 7, a result similar in magnitude but opposite in sign to that of increasing Y alone.

Figures 4–7 show virtually no exceptions to the direction of response of soil moisture to either increases or decreases in Y and P. This supports the use of the national average soil moisture simulations in Table 4 as a general indicator of response to the sensitivity test. Also all the tests show the greatest impact at

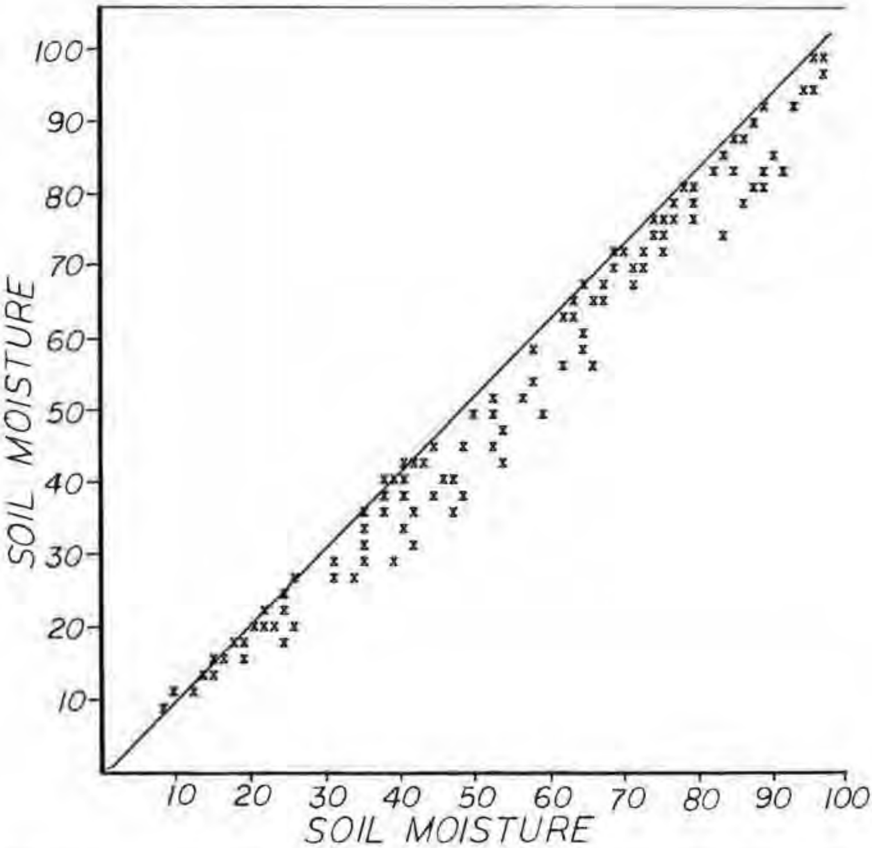

FIGURE 6. Comparison of soil moisture simulations, expressed as % of field capacity, where the number(s) of days with precipitation have been decreased by 20% and rescheduled according to PROXDAYS without a corresponding decrease in the actual precipitation amount (Y-axis) with soil moisture simulations based on 1951–80 normal precipitation (X-axis) at 140 synoptic stations across Canada.

mid-level values of simulated soil moisture, with little change close to the permanent wilting point and to field capacity.

DISCUSSION

The shape of the curve described by eq. 2 suggests that Y is more responsive to changes in P at drier stations. Eq. 2 also suggests a doubling in Y if P rises from about 20 to 80 mm. From P = 150 to P = 200 mm, Y increases much more slowly (Figure 2). However, because of the scatter apparent in Figure 1, it is understandable that the interaction between the monthly total (P) and the number of days per month with precipitation (Y) has been ignored in many climate-change

