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Bulletin climatologique

Canadian Meteorological and Oceanographic Society

La Société Canadienne de Météorologie et d'Océanographie

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

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

TITLE PAGE should include the full names of author(s), and professional affiliation(s).
The ABSTRACT should be less than 250 words, and typed on a separate page.
The TEXT of longer contributions should be typed double spaced on numbered pages, and divided into sections, each with a separate heading and numbered consecutively. The section heading should be typed on a separate line.
ACKNOWLEDGEMENTS are typed on a separate sheet immediately following the text.
If FOOTNOTES are required, they should be typed, double spaced, on a separate sheet under the heading "Notes" at the end of the text.
REFERENCES should be arranged alphabetically by senior author's last name. The text citation should consist of name(s) of the author(s) and the year of publication, for example Jones (1975) or (Jones, 1975). When there are two or more cited publications by the same author in the same year, distinguishing letters a, b, etc., should be added to the year. A reference to "in press" implies that the paper has been accepted for publication. Titles of periodicals should be given in full.
FIGURE LEGENDS must be provided for each figure, and should be typed together, double spaced, on a separate sheet.
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Each TABLE should be numbered sequentially. Type all tables double spaced on separate sheets.

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

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

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

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

LA PAGE DE TITRE doit comprendre: nom, prénoms des auteurs, ainsi que les affiliations professionnelles.

LE RÉSUMÉ, dactylographié sur une page à part, ne doit pas compter plus de 250 mots.

LE TEXTE. Il faut taper à double interligne, sur des pages numérotées, le texte des articles plus longs et le diviser en sections, chacune dotée d'une en-tête à part et numérotée dans l'ordre. Il faut dactylographier l'en-tête de section sur une ligne à part.

LE REMERCIEMENTS doivent être dactylographiés sur une page à part, après le texte.

LES NOTES DE BAS DE PAGE doivent être dactylographiées à double interligne, sur une feuille à part, au-dessous de l'en-tête "Notes", à la fin du texte.

LES RÉFÉRENCES doivent être disposées dans l'ordre alphabétique, d'après le nom de l'auteur principal. Les citations doivent comprendre le ou les noms du ou des auteurs et l'année de publication, comme Jones (1975) ou (Jones, 1975). Si l'on cite deux ou plusieurs publications du même auteur pendant la même année, il faut ajouter à l'année des lettres qui permettent de les différencier, comme a, b, etc. La mention "à l'impression" implique qu'on a accepté de publier la communication. Il faut indiquer les titres des périodiques en entier.

LES LÉGENDES: elles sont requises pour chaque figure. On dactylographiera ces légendes ensemble, à double interligne, sur une feuille à part.

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Les auteurs doivent utiliser le système international de mesure, mais ils peuvent indiquer d'autres mesures entre parenthèses. Les auteurs doivent porter dans la marge des instructions pour tout caractère spécial voulu (lettres grecques, majuscules, caractères gras, etc.).

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

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

Climatological Bulletin
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Vol. 22, No. 3, December/Décembre 1988

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Foreword / Avant-Propos

Climatological Bulletin has published nine articles and notes in 1988. Given the budget situation, this has meant a reduction in the news and comments section of the journal. Is this change in balance acceptable? My personal feeling is that *Climatological Bulletin* should carry out both functions. However, this would require additional pages, with a corresponding increase in production costs.

We have just instituted publication charges of $50 per page for articles and notes. We can no longer afford to publish ten or fifteen pages of news and comments which produce no revenue. Should we perhaps extend publication charges to any comments in excess of half a page? Reactions from readers would be welcomed by the Editorial Board.

Bulletin climatologique a publié neuf articles et notes en 1988. Vu la situation financière, il a fallu réduire la section de nouvelles et commentaires du journal. Ce changement de bilan est-il acceptable? A mon avis, le journal devrait exécuter les deux fonctions. Ceci demanderait des pages additionnelles, donc une augmentation des frais de production.

On vient d'établir les frais de publication de 50 $ la page en cas des articles et des notes. On ne peut plus publier dix ou quinze pages de nouvelles et commentaires sans en gagner des revenus. Devrait-on demander peut-être les frais de publication des auteurs des commentaires qui excèdent une demie-page? Les réactions de nos lecteurs seraient appréciées par le comité de rédaction.

Finalement, *Bulletin climatologique* accueillit les manuscrits en français.

Alec Paul
Editor/Rédacteur en chef

Statistical Relationships Between Northeast Pacific Atmospheric Surface Pressure and the Sea Surface Temperature Along the British Columbia Coast

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[Original manuscript received 25 September 1987; in revised form 13 June 1988]

ABSTRACT

Through the construction of atmospheric circulation indices, it is shown that the sea surface temperature (SST) along the coast of British Columbia is strongly controlled by the regional atmospheric wind. These atmospheric circulation indices are also used to estimate the seasonal mean SST anomaly at two stations on the British Columbia coast back to the turn of the century. An application of the derived SST anomaly data to predicting sockeye salmon migration paths is discussed. Finally, the seasonal variability of the relationship between the sea level pressure in the Gulf of Alaska and the coastal SST is briefly presented.

RÉSUMÉ

La construction des indices de la circulation atmosphérique suggère que c'est le vent régional qui contrôle fortement la température superficielle de l'océan (TSO) près du littoral de la Colombie Britannique. On utilise également ces indices pour estimer l'anomalie saisonnière de TSO moyenne à deux stations côtières de la Colombie Britannique du tournant du siècle jusqu'au présent. À partir de ces anomalies estimées de TSO, on discute de la prédiction des routes de migration du saumon. Finalement, la variabilité saisonnière du rapport entre la pression atmosphérique au niveau de la mer dans le golfe d'Alaska et la TSO littorale est bref présentée.

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1. INTRODUCTION

There has been a long history of investigation of the interrelationships between sea surface temperature (SST) in the North Pacific Ocean and the overlying atmospheric circulation. Early workers established a clear correlation between seasonal mean SST and atmospheric sea level pressure (SLP) patterns (e.g., Namias, 1959). There has been some controversy concerning the question of whether this empirical relationship results primarily from atmospheric influence on ocean circulation or from oceanic influence on the circulation of the atmosphere. On the basis of both numerical modelling studies (e.g., Huang, 1978) and sophisticated statistical analyses (Davis, 1976) it is now believed that atmospheric forcing largely determines the North Pacific SST pattern.

Emery and Hamilton (1985) recently examined the connection between the winter SST in the Northeast Pacific and the coincident atmospheric surface circulation on a year by year basis. Figure 1a shows the long term mean (1947–82) climatology of the winter (December through February) surface pressure in the North Pacific. The atmospheric circulation in this figure is dominated by the Aleutian Low. Emery and Hamilton (1985) noted that the winter SLP pattern in individual winters differed principally in the strength of this Aleutian Low. They constructed an index of the intensity of the Low by taking the pressure difference between the two points (170°W, 50°N and 120°W, 40°N) marked by the circled points on Figures 1a–d. The winter mean value of this particular pressure index was found to correlate quite well with the winter mean SST anomalies at stations along the British Columbia outer coast. Winters with anomalously strong (weak) Aleutian Lows were found to have anomalously warm (cold) coastal SSTs as more (less) warm water was advected northward from further south. The correlation between the time series of winter mean index and the SSTs at individual stations averaged out to around 0.7.

In this paper we generalize the earlier work of Emery and Hamilton (1985) through the construction of atmospheric circulation indices that involve pressure data from several points in the Gulf of Alaska (see Figures 1a–d). These indices were designed to correlate as well as possible with the time series of coastal SSTs. We undertake this exercise in order to demonstrate the strong control of coastal SST by the regional atmospheric wind forcing, and to see how the relationship between SLP and SST changes with season. In addition, the results of this analysis are useful in that they can be used to estimate the seasonal mean SST from a knowledge of the SLP field. This feature is of considerable interest since SLP analyses for the Northeast Pacific region are available back to 1899, while SSTs along the outer coast have been measured only since 1934. Estimates of the pre-1934 SST may be of value for studies of the environmental effects on the commercial fisheries of British Columbia (e.g., Mysak *et al.*, 1982, 1986, Hamilton, 1985, 1987, Mysak, 1986).

The outline of this paper is as follows. The data used in this study are described in Section 2 below. Section 3 discusses the pressure indices that were constructed and the correlation between the time series of the indices and the observed SST at different stations. Section 4 considers the extension of the SST time series back to the turn of the century using the relations determined between SST and the pressure indices. A brief discussion of the application of the derived SST time series to the problem of predicting the "Johnstone Strait diversion" is also included in Section 4. A summary is presented in Section 5.

2. DATA

Observations of SST have been taken at several lighthouse stations along the British Columbia coast. In this study monthly mean SST data were employed from Langara Island in northern British Columbia and from the more southerly station on Kains Island (see Figure 2). The monthly means were available for 1935–1977 at Kains Island and for 1941–1977 at Langara Island. The long-term mean (1935–1977 for Kains Island; 1941–1977 for Langara Island) SST for each month was removed from the SST time series to produce a monthly SST anomaly time series. Seasonal SST anomalies were then derived as discussed in the next section. According to Emery and Hamilton (1985), the seasonal SST anomalies along the British Columbia coast are generally representative of those in the region at least 500 km offshore.

Monthly mean SLP analyses for the region north of 15°N for the period 1899–1982 were obtained from the Data Support Section at NCAR. This data set was originally constructed at NCAR from various sources throughout the period considered (Jenne, 1975). Trenberth and Paolino (1980) reworked some of the data to eliminate spurious trends and to fill in some of the missing observations. The analyses are on a 5° by 5° latitude-longtitude grid. Data were available for each month except September 1935 and December 1944 (in the analysis to be described below the SLP for these months were simply taken from adjacent months).

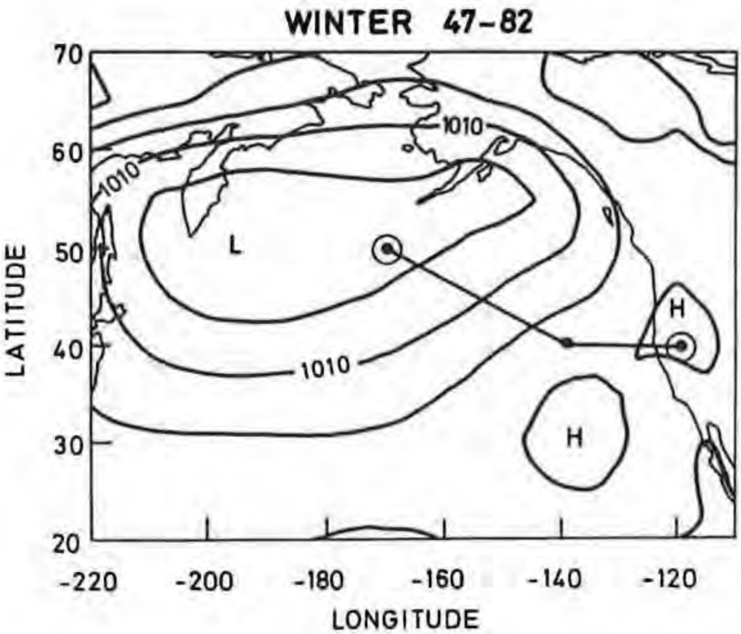
3. ANALYSIS

The pressure indices were arrived at through least squares fits of linear combinations of grid point pressure values to the station SST time series. That is, choices were made of a_γ and b_γ so that the following expression produced the best fit to the observed time series of SST anomalies in season n:

$$\text{Predicted SST}(n) = \sum_\gamma a_\gamma P_\gamma(n) + \sum_\gamma b_\gamma P_\gamma(n-1), \qquad (1)$$

where the season n represents a two-month period of the year (i.e., *winter* is January and February, *spring* is April and May, *summer* is July and August, and *autumn* is October and November), $n-1$ labels the two-month period immediately before season n, and $P_\gamma(n)$ is the mean pressure at the gridpoint γ over the season n. The sums in expression (1) were taken over three or four grid points. In a particular season, the pressure at each grid point is not independent of the pressure

a



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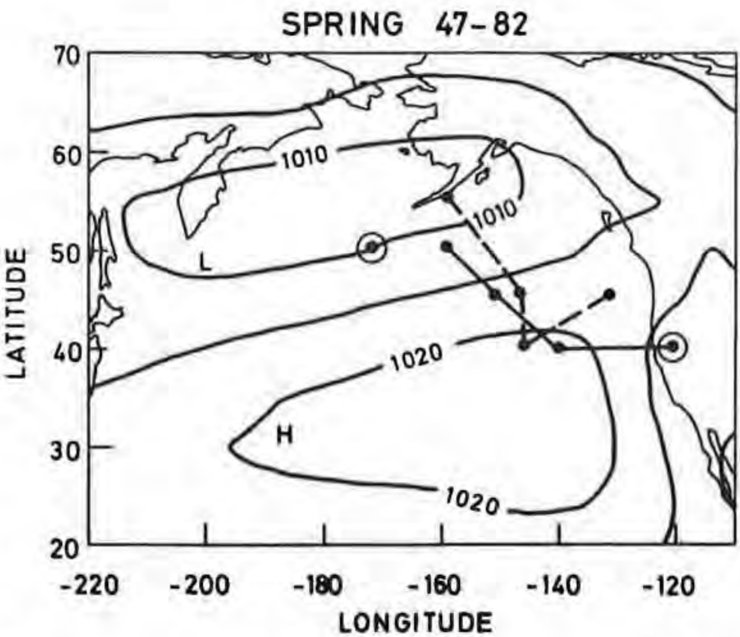
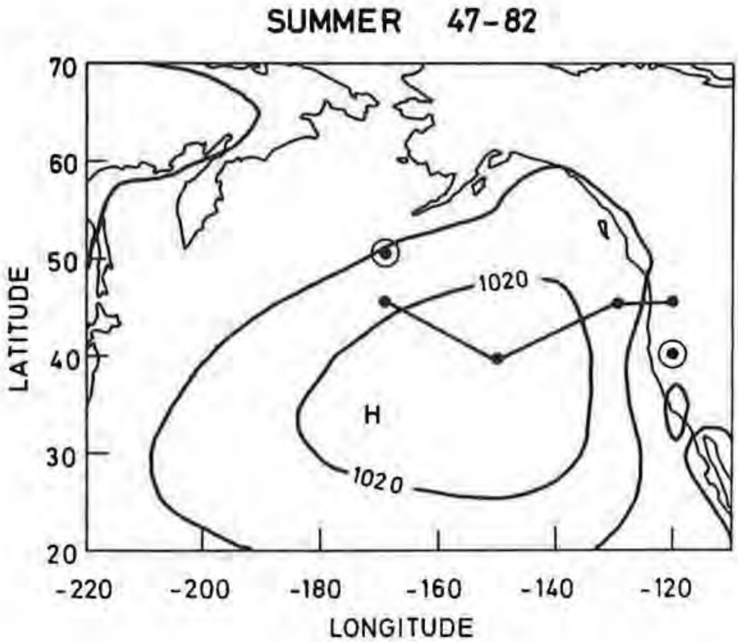


