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

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Foreword / Avant-Propos

The three issues of Volume 24, 1990 contained 11 articles and notes, 1 climate-review piece, and 9 news items. The total of 183 pages represents a healthy 35 per cent increase over Volume 23, 1989. The number of manuscripts submitted is also continuing to rise, with 17 arriving in 1990 compared with 13 in 1989.

CMOS's *ad hoc* committee to consider the options for continuing to publish climate-related material after the end of 1991 is active at the present time. Its report will be available for discussion before the Winnipeg Congress in June.

Les trois numéros du volume 24 (1990) contenaient 11 articles et notes, 1 revue du climat, et 9 faits divers. Le total de 183 pages représente une augmentation significative de 35 pour cent par rapport au volume 23 de 1989. Le nombre de manuscrits soumis a également passé de 13 en 1989 à 17 en 1990.

Le comité *ad hoc* de la SCMO chargé d'étudier la question de la publication du matériel climatologique après la fin de 1991 est présentement au travail. Son rapport sera disponible avant le Congrès de Winnipeg en juin.

Alec Paul
Editor/Rédacteur en chef

The Frequency and Surface Characteristics of Sea Breezes at St. John's, Newfoundland

Colin E. Banfield
Department of Geography
Memorial University of Newfoundland
St. John's, Newfoundland A1B 3X9
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in revised form 10 January 1991]

ABSTRACT

The frequency and surface characteristics of sea breezes at St. John's, Newfoundland over a ten year period were investigated. The primary sea breeze identifier was the occurrence of reversals of surface wind direction within specified portions of a 24-hour period, determined from the hourly record at St. John's Airport. Surface synoptic charts were examined in order to screen out wind shifts due to synoptic-scale control. The overall frequency is relatively low, averaging two or three events per month from May through August. Sea breeze duration varies from a median of two hours for June to six hours for July. A bi-modal distribution of directional frequencies and speeds is observed. Almost half of the sea breezes produced cooling of 1.0 to 3.0°C; approximately 10% resulted in a temperature drop of at least 5.0°C. The Biggs-Graves Lake Breeze Index (BGI) was determined as a check on the validity of the selection method; 78% of the days satisfying the other sea breeze tests met the criterion of BGI < 3.0. The majority of cases with BGI > 3.0 were associated with a specific synoptic gradient wind pattern which may, in some cases, lead to meso-scale features affecting coastal wind conditions.

RÉSUMÉ

Cette étude porte sur la fréquence et les caractéristiques à la surface des brises de mer à Saint-Jean, Terre-Neuve durant une période de dix années. Le critère principal employé pour identifier les brises de mer est un changement en sens opposé de la direction du vent à la surface à l'intérieur de certaines parties d'une période de 24 heures, à partir des données horaires à l'aéroport de Saint-Jean. On a étudié des cartes synoptiques de surface afin d'éliminer les changements dus à des phénomènes d'échelle synoptique. La fréquence générale est relativement faible; on a noté un moyen de 2 à 3 brises de mer par mois pendant la période du mois de mai au mois d'août. La durée médiane de cette brise varie de 2 heures en juin à 6 heures en juillet. On a observé une distribution bi-modale des fréquences de direction et de vitesse. Presque la moitié des brises de mer ont produit un refroidissement de 1,0 à 3,0°C et à peu près 10 pour cent ont résulté en une baisse de température d'au moins 5,0°C. L'indice de Biggs-Graves Lake Breeze (BGI) a été utilisé afin de vérifier la précision des critères selectionnés; 78 pour cent des jours répondant aux autres critères d'identification de la brise de mer ont également une valeur du BGI 3,0. Pour la plupart des cas où le BGI > 3,0 la situation se caractérise par un patron particulier du vent à l'échelle synoptique. Ce patron, en certains cas, peut produire des phénomènes à l'échelle moyenne qui peuvent affecter les vents d'une région côtière donnee.

1. INTRODUCTION AND OBJECTIVES

The study of the sea breeze has largely been prompted by recognition of its implications for low-level dispersion of natural and man-made atmospheric particulates and gases, impacts on outdoor human activity and/or the need to incorporate knowledge of its characteristics into local weather forecast preparation. Interest in the subject has generated much research on several methodological fronts in contrasting climatic regions; Atkinson (1981) provides a thorough review of major contributions up to the 1970's.

Empirically-based studies have expanded over the years to encompass not only the surface manifestations of the sea (or lake) breeze but the spatial and temporal evolution of the entire vertical circulation system involved. Such work is exemplified by the contributions of Staley (1957), Frizzola and Fisher (1963), Gill (1968), Lyons (1972), Barbato (1979), Sturman and Tyson (1981) and Prezerakos (1986) at mid-latitude locations, and by Moritz (1977) and Kozo (1978) in a Low Arctic environment. During the past three decades the earlier theoretical foundations of the sea breeze mechanism have been subjected to increasing scrutiny using analytical and numerical modelling approaches, occasionally supported by observational testing (for example Fisher, 1961; Estoque, 1961; Pielke, 1974). While some of these analyses have modelled the effects of differing topographic and/or synoptic meteorological settings on the evolution and form of the sea breeze (Estoque, 1962; Mahre and Pielke, 1977; McKendry *et al.*, 1988), this aspect clearly requires further research. Moreover, in order to improve the design and utility of the models further empirical study of the sea breeze is required under varying synoptic conditions, as noted by Sturman and Tyson (1981) and McKendry (1989). Hence the present paper will provide information on the climatology of the sea breeze, and its accompanying synoptic weather situations, within an area of the Canadian east coast from which the phenomenon has not yet been reported in the literature.

Recognition of a sea breeze normally requires a local to meso-scale onshore component of the surface wind to override or amplify the synoptic-scale gradient flow, as a result of horizontal pressure gradient forces produced by unequal heating of land and sea surfaces. In the Newfoundland context the cold waters of sub-Arctic origin that surround the island portion of the province can lead to considerable horizontal temperature gradients across the coastline during the season of strongest solar irradiance. However, the synoptic-scale pressure patterns often produce fairly strong gradient winds, which may act to reduce the frequency with which small-scale thermally-driven circulations are allowed to develop. Thus, there are two objectives of this particular analysis, namely:

1. to document the frequency, duration, speed, direction and accompanying cooling effects of the sea breeze (as defined below) at St. John's, Newfoundland, based upon a data set of ten years duration,
2. to characterise the synoptic-scale meteorological conditions that were associated with the development of these sea breeze occurrences, including an examination of the applicability of the Biggs-Graves Lake Breeze Index (Biggs and Graves, 1962) for identifying sea breeze onset at St. John's.

2. DATA SOURCES AND SEA BREEZE DEFINITION

In the vicinity of St. John's the Atlantic coastline is characterised by a series of hills and headlands dissected by the short valleys of streams draining from the higher terrain which separates the city area from the Conception Bay coastal zone to the west (Figure 1). Local relief is generally in the range 150–250 m.

The identification and characterisation of sea breezes was based upon examination of meteorological records from St. John's Airport, located 6–7km from the east coast at 140m asl, and Memorial University of Newfoundland (M.U.N.), 4km west of St. John's harbour at an elevation of 60m. The hourly wind record at the airport meteorological station served as the initial data source for the identification of sea breezes. Subsequent analysis of accompanying temperature and humidity changes focused upon the thermohygrograph record at the Memorial University station, in order to take advantage of its greater time resolution.

Figure 1 also indicates the wind directional sectors that are regarded as "onshore" and "offshore" for the definition of the diurnal wind reversals. With reference to St. John's Airport the onshore sector was chosen to lie between the true azimuths of 20 and 150 degrees, *i.e.* blowing directly off the Atlantic Ocean. The definition adopted for offshore (200–320°) relates to the location of the city with reference to the island as a whole and includes winds whose fetch extends across the interior of the Avalon Peninsula to the southwest or via central Newfoundland further to the west. Strictly, however, airflow from Conception Bay to the west of the city can also be regarded as onshore and the possibility exists for sea breezes from this direction to reach St. John's Airport. Also, sea breezes are known to develop contemporaneously on opposite sides of a peninsula under suitable synoptic situations (Lalas *et al.*, 1983; Noonan and Smith, 1986; McKendry, 1989). The progression of a sea breeze from Conception Bay as far as St. John's Airport could conceivably occur, for example, during westerly gradient flow, if the latter were strong enough to prevent an easterly sea breeze reaching the airport. Identification of this particular condition would have to rely upon detection of a sea-breeze induced diurnal variation in the speed of the general westerly flow at the airport, since meteorological information was lacking for the Conception Bay coastal area. Given the uncertainties involved in confirming any

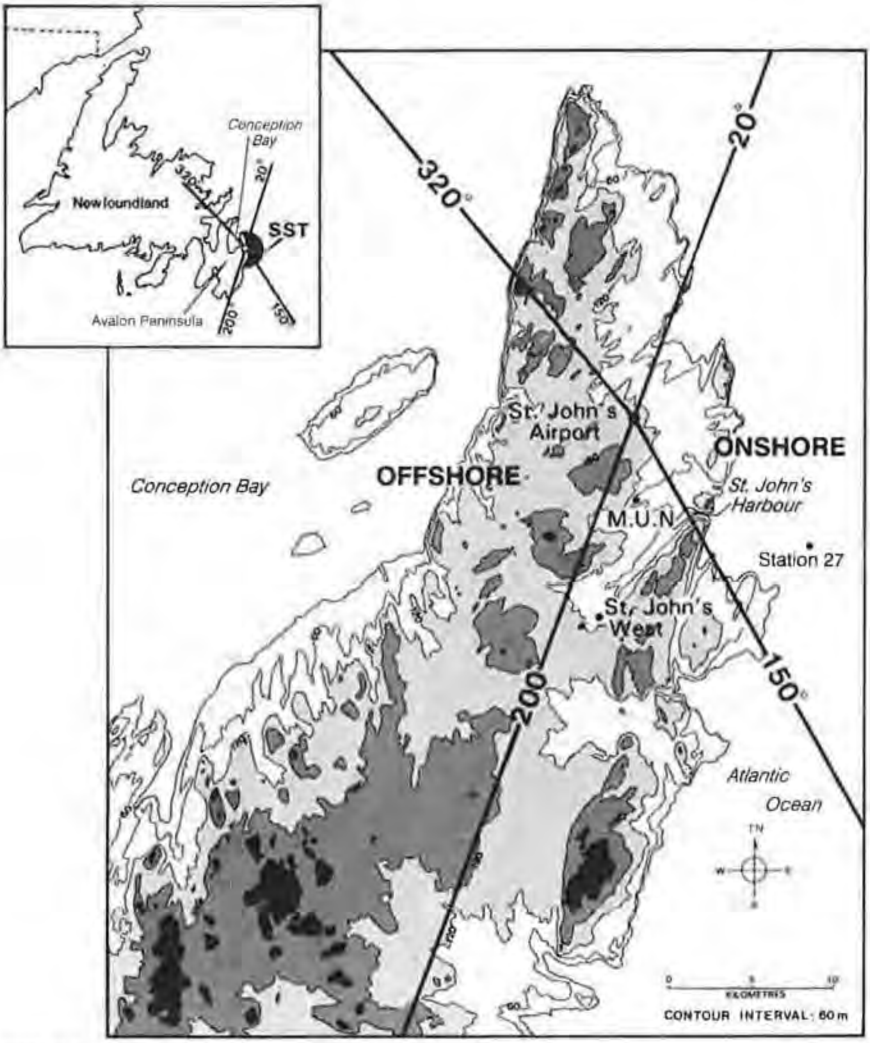

FIGURE 1. Study area, showing topography, meteorological stations and onshore/offshore airflow sectors.

westerly sea breezes at the aiport, the onshore flow sector has been limited in this study to the open ocean area east of St. John's, as defined above.

Accordingly, the principal criterion used to recognize a sea breeze at the airport was the occurrence of a distinct reversal of surface wind direction within a particular 24-hour period which could not be attributed to synoptic scale circulation features. Specifically, the diurnal wind reversal was defined by the following sequence:

(i) winds are predominantly from the offshore sector between 2200 and 0600 Newfoundland Standard Time (NST);

(ii) a windshift of at least 40 degrees from the offshore to the onshore sector occurs for a minimum of one hourly observation from 0800 to 2000 NST. This windshift must be abrupt, *i.e.* occur within a one-hour period.

(iii) a directional shift back to the offshore sector occurs by 2200 NST on the same day.

All days meeting this initial screening criterion during the study decade 1979–1988 were identified as the initial set of "potential sea breeze days". For each of these days the surface synoptic analysis charts from the Newfoundland Weather Centre (Gander) were inspected to determine whether the observed changes in wind direction could have resulted from synoptic-scale control over local wind behaviour, such as passage of a front, trough line, centre of a closed isobaric system or strongly curved isobars. The surface analyses for 1200Z (0830 NST), 1800Z (1430 NST) and 0000Z (2030 NST) on each of the potential sea breeze days were examined for any possibility of the onshore flow resulting from such synoptic situations. If the surface analyses revealed (a) no evidence of synoptic control over the windshift to onshore and (b) an offshore surface gradient airflow over the St. John's area, then the wind reversal was attributed to local-scale thermal control and classed as a sea breeze occurrence. A total of 90 sea breeze days were identified following these criteria, over the ten-year period. This may be a conservative total since the screening process may have resulted in the omission of some cases of sea breezes that were superimposed upon synoptically aided onshore flow; also, by definition, any westerly sea breezes from Conception Bay that may have reached the airport are excluded. The 90 sea breeze days all occurred within the period April through September; during these months an additional 27 days that satisfied the wind reversal criteria were rejected because of synoptic effects. All subsequent climatological and meteorological attributes were determined using this 90-day data set.

In addition, for each sea breeze day, the Biggs-Graves Lake Breeze Index (Biggs and Graves, 1962) was determined in order to examine its potential as a sea breeze predictor at this location. Initially developed to aid prediction of the lake breeze at the western end of Lake Erie, this index has also been found to be reasonably successful in predicting sea breeze occurrence across the Lower Mainland of British Columbia (Steyn and Faulkner, 1986) and the east and south coasts of New Brunswick (Neumann and Mukammal, 1979). The authors determined daily values of this index from:

$$BGI = \frac{u^2}{c_p\ \Delta T}$$

where u = a representative local surface wind speed preceding the onset of onshore flow (ms^{-1})

ΔT = difference between local offshore water surface temperature and a representative daytime maximum temperature reached inland (K);

c_p = specific heat of air (1.003 $Jg^{-1}K^{-1}$) (original authors' units).

In this study u is defined as the mean hourly surface wind speed at St. John's Airport for the three hours immediately preceding the shift to onshore flow on a sea breeze day. In the determination of the ΔT values, rather than use the daily maximum air temperature reported at an inland station (which could conceivably occur following, instead of before, a brief sea breeze) the highest temperature observed from the Memorial University thermohygrograph record prior to the onset of the sea breeze was used. This was considered more representative of the degree of solar heating required for local sea breeze development. Estimates of local sea surface temperature (SST) on sea breeze days were obtained from examination of weekly SST maps issued for Atlantic Canada waters by Canadian Forces METOC Centre, Halifax. These maps are recompiled twice weekly using data collected via satellite and bathymetric soundings from aircraft and ships-of-opportunity. Given the limitations imposed by the spatial and temporal coverage of these data, the maps (and hence the SST values determined in this work) probably have a margin of error in the range of 1.0–2.0°C (*personal communication*, Canadian Forces METOC Centre, Halifax).

3. SEA BREEZE CLIMATOLOGY

3.1 Relevant features of the St. John's climate

Figure 2 illustrates the annual cycles of two factors important for sea breeze development, namely the local intensity of solar irradiance at the surface and the maximum land-sea temperature contrast; the latter was obtained by subtraction of the long-term monthly mean values of the sea surface temperature at "Station 27" (an oceanographic buoy located approximately 7km east of St. John's) from the daily maximum air temperature at St. John's West. Monthly frequencies and speeds of winds from the offshore directions are given by Table 1.

3.2 Sea breeze frequency and duration

The total number of sea breeze days identified over the ten-year period, by month (Table 2), shows a clear "season" of most frequent occurrences from May until August; from one to four sea breezes were recognized for each of these months in each year. No sea breezes were detected for the period October through March. These frequencies are significantly less than reported for eastern New Brunswick (Neumann, 1979), Halifax, Nova Scotia (Dexter, 1958) and for the Vancouver area (Steyn and Faulkner, 1986). A major factor preventing a greater sea breeze frequency at St. John's is considered to be the relatively high mean strength of the prevailing offshore wind compared with other mid-latitude sites in Canada (Environment Canada, *Canadian Climate Normals*, Volume 5 – Wind; 1951–1980).

TABLE 1. Mean percentage frequency and speed (ms^{-1}) of offshore wind directions, St. John's Airport.

	SSW		SW		WSW		W		WNW		NW		All offshore	
	%	$\overline{u}$	%	$\overline{u}$	%	$\overline{u}$	%	$\overline{u}$	%	$\overline{u}$	%	$\overline{u}$	%	$\overline{u}$
April	4.1	6.7	7.3	7.0	14.5	7.5	12.0	6.8	5.6	7.0	6.8	7.5	50.3	7.1
May	4.8	6.3	7.3	6.9	17.3	7.5	12.9	7.1	3.5	6.6	4.2	6.9	50.0	6.9
June	5.6	6.0	9.7	6.75	23.4	7.6	13.1	6.9	3.7	6.1	3.1	6.2	58.6	6.6
July	6.9	6.0	12.7	6.6	26.2	7.1	15.1	6.7	2.4	5.3	2.1	5.6	65.4	6.2
August	7.0	5.9	12.4	6.25	23.8	6.7	14.4	6.4	3.3	5.6	3.1	5.8	64.0	6.1
September	6.4	6.2	10.7	6.3	19.0	6.9	16.1	6.8	5.5	6.3	4.3	6.0	62.0	6.4

Source: Environment Canada, *Canadian Climate Normals*, Volume 5 – Wind; 1951–1980.