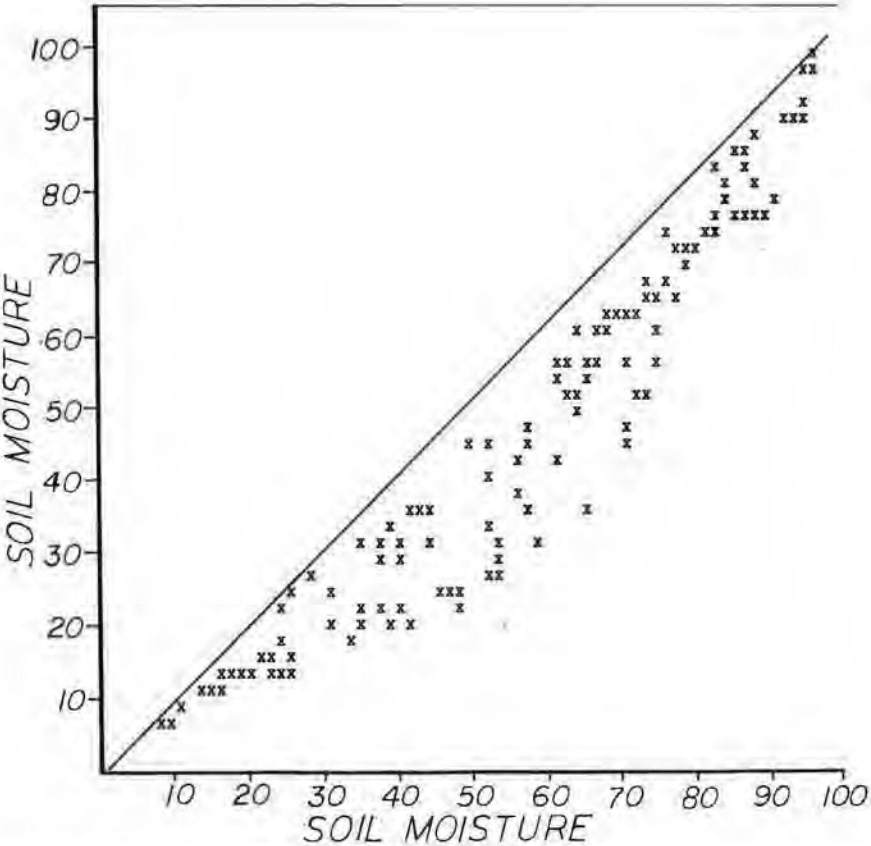

FIGURE 7. Comparison of soil moisture simulations, expressed as % of field capacity, where the actual precipitation amounts have been decreased by 20% without a corresponding decrease in the number(s) of days with precipitation (Y-axis) with soil moisture simulations based on 1951–80 normal precipitation (X-axis) at 140 synoptic stations across Canada.

impact studies. The relationship between Y and P is partly masked by this variability.

Although not the dominating factor, the periodicity of days with precipitation should be taken into account in estimating normal soil moisture reserves. Changes in this periodicity have important implications for crop weather analysis. Figures 5 and 6, which represent the same amount of water applied to the soil, strongly suggest that the frequency of days with precipitation could have a significant impact on the effectiveness with which soils store water, particularly in semi-arid climates.

The sensitivity of estimated soil moisture levels to changes in the number of days with precipitation has an impact upon the rate at which soil water is depleted in the various models, including the VB3 used here. This is because the ratio of actual to potential evapotranspiration (AE:PE) is taken to be controlled by the current level of soil moisture. Given the same total monthly precipitation, a low frequency of recharge means more water added to the soil during any one recharge event, with brief periods of high soil moisture reserves characterized by an AE:PE ratio close to one. These brief periods of high evapotranspiration account for a net loss of moisture which is greater than when recharge is more frequent and in smaller amounts. In the latter case these peak periods, where actual evapotranspiration is close to potential, are avoided and the net loss of soil moisture is reduced. From the perspective of plants, greater precipitation also means fewer periods of drought stress. This suggests that in wetter climates, not only is water supply increased, but water-use efficiency is improved as well, due to increased frequency of soil moisture recharge events.

The consistently lower moisture reserves that will result from fewer days with precipitation will also have an effect on crop growth, because of increased drought stress. As a follow-up to this study, the PROXDAYS procedure used here to generate input data for soil moisture simulations should also be tested as a means of generating input data for more complex crop-growth simulation models to evaluate the role of precipitation frequency in estimation of biomass and crop production.

In a climate altered by changes in atmospheric chemistry, there is no assurance that a reduction in precipitation amounts would lead to a reduced frequency of days with precipitation exactly according to eq. 2. However, the analysis conducted here strongly implies that P and Y under a changed climate would be better described by eq. 2 than by assuming no sensitivity of Y to changes in P. It is therefore recommended here that simulation models of crop growth and crop production, such as used by Stewart (1986) and by Savdie (1989) to determine the impact of climate change on agriculture, should incorporate the relationship of eq. 2 and use PROXDAYS. This would reschedule and reduce the number of days with precipitation in the simulation of drier climates, rather than simply reduce daily amounts without changing the number of days with precipitation given by normals for the current climate. The number of days with precipitation would be revised by the ratio of the squared log of monthly precipitation in a changed climate to the squared log of monthly precipitation in the present climate. With this adjustment in the projected frequency of precipitation, the procedure used by Stewart (1986) to analyze the Canadian Prairies offers a suitable approach for assessing the impact of both the thermal and hydrological aspects of climate change on Canadian agriculture.