FIGURE 1. Long-term mean (1947–1982) climatology of the a) – winter (December, January, February); b) – spring (March, April, May); c) – summer (June, July, August); d) – autumn (September, October, November) surface pressure in the North Pacific (from Hamilton, 1984). The

c



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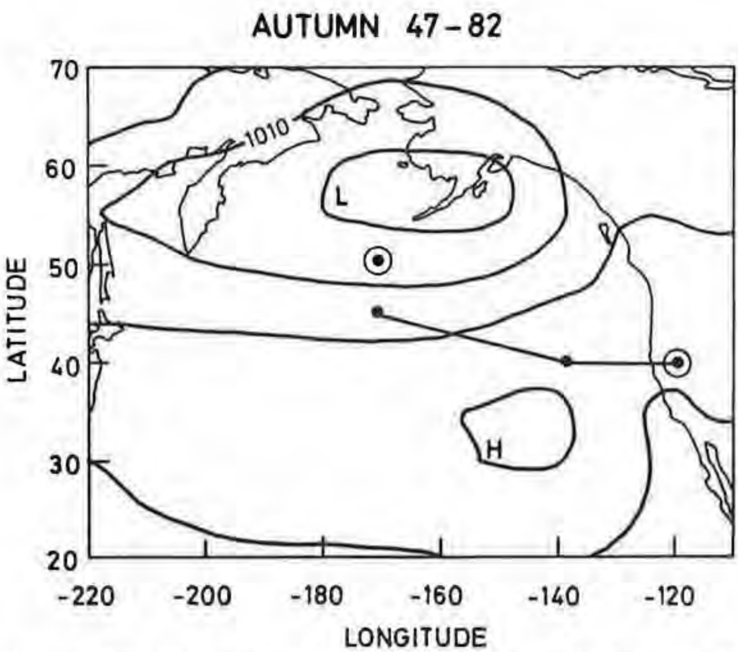


circled points at 170°W, 50°N, and 120°W, 40°N were used by Emery and Hamilton (1985). The dashed line in b) indicates the points used in predicting the temperature change between spring and winter (Table 3). Contours are labelled in millibars and the contour interval is 5 mb.

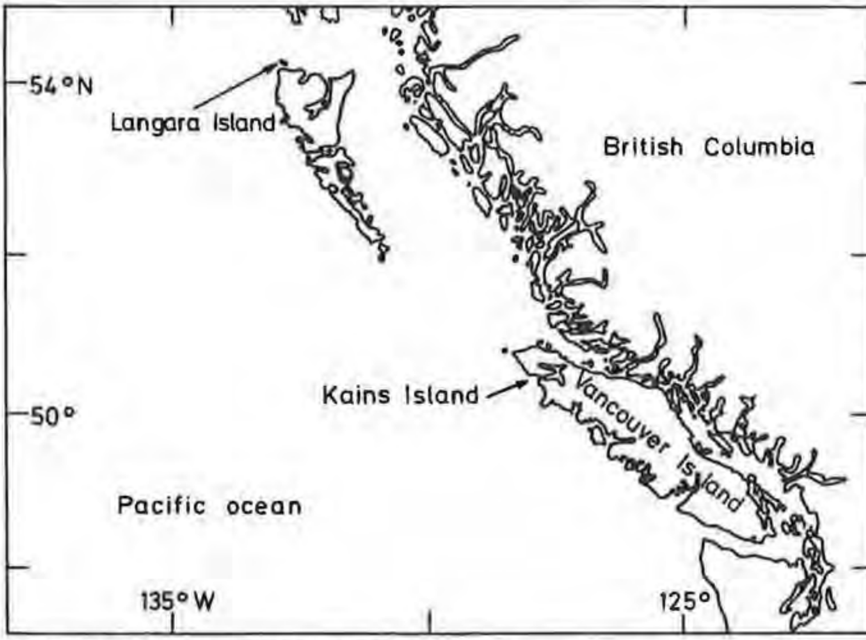


FIGURE 2. Map of the coast of British Columbia showing the two lighthouse stations at Kains Island and Langara Island.

TABLE 1. Seasonal mean North Pacific pressure indices (used for predicting seasonal SST anomaly) and corresponding least squares coefficients for each reference point (see Figures 1a–d).

Season	Position	Kains Island $a\gamma$	Kains Island $b\gamma$	Langara Island $a\gamma$	Langara Island $b\gamma$
winter	170°W 50°N	−0.0561	−0.0096	−0.0785	−0.0048
	140°W 40°N	−0.0413	−0.0950	−0.0334	−0.0777
	120°W 40°N	0.0973	0.1046	0.1118	0.0825
spring	160°W 50°N	−0.0667	−0.0852	−0.0699	−0.1051
	150°W 45°N	0.1845	0.1383	0.1993	0.1529
	140°W 40°N	−0.1844	−0.1621	−0.1965	−0.1554
	120°W 40°N	0.0666	0.1089	0.0671	0.1075
summer	170°W 45°N	0.0728	0.0373	0.0402	0.0629
	150°W 40°N	−0.1031	−0.0174	−0.1477	−0.0842
	130°W 45°N	−0.3752	−0.1676	0.0270	−0.1372
	120°W 45°N	0.4055	0.1476	0.0806	0.1586
autumn	170°W 45°N	−0.0356	−0.0073	−0.0547	−0.0540
	140°W 40°N	−0.1007	−0.1311	−0.0751	0.0122
	120°W 40°N	0.1364	0.1384	0.1298	0.0418

at other grid points (i.e., they are part of the same large-scale circulation pattern). We also wish to consider pressure differences, as in Emery and Hamilton (1985), in order to get an estimate of the geostrophic winds (see discussion below). Thus the choice of the $a\gamma$ and $b\gamma$ coefficients was constrained by the requirement that the sum of the $a\gamma$'s and of the $b\gamma$'s be zero. Therefore, in cases where three (four) grid points were used in the construction of the index, there are four (six) independent parameters in the linear regression (1).

The regression of the SST time series for each season was repeated using various combinations of grid points in expression (1), with the aim of finding the locations allowing the best fit to the SST data. This trial and error analysis was done using SLP data at three grid points; if an adequate fit to the temperature data could not be obtained, then SLP data at four grid points were employed. The indices yielding the best fit to the observed SST data were not obtained in a completely random manner. The grid points used in obtaining these indices (described in Table 1) have been plotted in Figures 1a–d (the climatological mean SLP maps constructed for each season using the SLP data during the period December 1946 to November 1982) and connected by a solid line. The dashed line in Figure 1b will be discussed later. Since the isobars of Figures 1a–d tend to be perpendicular to the lines connecting the grid points, the indices give an indication of the magnitude of the flow across the lines. For example, in the winter of major North Pacific warming events, when the Aleutian Low is often very intense, we get an indication of the magnitude of warm water transport (along the isobars) from the south (see Section 4).

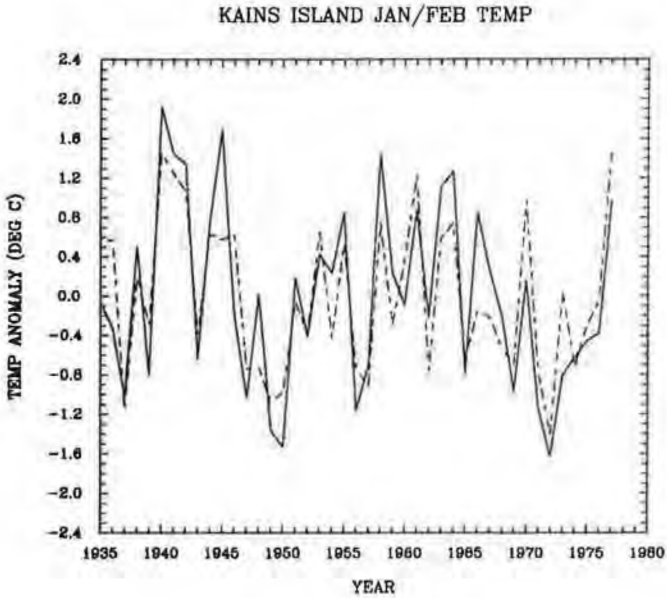
Table 1 gives the optimum choices of the grid points and of the $a\gamma$ and $b\gamma$ coefficients needed for pressure indices that predict the seasonal SST anomalies. These parameters are given for both Kains Island and Langara Island. The coefficients are quoted in units of °C mb^{-1}.

Table 2 shows the correlation coefficients computed between the actual time series of seasonal SST anomalies and those predicted by (1) with

TABLE 2. Correlation coefficients r between the seasonal mean predicted SST anomalies, obtained from the pressure indices defined in Table 1, and the observed seasonal mean temperature anomalies. Correlation coefficients were calculated at Kains Island for the period 1935 to 1977 and Langara Island for the period 1941 to 1977.

Season	Kains Island r	Langara Island r
winter	0.832	0.888
spring	0.616	0.636
summer	0.696	0.716
autumn	0.773	0.737

a



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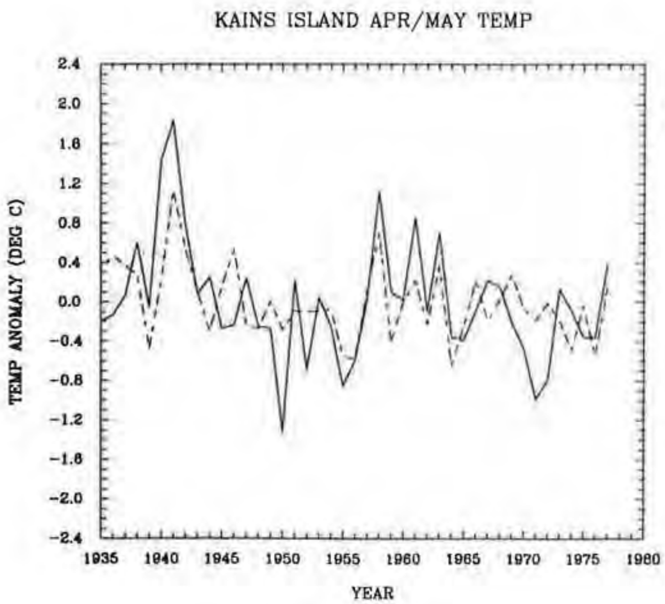
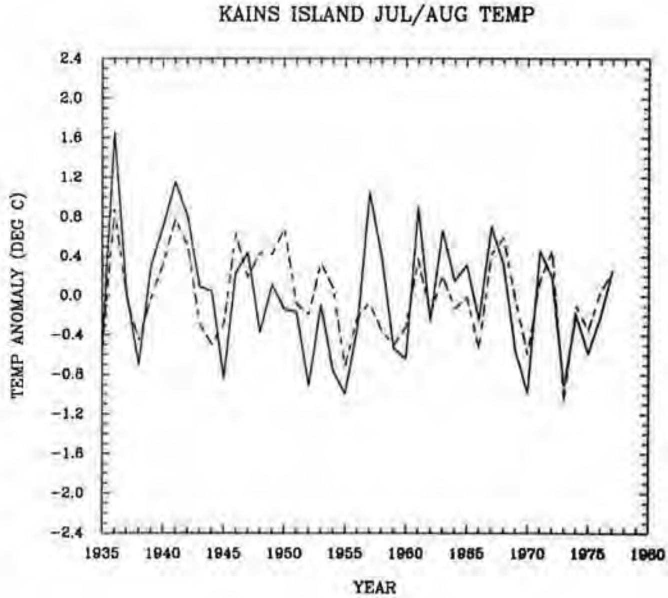


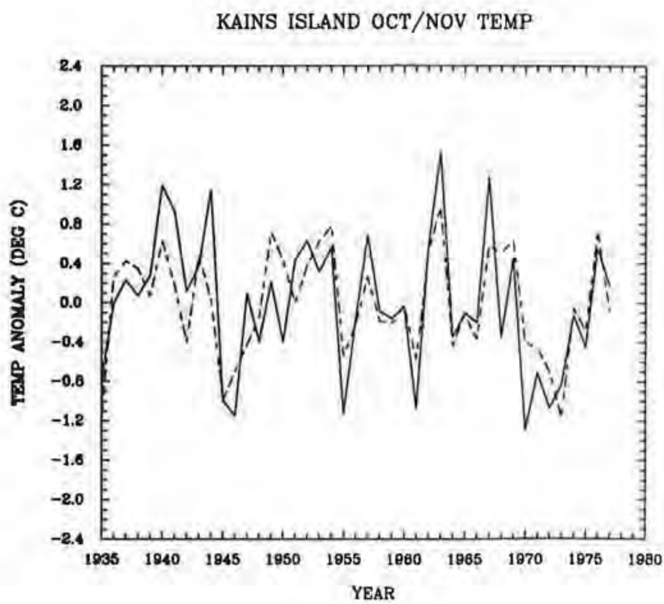
FIGURE 3. Comparison of the time series of the observed (solid) and predicted (dashed) seasonal SST anomalies from Kains Island for the period 1935–1977. a) – winter; b) – spring; c) – summer; d) – autumn.