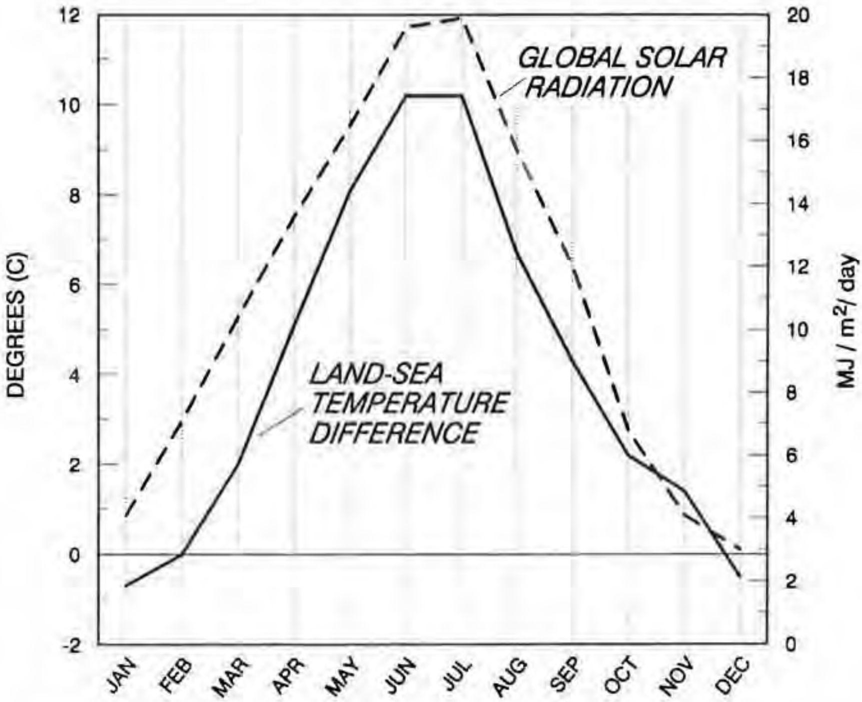

FIGURE 2. Annual cycles of mean daily global solar radiation on a horizontal surface at St. John's West and mean excess of daily maximum air temperature (St. John's West) over local offshore sea surface temperature.

TABLE 2. Frequency of sea breezes at St. John's Airport, 1979–1988.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Overall Total	0	0	0	6	21	15	24	20	4	0	0	0
Least per year	0	0	0	0	0	0	1	1	0	0	0	0
Most per year	0	0	0	3	4	3	4	3	1	0	0	0

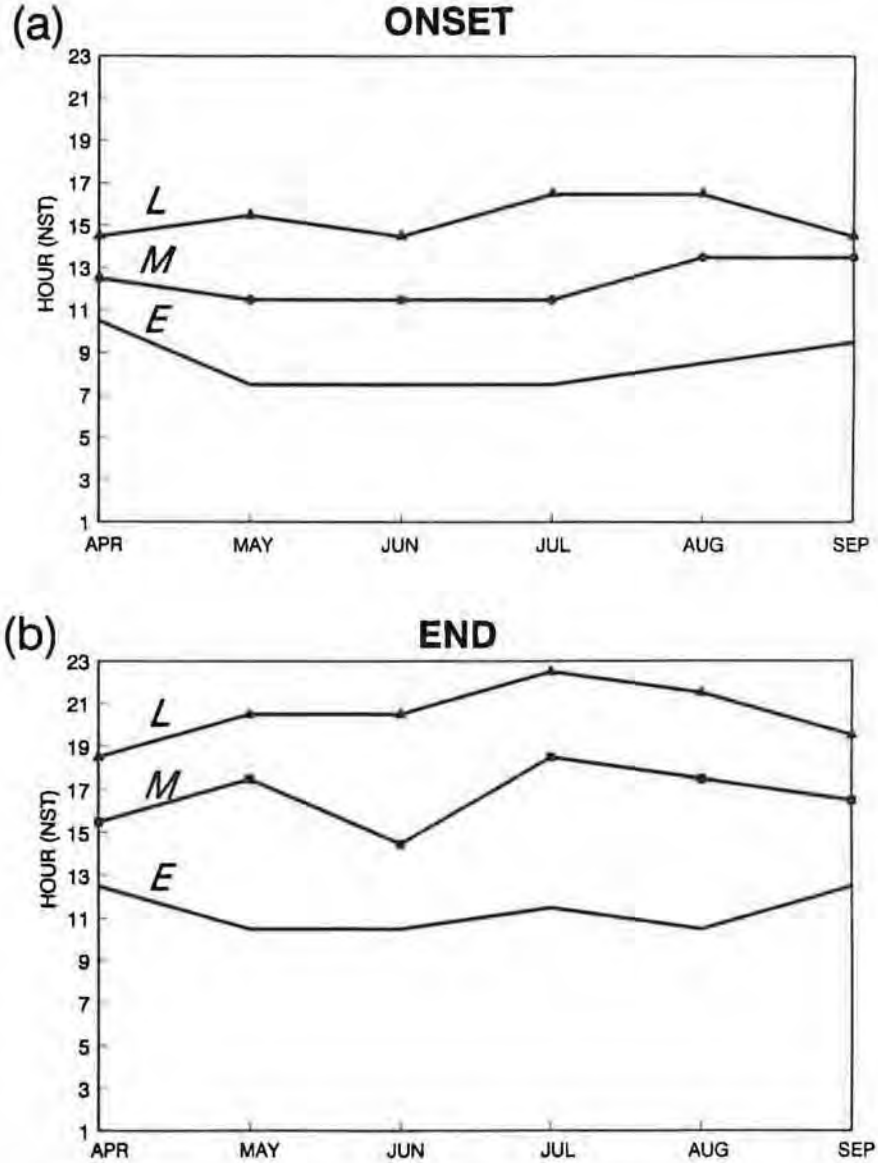

FIGURE 3. Times of onset (a) and ending (b) of the sea breeze at St. John's Airport, 1979–1988. M = median; E = earliest; L = latest.

A fairly wide range of times of onset and ending of the sea breeze, and resulting durations, is apparent from Figure 3 and Table 3. The median time of onset occurs shortly before noon (NST) during the months of greatest land-sea temperature contrast (May through July) but is delayed by two hours later in the summer, when the later sunrise and the diminished land-sea temperature difference would act to delay sea breeze onset. Sea breezes are capable of setting in as early as 0730 NST but may be extinguished before noon. The median duration is generally between two and four hours, but increasing to six hours for July.

TABLE 3. Duration (hours) of the sea breeze at St. John's Airport, 1979–1988.

	April	May	June	July	August	September
Median duration	2.5	4	2	6	3	3
Shortest	1	1	1	1	1	1
Longest	8	9	9	12	6	8

3.3 Sea breeze strength, cooling effect and directional frequencies

Given that theoretical considerations imply that the speed and cooling effect of a sea breeze are a function of the land-sea temperature gradient and the strength of the preceding offshore airflow, the mean monthly values of these parameters are compared in Figures 4a and 4b for the April-September period of sea breeze occurrence. The cooling effect was defined as the fall in temperature (determined from the M.U.N. thermohygrograph) over a period of approximately two hours following the estimated time of onset of the sea breeze. This duration was chosen in order to reduce the likelihood of cooling from the sea breeze being confused with radiational cooling in the late afternoon and evening.

The average sea breeze strength ranges from 3.1 ms^{-1} for July to 4.7 ms^{-1} for May, with an overall average of 3.7 ms^{-1}. This is similar to speeds reported from comparable latitudes elsewhere (Dexter, 1958; Brittain, 1978; Burns *et al.*, 1980; Steyn and Faulkner, 1986). However the antecedent speeds (previous three hours) are somewhat greater, reflecting the stronger prevailing offshore winds encountered in this area. It follows that in order to overcome a stronger offshore wind the thermal driving force, represented by the land-sea temperature contrast, must be sufficiently pronounced. In this respect the characteristic low offshore sea temperatures would serve to magnify this force and improve the chances of local sea breeze development. In this regard the magnitude of (MAX T – SST) shown by Figure 4b refers to the estimated local land-sea temperature difference immediately prior to sea breeze onset, averaged for all sea breeze cases by month.

The mean sea breeze cooling effect was greater during the months of strongest land-sea temperature difference (May, June, July), as may be expected. However, the relatively strong cooling effect for the month of May (which was

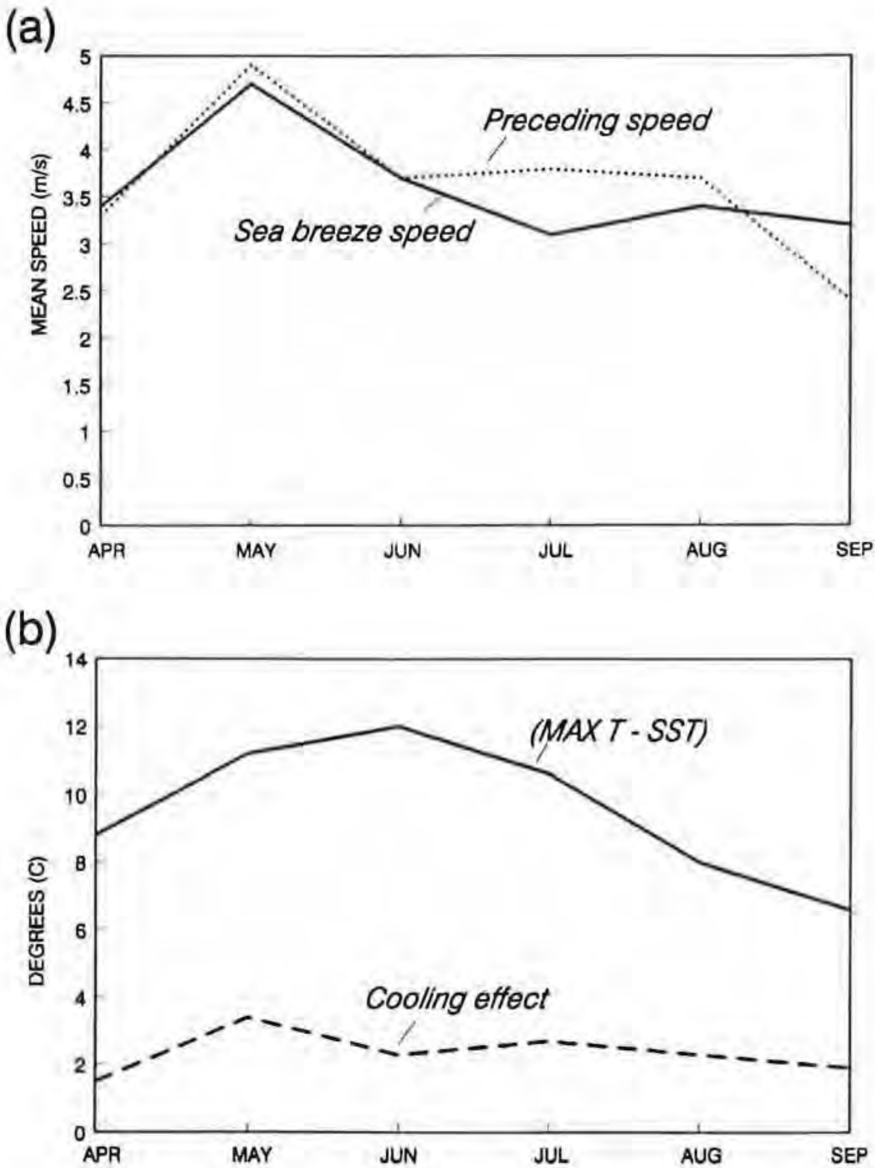

FIGURE 4. (a) Mean speed of sea breeze and preceding wind, St. John's Airport, 1979–1988.
(b) Mean cooling effect of sea breeze related to daytime land-sea temperature difference.

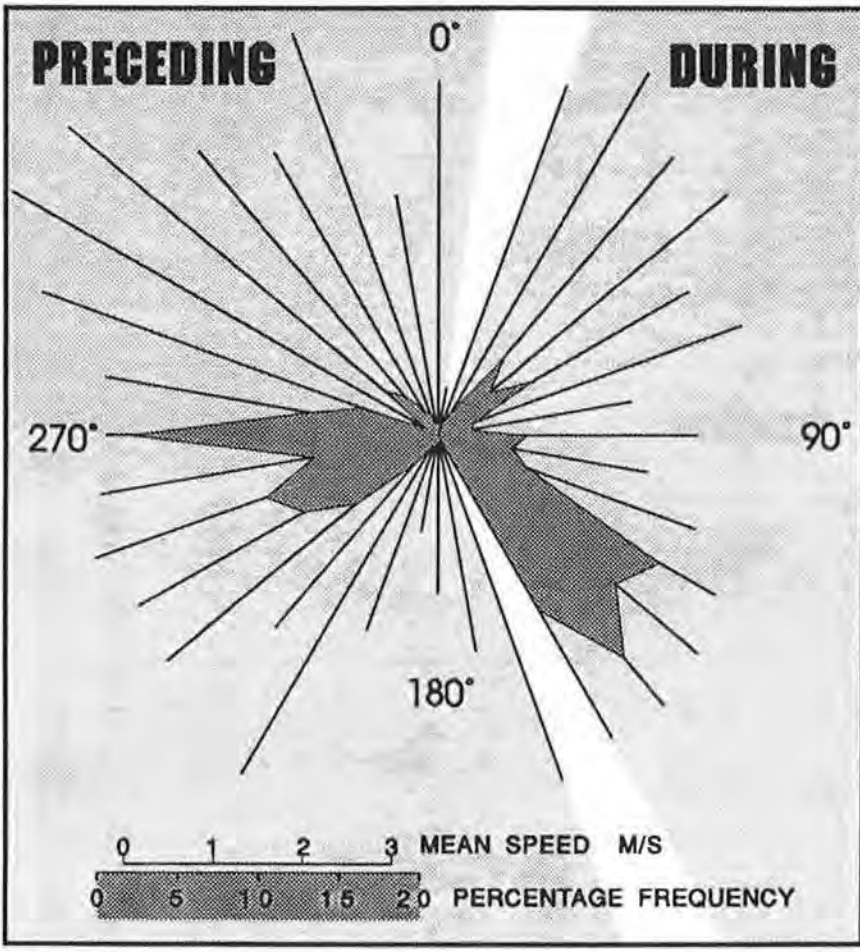

FIGURE 5. Directional frequencies (10 degree intervals) and mean speeds during sea breezes, and for the three hours preceding sea breeze onset, at St. John's Airport, 1979–1988.

significantly greater than for April, June, August and September) is probably also partly due to the significantly stronger sea breezes during this month. The reduced cooling effect for June, despite its relatively large value of (MAX T – SST), is likely related to the fact that sea breeze duration was noticeably shorter for that month (less than two hours for 40% of the cases). Of the 90 sea breeze cases examined, 45% produced a cooling effect of 1.0–3.0°C; cases of strong cooling (5.0–10.0°C) were limited to 11% of the study sample.

A closer examination of the relative strength and frequency of the sea breeze according to specific onshore directions is afforded by the right-hand side of Figure 5, which was compiled from all hourly winds observed at the airport during the 90 cases examined. Directions from the southeast sector (120–150°) are clearly dominant, with speeds averaging 3.0–4.2 ms^{-1}. A secondary peak in frequency exists from the northeast (40–60°), having marginally greater mean velocities in the range of 3.3–4.7 ms^{-1}. Sea breezes from the intervening sector are relatively weak (2.2–3.3 ms^{-1}) and less frequent, especially from 70–80°. The possibility of synoptic-scale control over sea breeze direction is addressed in section 4 below.

4. METEOROLOGICAL CONDITIONS ASSOCIATED WITH SEA BREEZE DEVELOPMENT

With respect to the second principal study objective, certain aspects of the synoptic-scale meteorological situation at the time of sea breeze development were investigated in order to establish some aids to local forecasting of the phenomenon.

4.1 Antecedent wind conditions

The distribution of surface wind conditions observed during the three hours prior to onset of the sea breeze is summarised by the left-hand side of Figure 5. The majority of these antecedent offshore winds were from 230–310°, with a peak frequency from 270° and a broader secondary maximum from 240–250°. It should be noted that winds from 270–320° will have a previous fetch over the eastern sections of the island's interior and the northern Avalon Peninsula. Between SSW and WSW (200–250°) the upwind fetch lies across the smaller interior of the Avalon Peninsula. Antecedent winds from the northwest (290–320°) were stronger on average (4.75 ms^{-1}) than those from west or southwest (average 3.6 ms^{-1}) due to the fact that a significant portion of the former group occurred in association with fairly strong northwesterly gradient winds at the 850 mb and surface levels (as illustrated in subsection 4.3 below).