The conclusions drawn from the sensitivity analysis described in Figures 4 to 7 represent only relative truths, as the values for soil moisture are not determined from actual measurements. In theory the true normal for soil moisture reserves should be a long-term average based on a 30-year record of actual field observations. Such long-term measurements are not readily available. The chances of gathering thirty years of soil moisture data without changes in the measurement site or deterioration, replacement or relocation of the instruments are very low. Time series of weather records are much less susceptible to such discontinuities. Weather-based simulations of soil moisture, using a computer model known to have acceptable accuracy (Baier *et al.*, 1979), represent a reasonable alternative to actual measurements, particularly when weather-related variability is being analyzed.

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Mean Daily Temperature Normals from 1901–30 to 1961–90 on the Eastern Canadian Prairies

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[Original manuscript received 24 January 1991;
in revised form 3 June 1991]

ABSTRACT

Preliminary 1961–90 normals of annual and monthly mean daily temperatures have been compiled for seven locations on the eastern Canadian Prairies and compared to values for six previous normal periods. For 1961–90, the areally-averaged normal shows a marked warming – ending a cooling trend that extended through three successive normal periods (1931–60, 1941–70 and 1951–80). The new monthly areal-normals show that, during the first eight months of the year, the 1961–90 values are all higher than those for the 1951–80 period. For February and March, they are the warmest this century. A reversal to cooler normals begins with October and is most pronounced for November and December. The 1961–90 areal-normals for the last two months of the year are the coldest this century.

RÉSUMÉ

On a compilé les normales préliminaires pour les températures moyennes mensuelles et annuelles enregistrées entre 1961 et 1990 dans sept localités de l'est des Prairies canadiennes. Ces valeurs ont ensuite été comparées à celles de six périodes antérieures. De 1961 à 1990, les normales calculées par moyenne aréolaire témoignent d'un réchauffement appréciable, qui marque la fin du refroidissement progressif constaté pendant trois périodes normales successives (1931–1960, 1941–1970 et 1951–1980). Les normales aréolaires mensuelles de 1961 à 1990 révèlent que, pendant les huit premiers mois de chaque année, les valeurs sont supérieures à celles enregistrées entre 1951 et 1980. Les normales consignées pour les mois de février et de mars sont les plus chaudes du siècle. Les normales pour le mois d'octobre sont en revanche inférieures à celles des périodes précédantes, et l'écart devient encore plus prononcé pour novembre et décembre. Les normales aréolaires de 1961 à 1990 pour les deux derniers mois de l'année sont les plus froides du siècle.

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INTRODUCTION

The climate of a region is typically delineated by statistics based on a 30 year reference period which is updated at the end of each decade. The average or "normal" mean daily temperature is one such measure. The purpose of this research note is to compare new 1961–90 monthly and annual normals of mean daily temperature on the eastern Canadian Prairies with previous values derived from composite-site records.

PROCEDURE

An in-house data base at the Winnipeg Climate Centre (WCC) for the major Prairie centres was used to calculate monthly and annual normals of mean daily temperature for three locations in southern Manitoba and four in Saskatchewan (Figure 1). Combining observations from separate weather stations at some locations extended the complete record (i.e., at least 23 years of data per normal period) back over seven normal-periods to 1901–30. Areal-normals were calculated as the average of the seven location-specific normals.

This analysis is preliminary as it is not based on the official records from the Canadian Climate Centre archive. In addition, composite rather than station-specific normals have been employed.