c



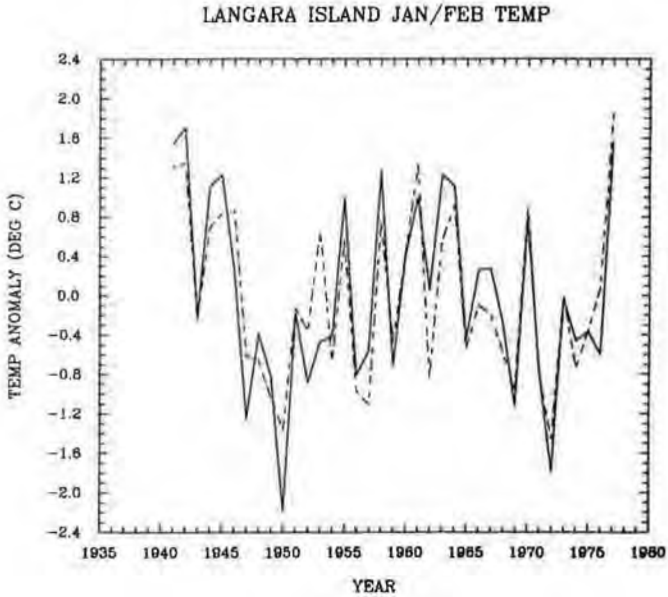
KAINS ISLAND JUL/AUG TEMP
TEMP ANOMALY (DEG C)
2.4
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
YEAR

d



KAINS ISLAND OCT/NOV TEMP
TEMP ANOMALY (DEG C)
2.4
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
YEAR

a



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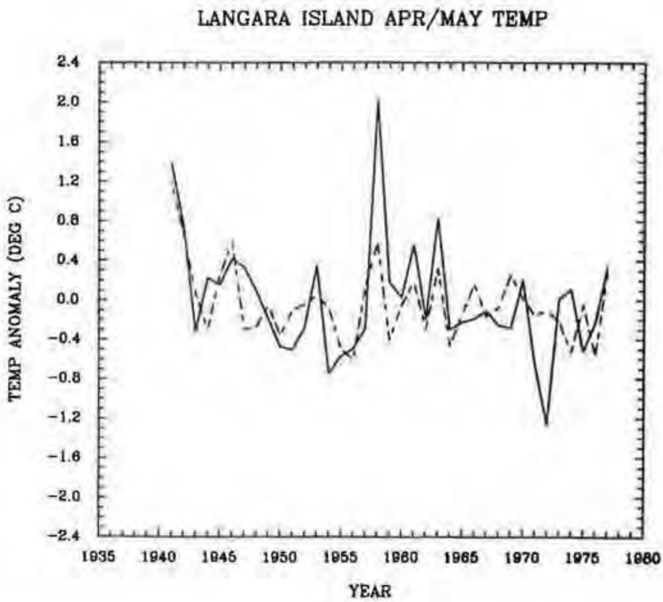

FIGURE 4. Comparison of the time series of the observed (solid) and predicted (dashed) seasonal SST anomalies from Langara Island for the period 1941–1977. a) – winter; b) – spring; c) – summer; d) – autumn.

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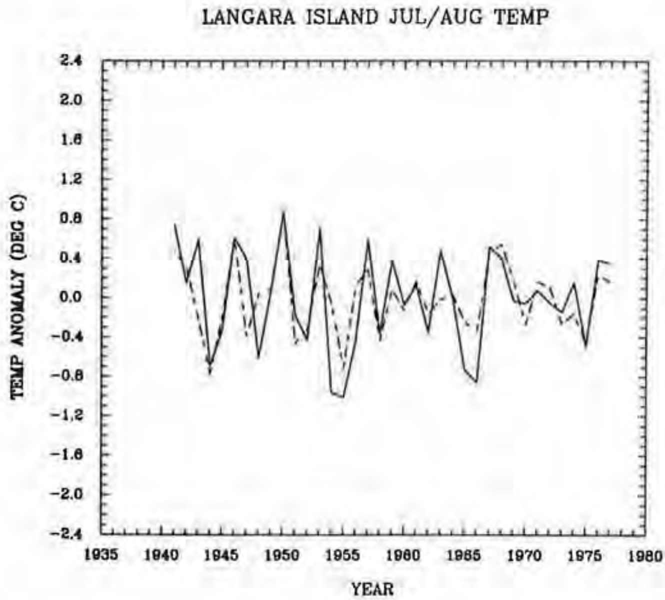
LANGARA ISLAND JUL/AUG TEMP
TEMP ANOMALY (DEG C)
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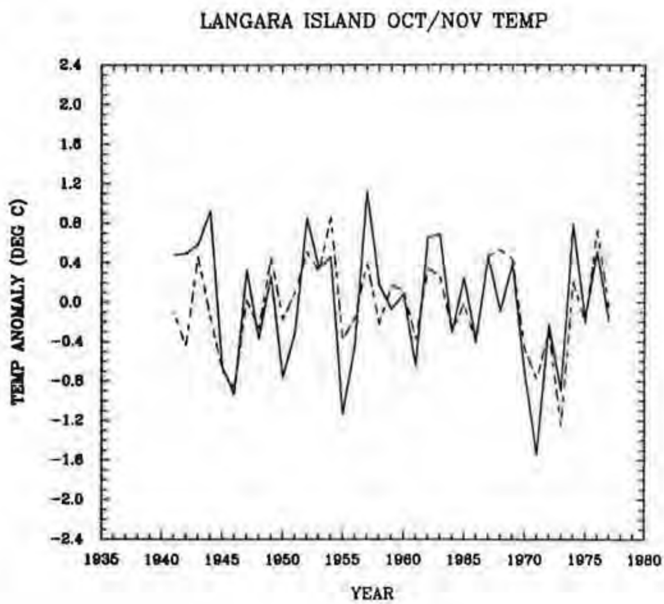
LANGARA ISLAND OCT/NOV TEMP
TEMP ANOMALY (DEG C)
2.4
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1.6
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YEAR

optimal indices in Table 1. It is apparent that very high correlations can be obtained in both winter and autumn using only three grid points to define the SLP index. The correlations in spring and summer are weaker, despite the use of four grid points in the index (see Table 1). Figures 3 and 4 show comparisons of the time series of the observed and predicted seasonal SST anomalies for Kains Island and Langara Island, respectively. In these figures the predicted SST anomalies are shown by the dashed curves, the observations by the solid curve.

The analysis discussed above was also applied to find pressure indices that correlate well with SST differences between seasons. Thus the time series of differences between January-February (*winter*) average SST and the October-November (*autumn*) average SST was fit with a linear combination of grid point SLP values for January-February (involving the $a\gamma$ coefficients in expression 1) and for November-December (the $b\gamma$ coefficients). A similar analysis was carried out for the SST differences between spring and winter (*spring-winter*), between summer and spring (*summer-spring*), and between autumn and summer (*autumn-summer*). The indices that were finally obtained are described by the parameters listed in Table 3. The grid points used in obtaining these indices were identical to those used in the previous analysis with the exception of *spring-winter*. The difference between spring and winter average SST was fit using the four grid points shown connected by the dashed line in Figure 1b. The correlation coefficients between the observed and predicted SST differences are given in Table 4. All the correlation coefficients in Table 4 are less than the corresponding coefficients in Table 2 with the exception of *spring-winter*.

TABLE 3. Seasonal mean North Pacific pressure indices (used for predicting SST changes between seasons) and corresponding least squares coefficients for each reference point (see Figures 1a–d).

Season	Position	Kains Island $a\gamma$	Kains Island $b\gamma$	Langara Island $a\gamma$	Langara Island $b\gamma$
winter–	170°W 50°N	−0.0632	−0.0040	−0.0806	0.0087
autumn	140°W 40°N	−0.0621	−0.0561	−0.0423	−0.1215
	120°W 40°N	0.1253	0.0602	0.1229	0.1128
spring–	160°W 55°N	−0.0165	−0.0645	0.0002	0.0786
winter	145°W 45°N	−0.0878	0.0000	−0.0254	−0.1460
	145°W 40°N	−0.0307	−0.0493	−0.1306	0.0532
	130°W 45°N	0.1350	−0.0153	0.1559	0.0142
summer–	170°W 45°N	0.1420	0.0527	0.1637	0.0626
spring	150°W 40°N	−0.1801	−0.0530	−0.1935	−0.1893
	130°W 45°N	−0.2640	0.0290	−0.1730	0.2784
	120°W 45°N	0.3020	−0.0287	0.2028	−0.1517
autumn–	170°W 45°N	−0.0179	0.0564	−0.0410	−0.0278
summer	140°W 40°N	−0.1241	−0.0886	−0.1194	0.1395
	120°W 40°N	0.1419	0.0322	0.1603	−0.1117

TABLE 4. Correlation coefficients r between the seasonal mean predicted SST changes, obtained from the pressure indices defined in Table 3, and the observed seasonal mean temperature changes with respect to the previous season. Correlation coefficients were calculated at Kains Island for the period 1935 to 1977 and Langara Island for the period 1941 to 1977.

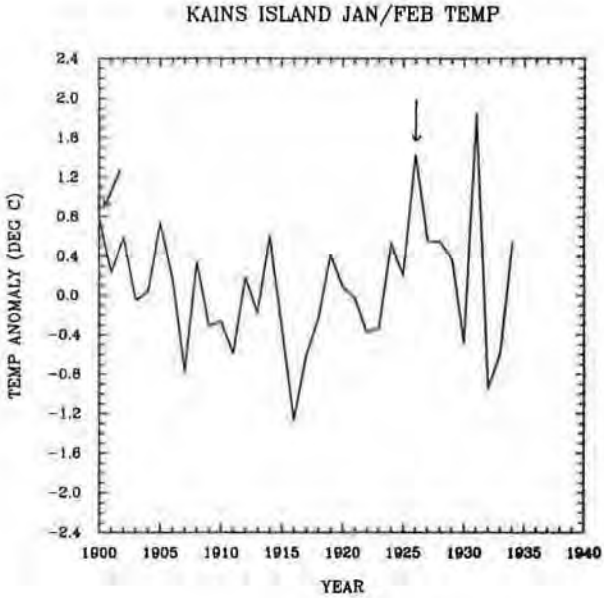
Season	Kains Island r	Langara Island r
winter–autumn	0.738	0.809
spring–winter	0.634	0.698
summer–spring	0.657	0.712
autumn–summer	0.596	0.638

4. ESTIMATES OF SST ANOMALIES SINCE 1900

It is straightforward to employ the indices above to construct estimates of coastal SST anomalies in the years before direct observations are available. Table 5 gives the estimates for the winter and summer SST anomalies at Kains Island for the period 1900–1934, and at Langara Island during 1900–1940. The time series of these SST estimates are shown in Figures 5 and 6. As mentioned in Section 1, these data may be of importance in the study of environmental effects on the commercial fisheries of British Columbia. Mysak (1986) postulates that the migration routes of sockeye salmon returning to the Fraser River spawning grounds may be influenced by North Pacific warming events, often associated with El Niño. For example, strong El Niño events occurred in 1899–1900, 1925–1926 and 1940–1941 (Quinn *et al.*, 1978). The SST data of Table 5 and Figures 5 and 6 indicate the presence of winter North Pacific warming events associated with these El Niños. Similarly, Table 5 and Figures 5 and 6 indicate the presence of a winter warming event in 1931 independent of an ENSO event. These warming events may in turn influence the percentage of sockeye salmon returning to the Fraser River through the Johnstone Strait at the northern end of Vancouver Island (Figure 2) rather than through Juan de Fuca Strait (at the southern end of Vancouver Island), as they often persist until summer (e.g., 1926). Research is currently under way at the University of British Columbia to study this "Johnstone Strait diversion", under the project name of Meteorological and Oceanographic Influences on Sockeye Tracks (MOIST). For a review of project MOIST see Mysak *et al.* (1986).