4.2 Application of the Biggs-Graves Lake Breeze Index

It is also instructive to examine the distribution of the calculated values of the Biggs-Graves Index and its relation to the surface wind preceding the sea breeze. The original study by Biggs and Graves determined that approximately 90% of the lake breezes at the western end of Lake Erie occurred when the calculated Index for the day was less than 3.0 (given the units employed). This criterion has also been found to predict successfully the majority of the sea breezes occurring in the Vancouver, British Columbia area (Steyn and Faulkner, 1986) and over the eastern New Brunswick coast (Neumann and Mukammal, 1979). In this study the Index was calculated for each of the 90 days on which a sea breeze is considered to have developed, using the values defined above for the Index components. Figure 6 relates each of the daily ΔT values used in the calculations of the Index (*i.e.* MAX T – SST) to the corresponding mean surface wind speed for the three hours preceding the sea breeze; it also distinguishes those cases having calculated

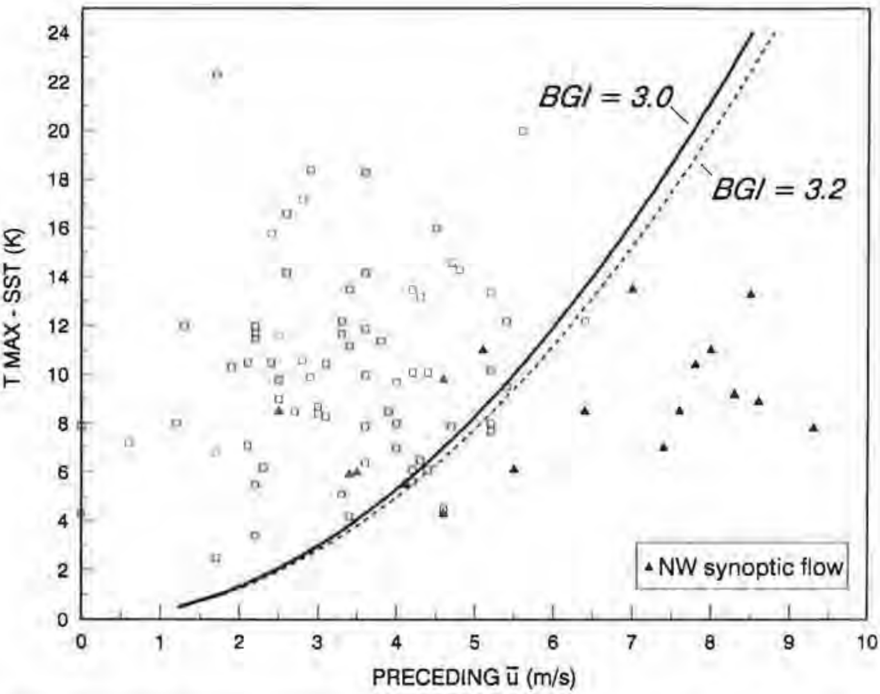

FIGURE 6. Local land-sea temperature difference (T MAX – SST) and mean surface wind speed (ū) preceding the onset of sea breezes at St. John's, 1979–1988. Parabolic lines define BGI = 3.0 and BGI = 3.2

BGI < 3.0 and cases with BGI > 3.0. There were 70 cases with BGI 3.0 (78% of the total) and an additional 4 cases of BGI 3.0–3.2 that may be considered "marginal", following Biggs and Graves; the remaining 18% were characterised by a wide range of BGI values above 3.2.

Figure 6 also indicates that of the sixteen events with BGI > 3.2, twelve had been identified, from the synoptic charts, as occurring in association with northwesterly gradient flow. In comparison, this type of flow occurred with only five of the 70 sea breeze cases with BGI < 3.0. The majority of these twelve events were characterised by a relatively strong preceding wind from WNW or NW (> 4.0 ms^{-1}), followed by an abrupt shift to onshore flow from the northeast. A pronounced fall in temperature amounting to 5.0–9.0°C accompanied the windshift in several cases. Two examples are included with the sea breeze synoptic situations described below.

4.3 Synoptic patterns

Representative examples of the types of synoptic-scale pressure patterns associated with sea breeze development at St. John's are illustrated by Figure 7.

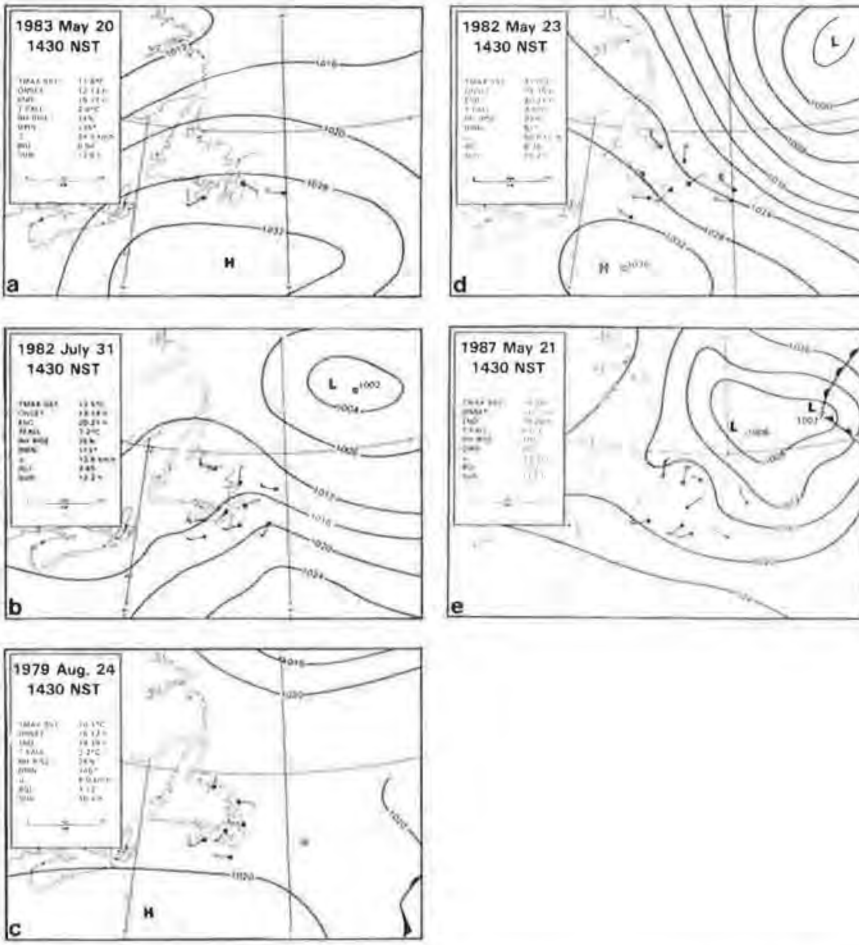

FIGURE 7. Examples of surface synoptic patterns accompanying sea breeze development at St. John's: (a) anticyclone to south, (b) transient ridge, (c) slack pressure gradient, (d) and (e) northwesterly flow. "T FALL" AND "RH RISE" refer to cooling effect in °C and increase in relative humidity in percentage points within two hours following sea breeze onset.

Included with each is a summary of conditions observed or determined for that case, and the observed winds for the closest synoptic hour at stations in the eastern Newfoundland region and offshore. Based upon the isobaric curvature in the vicinity of the study area at the time, 65% of all the sea breezes identified developed under anticyclonic flow situations, which are normally regarded as most suitable for sea breeze development (exemplified by Figures 7a and 7b). A further 15% occurred with slight cyclonic curvature and the remaining 20% can be classed as indeterminate or transitional patterns such as straight isobaric flow or col regions, *e.g.*, Figure 7c.

The northwesterly gradient flow type that occasionally precedes a marked northeasterly sea breeze, with a BGI value well in excess of 3.0, is illustrated by Figures 7d and 7e. In the case of May 23, 1982 the isobaric analysis suggests the possibility of a weak trough near the east coast of the island, although at St. John's Airport the only pressure fall amounted to 0.1mb between 1130 and 1230 NST. The windshift, from 280° at 8 ms^{-1} to 50° at 5 ms^{-1}, occurred abruptly at 1410 NST; sky conditions changed from cloudless at 1230 NST to scattered cumulus from 1330 to 1730 NST. Hence it appears more likely that fairly strong solar heating inland was a prime factor in producing a sea breeze on this occasion.

A very similar type of windshift occurred on May 21, 1987, again preceded by moderate gradient flow from 280–310°. In this instance the surface analysis, including the light WNW wind observed by the ship 150km to the NNE of St. John's, suggests that a meso-scale high pressure area developed off the east coast of the island, contributing to onshore northeast flow over the study area by midday. Such a feature could have developed as a result of the prevailing low offshore sea surface temperatures (1–4°C) contrasting with the solar heating inland and producing a meso-scale "cold high" circulation system over the offshore waters. Support for this hypothesis can be drawn from the work of Burns, Dickison and Neumann (1980), who were able to identify "regional anticyclones" developing during daytime over the cool waters of the Gulf of St. Lawrence during slack synoptic-scale pressure gradients in summer. These systems were held responsible for a particular category of sea-to-land flow observed over eastern New Brunswick at this time of the year. It can be argued that a similar type of situation occurred over eastern Newfoundland on May 21, 1987; if so, this was not a straightforward sea breeze but an onshore flow partly directed by the location of the meso-high offshore, which itself was the result of the land-sea temperature contrast.

5. SUMMARY AND CONCLUSIONS

The reduced frequency with which sea breezes occur at St. John's, compared with most other cases reported from similar latitudes, is attributed largely to the local prevalence of relatively strong offshore gradient winds and a lower frequency of large land-to-sea temperature gradients. It is likely that in a minority of cases the daytime wind reversal resulted from the offshore development of sub-synoptic scale systems such as a meso-scale anticyclone.

Research into other aspects of this question, such as the inland penetration of sea breezes under different gradient flow conditions and their occurrence along the Conception Bay coast to the west of St. John's (and whether these are linked to or distinct from those of the Atlantic shoreline), would enhance the understanding of the sea breeze process. On the applied side the impact of the sea breeze upon indices of outdoor human comfort may reveal contrasts with other regions. For many mid-latitude and tropical locations sea breezes are viewed as welcome relief from uncomfortable heat. Along the Newfoundland coast the cooling sensation from sea breezes can be more drastic, especially in spring and early summer, due to low sea temperatures.

ACKNOWLEDGEMENTS

The assistance of Stuart Porter (Scientific Services, Atmospheric Environment Service, St. John's) and Harold Janes (Officer-in-Charge, St. John's Weather Office, Atmospheric Environment Service) in providing data in support of this work is appreciated. The figures were prepared by staff at the Memorial University of Newfoundland Cartographic Laboratory.

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Break-up in Hudson Bay: Its Sensitivity to Air Temperatures and Implications for Climate Warming

D.A. Etkin
Arctic Climatology Section
Canadian Climate Centre
4905 Dufferin Street
Downsview, Ontario M3H 5T4
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ABSTRACT

A gridded data set of sea ice concentration for Hudson Bay and James Bay generated by Ice Branch, Atmospheric Environment Service, Canada was compared to melting degree day data in order to assess the sensitivity of the ice to climate warming. The comparison showed that the two variables correlate well over some parts of the Bays while over others they correlate very poorly. A sensitivity analysis indicates that a climate warming of 1°C could advance break-up by over 2 weeks in eastern Hudson Bay, while the southwestern part of the Bay shows a lower sensitivity of 6 to 8 days, and James Bay 4 to 7 days. The precise pattern of break-up depends upon such factors as ice advection, fresh water inflow in the Bays and modification within the boundary layer as the air flows over the ice and water.

RÉSUMÉ

Pour évaluer la sensibilité de la glace au réchauffement climatique, on a comparé aux données des degrés-jours de fonte un ensemble de données de la concentration des glaces de mer pour la baie d'Hudson et la baie James établi sur quadrillage par la Direction des glaces du Service de l'environnement atmosphérique du Canada. La comparaison a révélé une bonne corrélation des deux variables dans certaines zones des baies, mais une mauvaise corrélation dans d'autres. D'après une analyse de la sensibilité, un réchauffement de 1 °C du climat pourrait faire avancer la débâcle de plus de deux semaines dans l'est de la baie d'Hudson, alors que, sous l'effet d'une sensibilité inférieure, la débâcle pourrait avancer de 6 à 8 jours dans le sud-ouest de cette baie et de 4 à 7 jours dans la baie James. La configuration précise de la débâcle dépend, d'entre autres, de l'advection des glaces, l'apport d'eau douce dans les baies et la modification survenant dans la couche limite quand l'air circule au-dessus de la glace et de l'eau.

1. INTRODUCTION

Climate models are predicting significant increases in tropospheric temperatures as a result of changes in greenhouse gas concentrations within the atmosphere. The winter temperature change in polar regions, especially within the marginal snow and ice zones, is expected to be several times larger than that in more temperate latitudes. Output from general circulation models indicates that winter temperature increases over northern Canada resulting from a doubling of global atmospheric carbon dioxide could range from 4 to 15°C, with summer temperature increases ranging from 2 to 6°C (Etkin, 1990a).

Especially within the marginal sea ice zones, the predictions are likely to differ from each other, depending upon how the ice is parameterized and upon the sensitivity of the model to various feedback loops involving the albedo of snow and ice. For example, in the middle of Hudson Bay, one model shows January temperature increases exceeding 14°C, while another shows about 4°C (Etkin, 1990a). The effect of these anticipated temperature increases on sea ice is expected to be very significant. However, it is difficult to assess. As pointed out by Mitchell *et al.* (1990), "on the basis of current simulations, it is not possible to make reliable quantitative estimates of the changes in the sea-ice extent and depth."

The oceans and lakes in the marginal ice zones of polar regions respond to freezing winter temperatures by forming a layer of relatively thin floating ice, and to summer temperatures by melting the ice. The timing of melt and freezing depends upon a number of oceanographic and atmospheric parameters, the most important of which is usually air temperature (Rogers, 1978; Mackay, 1952) although other factors such as salinity, winds and ocean currents can be significant (Mysak and Manak, 1989; Walsh and Chapman, 1990). Since air temperatures can be highly variable from year to year, the pattern of sea ice formation is subject to variations as well; as a result the historical relationship between sea ice and air temperature is potentially an indicator which can gauge the sensitivity of the ice-season to change in climate. Previous studies have shown that such relationships can be valuable (*e.g.* Palecki *et al.*, 1985; Barry, 1978; Walsh and Johnson, 1979) and a general review of this subject can be found in Skinner (1986).

The purpose of this paper is to assess whether the statistical relationship between air temperature, or some derivative thereof, and sea ice concentration is sufficient to estimate the sensitivity of the timing of ice break-up to climate warming. The geographical area selected for this study is Hudson Bay and James Bay, which together form the world's largest inland sea. Martini (1986) provides a complete review of geology, climate, geography, oceanography and ice conditions.

2. DESCRIPTION OF STUDY AREA

Hudson Bay and James Bay (Figure 1) together form a large saline body of water

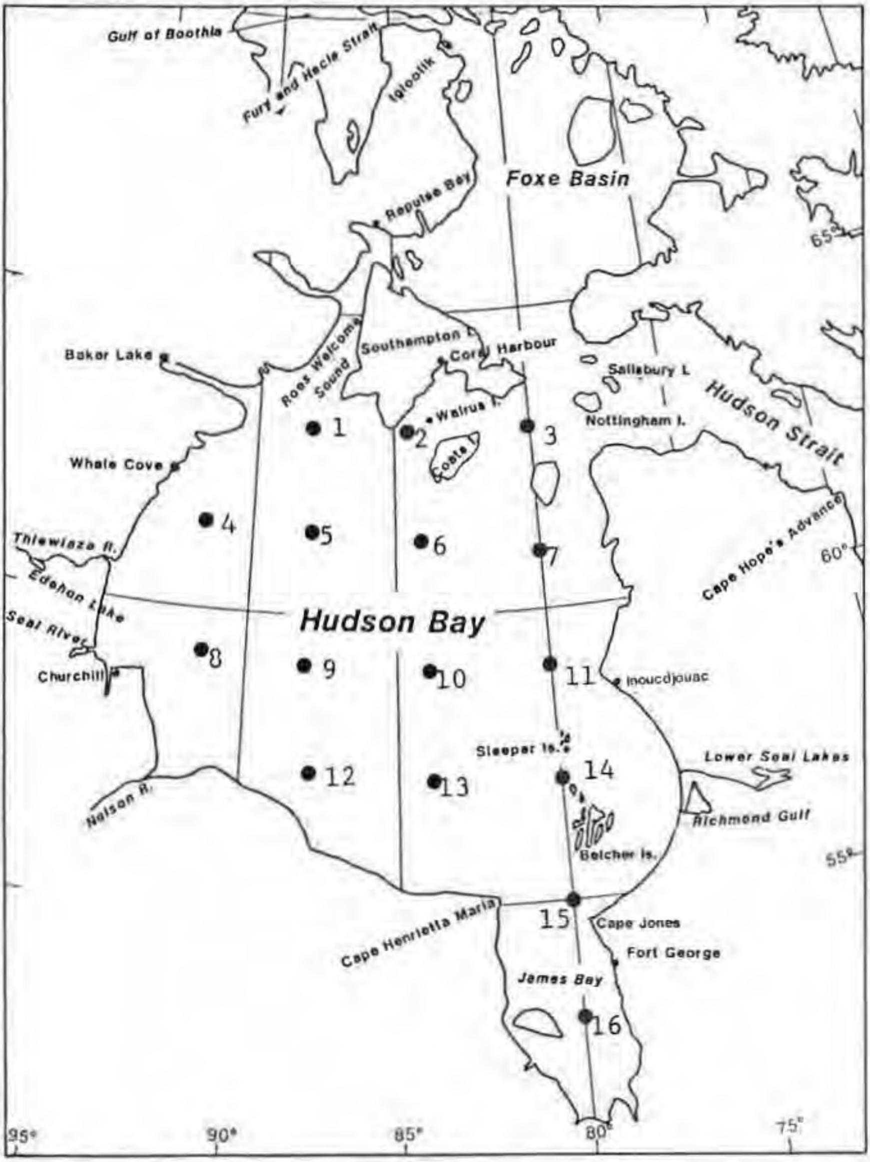


FIGURE 1. Location map of Hudson Bay. The numbered dots indicate grid points used in the regression analysis.