RESULTS AND DISCUSSION

The 1901–30 to 1961–90 annual normals of mean daily temperature for seven eastern Prairie locations are given (Table 1) along with the regional average or

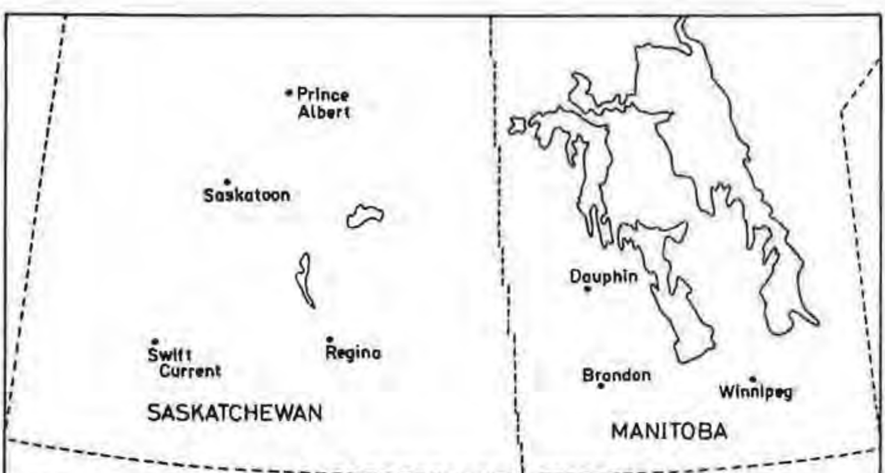

FIGURE 1. Map of the eastern Canadian Prairies showing the seven locations used in this analysis.

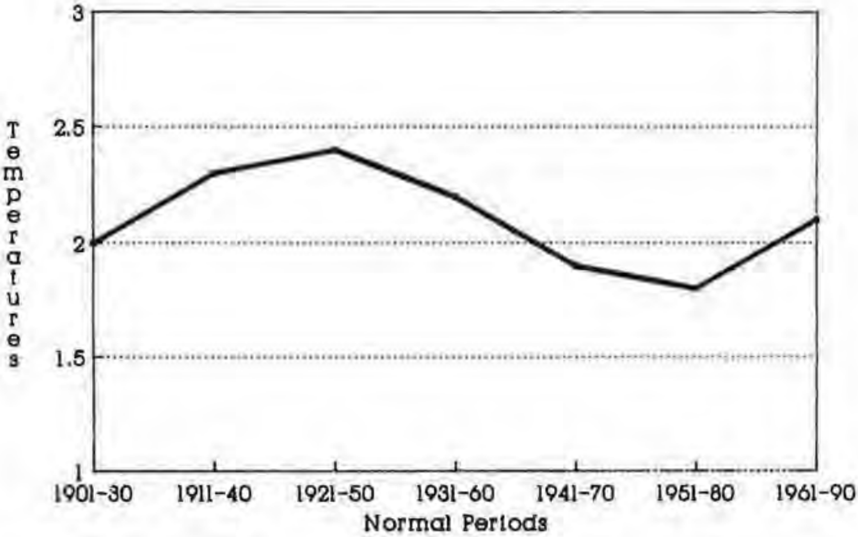

FIGURE 2. Annual normals of mean daily temperatures (C) averaged over seven locations.

areal-normal values. These regionally averaged values are also plotted (Figure 2). The areal-normal for the eastern Prairies has exhibited noteworthy changes over the seven normal periods, but no statistically significant trend (at the 0.01 level based on the nonparametric Wilcoxon sign-rank test – Panofsky and Brier, 1968). The normal rose from 2.0 C (1901–30) to 2.4 C (1921–50), then declined to 1.8 C (1951–80) before rising to 2.1 C (1961–90). The variation is similar to that exhibited by the northern hemisphere in general (Jones, 1988).

An interesting pattern emerges when the monthly areal-normals are examined (Table 2). During the first eight months of the year, the 1961–90 values are all higher than those for the 1951–80 period. For February and March, they are the warmest this century. A reversal to cooler normals begins with October and is most pronounced for November and December, whose 1961–90 areal-normals are the coldest this century. However, there are no significant trends in the monthly areal-normals over the 1901–1990 period (at the 0.01 level based on the Wilcoxon sign-rank test). This finding is consistent with the more rigorous result of Karl *et al.* (1991) for the seasonal mean temperatures, 1895–1989, of the central United States, to the south of our study area.

The intra-annual pattern of change evident in the areal-normal is common to most locations (Table 3). For January through June, the most recent 30 year period was, on average, warmer than the 1951–80 period at all seven locations while the October through December period was generally colder. February's new normals are the warmest this century at five of the seven sites while December's are the coldest at all seven locations.

TABLE 1. Annual Normals of Mean Daily Temperature (C) for seven locations and the Areally-Averaged Value for the Eastern Canadian Prairies.