Hamilton (1985) has estimated the Johnstone Strait diversion from 1906 through 1983 using historical catch statistics and environmental data (with gaps in 1942 and 1946–1950). The results which he used after 1953 were official estimates from the International Pacific Salmon Fisheries Commission (New Westminster, British Columbia). He showed that between 1906 and 1977 typically 10 to 15 percent of homing sockeye salmon returned through Johnstone Strait, with the largest divergence of around 50% in 1926, in a year of a major El Niño

a



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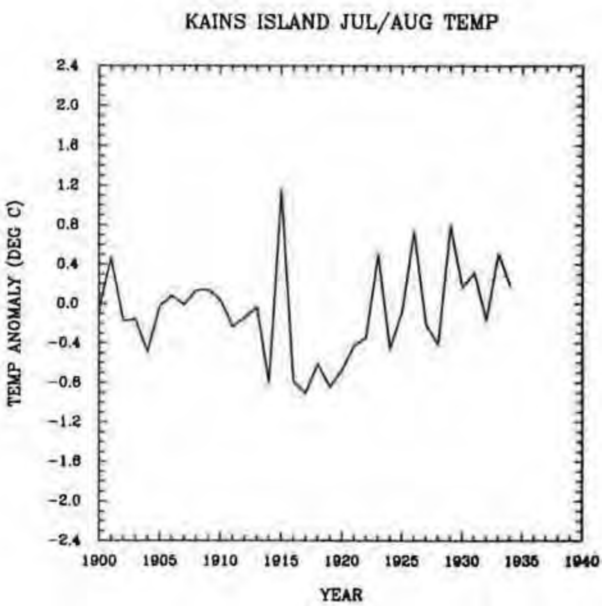
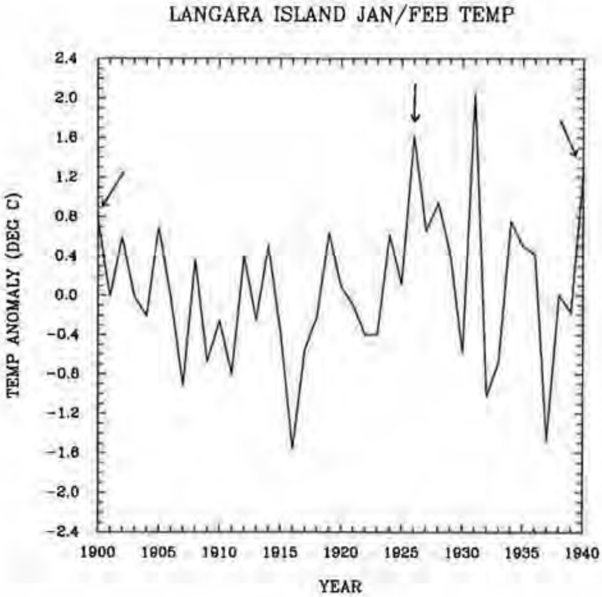


FIGURE 5. Predicted SST anomalies at Kains Island for the period 1900–1934. a) – winter; b) – summer. The data are given in Table 5. The arrows in a) indicate warming events associated with the strong El Niño events of Quinn *et al.* (1978) as discussed in text.

a



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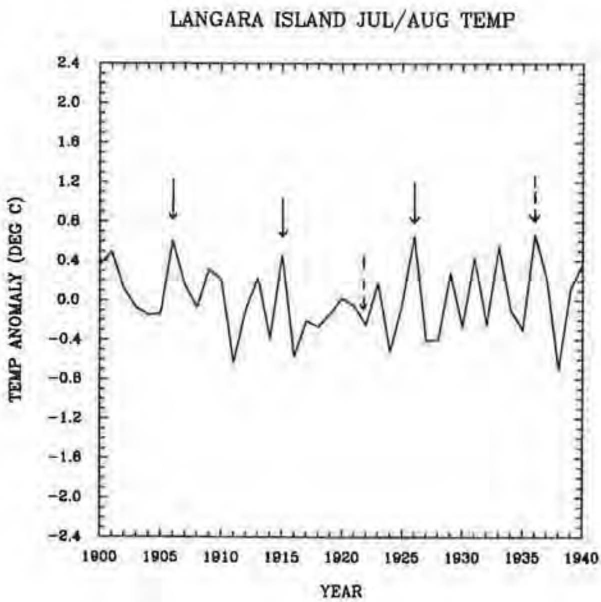

FIGURE 6. Predicted SST anomalies at Langara Island for the period 1900–1940. a) – winter; b) – summer. The data are given in Table 5. The arrows in a) indicate warming events associated with the strong El Niño events of Quinn *et al.* (1978) as discussed in text. The solid arrows in b) indicate the summer following El Niño events where the Johnstone Strait diversion was large. The dashed arrows in b) indicate the two other years of larger than normal diversions (from Hamilton, 1985, 1987).

event. Hamilton (1987) further discussed how many of the other years of high diversion occurred in summers following weaker ENSO events. In the years before 1940 (for which we make SST anomaly predictions herein) these were in 1906 and 1915. He quoted Thomson *et al.* (1984), who stated that in the summer of 1926

TABLE 5. Predicted mean seasonal temperature anomalies (°C) for the winter and summer seasons. The mean seasonal pressure indices are as given in Table 1.

Year	Kains Island winter	Kains Island summer	Langara Island winter	Langara Island summer
1900	0.788	−0.065	0.780	0.361
1901	0.234	0.468	−0.008	0.492
1902	0.589	−0.176	0.592	0.121
1903	−0.048	−0.153	−0.006	−0.071
1904	0.036	−0.489	−0.209	−0.147
1905	0.738	−0.026	0.700	−0.133
1906	0.174	0.084	−0.021	0.606
1907	−0.770	−0.010	−0.913	0.161
1908	0.343	0.137	0.363	−0.068
1909	−0.309	0.142	−0.673	0.316
1910	−0.262	0.039	−0.254	0.207
1911	−0.591	−0.232	−0.801	−0.632
1912	0.182	−0.139	0.402	−0.088
1913	−0.174	−0.034	−0.249	0.237
1914	0.608	−0.802	0.509	−0.384
1915	−0.329	1.153	−0.379	0.463
1916	−1.264	−0.788	−1.562	−0.568
1917	−0.616	−0.908	−0.549	−0.205
1918	−0.237	−0.609	−0.221	−0.266
1919	0.418	−0.844	0.636	−0.134
1920	0.091	−0.676	0.091	0.025
1921	−0.021	−0.422	−0.098	−0.050
1922	−0.373	−0.346	−0.406	−0.243
1923	−0.331	0.506	−0.393	0.183
1924	0.530	−0.457	0.616	−0.518
1925	0.202	−0.085	0.116	−0.035
1926	1.432	0.736	1.630	0.658
1927	0.552	−0.216	0.651	−0.408
1928	0.543	−0.410	0.941	−0.396
1929	0.368	0.792	0.408	0.285
1930	−0.480	0.167	−0.585	−0.264
1931	1.844	0.319	2.054	0.437
1932	−0.938	−0.164	−1.027	−0.243
1933	−0.590	0.515	−0.675	0.549
1934	0.535	0.180	0.753	−0.095
1935	—	—	0.503	−0.295
1936	—	—	0.419	0.679
1937	—	—	−1.478	0.221
1938	—	—	0.011	−0.699
1939	—	—	−0.177	0.125
1940	—	—	1.275	0.368

British Columbia coastal waters were anomalously warm. He further quoted "Unfortunately there are no ocean temperature observations for the years 1906 and 1915". If we look, for example, at the Langara Island summer SST anomaly predictions for these years (Figure 6b), we see that warmer than normal SST are indeed predicted. Using the analysis of Hamilton (1985), Hamilton (1987) pointed out that in the years 1922 and 1936 larger than normal diversions also occurred (not associated with El Niño events). He quoted Tully *et al.* (1960), who found that coastal waters off British Columbia were anomalously warm in the summer of 1936, but made no mention of 1922. Once more Figure 6b predicts a strong positive coastal summer SST anomaly at Langara Island in 1936, although in the summer of 1922 there appears to be no warming event (in fact the anomaly is slightly negative).

The number of SLP observations available in the Northeast Pacific region increased enormously during this century. Thus it is possible that some kinds of systematic errors in the SLP analyses may affect the present predictions of SST anomalies in the early years. In particular, one might reasonably expect that in the absence of much data there would be a tendency to underestimate pressure contrasts and hence to underestimate the strength of the Aleutian Low. If such

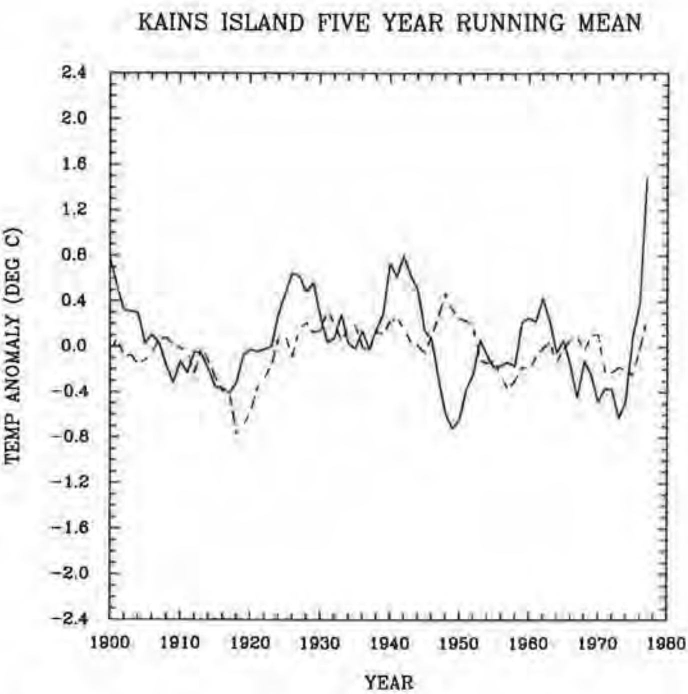

FIGURE 7. Five year running mean from 1900–1977 of the predicted SST anomalies at Kains Island in winter (solid curve) and summer (dashed curve).

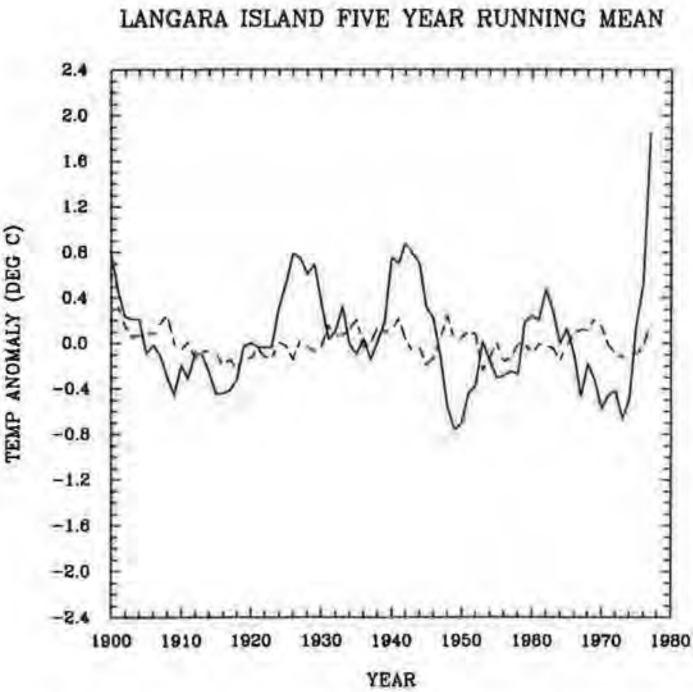

FIGURE 8. Five year running mean from 1900–1977 of the predicted SST anomalies at Langara Island in winter (solid curve) and summer (dashed curve).

errors did affect the SLP analyses, this would be reflected in a tendency of the present calculations to underestimate the coastal SST in the early years. Figures 7 and 8 show the five-year running means of the predicted SST anomalies in winter and summer at both stations over the entire 1900–1977 period. There are some systematic long-term trends evident in these figures, particularly for the winter SST where there are general warmings centered about the major El Niño events of 1899–1900, 1925–1926 and 1940–1941. It is comforting, however, that the general behaviour of the predicted SST shows no obvious difference between the early and later parts of the period. In particular there is no tendency for predicted cold SSTs in the earliest part of the record.

Another check which we may use for the predicted SST anomalies is for the years 1935–40, in which there exist Kains Island SST data but no Langara Island data. When we compare Figure 3 to Figure 4 we see that SST anomalies at Kains Island are strongly correlated with SST anomalies at Langara Island, as one would expect. If we compare Figure 6a to Figure 3a we see that in the years 1935 to 1940 both Kains Island and Langara Island winter SST anomalies are well correlated. In particular, the strong warming event of 1940 and cooling event of 1937 (Figure 3a, solid curve) at Kains Island both show up in the predicted SST anomaly for Langara Island (Figure 6a). Similarly, both the summer cooling events in 1935 and 1938 and the summer warming event in 1936 at Kains Island (Figure 3c) show up in the predicted summer Langara Island SST anomaly (Figure 6b).

5. CONCLUSION

In this paper we have demonstrated the strong control of the SST along the coast of British Columbia by the regional atmospheric wind forcing. We showed that by constructing simple atmospheric pressure indices (an extension of Emery and Hamilton, 1985), it was possible to obtain high correlations between predicted and observed seasonal mean SST anomalies at Kain Island and Langara Island. These correlations were especially high in winter since the atmospheric winter circulation is dominated by the climatological Aleutian Low. The statistical analysis allowed us to obtain a fairly credible estimate of seasonal mean SST anomalies at Kains Island and Langara Island back to the turn of the century. These constructed data were shown to be of importance in the understanding of environmental effects on the Johnstone Strait diversion. Furthermore, the derived SST data may also be useful for data assimilation using hindcast models of the Northeast Pacific which are currently being developed at the University of British Columbia as part of MOIST.

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Redistribution of the Canadian Boreal Forest Under a Warmed Climate

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ABSTRACT

A scenario of climate under atmospheric CO_2 levels double those of the present is used to derive a scenario of corresponding changes in the distribution of boreal forest in Canada. Box's model of the response of vegetation to climate is used to obtain more credible results than those obtained by earlier authors using Holdridge's scheme. It appears that the area climatically suitable for boreal forest would advance by 0.7×10^8 ha north of its northern edge and retreat 1.7×10^8 ha north of its southern edge.

RÉSUMÉ

Un scénario de climat qui suppose un doublement de CO_2 atmosphérique du niveau actuel est employé afin de suggérer un scénario des changements correspondants de la distribution de la forêt boréale au Canada. L'utilisation du modèle selon Box de la réaction de la végétation au climat mène à un résultat plus croyable que ceux d'autres chercheurs qui suivaient le schéma de Holdridge. Il paraît que la région qui convient à la forêt boréale subirait une augmentation de superficie de $0,7 \times 10^8$ ha au nord de sa limite septentrionale actuelle ainsi qu'une diminution de $1,7 \times 10^8$ ha au nord de sa limite méridionale actuelle.

1. INTRODUCTION

Current long-term planning usually takes account of expected changes in technology, population, resources or society. Changes in climate are rarely taken into consideration, mainly because we have never had much reason to expect what they might be. Recently, however, some progress has been made in modelling how human activities might change the climate, intentionally or otherwise.

One proposed mechanism of climate change is that increased atmospheric CO_2 content would result in an alteration of the radiation balance of the earth's surface, producing a warming trend. Meteorologists have developed General Circulation Models (GCMs) which simulate how temperatures, winds, pressures and humidities around the world would behave if they and their interactions were governed only by the classic thermo- and fluid-dynamical equations derived by physicists. Such models permit simulation of typical atmospheric circulation (climate) under a wide variety of assumptions. Manabe and Stouffer (1980) have used their General Circulation Model at the Geophysical Fluid Dynamics Laboratory (GFDL) to simulate details of a climate assuming levels of atmospheric CO_2 four times those of the present. Using data derived from their scenario of possible changes, this paper describes the possible climate response to a doubling of CO_2 which could occur in the next century.