extending over 12 degrees of latitude and 19 degrees of longitude in central and northern Canada. It is connected to the oceans through a set of relatively narrow channels located along its northern edge. As such, it tends to act more like a closed system than many other parts of the world's ocean system, and this is one of its advantages; one can expect simpler relationships between atmospheric and oceanographic variables as a result. For convenience, Hudson and James Bays together will be referred to as Hudson Bay or the Bay for the remainder of this paper. Cold Arctic Ocean water enters the Bay mostly through Roes Welcome Sound at the extreme northwestern part of the Bay, and Atlantic water (at least

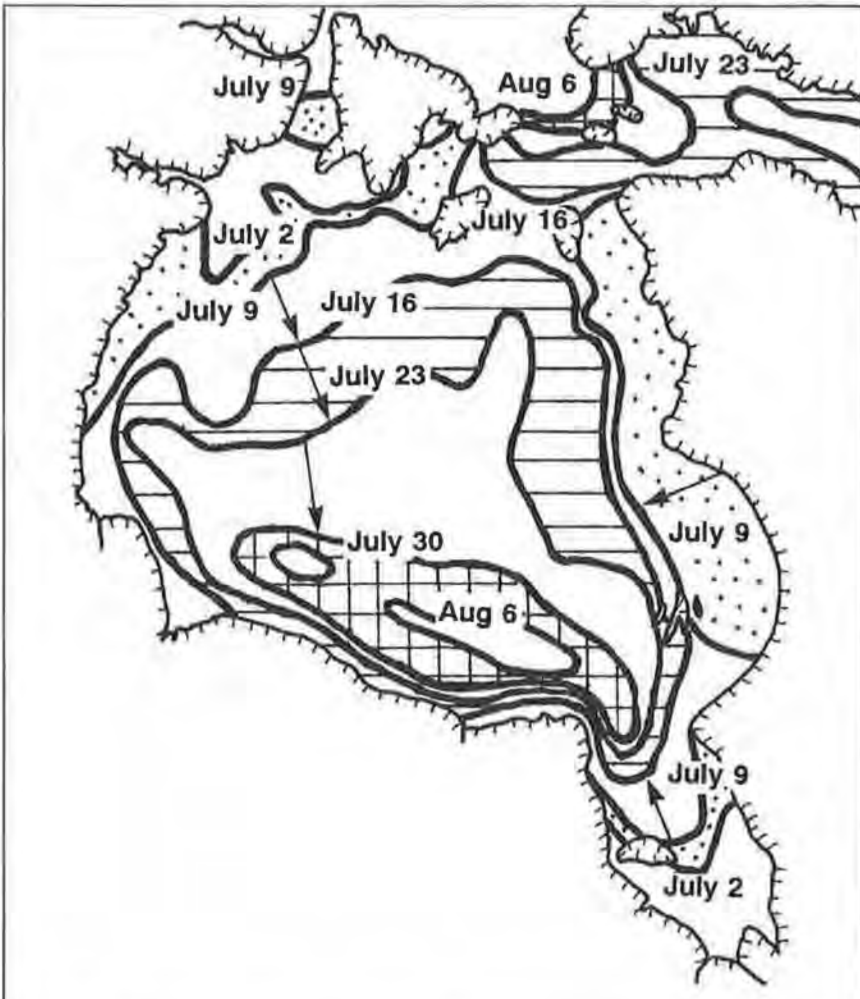


FIGURE 2. Typical break-up of sea ice in Hudson Bay (after Markham, 1988).

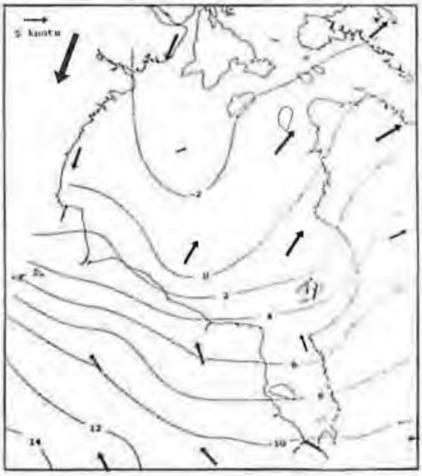
according to a rather limited number of measurements) enters the Bay east of Southampton Island; warmer water from the Bay exits through Hudson Strait east of Southampton Island (Prinsenberg, 1986). The Bay is also fed by numerous freshwater rivers around its perimeter (Prinsenberg, 1988). Within Hudson Bay, summer currents revolve cyclonically with an average current strength of 5 cm/s (Prisenberg, 1986).

Complete freeze-over occurs each winter as the Bay becomes filled with first-year ice. Only the extreme northwestern portions of Hudson Bay experience multi-year ice. During break-up open water appears first in southern James Bay as one would expect, but also in eastern Hudson Bay due to spring run-off (Markham, 1986), and just southwest of Southampton Island as ice is removed from that region by the currents and wind faster than it can be replaced from the narrow Roes Welcome Sound. These open areas grow with time, with open water expanding northward along the eastern shore of the Bay, and ice being advected southward and then southeastward along the western and southern shores. By early August the Bay is essentially ice-free (Figure 2). This description of Hudson Bay ice is consistent with the data presented in Mysak and Manak (1989).

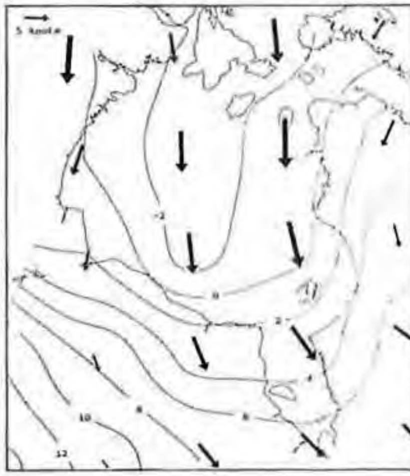
Prevailing winds in the Bay during July are west to northwesterly although James Bay shows a strong southwesterly component (Maxwell, 1986). As the air in the boundary layer passes over the ice and water, it tends to come into equilibrium with the surface. Following snowmelt, which begins in May to the south but can occur in mid-June to the north, relatively warm air begins to pass over the Bay (Etkin, 1990b). This air tends to have the most effect near the shore, with its ability to melt ice diminishing as it moves progressively over the Bay. The result of both these factors (ice advection and airflow) is that the last areas to melt are along the southern coast of the Bay and in the extreme north, just east of Southampton Island.

The spatial pattern of weekly mean air temperature, wind, and ice concentration from May 28 to July 29, 1980 is shown in Figure 3. The year 1980 was typical for Hudson Bay weather and ice conditions (Mysak and Manak, 1989). In late May and early June most of the Bay was ice-covered although break-up had begun along the eastern shore and in James Bay. Temperatures were fairly zonal with below-freezing values in the northern half of the Bay. As time progressed, the air temperatures became increasingly meridional (with the exception of June 25 to July 1), with colder temperatures in the eastern half of the Bay, the region where break-up occurs first! This tendency for the isotherms to lie north to south is assumed to exist because of the continual cooling of the air as it progresses across the Bay. The inclination for the contours of constant ice concentrations to lie at large angles to the isotherms confirms the importance of processes such as ice advection in determining regional ice concentrations. By the end of July, ice had disappeared everywhere except for a few tenths in the extreme north and along the southern coast of Hudson Bay and James Bay, where temperatures ranged from 9 to 15°C.

Surface Air Temperature + Wind: May 28 to June 3, 1980



Surface Air Temperature + Wind: June 4 to June 10, 1980



Mean Ice Concentration: May 28 to June 3, 1980

Mean Ice Concentration: June 4 to June 10, 1980

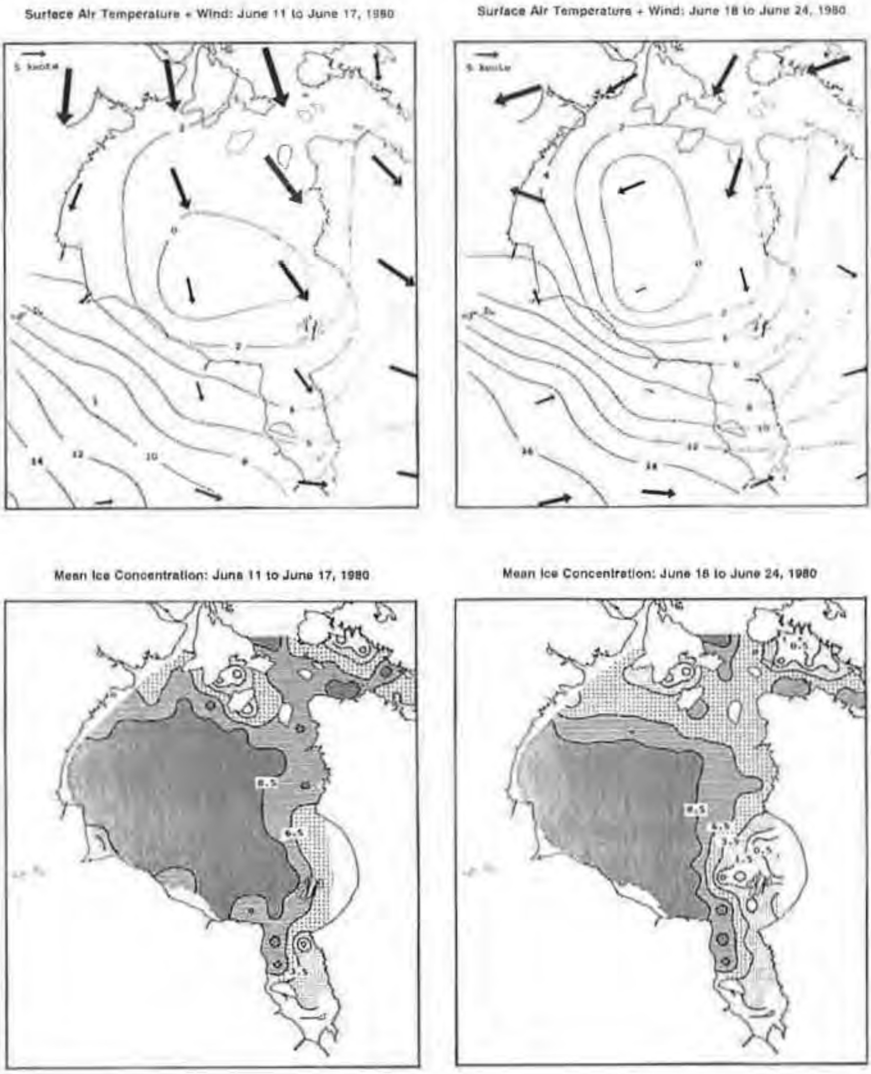
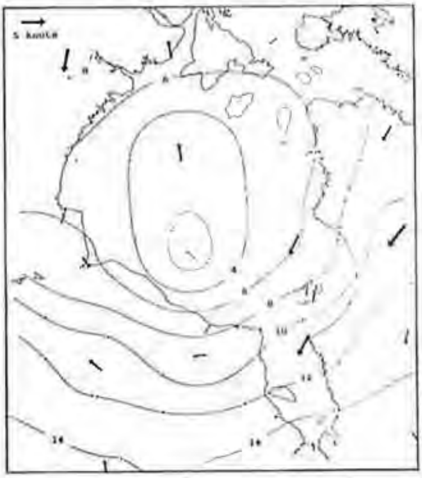
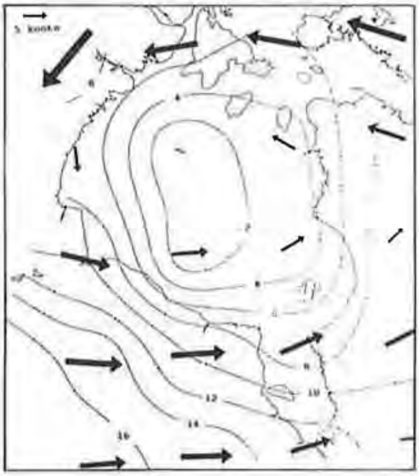


FIGURE 3. Mean air temperatures (°C), winds and ice concentrations over Hudson Bay and James Bay during break-up of 1980, by week.

Surface Air Temperature + Wind: June 25 to July 1, 1980



Surface Air Temperature + Wind: July 2 to July 8, 1980



Mean Ice Concentration: June 25 to July 1, 1980

Mean Ice Concentration: July 2 to July 8, 1980

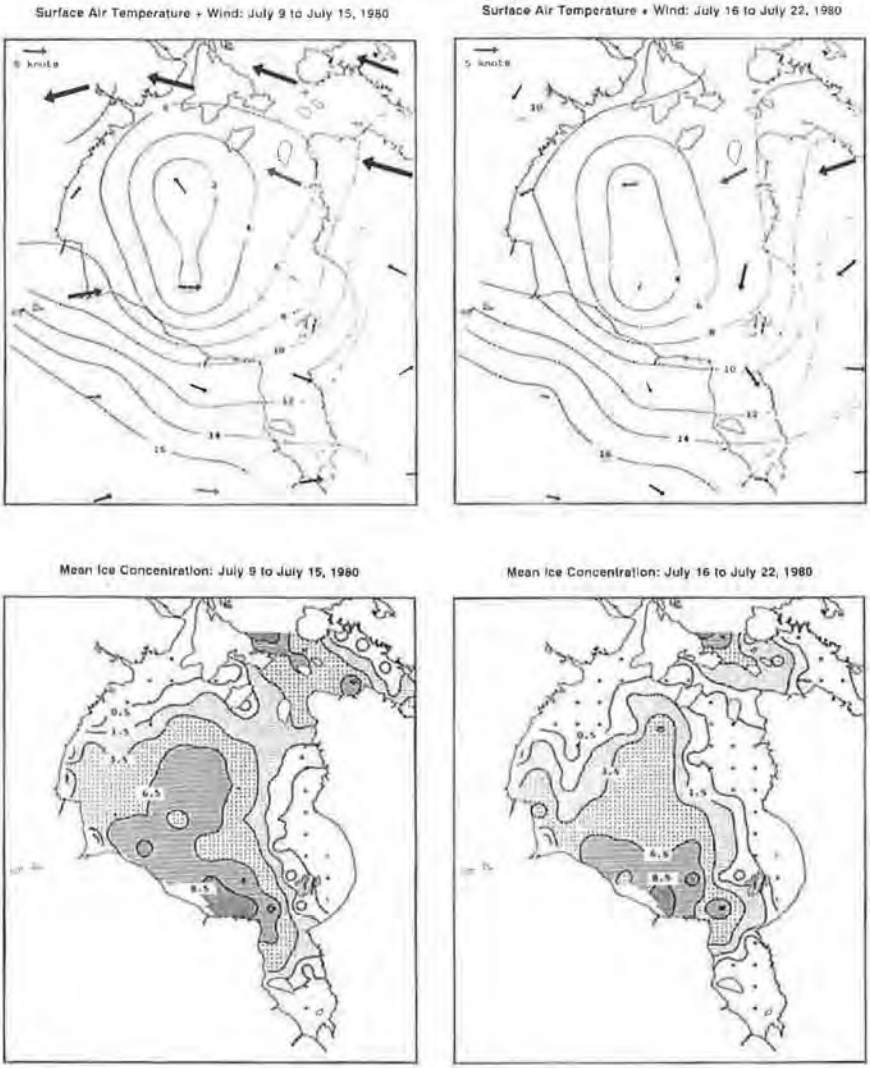


FIGURE 3. (continued) Mean air temperatures (°C), winds and ice concentrations over Hudson Bay and James Bay during break-up of 1980, by week.

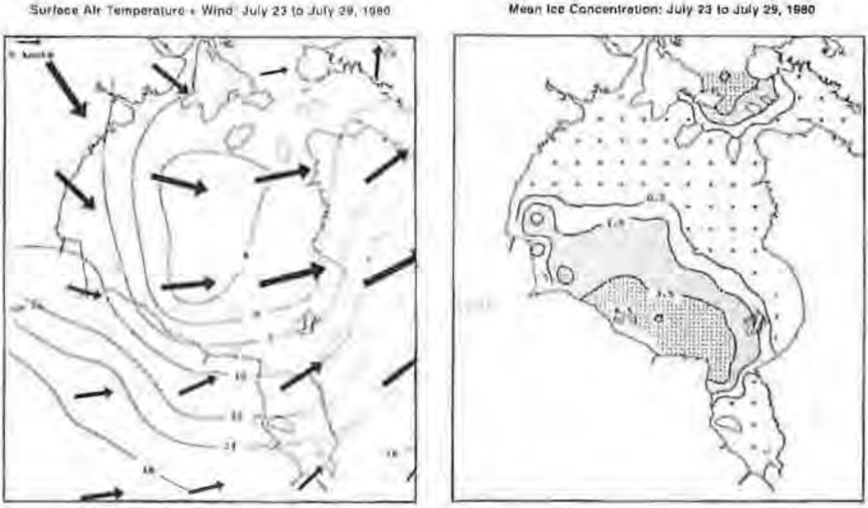


FIGURE 3. (concluded) Mean air temperatures (°C), winds and ice concentrations over Hudson Bay and James Bay during break-up of 1980, by week.

3. ANALYSIS

A data set of sea ice concentration for Hudson Bay covering the period 1963 to 1984 was created and digitized by Ice Branch, Atmospheric Environment Service (AES) (Markham, 1988). This data set provides one ice concentration value per week at each grid point. Ice concentrations from this data set were compared to air temperatures over the Bay using data from the Naval Environmental Data Network Set (NEDN), which extends from 1974 onward (Brown, 1988). The two data sets were regridded on identical grids in the Bay (Figure 1) using two programs resident on the AES mainframe computer, 'Climate Research in Ice Statistics' (CRISP) and 'Contour Analysis Software Package' (CONAN). These two programs are described in Agnew and Maxwell (1987) and Brown (1988).