	Normal or 30 Year Average						
Station	1901–1930	1911–1940	1921–1950	1931–1960	1941–1970	1951–1980	1961–1990
Brandon	1.4	1.7	1.9	2.1	1.9	1.9	2.2
Dauphin	2.4	2.7	2.8	2.3	1.8	1.4	1.7
Prince Albert	1.1	1.4	1.1	0.7	0.2	0.1	0.5
Regina	1.6	2.1	2.4	2.3	2.1	2.2	2.6
Saskatoon	1.3	1.6	1.8	1.7	1.6	1.6	2.0
Swift Current	3.8	4.0	4.0	3.6	3.3	3.2	3.5
Winnipeg	2.5	2.6	2.6	2.5	2.3	2.2	2.4
Average	2.0	2.3	2.4	2.2	1.9	1.8	2.1

TABLE 2. Monthly Normals of Mean Daily Temperature (C) averaged over seven locations on the Eastern Canadian Prairies.

	Normal or 30 Year Average						
Month	1901–1930	1911–1940	1921–1950	1931–1960	1941–1970	1951–1980	1961–1990
January	−17.8	−17.7	−16.8	−17.2	−18.0	−18.8	−17.4
February	−15.0	−14.7	−14.4	−14.6	−14.6	−14.5	−14.0
March	−7.3	−7.2	−7.1	−8.0	−8.4	−8.3	−6.8
April	3.5	3.7	3.4	3.2	3.0	3.0	3.6
May	10.5	11.3	11.0	11.0	10.2	10.7	11.1
June	15.7	16.1	15.8	15.5	15.4	15.7	16.1
July	18.5	19.3	19.5	19.3	18.8	18.6	18.7
August	17.0	17.6	17.7	17.8	17.7	17.4	17.6
September	11.4	12.0	12.0	11.9	11.5	11.4	11.4
October	4.9	4.9	5.4	5.4	5.5	5.3	5.1
November	−4.3	−4.8	−5.2	−5.3	−5.1	−5.2	−5.5
December	−13.0	−12.9	−13.2	−12.8	−13.4	−13.7	−14.4

TABLE 3. Comparison of the 1961–90 Monthly Mean Daily Temperature Normals with six previous Normals for seven locations on the Eastern Canadian Prairies.

Month	Warmest* Since 1901–1930	Warmer Than 1951–1980	Tied With 1951–1980	Colder Than 1951–1980	Coldest* Since 1901–1930
January	1	7			
February	5	7			
March	3	7			
April	3	7			
May	3	7			
June	3	7			
July		5	2		
August	1	6	1		
September		1	3	3	2
October			1	6	2
November				7	3
December				7	7

* Ties not included.

The changes in the monthly normals, from the 1951–80 to 1961–90 period, imply an apparent shift of the seasons with warmer late winters and springs and colder falls and early winters. December, rather than February, is now second to January as the coldest winter month. Schindler *et al.* (1990) reported results consistent with ours for the Experimental Lakes Area (ELA) of northwestern Ontario, to the east of our study area. The ELA has experienced an increase in the ice-free season of about 20 days during 1969–1987, primarily due to warmer springs.

The cause of the intra-annual pattern of change in mean daily temperature normals from the 1951–80 to 1961–90 period is not known. A possible explanation is that air temperatures were more responsive to the annual solar radiation cycle (i.e., less lag) in the dry 1980's than they were during the wetter regime of the 1950's. Urban heat island effects may have contributed to the general upswing in the annual mean daily temperature normals from the 1951–80 to 1961–90 period but urban warming does not offer a reasonable explanation for the observed intra-annual pattern of change.

In summary, preliminary 1961–90 normals for three southern Manitoba and four southern Saskatchewan locations indicate that an upturn to warmer annual mean daily temperatures has occurred across the eastern Prairies. The warming was confined to the first eight months of the year. A reversal to cooler monthly mean daily temperatures, not evident from the annual normals, occurred for the October through December period.[1]

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[1] If any readers have data available which would allow comparisons with other parts of Canada, *Climatological Bulletin* would be interested to hear of their findings – *Editor*.

News and Comments
Nouvelles et commentaires

ALBERTA CLIMATOLOGICAL ASSOCIATION ANNUAL MEETING

The 15th Annual General Meeting of the Alberta Climatological Association was held February 21, 1991 at the Alberta Research Council facility in Edmonton, Alberta. The theme was Environmental Monitoring and Instrumentation for the 1990's. The ACA this year invited manufacturers and distributors of environmental monitoring equipment to participate in the technical session portion of the Annual General Meeting. There was an excellent response with ten different firms represented and participating. There were both displays of equipment and short presentations made to the assembled meeting.