This climate scenario is used as input to a model of vegetal response to climatic parameters in order to preview its effects upon the Canadian boreal forest. A similar approach has been presented by Shugart *et al.* (1986) who applied the vegetal response model of Holdridge (1947) and Holdridge *et al.* (1971) to estimate the consequences of a warmer climate upon the boreal forest. Their results are reported in Harrington, 1987. Using a climate scenario in which CO_2 doubled, Solomon *et al.* (1984) applied a more sophisticated dynamic model of the response of a forest stand to climate at several points in eastern North America. Their results are largely consistent with Shugart's. In the present paper some maps are presented indicating the size of temperature and precipitation changes on a continental scale found in the GFDL scenario. This scenario is then used as input to a model by Box (1981) which is an improvement upon that by Holdridge and allows a continental view of changes indicated in the boreal forest.

2. METHOD

The method used in this paper is to define the location of the boreal forest in terms of climate parameters, as judged by the present climate and boreal forest distribution, and then to use that definition of the boreal forest to determine its location given a scenario of climate under doubled CO_2 levels. First it is necessary to discuss the construction of a scenario of climate under doubled CO_2.

In the late 1960's the concentration of atmospheric CO_2 was around 300 parts per million (ppm) and increasing. About the same time meteorologists started realizing that changes in CO_2 could have noticeable climatic consequences. Present thinking is that, as a result of human activities, CO_2 and other trace gases will accumulate in the atmosphere at such a rate that their effect will be radiatively equivalent to a concentration of 600 ppm of CO_2 between the years 2020 and 2060 (Bolin *et al.* 1986). In an attempt to see what kind of climate changes might be caused by changes in CO_2 concentrations Manabe and Stouffer (1980) at GFDL produced scenarios of climate for two sets of circumstances: 300 and 1200 ppm of CO_2. The climatic effects of quadrupling CO_2 are estimated to be approximately twice those of doubling it but much more easily detected in a crude climate simulation.

The results of their experiment are presented by GFDL as fields T_1 and P_1 of temperature and precipitation respectively for the 300 ppm CO_2 case and a corresponding set T_4 and P_4 for the 1200 ppm case. Two considerations guided the estimation in the present study of a plausible scenario T_e and P_e for the 600 ppm case. First it was assumed that at each point monthly average temperatures and precipitation would be given by

$$T_e = T_n + d \qquad (1a)$$

and

$$P_e = P_n \times e \qquad (1b)$$

where T_n and P_n are the currently *observed* normal (average) climatic values of temperature and precipitation (as opposed to the values T_1 and P_1 *modeled* to occur under present conditions), and d and e represent changes in temperature and precipitation expected to occur as CO_2 is doubled from 300 to 600 ppm. Second, as noted above, the quantities d and e for CO_2 doubling were taken to be half those simulated to occur if CO_2 were quadrupled:

$$d = (T_4 - T_1) / 2 \qquad (2a)$$

$$e = (P_4 - P_1) / 2 \qquad (2b)$$

Note that the changes in precipitation are handled multiplicatively while those in temperature are treated additively. This makes it possible to guarantee that P_e will remain positive for all positive values of P_1, P_4 and P_n. No such guarantee is required for temperatures. For the purposes of this scenario, values T_n and P_n were taken from *Canadian Climate Normals* (Canadian Climate Program, 1982) for 74 stations evenly distributed throughout Canada, and then interpolated to a 1.4° × 1.4° latitude-longitude grid using bicubic splines. T_1, T_4, P_1 and P_4 were also interpolated to this grid from the GFDL grid. A map showing the location of observing stations used in constructing normals for this study is presented in Figure 1.

The second element in the method used here is a model of the response of boreal forest to climate. The model chosen is, with minor modifcations, that presented by Box (1981). He proposes that the range of a vegetative species falls within environmental limits delineated by the climatic extremes which that species can tolerate, and then proceeds to estimate actual environmental limits for 93 groups of plant species around the world. According to Box there are eight climatic parameters limiting plant survival: minimum and maximum monthly average temperature (TMIN, TMAX), annual range of monthly average temperatures (DTY), minimum and maximum monthly average precipitation (PMIN, PMAX), annual precipitation (PRCP), average precipitation of the warmest month (PMTMAX), and a moisture index (MI = PRCP / Thornthwaite potential evapotranspiration for the year). In Box's model if, at a certain location, any one of these eight climatic paramaters falls outside its allowable limits for a given species group then the environment is considered unsuitable for the survival of individuals from the group.

In this study the Canadian boreal forest was taken to be delimited by

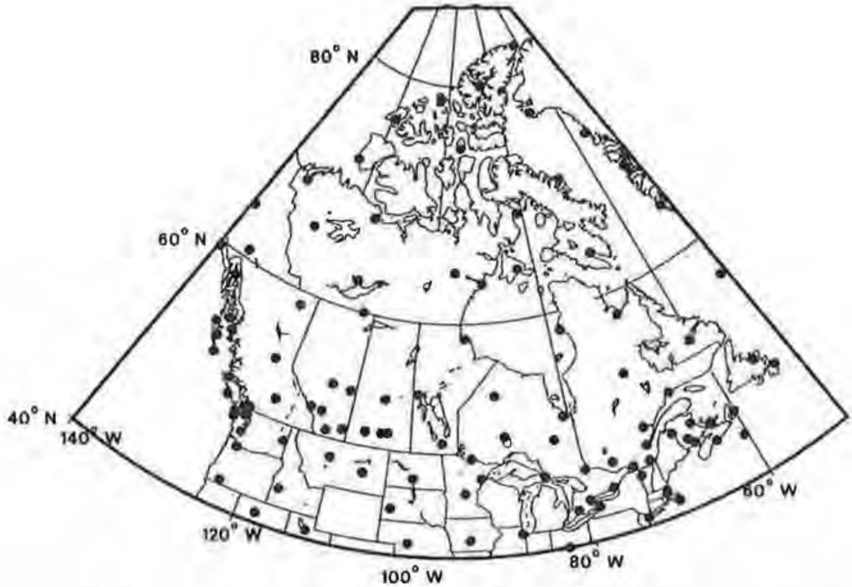


FIGURE 1. Locations of climate observing stations used in constructing the scenario of presently observed climate of Canada.

the eight sets of climatic parameter limits shown in Table 1. No evidence exists to establish upper limits to values of the last five parameters which the boreal forest may tolerate. The values in Table 1 were selected after scrutinizing existing climatological maps in conjunction with Rowe's (1972) maps of the distribution of the present boreal forest (excluding his northeast and northwest transition sections). The differences between these limits and similar sets proposed by Box are discussed below.

A point in Canada lying within the limits specified in Table 1 under the present climate might no longer do so if the climate there changed sufficiently. The primary purpose of this paper is to compare the area of Canada falling within these

TABLE 1: Environmental limits for the Canadian boreal forest

	TMAX	TMIN	DTY	PRCP	MI	PMAX	PMIN	PMTMAX
maximum	20	−8	60	—	—	—	—	—
minimum	13	−29	10	100	0.6	25	5	55

Climatic limits in the manner of Box (1981) derived from maps of the Canadian boreal forest (excluding transition zones) and *Canadian Climate Normals*. Maximum and minimum limits are given for maximum and minimum monthly mean temperature (TMAX, TMIN), annual range of monthly mean temperatures (DTY), annual precipitation (PRCP), moisture index (MI, see text), maximum and minimum monthly precipitation (PMAX, PMIN), and monthly precipitation in the warmest month (PMTMAX). All units are in deg C and mm except MI which is dimensionless.

limits (and thus representing the domain of the boreal forest) under the present climate with the area which would fall within them given the scenario of climate under increased CO_2.

a

b

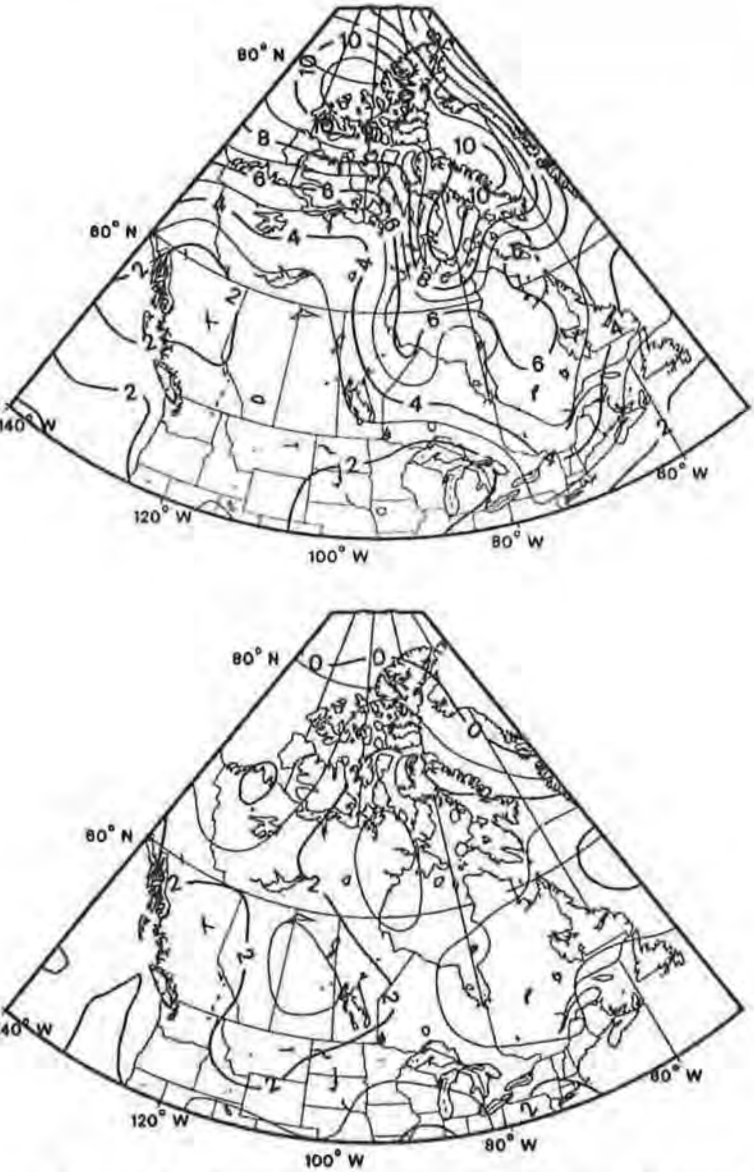


FIGURE 2. The increase, in °K, in monthly average temperature under the doubled CO_2 scenario for a) January and b) July over Canada. The warming occurs mostly in winter in the north and east.

3. RESULTS

The finished climate scenario, prepared as described above, is a series of twelve monthly averages for temperature and precipitation. As an indication of the types of changes which are found between current climate and the doubled CO_2 scenario, changes in average temperature and precipitation for January and July are shown in Figures 2 and 3. The complete scenario (not shown here) comprises a set of maps like these for each month of the year. A characteristic feature of both Manabe and Stouffer's and Hansen *et al.*'s increased CO_2 scenarios is the warm arctic winter. The 'warming' is much less prominent in the summer and at lower latitudes. In this scenario eastern Canada is warmed two or three times as much as western Canada. Patterns of precipitation change in the scenario are less stable from month to month but the overall tendency is for an increase.

That part of Canada where the present climate falls within the limits presented in Table 1 is shaded in Figure 4. As indicated above this is an approximation to (the non-transitional portion of) Rowe's (1972) boreal forest zone. The interesting question is how this climatologically determined area would shift under the scenario of climate under doubled CO_2. Differences between the area shown in Figure 4 and the area that would fall within the limits of Table 1 under the doubled CO_2 climate scenario are shown in Figure 5. Whether the difference represents a gain or loss of area is represented by the type of shading used.

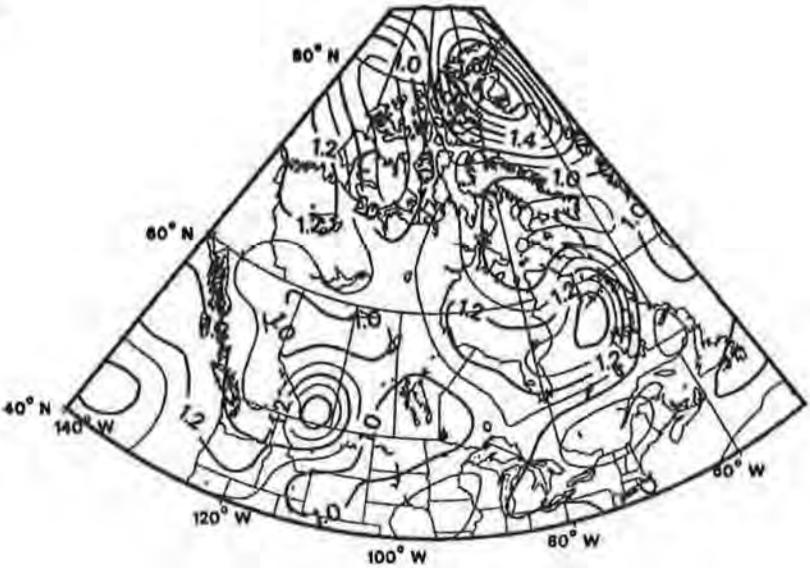
It appears that under this warmer doubled CO_2 scenario the area *climatically* suitable for non-transitional boreal forest would shift northward out of southerly lands and into more northerly lands. Retreat northward of the southern boundary can be seen in every province. Advances northward of the northern boundary occur only in Saskatchewan, Manitoba, Quebec, Labrador and the Northwest Territories. (Note that such shifts do not always correspond to the areas of change for January and July shown in Figures 2 and 3, for Box's model is responding to the total scenario of change for all twelve months of the year.) According to this scenario and forest model there would appear to be a gain of area climatically suitable for boreal forest in northern Canada of approximately 0.7×10^8 ha versus a loss in the south of approximately 1.7×10^8 ha.