Due to the temporal limitations of the data, only the years from 1974 to 1984 inclusive could be analyzed. For each of the 16 grids, a cumulative melting degree day (MDD) value beginning June 1 was calculated (MDD = mean daily temperature above 0°C), for comparison with ice concentrations. The latter (the dependent variable) were linearly regressed against MDD data (the independent variable). Each regression included 99 data points. Correlation coefficients (R) were used to estimate the goodness of fit between the two variables. An R value of $+1$ or -1 indicates a perfect fit, while a value of 0 indicates no correlation. The results of these regressions are shown in Table 1.

The best fits occurred over James Bay and in a swath ranging from the northeastern part of Hudson Bay west-southwestward. The highest values of R tended to occur in the centre of the Bay, which makes sense intuitively as this is the area where there are no coastal effects and climate variability would be at a

TABLE 1. Summary of Linear Regression: Ice Concentration (y) and MDD (x).

Grid Point	Equation	Correlation Coefficient (R)
1	$y = 6.21 - .00939\,x$	0.34
2	$y = 6.12 - .00943\,x$	0.34
3	$y = 6.95 - .0148\,x$	0.63
4	$y = 7.97 - .0167\,x$	0.69
5	$y = 9.54 - .0194\,x$	0.77
6	$y = 8.79 - .0215\,x$	0.80
7	$y = 6.56 - .0195\,x$	0.74
8	$y = 9.07 - .0143\,x$	0.75
9	$y = 10.3 - .0144\,x$	0.76
10	$y = 9.40 - .0207\,x$	0.81
11	$y = 6.52 - .0191\,x$	0.77
12	$y = 9.81 - .0129\,x$	0.69
13	$y = 9.63 - .0108\,x$	0.78
14	$y = 7.40 - .0155\,x$	0.68
15	$y = 8.45 - .0139\,x$	0.75
16	$y = 7.83 - .0116\,x$	0.81

– where ice concentration (y) is measured in tenths and melting degree days (x) is measured in days–°C.

TABLE 2. Number of Days after June 1 Required for Break-up under Current Climate and under a Climate Warmed by 1°C.

Grid Point	MDD for Break-up	Days Under Current Climate	Days Under Climate with 1°C Warming	Difference
5	234	46	38	8
6	176	49	38	11
7	80	46	29	17
8	285	45	39	6
9	371	56	49	7
10	212	56	44	12
11	80	47	30	17
12	429	61	53	8
15	249	46	39	7
16	245	35	31	4
average	236	48.7	39	9.7

minimum. Presumably those areas with the lower values are more subject to variations in ice concentration due to ice advection by winds and currents, a more complicated ice regime due to the presence of such factors as polynyas or fast ice, or a more complicated climate regime such as would exist near coastal areas.

An estimate of the MDD total required to melt ice to five-tenths (5/10) concentration (break-up), as determined by the regression equation, is shown in Table 2, which uses only grid points with a R value of 0.7 or higher; lower R values bring into question the value of any analysis as the variables are not well correlated. The pattern clearly shows that the southwest part of the Bay requires the most heating in order to melt the ice to 5/10. This is reasonable as that is the area which experiences the most ice advection. The smallest MDD totals required to melt the ice to 5/10 occur in the northeastern part of the Bay. Again, as the current pattern brings warmer waters and ice-free areas from James Bay and southern Hudson Bay up the east coast, this is an expected result. Note that the MDD totals required in the southwest are over 5 times as large as those required in the northeast. The pattern of maximum winter ice thickness (Markham, 1981) appears to be poorly related to the melt pattern, as the areas which break up earliest experience some of the thickest ice, while the areas of thin ice (James Bay) require MDD totals near the mean value.

For each grid point, the average MDD required to reach 5/10 ice can be calculated. With climate warming, MDDs will accumulate more rapidly, and melting will occur earlier. The number of days required to melt the ice under warmer climate conditions can be estimated (Table 2) by multiplying the number of days required to melt the ice under current climate conditions by the ratio at which the MDD accumulate under a warmed climate to the rate under the current climate.

Table 2 shows that if the climate were to warm by 1°C, the northeastern part of Hudson Bay would break up about 17 days earlier, southwestern Hudson Bay 6 to 8 days earlier and James Bay only about 4 days. These estimates are consistent with a study by Hamilton (1985) who noted that strong ENSO events (assuming an associated warming of about 1°C in central Canada) resulted in break-up in James Bay occurring on average 5.6 days earlier than normal. By comparison, the standard deviation of break-up for an average of all points with $R \geq 0.7$ is 7 days; individual grid points typically have standard

TABLE 3. Ice Concentration by Year: Central Hudson Bay.

MO/DY	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
05/21					9+	9+	9+	9+	9+	9	9+												9	9+	9+
05/28	9				9	9+	8	9	9+	9+	9+	9+	9	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+	9+
06/04	9	8			8	9+	9+	9	9+	8	9+	9	9+	9	9+	9+	9+	9+	9+	9+	9+	9+	9	9+	9+
06/11	9	8	9+		8	9+	7	9	9+	8	9	9	9	9	9+	9+	9+	9	9+	9+	9+	9+	9	9+	9+
06/18	9	8	9+	9	9	9	9+	9	8	9	9	9	8	9	9+	9+	9+	9	9+	9	9	9+	9	9	9+
06/25	9	8	8	9	6	9+	8	9	9+	9	9	9	5	8	9	9+	9+	9+	9	9	9+	9	9	8	9+
07/02	9	8	8	7	5	9+	7	9+	8	7	8	7	4	4	9	8	9+	9	8	7	7	9	8	7	9+
07/09	7	8	8	8	0+	9	6	9	8	4	9	6	3	2	6	4	9+	5	7	8	4	8	3	7	9+
07/16	6	8	8	4	0	6	2	9	7	0+	7	3	2	0+	5	0	9+	3	3	4	4	8	2	7	8
07/23	0+	8	6	2	0	5	0	9+	7	0	5	0+	0+	0	0+	0	6	0	0+	1	0+	3	2	0	8
07/30	0	6	2	0+	0	2	0	7	0	0	2	0	0	0	0	0	4	0	0	0	0	0	0	0	5
08/06	0	4	0	0	0	0+	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08/13	0	0	0	0	0	0				0	0+	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08/20	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08/27	0	0	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1962–1983 . . . AES data
1984–1986 . . . U.S. NOAA/Navy data

deviations over the 11 years of between 1 and 2 weeks. A time series of ice concentrations, with break-up, is shown in Table 3, for an area encompassing grid points 6 and 10 for the period 1962–86. Break-up has occurred as early as June 25 and as late as the first week of August.

4. DISCUSSION AND CONCLUSION

The sensitivity calculations in Table 2 assume that other factors are unchanged; however, this assumption becomes more and more questionable as one considers increasingly warmer climates. For example, it is likely that ice thickness would be less during a warmer winter, and that break-up would require fewer MDD than are needed under current climate conditions. This would lead to an even larger difference than that calculated above, as the critical MDD would be reached sooner than assumed. If wind and ocean currents changed, then the advective component of the ice regime would be affected. The relative importance of air temperature to other meteorological parameters could shift as well, in an unknown way. Increased runoff, a likely result of increased precipitation in a 2 × CO_2 environment, would tend to enhance the formation of sea ice, for instance.

Despite these uncertainties, this study has shown that the concentration of sea ice in most of Hudson Bay and James Bay is significantly controlled by air temperature, and is sensitive to variations thereof. A warming of 1°C (small relative to those predicted by climate models) could impact the date of break-up in northeastern parts of Hudson Bay by 2 weeks or more, while other areas such as James Bay would likely be affected to a much smaller degree. Larger climate changes, which the climate models suggest are highly likely for the Hudson Bay region, would impact the ice regime in increasingly significant but also increasingly uncertain ways.

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Estimation des flux de chaleurs latente et sensible à partir de l'énergie radiante pour certaines surfaces: Nouveau-Québec

Gérald Renaud et *Bhawan Singh*
Département de géographie
Université de Montréal
C.P. 6128, succursale A
Montréal, Qué. H3C 3J7
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RÉSUMÉ

Dans cet article nous examinons la possibilité d'estimer les flux turbulents d'énergie calorifique (QE + QH) par le biais du rayonnement net (Q*), du flux d'énergie calorifique dans le milieu (QG) et du rayonnement solaire global (K↓). Plus précisément, nous examinons le comportement relationnel du Q* − QG par rapport au K↓, et ce afin d'établir un modèle d'estimation qui, en admettant Q* − QG = QE + QH, devient celui des flux turbulents d'énergie calorifique de l'air.

Notre étude utilise les données mesurées à trois différents types de surface de la région de Kuujjuarapik, soit : une lande à lichens et affleurements rocheux (LICHEN); une prairie humide à graminées (FEN); et une pessière à lichens et mousses (BOISE).

Nos résultats montrent que le Q* − QG diurne est fortement corrélé au K . Bien que le Q* − QG peut être estimé par le K↓ à l'aide d'une simple équation linéaire, il ressort de notre étude que cette estimation gagne à être établie à l'aide d'une fonction sinusoïdale qui prend en compte l'heure de la journée. Ceci est surtout vrai au site LICHEN où les échanges énergétiques ne suivent absolument pas le schéma évolutif horaire habituellement imposé par le rayonnement solaire (K↓).

ABSTRACT

This article examines the possibility of estimating the turbulent fluxes of energy (QE + QH) from measurements of the net radiation (Q*), the soil heat flux (QG) and the incident solar radiation (K↓). More specifically, we examine the relationship between Q* − QG and K↓, in order to derive a method of estimating the turbulent fluxes of energy, assuming that Q* − QG = QE + QH.

Our study is based on data collected over three types of surface in the vicinity of Kuujjuarapik, namely, a lichen mat interspersed with rocky outcrops, a wet sedge-covered bog and an assemblage of pine trees with a lichen and moss understory.

Our results show that on a daily basis, $Q* - QG$ is strongly correlated with K↓. Although $Q* - QG$ can be adequately estimated from K↓ by means of a simple linear equation, it is shown that this estimation can be made more precisely by utilising a sinusoidal function which takes the hour of day into consideration. This is especially true in the case of the lichen surface, where the energy exchanges did not follow the diurnal pattern normally imposed by K↓.

INTRODUCTION

Les multiples difficultés liées à l'instrumentation, inhérentes au domaine de la recherche en microclimatologie et à la logistique que présente toute recherche dans les écosystèmes, notamment ceux des régions nordiques, canalisent souvent les chercheurs vers une simplification de la collecte d'information. Un bel exemple de cela est l'estimation du rayonnement net (Q*) diurne de chaque type de surface par une fonction algébrique du premier degré définie ainsi :

$$Q*_x = b_x K\downarrow + a_x \quad (1)$$

où Q* est le rayonnement net (Wm^{-2}),
b et a sont des constantes,
K↓ est le rayonnement solaire global (direct et diffus) de la région considérée (Wm^{-2}),
x est un souscripteur qui réfère à la surface considérée.

Le Q* diurne étant fortement conséquent du K↓ (Gay, 1971; Wilson, 1975; Polavarapu, 1970; Idso *et al.*, 1969; Federer, 1968; Davies, 1967; Fritschen, 1967), cette fonction permet une bonne estimation. En calibrant les constantes de l'équation 1 pour une région donnée il est donc possible d'estimer le Q* de plusieurs surfaces par une mesure simple du K↓.

A l'instar de l'équation 1 et tenant compte que le flux d'énergie calorifique capté par la surface (QG) est aussi fortement conséquent du K↓ et qu'il représente généralement une faible proportion du Q* (Oke, 1978; tableau 1), nous émettons l'hypothèse d'une possibilité d'estimer le $Q* - QG$ diurne de certaines surfaces à l'aide du K↓.

TABLEAU 1. Proportion du rayonnement net captée par la surface (QG / Q*) des régions nordiques.

Type de surface	QG/Q*
Fen ou tourbière	0,06 – 0,13
Toundra	0,06 – 0,15
Boisé de conifère	0,07 – 0,16

Sources : Ohmura (1982), Payant (1976), Rouse (1984), Singh *et al.* (1984), Stewart et Rouse (1977) et Wright (1981).

Cette estimation du Q* – QG pourrait s'avérer intéressante puisqu'en admettant :

$$Q*_x = QE_x + QH_x + QG_x \quad (2)$$

où QE est le flux turbulent d'énergie calorifique latente (évaporation ou évapotranspiration, Wm^{-2}),
QH est le flux turbulent d'énergie califorique sensible (Wm^{-2}),
QG est le flux d'énergie calorifique dans le milieu (Wm^{-2}),

l'estimation de (Q* – QG) traduirait (QE + QH), soit les flux turbulents d'énergie calorifique. Plus encore, en exploitant l'approche tirée de Bowen (1926), il serait possible d'estimer soit QE ou soit QH ainsi :

$$QE_x = (Q* - QG)_x / (1+Br_x) \quad (3)$$
$$QH_x = QE_x \cdot Br_x \quad (4)$$
$$Br_x = QH_x / QE_x = \gamma (\Delta Ta_x / \Delta e_x) \quad (5)$$

où Br_x est le taux de Bowen,
γ est la constante psychrométrique (= 0,066 × 10^3 Pa $°C^{-1}$),
ΔTa_x est l'écart de températures de l'air entre deux points de mesure verticale (°C)
Δe_x est l'écart de pressions partielles de vapeur d'eau entre deux points de mesure verticale (Pa).

Le taux de Bowen (Br) peut être fixé afin de correspondre à des valeurs moyennes associées aux surfaces étudiées (Oke, 1978). Il peut également être estimé de différentes façons; en exploitant, par exemple, le concept de Priestley et Taylor (1972), ou encore l'approche de l'origine des vents de Renaud et Singh (1988).

Notre étude examine la possibilité d'estimer le Q* – QG de certaines surfaces de la côte hudsonienne du Nouveau-Québec. Les surfaces étudiées sont :
1) une lande à lichens et affleurements rocheux;
2) une prairie humide à graminées;
3) une pessière à lichens et mousses.

MÉTHODE

L'étude a été réalisée dans un secteur en aval du bassin hydrographique de la Grande rivière de la Baleine, près du village de Kuujjuarapik (Poste de la Baleine : 55°17'N; 77°45'0). Ce secteur est approximativement à 2km à l'est de la baie d'Hudson et à 3km au nord-est de l'embouchure de la Grande rivière de la Baleine. La localisation précise de nos sites expérimentaux est montrée dans Renaud et Singh (1988). Dans la mesure du possible, leur localisation respective a été faite de façon à minimiser l'effet de l'advection locale.

Le site de la lande à lichens et affleurements rocheux (ci-après identifié LICHEN) est couvert à 80% par la végétation. Cette végétation d'une épaisseur de 7 cm est installée sur un champ de blocs (moraine lessivée) inondé de sable grossier; quelques blocs sont en saillie.

Le site de la prairie humide à graminées (ci-après identifié FEN) est occupé à 15% par des petits étangs d'eau de 2 à 20 cm de profondeur. La couche de *Sphagnum* atteint à cet endroit 1,5 m. Le niveau de la nappe phréatique est pratiquement à la surface.

Le site de la pessière à lichens et mousses (ci-après identifié BOISÉ) se situe dans une zone à densité moyenne. Le *Picea Mariana* domine largement. La cime des arbres se situe à environ 8 m. La couche de lichens et mousses est dense. Elle a une épaisseur de 10 cm environ. Le substratum minéral est un sable grossier d'environ 50 cm d'épaisseur superposé à une moraine de 3 m. Les *Betula glandilosum* et *Alnus rugosa* étaient présents aux strates herbacées et arbustives pour occuper environ 20% de la surface.

Le rayonnement net (Q*) a été mesuré à l'aide d'un radiomètre à dôme de polyéthylène (MICROMET) mesurant les longeurs d'ondes comprises entre 0,3 à 60,0 microns; soit le visible et l'infrarouge. Le flux d'énergie calorifique dans le milieu (QG) a été établi à l'aide d'une plaque thermopile (MIDDLETON). Enfin, le rayonnement solaire global (K) a été obtenu à l'aide d'un solarimètre à dôme de verre (LINTRONICS) qui opère dans l'intervalle de longueurs d'ondes de 0,3 à 3,0 microns; soit le visible et le proche infrarouge. Ces instruments de mesures étaient reliés à un enregistreur électronique à imprimante mécanique (FLUKE 2240B) qui effectuait une lecture aux cinq minutes.

La cueillette de données a été exécutée au cours de juillet et août 1983. Nos observations ont été réalisées entre 6 h 45 et 17 h 15.

Compte tenu de la proximité de la baie d'Hudson et de son effet sur l'advection (Perrier *et al*, 1977); Plamondon-Bouchard, 1975; Wilson, 1968) et donc sur les échanges énergétiques (Brakke *et al*, 1978); Singh et Taillefer, 1986), nous élaborons notre recherche en distinguant l'advection marine de l'advection continentale. Et, afin de distinguer nettement ces deux types d'advection, nous excluons les vents qui longent la côte (Renaud et Singh, 1988).

Les données pour définir le type d'advection proviennent des observations de la station météorologique du Gouvernement du Canada à Kuujjuarapik. Notre appareil pour mesurer la vitesse et la direction du vent était défectueux. De plus la station météorologique était très près (à 1 km) de notre site, ce qui rendrait le calcul de l'advection valable. Ces observations sont aux heures. Afin d'établir une correspondance, nous avons calculé les moyennes de nos observations (mesurées aux cinq minutes) de sorte qu'elles correspondent à l'heure.