The attendance at the Annual General Meeting was about 75 people. The morning started off with brief presentations by the exhibitors outlining their product line. The technical program continued after the refreshment break with the presentation by Dr. John Maybank on "Integrated Weather and Climate Services in the '90's". Dr. Maybank is working with the Central Region of AES on a special project. He was followed by Mr. Hugh Howe and Mr. Karl Runions of Alberta Environment who gave a presentation on "Installation Procedures for Real Time Networks at Alberta Environment".

A lunch was provided for participants, courtesy of the exhibitors.

The afternoon technical session started off with Ben Jans speaking about "Capabilities and Limitations of Automated Data Acquisition Systems". Dr. Dave Halliwell then spoke about "The Ultimate Answer to Instrumentation, Data Collection, and Everything: What was the Question?" The technical program concluded with Mr. Peter Kociuba of AES, Edmonton speaking on "AES Guidelines for Auto Stations and Algorithms".

A number of the exhibitors provided small prizes for which a draw was held during the afternoon refreshment break.

The ACA held its annual business meeting from 3:00 to 4:30. There were 28 members in attendance. The ACA adopted a revised constitution and new bylaws. Anyone interested in joining the Alberta Climatological Association or receiving the proceedings of the 1991 Annual General Meeting can contact:

Peter Dzikowski, President
Alberta Climatological Association
c/o Alberta Agriculture
Room 206, 7000 – 113 Street
Edmonton, Alberta T6H 5T6

A COMMENT ON HAILSWATH LENGTHS

Grain prices are low at present and crop-hail losses are down in dollar terms as a result, but hailstorms have done a lot of property damage in Canada in recent years. Thus despite the demise of the Alberta Hail Project (AHP) in the mid-1980's, the weather and climate community in Canada retains an interest in the topic.

For almost thirty years the AHP made a contribution recognized by researchers around the world to our knowledge of hailstorm behaviour. From the viewpoint of hail climatology, its collection of a hundred thousand observer reports of hailfalls at the ground is the best in the world. It provides documentation on hundreds of hailswaths – perhaps even a thousand – but still leaves open the question of how long such swaths may be. These long, narrow tracks of hail arriving at the ground frequently extended outside the project area and beyond the range of the Red Deer Airport radar. How much further they extended was a question only partly answered by the additional study of crop-hail insurance records and the relatively few hail reports sent in by observers outside the AHP area (Figure 1).

Hailswath lengths have been reported from various mesoscale observing networks around the world. The reported frequency distributions are all biased towards shorter swaths because of the lack of information from outside the network areas. Thus Admirat *et al.* (1985), for example, report maximum hailswath lengths of 300 km, information attributable to Wojtiw, one of the co-authors, from Alberta. In the same article, hailswath lengths from Switzerland and South Africa are reported to be shorter. The Canadian prairies offer an excellent opportunity to research the question. There is a relatively continuous farmland area 1400 km "wide" from west to east, with good crop-hail insurance records and local newspaper coverage. To the south of the 49th Parallel is another agricultural area with similar characteristics and possibilities for study.

A first foray into the subject (Paul, 1973) was made almost twenty years ago. A single hailswath from a travelling thunderstorm of 23–24 July 1971 was easily traced from the vicinity of Sundre, Alberta all the way to Dinsmore in south-central Saskatchewan. And the AHP had no information on where the storm had been before it reached Sundre. So this hailswath was at least 535 km long, and the storm which produced it had a lifetime of 12 hours or more.

Recently three long hailswaths came to light within a short time. One in Alberta in 1958 was mentioned to me by a colleague who is a wildlife biologist, and is written up by Smith and Webster (1955). It reportedly killed twenty-eight thousand ducks. Another in Montana on 2 August 1981 was studied during the HIPLEX project (Wade, 1982; Miller, Tuttle and Knight, 1988). The storm came in one end of the Montana project area, i.e. the western edge of radar coverage, and out the eastern end (260 km as an absolute minimum). The third (Figure 1) was a swath of June 19–20, 1974 which originated in Saskatchewan (Clyde, 1976) – where it had been identified during the Saskatchewan Hail Research Project or