Different scenarios of climate change may produce different results. Accordingly a second scenario was constructed from a simulation of CO_2 doubling performed by Hansen *et al.* (1984) at the Goddard Institute for Space Studies (GISS). This second scenario was almost indistinguishable from the GFDL scenario in its estimated effects upon the boreal forest. Thus the results presented here are based on the scenario constructed from the higher-resolution GFDL data.

4. DISCUSSION

Many studies have attempted to make climate-vegetation connections. Holdridge (1947) and Holdridge *et al.* (1971) have worked out relations between local

a



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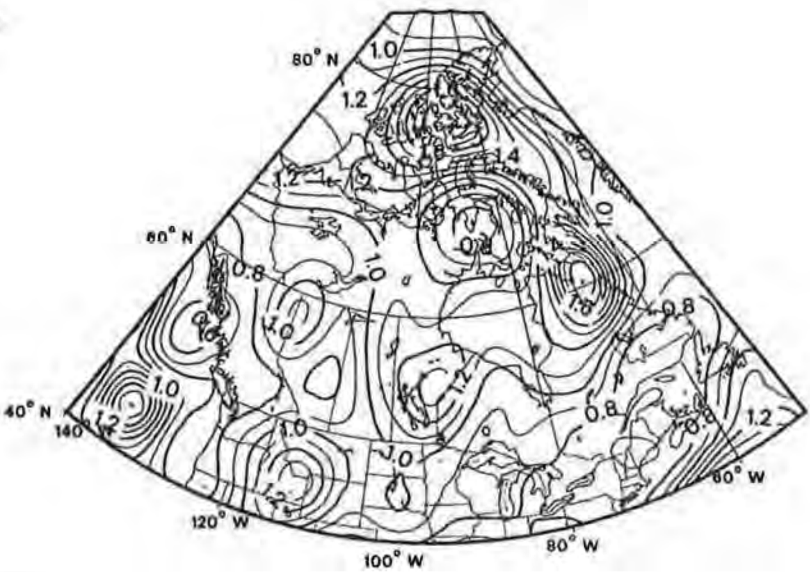

FIGURE 3. The increase in monthly average precipitation, expressed as a fraction, under the doubled CO_2 scenario for a) January and b) July over Canada. The patterns shift unstably from month to month and some areas show decreases but the overall trend is toward an increase of precipitation.

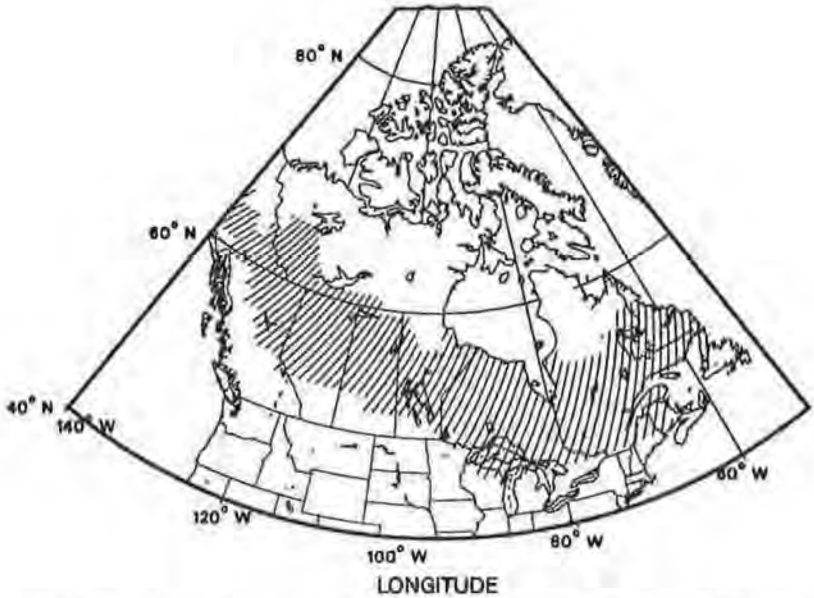

FIGURE 4. Distribution of areas (hatched) lying within the climatic limits indicated in Table 1 for the 1951–80 climate. These limits are taken to delineate the present extent of the Canadian boreal forest.

climate and vegetation. This classification scheme is basically a geometric division of a climate chart, which plots annual precipitation and growing degree days (base 0°C), into 30 areas along with a descriptive notation of the 'life-zones' or vegetational cover types normally observed to occur under the climatic conditions described by each area of the chart. For example, the life-zone called 'Wet Boreal Forest' is roughly associated with climates having 500–1000 mm annual precipitation and 1100–2200 growing degree days annually.

The Holdridge model of vegetation is easy to use and appears surprisingly successful at first glance but it suffers from four major faults: a) the classifications are delineated entirely in terms of climatic variables rather than vegetational limits and make no allowance for peculiar climatic requirements of any plant species or group (i.e. the scheme asks not where the climate is suitable for given plants to grow but rather how the plants may be characterized which grow in a given climate), b) no account is taken of response of vegetation to climatic variables other than annual precipitation and growing degree days, c) the scheme is static and gives only the climax vegetation to be expected, with no indication of how long it might take to establish itself or how it might respond in the short term to climate change, and d) non-climatic factors (soils, CO_2 concentrations, etc) affecting plant growth are not considered.

A dynamic model of vegetation with none of these faults would be much more satisfying but far more difficult to apply. Solomon *et al.* (1984) have applied such a model to a selection of forest sites in eastern North America with

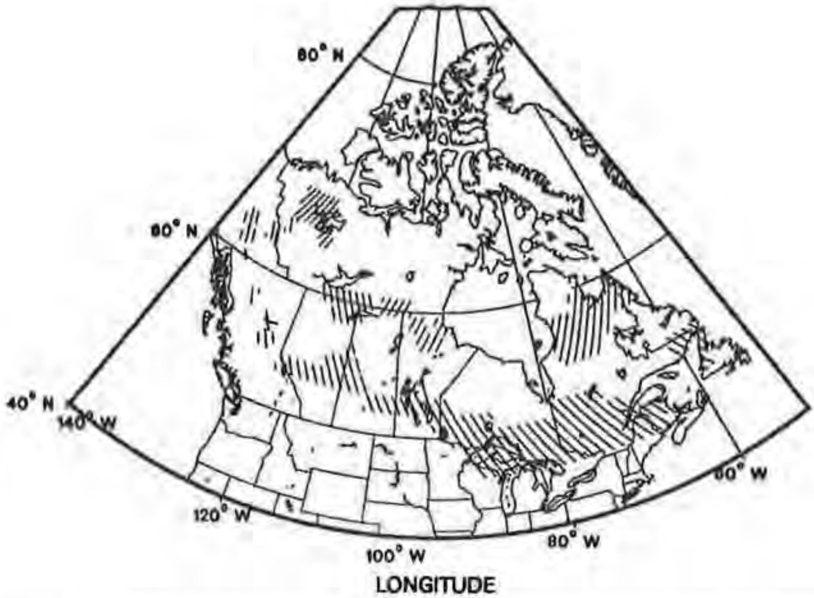

FIGURE 5. Areas lost and gained by the boreal forest in the change to a scenario of climate with twice current levels of CO_2. Lines slanting from northwest to southeast show areas becoming climatically unsuitable to these forests. Lines slanting from southwest to northeast show areas becoming climatically suitable. Large areas lost in Ontario and southern Quebec are only partly compensated by gains in northern Quebec and the Northwest Territories.

fascinating results. They follow month after simulated month, for centuries, the germination, growth, seeding and death of a small number of individual idealized trees and their descendents as they are affected by one another and by a hypothesized series of monthly average temperatures and precipitations, and by other factors influencing growth and mortality. The result is a fairly detailed dynamic picture of a typical forest stand and its evolution in response to the environment. A model of this type would appear to be the next level of technology in vegetation modelling but it has yet to be applied on a continent-wide basis.

In the meantime, the first two criticisms of Holdridge's scheme can be answered by the model developed by Box (1981). His climatic delineation of vegetation groups is determined quasiempirically on a group by group basis and involves eight climate parameters. This model is thus more flexible than that of Holdridge and permits greater precision in describing the response of vegetation to climate.

An example of this flexibility is that the model may be 'tuned' as follows. Box estimates, for example, that boreal short-needled trees (*Picea, Abies*), have the limits indicated in Table 2. Applying these limits to the present climatic normals outlines an area of Canada which is supposedly suitable for 'boreal short-needled trees'. Examination of maps of Canada's existing boreal

TABLE 2: Environmental limits for boreal short-needled trees

	TMAX	TMIN	DTY	PRCP	MI	PMAX	PMIN	PMTMAX
maximum	22	3	60	—	—	—	—	—
minimum	11	−30	10	100	0.6	25	5	10

Climatic limits which Box (1981) proposes for 'Boreal short-needled trees' (see the notes to Table 1 for a description of the column headings). The limits for TMAX, TMIN and PMTMAX are looser than those found in Table 1 and include an area under the present climate which extends in the south into the northern United States across most of the continent and in the north well into the boreal forest-tundra transition zone.

forest (e.g. Rowe, 1972), however, shows that the forest proper (excluding tundra transition sections) has a smaller range than this. It does not extend as far north across the country nor, in the prairies and eastern North America, as far south. This may be because what Rowe considers to be the boreal forest is more than just the range of boreal short-needled trees or because Box's model, constructed to answer to conditions around the world, is not precisely tuned to Canadian conditions. In any event, reference to maps of Canada's present climate shows that the non-transitional boreal forest seems to coincide with a narrower range of aceptable maximum and minimum temperatures and a higher requirement for moisture in the warmest month than that which Box assigns to his boreal short-needled trees group. As the limits in Table 2 are adjusted, the area delineated under the present climate changes until, when the values reach those presented in Table 1, the area matches that of the non-transitional boreal forest more closely than for any other set of limits. This tuning was performed manually and evaluated by eye.

The most noticeable change effected by the tuning was the increase in moisture requirement in the warmest month from 10 mm (for Box's boreal short-needled trees) to 55 mm (matching present climate normals and Rowe's boreal forest maps). On the southern prairies temperatures are, if anything, more favourable for the survival of boreal trees than elsewhere in the country, and the only one of Box's limiting climatic factors which could account for their absence there is this moisture requirement. Mean rainfall in July and August along the 49th parallel rarely falls as low as 25 mm and increases northward to the centre of the forest zone. Only values as high as 55 mm are not attained until approximately the southern limits of the present boreal forest. This moisture requirement does not appear to be a limiting factor anywhere else in the country.

In the west the area outlined by the limits in Table 1 coincides well with non-transitional boreal forest as outlined by Rowe. In the east this area includes New Brunswick and the St. Lawrence and Hudson Bay lowlands which cannot be considered productive boreal forest. No further adjustment of values in Table 1 could correct this without affecting correspondence elsewhere. It appears that in these areas soils, drainage, and other non-climatic conditions affect boreal forest distribution. The relatively sparse climatological network upon which the climate normals are based (as shown in Figure 1) also prevents recognition of other fine details of boreal forest distribution, as in the Mackenzie valley and elsewhere.

The northern boundary of boreal forest is delineated well by the 13°C July isotherm (Larsen, 1980). Box's model addresses this point directly (cf. the TMAX values in Table 1) and gives a more southerly and realistic northern limit for present boreal forest than do the Holdridge model results presented by Shugart *et al.* (1986). On the other hand the Holdridge model gives a more realistic southern limit from Lake Superior to the Atlantic Ocean. Over other areas of Canada the two models agree closely in their simulations of present boreal forest distribution.

Over most of Canada the climatic variables which limit the extension of the boreal forest according to Box's model are those relating to temperature. (The only exception occurs over the southern prairies where, as explained above, the present boreal forest seems to have a high requirement for moisture in the warmest month.) As a consequence of this, and of Figure 2a, the largest shift in the boreal forest under the increased CO_2 scenario is in the east, where the warming is greatest.

A few additional points deserve some mention. Proper account has not been taken in this study of the effect of soils and drainage upon the boreal forest limits, especially in the north. This problem warrants further study. Also worth mentioning in connection with the loss of area climatically suitable for boreal forest are the estimates which Bickerstaff *et al.* (1981) make of boreal forest areas. Based upon provincial inventories, they find the area of continuous boreal forest to be 1.48×10^8 ha with only 0.80×10^8 ha of that being economically accessible at present. It is worrisome that this estimate for economically accessible boreal forest is smaller than the 1.0×10^8 ha which may become climatically unsuitable for boreal forest under a warmed climate.

5. CONCLUSIONS

Amid much concern over consequences of a likely climatic warming in the next decades there has been a paucity of realistic information about how such a warming might affect the Canadian boreal forest. This paper attempts to fill that void. The vegetation model used here is different from that of Holdridge (1947) and Holdridge *et al.* (1971) which Shugart *et al.* (1986) used. Holdridge's model is based on the reasonable postulate that climatic variables contribute to limiting the habitat of vegetation types, but it lacks freedom to match the range of particular vegetation types to ranges of climatic variables. A more flexible model by Box (1981) provides more climatic parameters and ranges which can be adjusted to the requirements of particular plant species or groups.

Using the framework provided by Box's model a climatic definition is composed for the present boreal forest. This definition is then applied to a scenario of climate under doubled CO_2 derived from the GFDL GCM simulation by Manabe and Stouffer (1980). Results indicate that the kind of climate change which might result from an increase in CO_2 would shift significantly northward the area in Canada which is climatically suitable for boreal forest.

ACKNOWLEDGEMENTS

The author would like to acknowledge the encouragement and guidance of Howard Ferguson and many informative discussions with Allan Auclair. Philip Sajecki composed a global set of climate normals from various sources without which this work could not have been performed. Suggestions from the referees have been very helpful in revising the original manuscript.