RÉSULTATS

Nous présentons à la figure 1 le Q* – QG mis en relation avec le K↓. Nous constatons qu'il existe une forte relation entre ces variables, notamment aux sites FEN, BOISÉ. Exception faite du site LICHEN, ni les phénomènes

Fig. 1 - Relation entre (Q* - QG) et K↓ à chacun des sites

N nombre d'échantillon

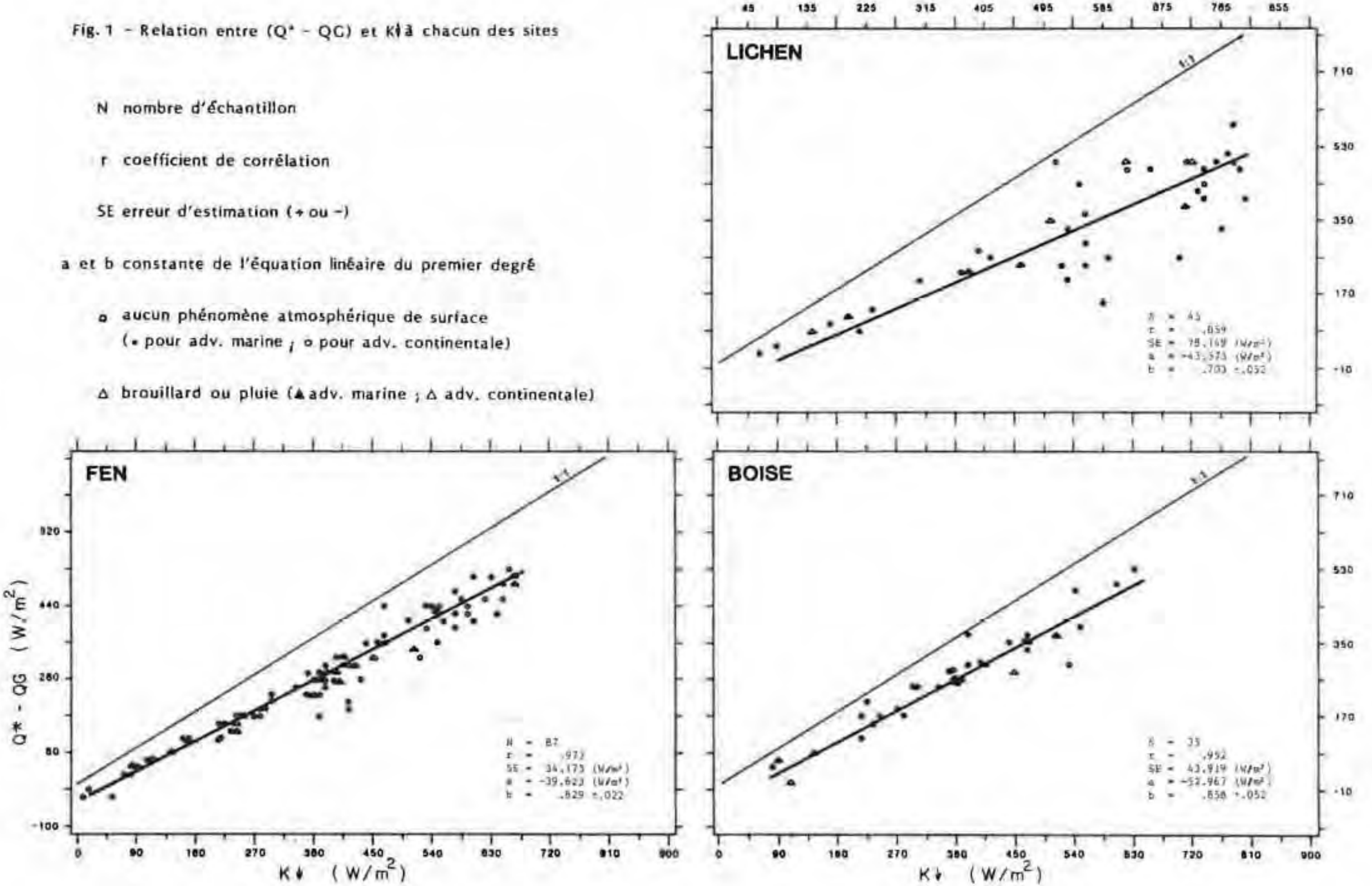
r coefficient de corrélation

SE erreur d'estimation (+ ou -)

a et b constante de l'équation linéaire du premier degré

o aucun phénomène atmosphérique de surface
(• pour adv. marine ; o pour adv. continentale)

△ brouillard ou pluie (▲ adv. marine ; △ adv. continentale)



atmosphériques de surface ni l'origine des vents (advection marine ou continentale) ne semblent introduire d'effet particulier sur la relation.

Au site LICHEN, l'origine des vents semble affecter la distribution des points de telle sorte que les valeurs correspondant à l'advection continentale se groupent au-dessus de la droite d'estimation (figure 1) et celles correspondant à l'advection marine se groupent au-dessous. L'explication vient du double fait que l'advection continentale était présente généralement l'avant-midi et l'advection marine l'après-midi, et que le comportement Q* versus K↓ de l'avant-midi différait de celui de l'après-midi (figure 2). Nous remarquons là un comportement qui s'apparente à un cycle journalier; de ce fait, la notion temps (heure) devient significative.

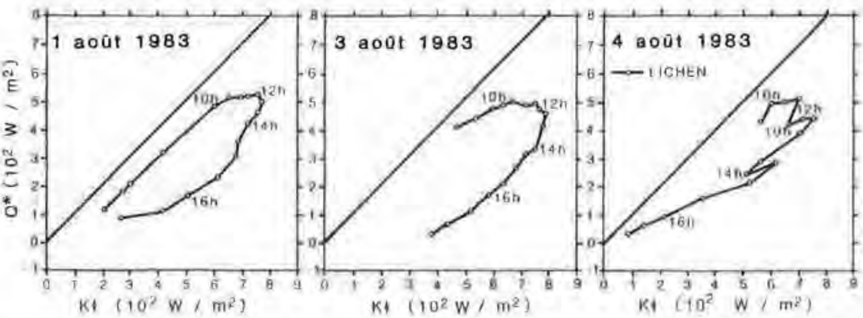


Fig.2 Relation entre Q* et K↓ au site LICHEN au cours des périodes diurnes du 1, 3 et 4 août 1983.

À partir de cela, nous avons reporté à la figure 3 les valeurs (Q* – QG) / K↓ versus l'heure. L'examen de la distribution révèle un comportement qui s'apparente à une fonction sinusoïdale définie comme suit :

$$FTM_x = (Tv - A \cos (Cx\ 0{,}26175H + Th))_x \qquad (6)$$

où FTM_x est un taux représentant le comportement horaire moyen du rapport (Q* – QG)/K↓.

H est l'heure locale,
A est une constante indiquant l'amplitude de la fonction,
C est une constante indiquant le nombre de cycles
Th est une constante de translation horizontale,
Tv est une constante de translation verticale.

La facteur 0,26175H transforme les heures en radians; pour transformer en degrés, il suffit de remplacer 0,26175 par 15. Il faut également que Th soit transformé en degrés de la façon suivante : 57,29578 Th.

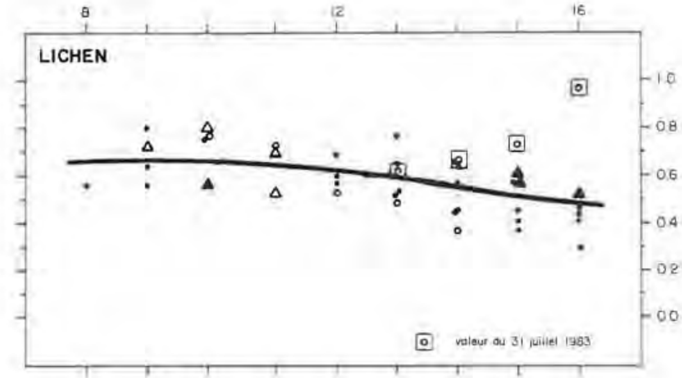
Les courbes dans cette figure ont été établies selon la méthode de Marquardt – Statistical Package for the Social Sciences (SPSS); sous-programme

Fig. 3 - Comportement horaire du ratio (Q* - QG) / K↓ à chacun des sites

le taux FTM

o aucun phénomène atmosphérique de surface (o pour adv. marine , • pour adv. continentale)

△ brouillard ou pluie (▲adv. marine ,△adv. continentale).



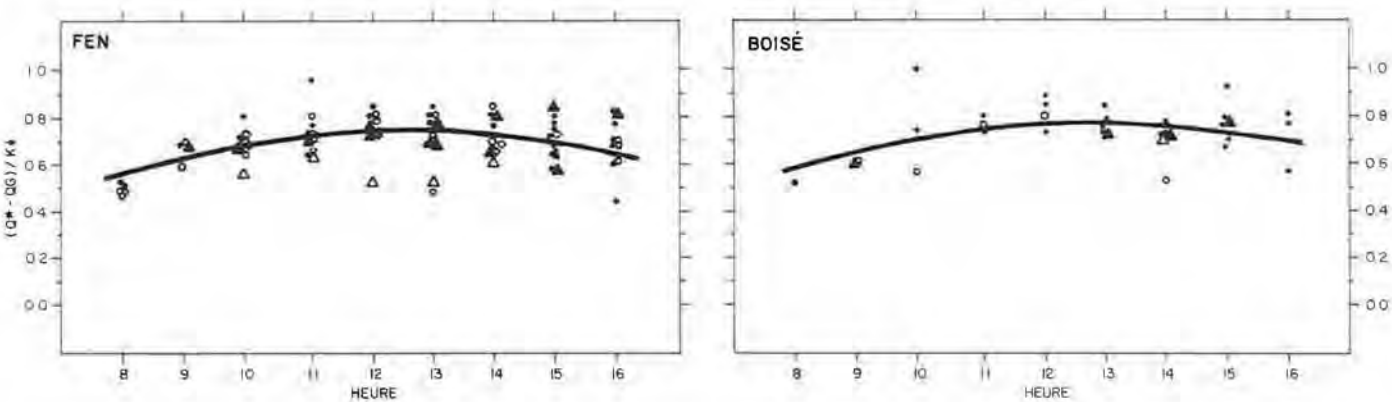


TABLEAU 2. Valeurs des paramètres de l'équation FTM = Tv – A cos (C(0,26175 H) + Th) qui définit (Q∗ – QG)/K↓ à chacun des sites.

Site	Tv	A	C	Th
LICHEN	0,52875	0,13393	1,0	0,87151
FEN	0,46705	0,27262	1,0	–0,20542
BOISE	0,50349	0,27323	1,0	–0,22552

NONLINEAR (non-linear regression) – et les constantes A, C, Th et Tv correspondantes sont données au tableau 2. La constante C (nombre de cycles) a été fixée à 1.0 pour emboîter la logique du cycle journalier donné par le K↓. Notons que nous avons considéré seulement les valeurs du rapport (Q∗ – QG)/K↓ supérieures ou égales à 0. En effet, compte tenu des conditions climatiques contemporaines, nous avons jugé improbables, donc erronées, les valeurs négatives enregistrées le 16 août à 8 et 9 heures et le 22 août à 12 heures.

Nous pouvons remarquer encore une fois que ni les phénomènes atmosphériques de surface ni l'origine des vents (advection marine ou continentale) ne semblent introduire d'effet particulier sur la relation (figure 3).

Le taux FTM introduit deux éléments intéressants. D'abord, il apporte une certaine connaissance de l'effet général des surfaces en ce qui concerne le comportement des échanges énergétiques se rapportant au rayonnement net diminué du flux d'énergie calorifique dans le milieu (Q∗ – QG). Plus encore, en admettant l'equation 2, le taux FTM devient un indicateur du comportement des échanges énergétiques turbulents (QE + QH). Ainsi, en comparant les courbes obtenues pour chacun des sites observés (figures 3 et 4), nous pouvons constater

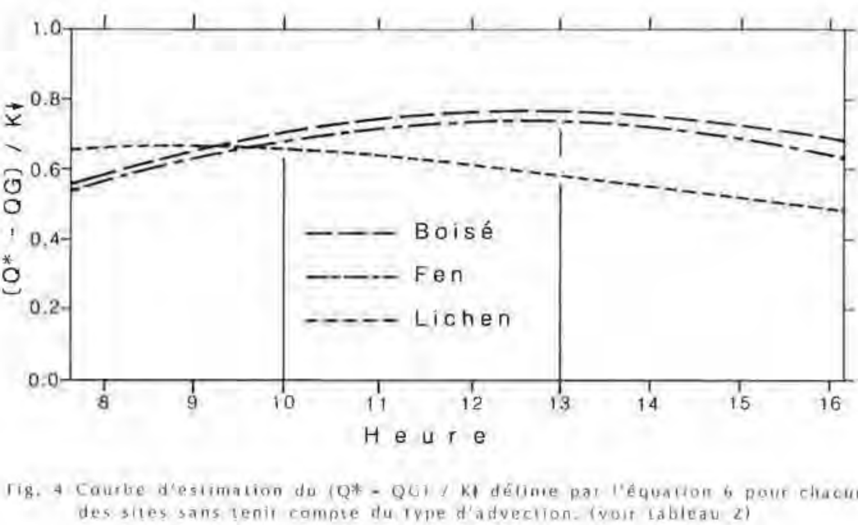


Fig. 4 Courbe d'estimation du (Q* – QG) / K↓ définie par l'équation 6 pour chacun des sites sans tenir compte du type d'advection. (voir tableau 2)

que le site LICHEN débute la journée avec un rendement supérieur à ceux des sites FEN et BOISÉ. Cependant, après 10 heures et particulièrement au cours de l'après-midi, le rendement du LICHEN devient nettement inférieur. Les sites FEN et BOISÉ ont un rendement respectif très apparenté, mais celui du BOISÉ est supérieur tout au long de la période diurne. Le maximum du rendement des échanges énergétiques turbulents semble se produire un peu avant 9 heures au site LICHEN alors qu'aux autres sites il semble se produire un peu avant 13 heures.

Selon nos observations sur le terrain, le comportement distinctif du taux FTM au site LICHEN semble intimement lié aux conditions hydriques générales de la surface. Nous avons remarqué en effet qu'au cours des journées ensoleillées la surface passait graduellement de l'état humide à l'état sec. Cette variabilité d'état a été constaté par Kershaw et Rouse (1971), Rouse et Kershaw (1971) et Rouse (1984). Selon eux, ceci est dû à la capacité qu'ont les lichens à capter l'humidité de l'air au cours de la nuit – la surface est très humide le matin – et à la nontranspiration des lichens parce qu'étant nonvasculaire – ce qui produit l'assèchement de la surface.

Le deuxième élément intéressant qu'introduit le taux FTM est qu'il contribue à améliorer sensiblement l'estimation de $Q* - QG$, et ce en multipliant les valeurs mesurées du rayonnement solaire global ($K\downarrow$) par le taux FTM (figure 5). L'amélioration est particulièrement notable au site LICHEN, où le coefficient de corrélation (r) a augmenté de 0,859 (fig. 1) à 0,908 – et où le coefficient passe à 0,944 – quand la valeur marginale du 31 juillet est excluse (valeur encadrée aux figures 3 et 5).