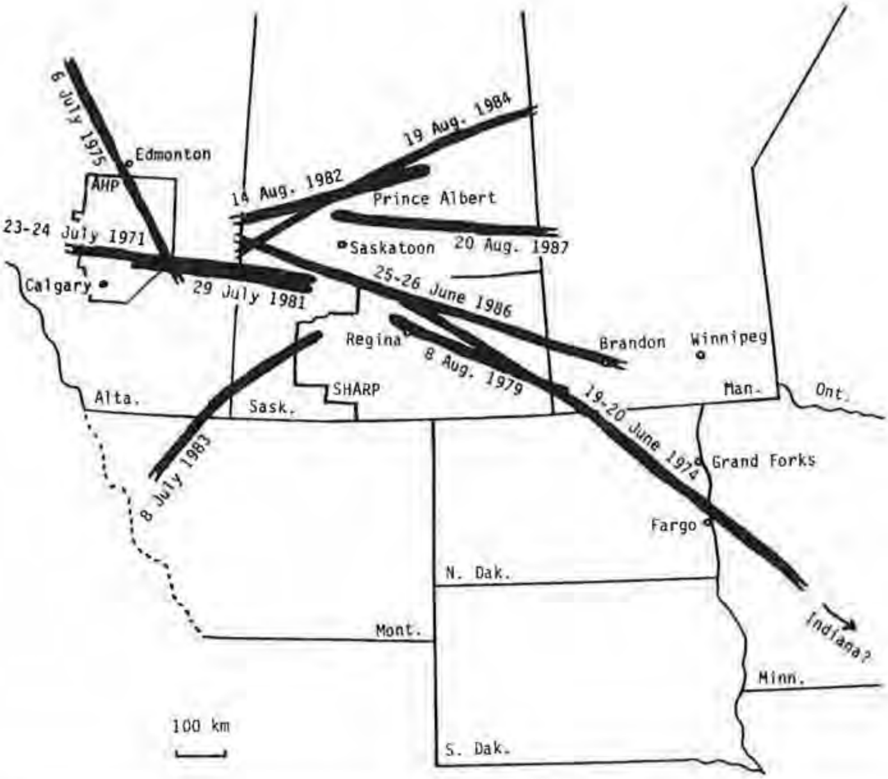

FIGURE 1. Hailswaths of ten long-track severe thunderstorms on the northern Great Plains.

SHARP (Paul, 1980) – but extended southeast into Manitoba. The Manitoba Crop Insurance Corporation records showed that it had continued into North Dakota. Further investigation, via NOAA's *Storm Data* and the hourly precipitation data, and contacts with North Dakota co-operative observers showed that it had passed on into Minnesota. *Storm Data* strongly suggests that it went on from there through northwest Iowa and southwest Wisconsin into Illinois and even Indiana, but all that needs further verification.

Thus a study of hailswath length has been initiated, using crop-hail insurance data from Saskatchewan as a starting point. It is early yet, but preliminary indications are that hailswaths longer than Wojtiw's *maximum* of 300 km are by no means exceptional. Supplements to the Saskatchewan information from neighbouring provinces and states are available but the process is time-consuming. Figure 1 shows ten hailswaths longer than 300 km which have been confirmed already. Numerous others will likely follow.

The implications of these preliminary results are intriguing. First, hailstorm circulations are capable of maintaining themselves for more than 5 hours in a great many cases. Second, while an individual thunderstorm at a given instant is a mesoscale circulation, if it persists for 12 hours and lays a hailswath 500–600 km long, is it not more appropriately considered as being sub-synoptic in scale? Third, these swaths are longer than those reported for hailstorms anywhere else in the world. Since prairie hailstorms have other characteristics similar to those elsewhere (Gokhale, 1975), it seems probable that hailswath lengths in other regions have also been underestimated in previous studies.

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WORKSHOP ON NATURAL RESPONSE TO CLIMATE VARIABILITY

This workshop was organized by the Saskatchewan Climate Advisory Committee and held in Regina on October 30, 1990. The Proceedings are now available from:

Ken Jones
Scientific Services
Atmospheric Environment Service
P.O. Box 4800
Regina, Sask. S4P 3Y4

The Proceedings include papers on the impacts of climate extremes; the effects of climate variation on forest fires in Saskatchewan, and on PFRA programs; the impact of the 1980s climate on agriculture and on electrical power usage in the province; and media marketing.

Elaine Wheaton
Saskatchewan Research Council