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The Longest Sub-Freezing Period in Newfoundland Winters

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ABSTRACT

The longest period of the winter with continuously sub-freezing temperatures was examined for eight sites in Newfoundland. The average length of the longest sub-freezing period of the winter is about 10 days along the southern coast, 15–25 days across interior Newfoundland, 30–45 days along the Labrador coast, and 40–60 days across inland Labrador. The mid-point date of the longest sub-freezing period occurs during mid-January across Labrador, late January across inland Newfoundland, and early February along the coasts of Newfoundland. Regional variability and atmospheric controls are examined.

RÉSUMÉ

On examine ici la période hivernale la plus longue de température moins de 0°C à huit stations de Terre-Neuve. La durée moyenne de cette période est à peu près 10 jours à la côte sud, 15–25 jours à l'intérieur de l'île, 30–45 jours à la côte du Labrador, et 40–60 jours à l'intérieur du Labrador. La date du mi-point de la période se trouve en mi-janvier au Labrador, vers la fin de janvier à l'intérieur de l'île, et la première semaine de février aux côtes de l'île. On traite aussi de la variabilité régionale et des contrôles atmosphériques.

INTRODUCTION

Days with a maximum air temperature below 0°C can be called "sub-freezing days". These have also been called "ice days" (Wexler, 1982) but this term may have other meanings and will not be used here. This paper summarizes the duration and temporal occurrence of the longest sub-freezing period of the cold season at eight sites in Newfoundland (Figure 1) for the period of 1952 to 1981. Data were taken from *Monthly Record: Meteorological Observations in Canada* (Environment Canada, 1952–81). The eight sites were chosen for a complete record with minimal station moves. Interior portions of the island of Newfoundland are poorly represented in the climate record, as are interior and northern sections of Labrador.

The duration and seasonality of sub-freezing days have a variety of applications. As long as air temperature remains below freezing, there is little or no freeze-thaw activity at the surface, little snow melt or surface water, and less biological activity if protective snow cover does not exist. Occasional winter days with air temperatures above freezing break the sub-freezing spell and cause changes in the density, texture, and albedo of snow, and affect water movement on roads, around buildings, and in soil. These factors, in turn, affect construction, winter recreation, highway maintenance, stream flow, flora, and fauna. The longest period of sub-freezing temperatures provides the "heart of winter."

Newfoundland's winter climate is dominated by frequent passage of cyclonic storms with rain and/or snow and wide temperature fluctuations (Hare and Hay, 1974: 62). Most winters have several periods when a polar anticyclone dominates and forces the storm track south and east of the province. These are cold, relatively tranquil periods in an otherwise stormy winter climate and often bring several days of sub-freezing temperatures. These sub-freezing periods are more frequent and of longer duration over the colder northern and interior sections of the province where maritime air masses have less influence during winter. The southern sections of the province are most likely to be affected by the warm sector in cyclonic storms and receive frequent thaws (Hare, 1952).

RESULTS AND DISCUSSION

The duration of the longest period with sub-freezing temperatures increases northward and toward the interior of Newfoundland (Table 1 and Figure 1). The local effects of terrain cannot be evaluated on this small-scale map with only eight climatic stations, but general patterns of these climatic elements across Newfoundland are clear. The average length of the longest sub-freezing period of the winter is less than ten days along the southern coast, 15 to 25 days over the interior, 30 to 45 days along the Labrador coast, and 40 to 60 days across interior Labrador. The longest sub-freezing period encountered in this study was 110 days at Goose Bay and Hopedale during 2 December through 21 March of the winter 1966–67.

A simple linear regression was performed between the average length of the longest sub-freezing period of the winter and the mean January temperature for the site, as published by Environment Canada (1982). The result is given in equation (1), where Y is the average length in days of the longest sub-freezing period of the winter, X is the 1951–80 mean January temperature in °C, and r is the linear correlation coefficient. Equation (1) is valid over the range of × from −3 to −17°C encountered in this research.

$$Y = -2.76X \qquad (1)$$

$$r = 0.986$$

Equation (1) was used with a map of average January temperature (Environment

TABLE 1. Statistics on the longest sub-freezing period at eight Newfoundland sites.

Station	Longest sub-freezing period				Mid-date	
	Ave	Std Dev	Longest	Shortest	Ave	Std Dev
Cartwright	32.6	14.1	76 12 Dec–25 Feb 1974–75	12 21 Feb–4 Mar 1968–69	21 Jan	26.2
Corner Brook	14.3	5.0	25 27 Jan–20 Feb 1974–75	6 21–26 Feb 1957–58	31 Jan	25.8
Daniel's Harbour	18.9	11.7	69 31 Dec–9 Mar 1960–61	5 5–9 Feb 1968–69	5 Feb	23.8
Gander	15.7	5.7	28 22 Jan–18 Feb 1960–61	6 21–26 Feb 1957–58	30 Jan	23.1
Goose Bay	43.3	21.8	110 2 Dec–21 Mar 1966–67	17 31 Dec–16 Jan 1957–58	14 Jan	27.5
Hopedale	48.7	23.9	110 2 Dec–21 Mar 1966–67	14 19 Feb–4 Mar 1968–69	31 Jan	26.0
Port aux Basques	11.9	6.0	29 21 Jan–18 Feb 1960–61	4 21–24 Feb 1957–58	4 Feb	19.1
St. John's Airport	11.3	6.7	28 22 Jan–18 Feb 1960–61	3 six periods in1953–54	5 Feb	19.3

Canada, 1984) to estimate the average length of the longest sub-freezing period of the winter (Figure 1) in regions where data were sparse.

The hypothesis that the frequency distribution of the lengths of longest sub-freezing periods fit a Gaussian, or normal, frequency distribution was tested with the Shapiro-Wilk Test for Normality (Shapiro, 1986: 15–19). The hypothesis of normal frequency distribution was rejected ($p < 0.05$) due to a positively skewed distribution with one or two very long sub-freezing periods in the climatic record. A positive skew is common in samples of data that have a lower bound at zero, a mean that is relatively near zero, and no upper bound.

In general, a warm winter will bring frequent thaws and few consecutive days below freezing. On the other hand, a cold winter, or an extended period of cold within an average winter, provides a substantial period with

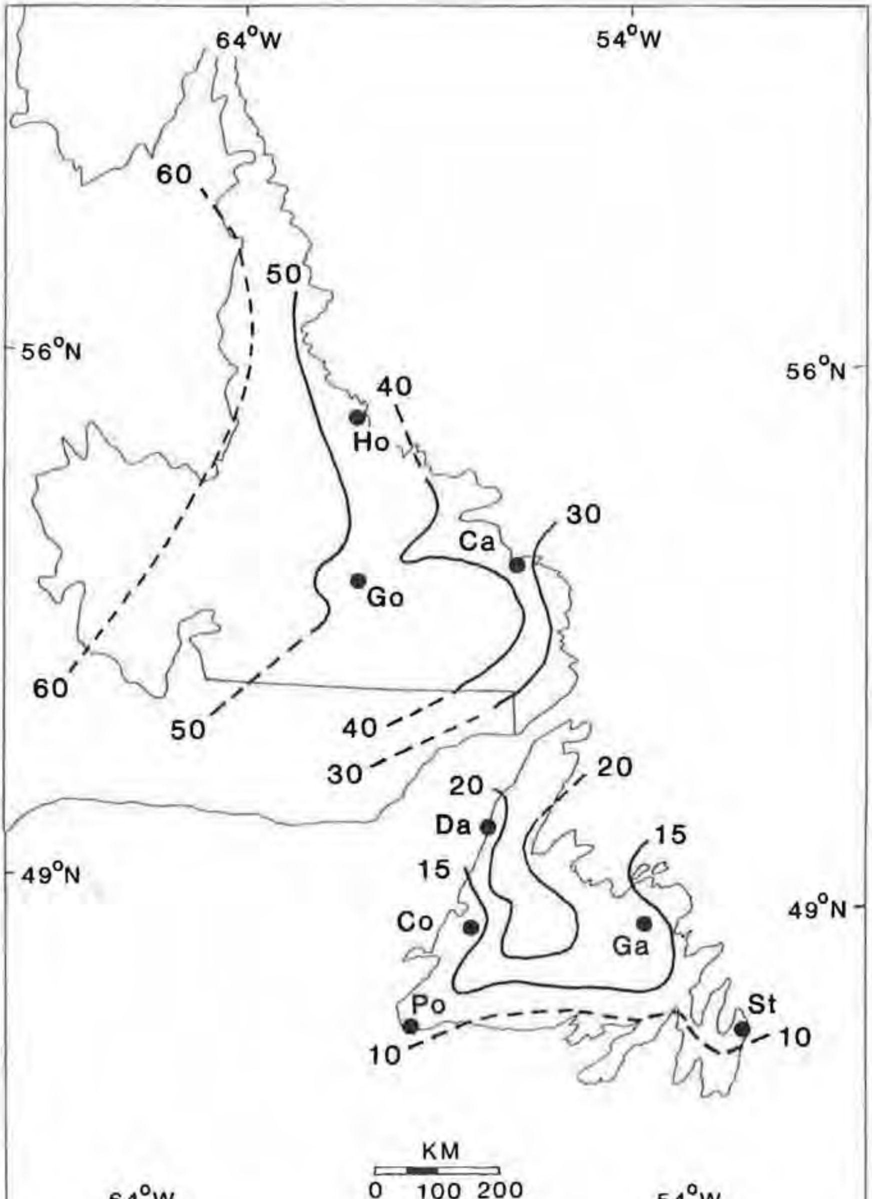

FIGURE 1. Locations of Newfoundland climate stations used in this analysis and the average length (days) of the longest period of the winter with sub-freezing temperatures. Dashed lines indicate regions of least confidence. Ho – Hopedale, Go – Goose Bay, Ca – Cartwright, Da – Daniel's Harbour, Co – Corner Brook, Po – Port aux Basques, Ga – Gander, St – St. John's.

sub-freezing temperatures. The winters 1957–58 and 1960–61 offer two examples. The winter 1957–58 was mild across Newfoundland. Positive temperature departures were 3°C to 6°C for the three-month winter period (December-February). Maxima reached 17°C at St. John's in December and 8°C at Goose Bay in January with frequent passage of storms. The longest period with sub-freezing temperatures in this winter was only 4 to 6 days on the island of Newfoundland and 14 to 17 days at the three Labrador stations. The winter of 1960–61, on the other hand, was mild during December but a very cold spell began during mid-January and continued through February. The winter averaged 1.5°C to 3.5°C colder than normal. Even southern coastal locations had 4 weeks of sub-freezing temperatures, while Goose Bay and Hopedale remained below freezing for over 10 weeks.

The proportion of the total number of sub-freezing days for the winter experienced during the longest sub-freezing period was examined at St. John's and Goose Bay. These two stations were chosen because they represent the extreme range of winter conditions examined in this study. At St. John's, a mild coastal site, the average annual number of days with sub-freezing maximum temperatures is 57. Approximately 20% of these occur during the longest sub-freezing period of the winter (average 11.3 days). The average number of sub-freezing days at Goose Bay, a colder interior site, is 121. Approximately 37% of these occur during the longest sub-freezing period of the winter (average 43.3). This difference between St. John's and Goose Bay is a reflection of the different climates. Frequent winter thaws at coastal sites lead to many short sub-freezing periods while more persistent cold causes a longer core of sub-freezing weather in the more continental winters of interior Labrador. The lengths of the longest sub-freezing periods at St. John's and Goose Bay are correlated with the total number of sub-freezing days in that winter ($r = 0.49$ at St. John's and $r = 0.53$ at Goose Bay).

The role of the average temperature during the longest sub-freezing period in determining the average temperature of that winter (December-February) was also examined at St. John's and Goose Bay. The average temperature during the longest sub-freezing period of the winter at St. John's is −7.5°C, which is 4.2°C colder than the winter (December-February) mean temperature of −3.3°C. The average temperature during the longest sub-freezing period at Goose Bay is −16.9°C, only 2.4°C colder than the winter mean temperature of −14.5°C. There were three winters at Goose Bay during the period examined in which the temperature of the longest sub-freezing period was actually warmer than the average temperature for that winter. This anomaly occurred when the longest sub-freezing period began during November or early December and produced no severe cold. The closer correspondence at Goose Bay between the mean temperature for the winter and that of the longest sub-freezing period is expected; the longest sub-freezing period is much longer at Goose Bay and therefore comprises more of the winter period. Correlation between the length of the longest sub-freezing period and the mean temperature for that winter is negative and significantly different from zero at St. John's (−0.57) and at Goose Bay (−0.56).

The synoptic-scale atmospheric control of the length and time of occurrence of the longest sub-freezing period is illustrated by the positive correlation among the stations. Correlation of the length of the longest sub-freezing period is significantly different from zero between all pairs of stations except between Goose Bay and three southern stations (St. John's, Port aux Basques, and Gander) and between St. John's and the two other Labrador stations. Correlations of the mid-point date of the longest sub-freezing period are also positive among stations on the island of Newfoundland. Correlations are not significantly different from zero between stations in Labrador and those on the island.

The average mid-point of the longest period with sub-freezing temperatures is during mid-January over interior Labrador, late January along the Labrador coast and interior sections of the island of Newfoundland, and early February along the coasts of the island (Figure 2). The moderating influence of ocean waters delays the "heart-of-winter", by about 2 weeks over coastal Newfoundland.

A regression was performed on the range of mean temperature between the warmest and coldest months, a measure of continentality, and the average mid-date of the longest sub-freezing period at the eight stations. The result is equation 2, where Z is the average mid-date of the longest sub-freezing period (1 Jan = 1), WC is the range (°C) between the warmest and coldest months at the site, and r is the linear correlation coefficient.

$$Z = 67.1 - 1.60WC \qquad (2)$$

$$r = 0.92$$

Equation 2 indicates that the average mid-date of the longest sub-freezing period is delayed about one week for each decrease of 4°C in the annual temperature range. There is considerable inter-annual variability in the time of the longest sub-freezing period of winter. The standard deviation of the mid-point date is about 20 days along the southern coast and 25 to 30 days elsewhere. In general, the longest sub-freezing period of the winter may occur any time from early December until late March and has begun as early as mid-November across Labrador. The frequency distributions of the mid-point of the longest sub-freezing period of the winter are normally distributed at all stations.