CONCLUSION

Selon notre étude, l'estimation du $Q* - QG$ diurne, et donc du $QE + QH$, si nous admettons l'équation 2, de certaines surfaces (x) du Nouveau-Québec peut être réalisée à l'aide du rayonnement solaire ($K\downarrow$). Dans le cadre spécifique de notre projet, soit la période estivale de juillet et août 1983, à Kuujjuarapik, le $(Q* - QG)_x$ peut être estimé à l'aide des équations linéaires suivantes :

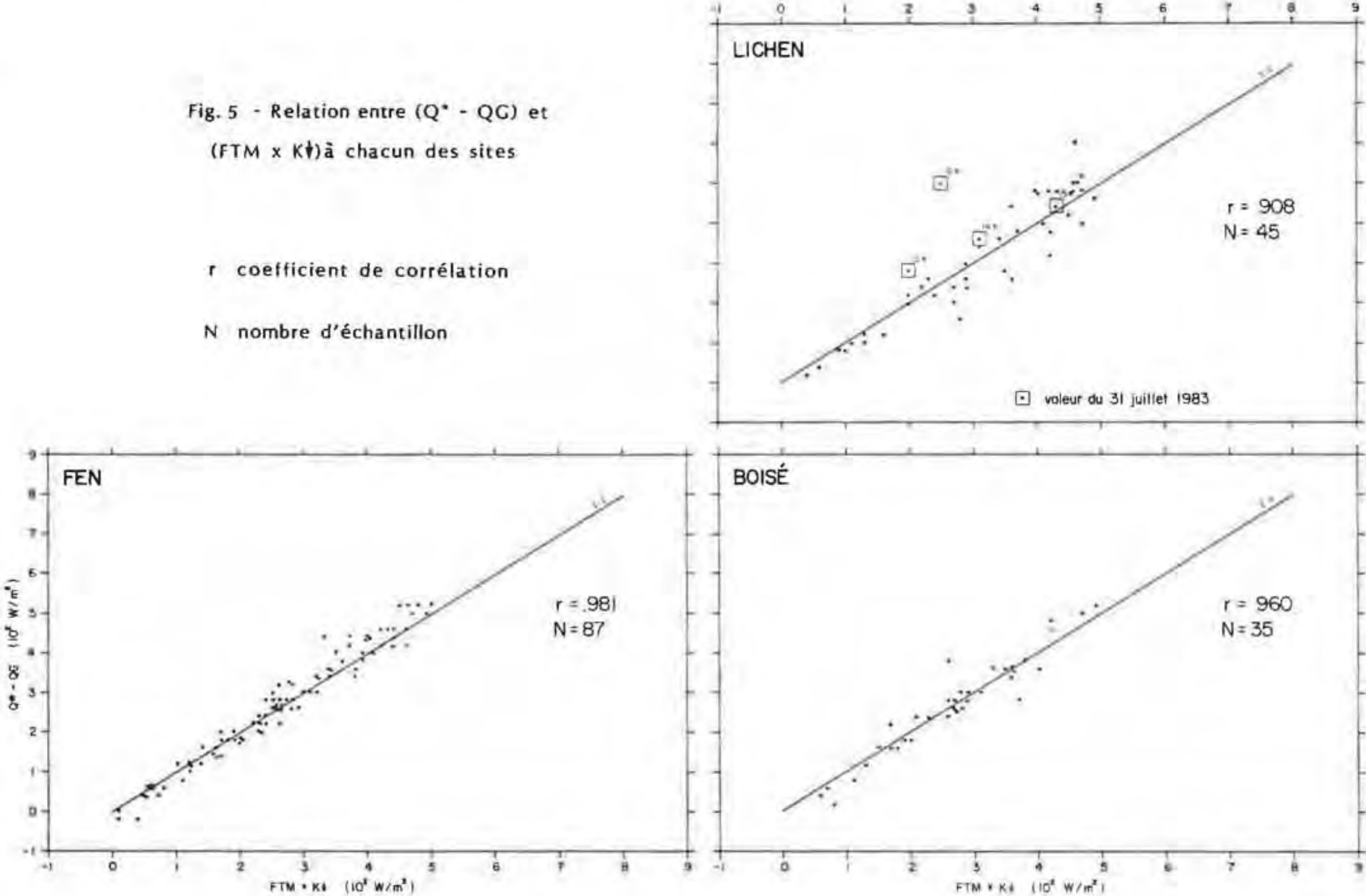
$$(Q* - QG)\ \text{LICHEN} = 0{,}703K\downarrow - 43{,}573$$
$$(Q* - QG)\ \text{FEN} = 0{,}829K\downarrow - 39{,}623$$
$$(Q* - QG)\ \text{BOISÉ} = 0{,}858K\downarrow - 52{,}967$$

Toutefois, le $(Q* - QG)_x$ gagne à être estimé par une fonction sinusoïdale qui prend en compte la notion du temps (heure de la journée). Ceci est surtout vrai au site LICHEN où les échanges énergétiques ne suivent pas le schéma habituellement imposé par le rayonnement solaire global ($K\downarrow$) (figures 2, 3 et 4). Ainsi, dans l'objectif d'une estimation proche de la réalité et toujours dans le cadre spécifique de notre projet, nous concluons que le $(Q* - QG)_x$ doit être estimé ainsi:

Fig. 5 - Relation entre (Q* - QG) et (FTM x K↓) à chacun des sites

r coefficient de corrélation

N nombre d'échantillon



$$(Q* - QG)\ LICHEN = (0{,}529 - 0{,}134 \cos(0{,}262H + 0{,}872))\ K\downarrow$$
$$(Q* - QG)\ FEN = (0{,}467 - 0{,}273 \cos(0{,}262H - 0{,}205))\ K\downarrow$$
$$(Q* - QG)\ BOISÉ = (0{,}503 - 0{,}273 \cos(0{,}262H - 0{,}226))\ K\downarrow$$

où H est l'heure locale de l'observation du K↓.

Bien entendu, nos résultats sont provisoires et ils doivent faire l'objet d'une validation dans le cadre d'autres études que nous encourageons fortement. Comme nous l'avons mentionné dans l'introduction, l'intérêt d'études de ce genre tient du fait qu'elles permettent d'introduire des moyens d'établir le comportement des paramètres étudiés en simplifiant la cueillette d'information; une simplification qui se traduit bien sûr par une économie de temps et d'argent. Ainsi, de telles estimations ouvrent la possibilité de réaliser des études sur de grands territoires, comme par exemple : étude d'impact régionale suite à la création d'un réservoir hydro-électrique (projet Baie James ou autres); ou encore, cartographie du QE moyen d'une mosaïque de surfaces; etc.

REMERCIEMENTS

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Climatology of Tornado Days 1960–1989 for Manitoba and Saskatchewan

R.L. Raddatz and *J.M. Hanesiak*
Winnipeg Climate Centre
Environment Canada
266 Graham Avenue, Room 1000
Winnipeg, Manitoba R3C 3V4
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in revised form 3 January 1991]

ABSTRACT

Tornado occurrences in Manitoba and Saskatchewan from 1960–89 have been tabulated by a number of researchers. These enumerations have been grouped by Statistics Canada census divisions and by occurrence dates to form a 30-year tornado day climatology. The tornado risk has been determined for two base areas (1) 10,000 km^2, and (2) the median area damaged per tornado day, 0.10 km^2. This analysis indicates that the frequencies of tornado days are relatively high, running, in general, from about 0.1 to 1.5 days per season per 10,000 km^2. A recurrence can be expected in most areas within a few years or possibly even that same season. However, a relatively small area is damaged on a typical tornado day. Therefore, the annual risk of a given location being hit by a tornado is very low; the odds generally range from one in a million up to one in seventy thousand. Manitoba and Saskatchewan residents should be aware of the risk but they should not be unduly alarmed.

RÉSUMÉ

Le nombre de tornades ayant touché le Manitoba et la Saskatchewan de 1960 à 1989 a été calculé par un certain nombre de chercheurs. Ces chiffres ont été regroupés selon la date de l'événement et les divisions de recensement de Statistique Canada de façon à réaliser une étude climatologique sur une période de trente ans basée sur le jour-tornade. Le risque de tornade a été établi pour deux superficies de base : la première mesure 10 000 km^2 et la deuxième, 0,10 km^2, soit la superficie moyenne endommagée par un jour-tornade. L'analyse révèle que la fréquence des jours-tornade est relativement élevée, variant entre 0,1 et 1,5 jours par saison pour 10 000 km^2. On peut s'attendre à ce que, dans la plupart des régions, une nouvelle tornade se produise dans les années qui suivent ou même pendant la même saison. Toutefois, une tornade endommage habituellement un secteur dont la superficie est relativement faible. Ainsi, le risque qu'un lieu donné soit touché par une tornade est bas; il varie entre 1 : 1 000 000 et 1 : 70 000. Les habitants du Manitoba et de la Saskatchewan doivent être conscients des risques de tornade sans pour autant en être effrayés outre mesure.

Tornadoes are violent, local storms of short duration which cannot be readily identified on weather charts, conventional radar or satellite imagery. Data gathering, therefore, relies on observations of funnel clouds on the ground and on the post-inspection of damage paths. Some under-reporting in Manitoba and Saskatchewan has, undoubtedly, resulted from their relatively sparse populations.

Tornado occurrences, including waterspouts, in various parts of Manitoba and/or Saskatchewan during the 1960's and 70's have been tabulated by a number of researchers (Lowe and McKay, 1962; Shannon, 1976; Tortorelli, 1979; Lemieux, 1980; Coté, 1981; Blair, 1983) – each focusing on a specific region and time period. Their primary data sources were the archives of selected newspapers from the area of interest. In 1978 for Manitoba and 1981 for Saskatchewan, the Atmospheric Environment Service (AES) established weather watcher or spotter networks and the Prairie Weather Centre began to issue annual Severe Weather Reports. These summaries (1978–89), which list the tornadoes

FIGURE 1. Saskatchewan and Manitoba Census Divisions.

reported directly to AES and those identified via a clipping service which monitors a large number of weekly and daily newspapers, have become the main source of information on tornadic events in the 80's.

These enumerations have been grouped by Statistics Canada Census Divisions (Figure 1) and by occurrence dates to form a 30-year (1960–89) tornado day climatology for Manitoba and Saskatchewan. In all cases, the judgement of the original enumerator that an event was, in fact, a tornado has been accepted. A chronological list containing the date and time of occurrence as well as a reference location for each tornadic report is available from the primary author.

This climatology, an update of the Canadian Climate Centre publication (CLI–6–83) – *Manitoba and Saskatchewan Tornado Days 1960–82*, Raddatz *et al.*, 1983, includes the seasonal and geographical distribution of tornado days as well as an analysis of their frequencies of occurrence, risks and recurrence periods.

2. DATA ANALYSIS

2.1 Tornado Days

Few detailed post-inspections of Manitoba's and Saskatchewan's tornadic events have been undertaken, leaving considerable uncertainty about times, paths and durations. Thus, it is difficult to distinguish multiple sightings from multiple occurrences and the separation of events on the basis of approximate times and locations becomes a matter of conjecture. This makes the total tornado count a somewhat unreliable figure. The number of tornado days, defined as calendar days with at least one recorded tornado occurrence, is known with considerably more certainty. Therefore, the statistics delineating the tornado climatology of Manitoba and Saskatchewan are based on tornado day counts rather than total occurrences.

2.2 Annual Counts and Trends

A total of 352 tornado days have been tabulated for the 30-year period for Manitoba and Saskatchewan from 1960 to 1989 (Table 1). Saskatchewan averaged 7.1 ± 3.4 tornado days per year while Manitoba's yearly counts averaged 5.0 ± 2.2.

The annual numbers of tornado days, by province, were plotted and trend lines were fitted to the data (Figure 2). Saskatchewan's trend, given by $Y = 0.23X + 3.58$, where Y is the number of tornado days and X is the year-number (*i.e.*, year minus 1959), reveals a notable positive trend while Manitoba's line, $Y = 0.08X + 3.71$, has a somewhat smaller slope. While Saskatchewan's tornado days were trending upward by over 3% of the mean number per year, the relative increase in thunderstorm days, based on ten synoptic stations in the southern half of the province, was less than 1% per year. Thus the upward swing in tornado days evident in both provinces is likely due to more rigorous tornado reporting coupled with enhanced public awareness rather than an actual increase in the annual

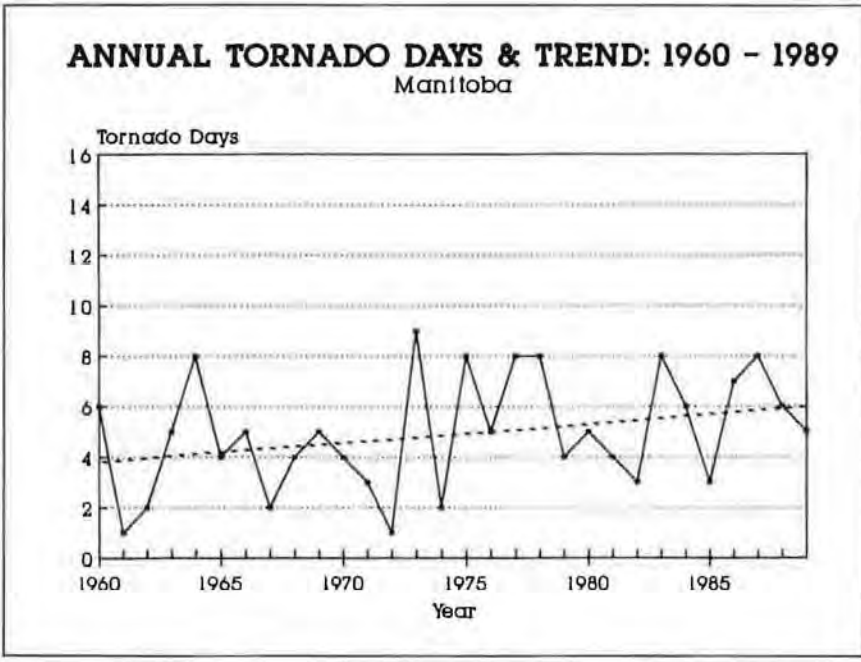
TABLE 1. Tornado Days, 1960–1989.

Year	Manitoba	Saskatchewan	Man. and Sask.
1960	6	3	8
1961	1	4	5
1962	2	5	7
1963	5	8	11
1964	8	5	13
1965	4	3	7
1966	5	3	8
1967	2	1	3
1968	4	6	10
1969	5	6	11
1970	4	6	10
1971	3	8	11
1972	1	4	5
1973	9	12	19
1974	2	7	9
1975	8	12	18
1976	5	6	11
1977	8	8	16
1978	8	9	16
1979	4	12	16
1980	5	7	12
1981	4	4	8
1982	3	7	8
1983	8	10	18
1984	6	6	12
1985	3	4	7
1986	7	13	20
1987	8	9	17
1988	6	11	17
1989	5	14	19
TOTAL	149	213	352
MEAN	5.0	7.1	11.7
STANDARD DEVIATION	2.2	3.4	4.8

number of days with tornadoes (Prairie Weather Centre, Severe Weather Reports, 1978–1989).

2.3 Seasonal Distribution and Length of Season

The total number of tornado days per month was graphed (Figure 3). The peak number of days was in July with June and August having fewer but still significant numbers. Table 2 contains the start date, end date and duration of each tornado season for the entire region. The mean date of the first tornado day was May 21; however, the season has begun as early as April 6. On average the last tornado day



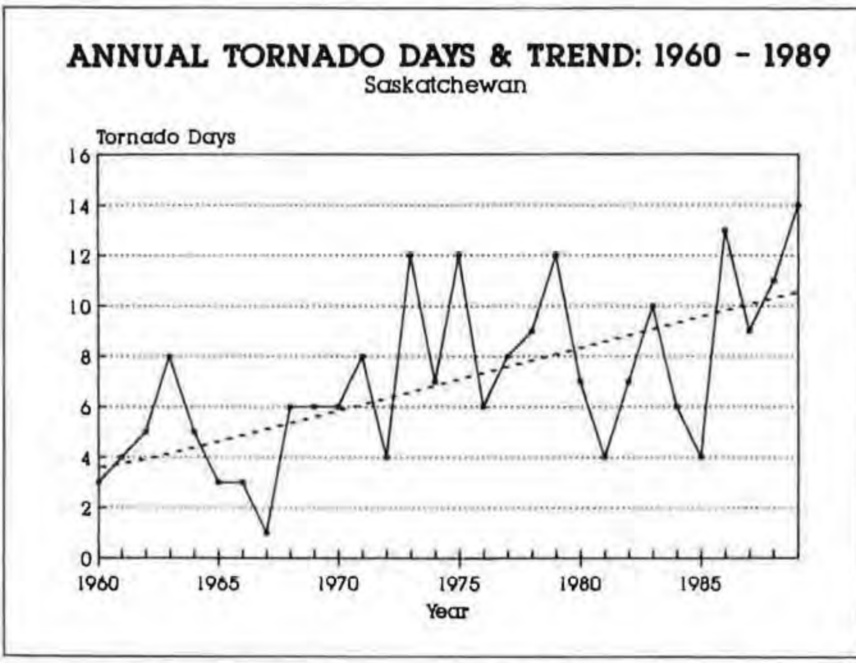


FIGURE 2 (a) Annual Tornado Days and Trend: 1960–1989, Manitoba.
(b) Annual Tornado Days and Trend: 1960–1989, Saskatchewan.

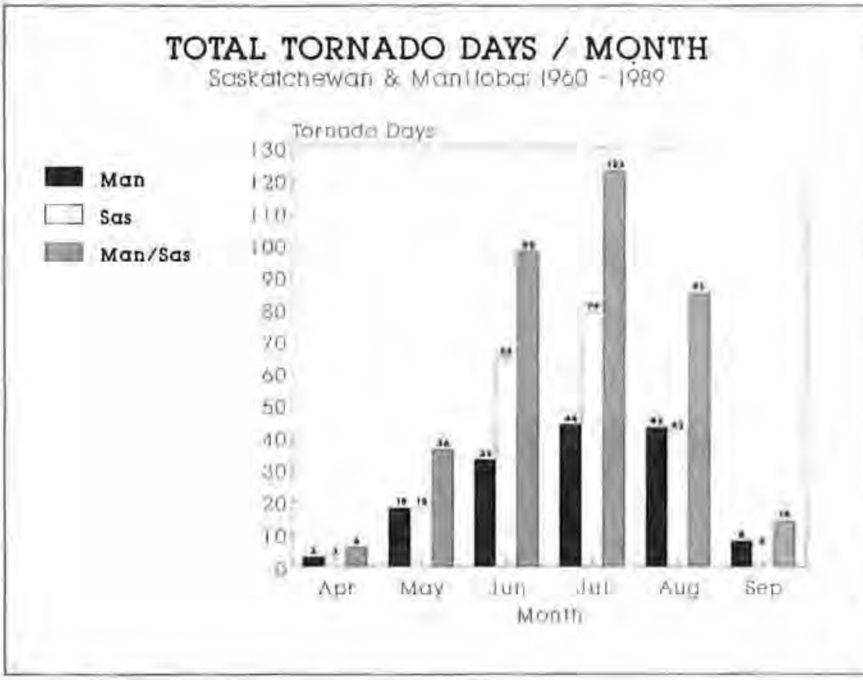


FIGURE 3. Tornado Days per Month.

was August 26; the season has lasted until September 26. The mean duration is 99 ± 25 days.

2.4 Geographical Distribution

The tornado days were plotted by Statistics Canada Census Division (Figure 4). Most of Manitoba's and Saskatchewan's census divisions have rural population densities greater than one person per square kilometre (Statistics Canada, 1976 and 1986). With densities of this magnitude all tornadoes, or at least their aftermaths, have a fairly high probability of being discovered (Newark, 1981). Nevertheless, most divisions have likely experienced more tornado days than the recorded number. Specifically, under-reporting may be significant in Manitoba's divisions 19 and 21 which have very sparse populations. Methods have been suggested, such as those described by Newark (1981) and by Schaefer and Galway (1982), to account for population bias. The use of population adjustment factors in the compilation of this climatology was tried but rejected due to their arbitrary nature and the apparent distortions that they introduced to the geographical distribution evident in the raw data.

TABLE 2. Start, End and Duration of Tornado Season, Manitoba and Saskatchewan.

Year	Start	End	Duration
1960*	Jun. 2	Sep. 5	96
1961	Jun. 29	Aug. 10	43
1962	Apr. 28	Aug. 27	122
1963	May 17	Sep. 16	123
1964*	May 15	Aug. 10	88
1965	May 5	Aug. 4	92
1966	Jun. 4	Aug. 16	74
1967	May 30	Jul. 31	63
1968*	Apr. 11	Aug. 18	130
1969	May 26	Sep. 20	118
1970	Jun. 24	Aug. 31	69
1971	Jul. 1	Sep. 11	73
1972*	May 8	Aug. 15	100
1973	Apr. 20	Aug. 27	130
1974	Jun. 19	Aug. 29	72
1975	May 24	Sep. 6	106
1976*	Jun. 3	Aug. 26	85
1977	Apr. 17	Sep. 26	163
1978	May 10	Aug. 25	108
1979	May 21	Sep. 9	112
1980*	Apr. 6	Aug. 10	127
1981	Jun. 4	Aug. 30	88
1982	Jun. 6	Aug. 18	74
1983	May 19	Sep. 5	110
1984*	May 11	Aug. 7	89
1985	May 25	Aug. 30	98
1986	May 4	Sep. 2	121
1987	May 28	Sep. 10	106
1988*	Apr. 29	Aug. 10	104
1989	Jun. 6	Aug. 17	73
MEDIAN	May 23	Aug. 28	99 days
MEAN	May 21	Aug. 26	99 days
STANDARD DEVIATION			25 days

Earliest date – April 6, 1980, Altona, MB.
Latest date – September 26, 1977, Viscount, SK.
* Leap year.

2.5 Occurrence Frequencies, Risks and Return Periods

The occurrence frequencies of tornado days per 10,000 km², f_i, and the probabilities of risks, R_i, (where the subscript i refers to the ith census division with area A_i and N_i tornado days) that a day will contain one or more tornadic events, and the periods during which there is a 50% chance of recurrence, $T(50{:}50)_i$ and a 95% chance of recurrence, $T(95{:}05)_i$, were calculated for each census division as follows (Kendall, 1959; Hendricks, 1983):

FIGURE 4. Tornado Days by Census Division.

$$f_i = \frac{N_i}{(30\ \text{seasons})(Ai/10{,}000\ \text{km}^2)}$$

$$R_i = f_i/99 \text{ days per average season}$$

$$T(50{:}50)_i = \ln(0.5)/\ln(1-R_i)$$
$$T(95{:}05)_i = \ln(0.05)/\ln(1-R_i)$$

The frequencies, f_i, approximate the annual probabilities of occurrence of a tornado day for each census division. Since the average tornado season is 99 days long, the daily risks can be calculated by dividing the annual frequencies by this number. The recurrence periods are then in days. The frequencies of occurrence (Figure 5) and the recurrence periods (Table 3), both per 10,000 km^2, are given. These calculations assume that each day during the tornado

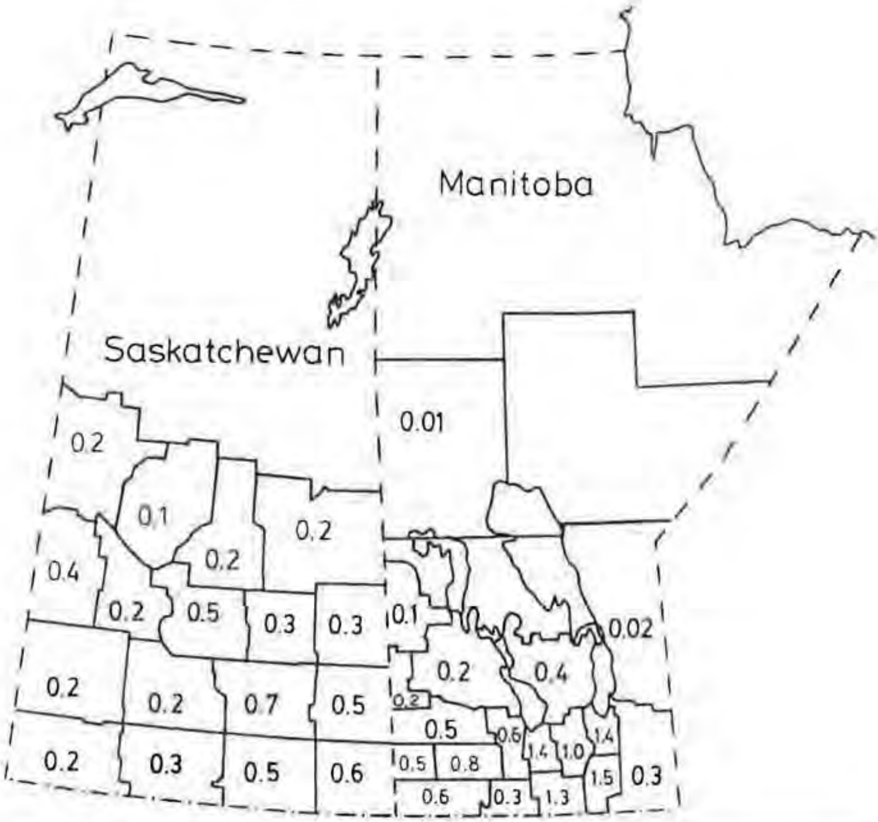


FIGURE 5. Frequencies of Tornado Days per 10,000 km^2 by Census Division and Annual Risks (x 10^{-1}%) of Tornado Damage by Census Division.

season has an equal probability of being a tornado day. However, an examination of the seasonal distribution of tornado days, Figure 4, clearly reveals that this is an over-simplification. The frequencies of tornado days by month (first column for each month in Table 4, headed "# Days") were, therefore, obtained by proportionally allotting each census division's tornado days to the various months in accordance with the seasonal distribution for the entire region. The seasonal distributions by census division were not used due to the sparseness of the data set at that level. The risks or probabilities of tornado days per 10,000 km^2 by month are given in the second column for each month in Table 4.

The frequencies of tornado days were brought to a common area base of 10,000 km^2 to eliminate the apparent higher risks in some census divisions due to their larger areas alone. This calculation assumes that there are no preferred locations for tornadoes, but rather that all of a division's sub-areas have an equal probability of experiencing a tornado day.

TABLE 3. Recurrence Period (Days) per 10,000 km² by Census Division

Census Division (i) Manitoba	Recurrence Periods (Days)** T(50:50)$_i$	T(95:05)$_i$	Census Division (i) Saskatchewan	Recurrence Periods (Days)** T(50:50)$_i$	T(95:05)$_i$
1	233	1006	1	118	511
2	46	198	2	145	626
3	52	227	3	253	1094
4	227	981	4	323	1396
5	118	508	5	149	646
6	131	564	6	99	429
7	88	381	7	326	1407
8	116	501	8	296	1279
9	49	212	9	259	1119
10/11/14*	70	304	10	226	979
12/13*	50	217	11	128	554
15	134	578	12	326	1410
16	323	1395	13	185	800
17	392	1694	14	461	1994
18	189	817	15	284	1228
19	4212	18205	16	510	2203
20	679	2934	17	414	1791
21	9530	41190			

* Areas combined due to small sizes.

** Return periods are interrupted by off-seasons.

An alternate base-area, inherent to the data, is the median area damaged on a tornado day. Schaefer *et al.* (1986), in an analysis of 22,840 tornadoes (1950–83) over the contiguous United States plus 900 tornadoes (1959–79) in the Canadian Climate Centre's data base, determined that the median area damaged per tornado occurrence was 0.10 km². This information is not specific to Manitoba and Saskatchewan; however, as tornadoes in this region are likely an extension of the U.S. Plains maximum (Newark, 1984), Schaefer's median tornado damage area was adopted for this analysis. In addition, the median or typical tornado day in Manitoba or Saskatchewan has one tornado occurrence (Raddatz *et al.*, 1983). It follows that the median damage area per tornado occurrence also applies to a typical tornado day. Therefore, the annual risks of damage at any location within each census division, RD_i (%) were calculated as follows:

$$RD_i\ (\%) = 100.0\,(f_iA_i/10{,}000)/(A_i/0.10)$$

and plotted (Figure 5). The resulting risk values visually mesh with the cross-border values in the neighbouring U.S. published by Schaefer *et al.* (1986).

MANITOBA:

DIVISION	APRIL # Days	APRIL Risk	MAY # Days	MAY Risk	JUNE # Days	JUNE Risk	JULY # Days	JULY Risk	AUGUST # Days	AUGUST Risk	SEPTEMBER # Days	SEPTEMBER Risk
01	0.22	0.02	1.29	0.09	3.52	0.27	4.42	0.32	3.05	0.22	0.50	0.04
02	0.31	0.08	1.89	0.48	5.14	1.34	6.46	1.63	4.46	1.12	0.73	0.19
03	0.33	0.07	1.99	0.42	5.41	1.17	6.80	1.43	4.70	0.99	0.77	0.17
04	0.07	0.02	0.40	0.10	1.08	0.27	1.36	0.33	0.94	0.23	0.15	0.04
05	0.23	0.03	1.39	0.19	3.79	0.52	4.76	0.64	3.29	0.44	0.54	0.07
06	0.10	0.03	0.60	0.17	1.62	0.47	2.04	0.57	1.41	0.40	0.23	0.07
07	0.22	0.04	1.29	0.25	3.52	0.70	4.42	0.85	3.05	0.59	0.50	0.10
08	0.17	0.03	0.99	0.19	2.71	0.53	3.40	0.65	2.35	0.45	0.39	0.08
09	0.20	0.08	1.19	0.44	3.25	1.25	4.08	1.52	2.82	1.05	0.46	0.18
10/11/14	0.25	0.05	1.49	0.31	4.06	0.88	5.10	1.07	3.52	0.74	0.58	0.13
12/13	0.23	0.07	1.39	0.43	3.79	1.22	4.76	1.49	3.29	1.03	0.54	0.17
15	0.23	0.03	1.39	0.16	3.79	0.46	4.76	0.56	3.29	0.39	0.54	0.07
16	0.05	0.01	0.30	0.07	0.81	0.19	1.02	0.23	0.70	0.16	0.12	0.03
17	0.12	0.01	0.70	0.06	1.90	0.16	2.38	0.19	1.64	0.13	0.27	0.02
18	0.20	0.02	1.19	0.12	3.25	0.33	4.08	0.40	2.82	0.27	0.46	0.04
19	0.05	0.00	0.30	0.01	0.81	0.01	1.02	0.02	0.70	0.01	0.12	0.00
20	0.05	0.01	0.30	0.03	0.81	0.09	1.02	0.11	0.70	0.08	0.12	0.01
21	0.02	0.00	0.10	0.00	0.27	0.01	0.34	0.01	0.23	0.01	0.04	0.00

SASKATCHEWAN:

DIVISION	APRIL # Days	APRIL Risk	MAY # Days	MAY Risk	JUNE # Days	JUNE Risk	JULY # Days	JULY Risk	AUGUST # Days	AUGUST Risk	SEPTEMBER # Days	SEPTEMBER Risk
01	0.43	0.03	2.59	0.19	7.04	0.52	8.83	0.63	6.10	0.44	1.01	0.07
02	0.40	0.03	2.39	0.15	6.50	0.43	8.15	0.52	5.64	0.36	0.93	0.06
03	0.25	0.02	1.49	0.09	4.06	0.24	5.10	0.30	3.52	0.21	0.58	0.03
04	0.22	0.01	1.29	0.07	3.52	0.19	4.42	0.23	3.05	0.16	0.50	0.03
05	0.33	0.03	1.99	0.15	5.41	0.41	6.80	0.50	4.70	0.35	0.77	0.06
06	0.60	0.04	3.58	0.22	9.75	0.62	12.23	0.76	8.45	0.52	1.39	0.09
07	0.20	0.01	1.19	0.07	3.25	0.19	4.08	0.23	2.82	0.16	0.46	0.03
08	0.27	0.01	1.59	0.07	4.33	0.21	5.44	0.25	3.76	0.18	0.62	0.03
09	0.20	0.01	1.19	0.08	3.25	0.24	4.08	0.29	2.82	0.20	0.46	0.03
10	0.18	0.02	1.09	0.10	2.98	0.27	3.74	0.33	2.58	0.23	0.43	0.04
11	0.45	0.03	2.69	0.17	7.31	0.48	9.17	0.59	6.34	0.40	1.04	0.07
12	0.15	0.01	0.90	0.07	2.44	0.19	3.06	0.23	2.11	0.16	0.35	0.03
13	0.31	0.02	1.89	0.12	5.14	0.33	6.46	0.41	4.46	0.28	0.73	0.05
14	0.25	0.01	1.49	0.05	4.06	0.13	5.10	0.16	3.52	0.11	0.58	0.02
15	0.23	0.01	1.39	0.08	3.79	0.22	4.76	0.26	3.29	0.18	0.54	0.03
16	0.15	0.01	0.90	0.04	2.44	0.12	3.06	0.15	2.11	0.10	0.35	0.02
17	0.18	0.01	1.09	0.05	2.98	0.15	3.74	0.18	2.58	0.13	0.43	0.02

3. CONCLUSION

The frequencies of tornado days for Manitoba's Census Divisions 1 to 21 and Saskatchewan's Divisions 1 to 17 are relatively large, running, in general, from about 0.1 to 1.5 days per season per 10,000 km^2. A recurrence can be expected somewhere in the area within a few years or possibly that same season. However, a relatively small area is damaged on a typical tornado day. Therefore, the annual risk of damage at a given location is very low, ranging generally from $0.1 \times 10^{-3}\%$ to $1.5 \times 10^{-3}\%$. Nevertheless, tornadoes, nature's most locally destructive storms, pose a danger to life and property especially in built-up areas with a concentrated population. Although the danger is real and Manitoba and Saskatchewan residents should be aware of the risk, they should not be unduly alarmed.

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News and Comments
Nouvelles et commentaires

CLIMATE/AGRICULTURE SYMPOSIUM

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

Phone (403) 422-4385
Fax (403) 422-0474

CANADA/CHINA INTERNATIONAL MESOSCALE WORKSHOP
June 8–11, 1991, Winnipeg, Manitoba

This Workshop follows directly the 25th Annual CMOS Congress to be held in Winnipeg June 3–7. It is being sponsored by the State Meteorological Administration of the Peoples' Republic of China, the Canadian Atmospheric Enironment Service, and the Canadian Meteorological and Oceanographic Society. Its purpose is to continue developing joint Canada-China activities in mesoscale meteorology. Invited speakers from China, the United States and Canada will address the nature and prediction of mesoscale weather in North America and China, with emphasis on current research plans.

There is no charge for registration at the workshop, but a fee will be assessed for those wishing to attend the banquet. Proceedings will be published after the conclusion of the conference. Sunday June 9 will be reserved for sightseeing, with a number of events planned by the local arrangements committee.

For further information: contact
Mr. Louis Legal
Workshop Coordinator
Atmospheric Environment Service
266 Graham Avenue, Room 900
Winnipeg, Manitoba, Canada R3C 3V4
Telephone: (204) 983-2079
Fax: (204) 983-0109

THE MACKENZIE BASIN CLIMATE IMPACT STUDY

As part of the Government of Canada's environmental initiative known as the Green Plan, the Canadian Climate Centre (CCC) of Environment Canada, in cooperation with a number of other government and non-government organizations, is planning a climate impact study on the Mackenzie Basin. This is a high-latitude region where projected greenhouse warming is expected to be greater than the global average temperature change.

The overall purpose of the Mackenzie Study is to describe the impacts of several scenarios of global warming (including General Circulation Model outputs) on the region of Canada bounded by the Mackenzie Basin watershed, including parts of British Columbia (BC), Alberta, Saskatchewan, Yukon and the Northwest Territories (NWT). This is meant to be a broad integrated interdisciplinary study of all regional issues that may be climate-sensitive, such as terrestrial and freshwater resources and ecosystems, resource extraction activities (mining, energy, forestry, etc.) and local/regional economies (wage, subsistence, mixed). Certain questions will not easily lend themselves to quantitative investigation, nor are quantitative methods necessarily the most appropriate in all instances. We expect, therefore, to employ a wide range of methodologies in order to provide an objective assessment of regional impacts which could be used by planners and decision makers.

This project has been identified as one of the activities within the Arctic component of the Canadian Global Change Programme. It is anticipated that the research will include a combination of existing in-house studies from various agencies, and new studies (government, academic, etc.) to be funded by the Green Plan and other sources.

Because of the issues involved, consultations with government and non-government agencies have been initiated during the early planning phase, and are continuing on an ongoing basis. As a result, an Interagency Working Committee is now in place. It facilitates coordination of research activities, and plays a key role in planning the overall thrust of this 5-year project. Committee members include representatives of federal government (Environment, Energy Mines and Resources, Indian and Northern Affairs, Forestry, Agriculture, Tourism, Fisheries and Oceans) and provincial/territorial agencies (Alberta Environment, BC Hydro, NWT-Renewable Resources, NWT-Energy Mines and Petroleum Resources), Native organizations (Dene, Metis, Inuvialuit), and private industry (ESSO). There is also an Advisory Group, composed of individuals with considerable Northern experience, who will not be participating directly in the Study but have agreed to provide advice on an *ad hoc* basis. These people come from federal government, academia, a Native organization (Inuit Tapirisat of Canada), a museum (Glenbow Alberta Institute), and the Government of Alaska (advisor to the Governor).

Future updates will cover a range of study-related issues, such as global warming scenarios, community consultation and integration of research results. For further information, contact

Dr. Stewart Cohen
Canadian Climate Centre
4905 Dufferin Street
Downsview, Ontario, Canada M3H 5T4