The longest sub-freezing period of the winter often does not include the coldest temperature of the winter. The coldest temperature recorded during the longest sub-freezing period of the winter averages near −15°C along the southern coasts, −20°C to −25°C across inland and northern Newfoundland, −30°C along coastal Labrador, and −30°C to −35°C across the interior of Labrador. In Labrador and the Great Northern Peninsula, the coldest temperature of the winter occurs during the longest sub-freezing period of the winter in 50–70% of the years. Across the remainder of the island of Newfoundland, the coldest temperature of the winter occurs during the longest sub-freezing period in just 30–50% of years.

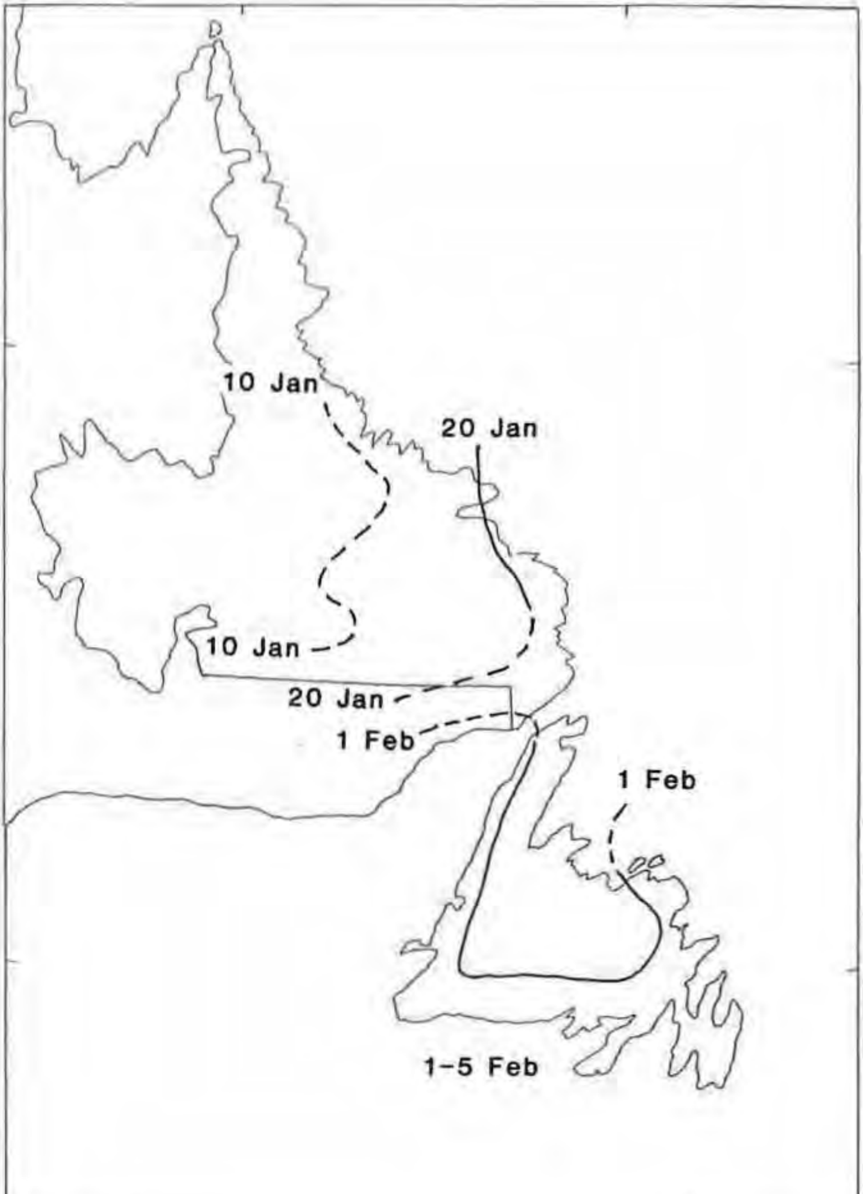

FIGURE 2. Average date of the mid-point of the longest period of the winter with sub-freezing temperatures. Dashed lines indicate regions of least confidence.

This may be surprising, but the longest sub-freezing period across most of the island of Newfoundland is just 10–20 days so there are many other opportunities for a brief cold spell to give the coldest winter temperature. The coldest temperature of the winter is likely to occur during periods of contorted meridional flow in the atmosphere with large thermal exchanges between the arctic and subtropics. This is favorable for extreme temperature fluctuations but is not favorable for long periods of consistent sub-freezing temperatures.

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News and Comments
Nouvelles et commentaires

TENTH CONFERENCE ON FIRE AND FOREST METEOROLOGY

This international conference will be held April 17–21, 1989 at the Skyline Hotel in Ottawa, Ontario, Canada. The conference theme is "Fire and Forest Meteorology in a Changing Environment: New Technologies and Concerns". It is being sponsored by Atmospheric Environment Service, Canadian Forestry Service, Ministère de l'Energie et des Ressources du Québec, and Ontario Ministry of Natural Resources with the cooperation of the American Meteorological Society, Canadian Institute of Forestry, Canadian Meteorological and Oceanographic Society and Society of American Foresters.

The purpose of the 10th Conference on Fire and Forest Meteorology is to exchange research and management information relevant to fire and forest meteorology with particular emphasis on the evolution of science and management in a rapidly changing technological environment. Participants are encouraged to use their free time to meet fellow scientists and managers to share their ideas and viewpoints.

Paper and interactive presentations will concentrate on the theme in terms of lightning and forest meteorology, prescribed burning and fire effects, fire behavior/danger, fire management, fire weather, climate change, smoke management and air quality, and forest health and productivity. Displays by relevant fire or meteorological equipment manufacturers and distributors as well as computer manufacturers will also be present during the conference. A half-day field trip of southeastern Ontario with forest-oriented stops is also scheduled.

For a brochure or further information, contact: Co-chairpersons, Mike D. Flannigan (Canadian Forestry Service) at 613-589-2880 or Dr. Paul Woodard (University of Alberta) at 403-432-4413.

16th STANSTEAD SEMINAR

July 10–14, 1989, Bishops University, Lennoxville, P.Q., Canada

Once again McGill University, Department of Meteorology will host the Stanstead Seminar in 1989, on the theme of: "High-latitude climate processes, with special emphasis on large scale air-ice-sea interactions".

As in the past, the daily program will consist of two comprehensive papers in the morning and two in the afternoon, thus providing ample time for discussion and interaction. Invited speakers include Drs. F. Bryan (National Center for Atmospheric Research), H. Cattle (British Meteorological Office), E. LeDrew (University of Waterloo), P. Lemke (Max Planck Institute für Meteorologie) and J. Walsh (University of Illinois). In addition, contributed papers are solicited. Participation at this seminar will be limited to 60–70 people including the speakers.

Those interested in presenting a paper or obtaining further information about Stanstead Seminar, which is held at a delightful conference setting in Quebec's Eastern Townships, should contact: Dr. Lawrence A. Mysak, Climate Research Group, Department of Meteorology, McGill University, 805 Sherbrooke St. W., Montreal, Quebec H3A 2K6, Tel: (514) 398-3759.

ALBERTA CLIMATOLOGICAL ASSOCIATION

Patti Papirnik and *Bonnie Magill*

The 12th Annual General Meeting of the ACA was held at the Alberta Research Council, Edmonton on 10 March 1988, with the theme of "How Do We Measure Climate Impacts?" Presentations covered a range of topics including social and resource impacts, and data collection and measurement problems. There was also a lively discussion of the role and scope of the association's newsletter, *The General Circulation*, which is edited by Patti Papirnik, Correspondence Unit, Department of Hospitals and Medical Care, 11010 – 101 Street, Edmonton, Alberta T5J 2P4.

The ACA also participated in the Symposium/Workshop on "The Impacts of Climate Variability and Change on the Canadian Prairies" of 9–11 September 1987. This event was sponsored in part by the Alberta Climate Advisory Committee, and the keynote speaker was Dr. F.K. Hare. The *Proceedings* are now available from Bonnie L. Magill, Standards Research and Development Branch, Environmental Assessment Division, Alberta Environment, 11th Floor, Oxbridge Place, 9820 – 106 Street, Edmonton, Alberta T5K 2J6.

The Proceedings of the combined Workshop and 11th Annual Meeting of the ACA in Edmonton on 24 February 1987 are available free of charge courtesy of the Northern Forestry Centre. Ask for *Current applied climatological research in Alberta*, T. Singh, compiler, Information Report NOR-X-294, from Northern Forestry Centre, Canadian Forestry Service, 5320 – 122 Street, Edmonton, Alberta T6H 3S5.

WEATHER MODIFICATION BIBLIOGRAPHY FOR ALBERTA

L. Wojtiw
Alberta Research Council

This extensive bibliography "lists all available reports, publications, papers and theses that have been produced in the past 30 years on weather modification and related topics relevant to Alberta storms." It is dated December 1986, compiled by L. Wojtiw, and entitled *A Bibliography of Weather Modification and Related Topics Conducted in Alberta*. It can be obtained from the Atmospheric Sciences Department of the Alberta Research Council, Edmonton.

QUELQUES NOUVELLES DU QUÉBEC

Richard Leduc
Direction de l'assainissement de l'air
Ministère de l'Environnement
Gouvernement du Québec
2360, chemin Ste.-Foy
Sainte-Foy, Qué. G1V 4H2

Parlons des deux derniers numéros de *Le Climat*, la revue de l'ACLIQ, Association de climatologie du Québec, qui entreprend sa sixième année de publication. Dans *Le Climat* se trouve une gamme de choses: articles scientifiques, comptes rendus, nouvelles, revues du temps au Québec, listes de nouvelles publications. Richard Leduc est rédacteur en chef.

Si vous voulez avoir des renseignements sur *Le Climat*, voire l'ACLIQ, adressez votre correspondance à: Association de climatologie du Québec, a/s Pierre Dubreuil, 100, boulevard Alexis-Nihon, suite 300, St. Laurent, Qué. H4M 2N8. Comme toutes autres sociétés, l'ACLIQ cherche à augmenter son adhésion.

Pour obtenir une copie d'un publication récente, *Réseau d'échantillonage des précipitations du Québec: Sommaire des données de la qualité des eaux de précipitations 1986*, par G. Jacques et G. Boulet (mai 1988), écrivez au Ministère de l'Environnement, Direction des communications et de l'éducation, 3900, rue Marly, 6ᵉ étage, Sainte-Foy, Qué. G1X 4E4.

CLIMATIC CHANGE AND THE BOREAL FOREST IN THE WESTERN INTERIOR

Elaine Wheaton
Climatologist
Saskatchewan Research Council

The report entitled *An Exploration and Assessment of the Implications of Climatic Change for the Boreal Forest and Forestry Economics of the Prairie Provinces and Northwest Territories: Phase One* has recently been published, as SRC Technical Report No. 211, dated November 1987, 282 pp. Copies are available at $40.00 (which includes handling and mailing costs) from: Information Centre, Saskatchewan Research Council, 15 Innovation Boulevard, Saskatoon, Saskatchewan S7N 2X8.

FROM THE CANADIAN GOVERNMENT PUBLISHING CENTRE

Recent publications of interest to climatologists include the following:

Map Series 4 – Bright Sunshine and Solar Radiation.
From Climatic Atlas Climatique – Canada. Map Series 4 contains 102 maps.
Bilingual. Cat. No.: Code CGPC 001301

Climate of Yukon.
Cat. No.: Code CGPC 001601

Ice Atlas – Hudson Bay and Approaches.
Bilingual. Cat. No.: EN56-75-1987.

Contact Canadian Government Publishing Centre, Ottawa K1A 0S9.

L'ASSOCIATION INTERNATIONALE DE CLIMATOLOGIE

Au cours du Colloque de Climatologie qui s'est tenu du 8 au 10 juin 1988 à Aix-en-Provence (France), sous la responsabilité du professeur A. Douguedroit, et qui a regroupé une cinquantaine de participants, une *"Association Internationale de Climatologie"* a été créée; elle va réunir des scientifiques de différentes nationalités qui ont en commun l'usage du français. Dans les activités prévues, on peut relever l'organisation d'un congrès annuel et la publication de "travaux" apériodiques. Le prochain congrès aura lieu à Pavie (Italie) du 1 au 3 juin 1989.

Toute demande de renseignement doit se faire aux adresses suivantes:

Professeur A. DOUGUEDROIT,
Institut de géographie
Université d'Aix-Marseille II
29 avenue Robert Schuman
13621, Aix-en-Provence Cedex
FRANCE

Professeur A. HUFTY
Département de géographie
Université Laval
Sainte-Foy, Québec, Canada
G1K 7P4

List of Referees / Liste des arbitres

The first of these lists was published in Volume 20(1), February 1986. This new list covers 1986, 1987 and part of 1988. *Climatological Bulletin* sincerely appreciates the time and care taken by the referees listed herein.

La première de ces listes a été publiée en Volume 20(1), février 1986. Cette nouvelle liste est consacrée à 1986, 1987, et une partie de 1988. *Bulletin climatologique* apprécie sincèrement le temps et les efforts des arbitres soulignés ici.

J.S. Boisvert
R.S. Bradley
T. Brazel

A.J.W. Catchpole
S.A. Changnon Jr.
J.G. Cogley
S.J. Cohen
M. Cote
R. Crowe

P. Dansereau
T.D. Davies
J. Dublin

D.A. Gauthier
J.F. Griffiths

J. Hall
J.E. Hay
C.D. Henry
D. Hickcox
W.D. Hogg

J. Jäger
K.H. Jones

L.S. Kalkstein

S.E. LaDochy
D. LeComte
E. LeDrew

J.Maybank
G.A. McBean
G. McBoyle
R.A. McGinn
G.A. McKay
N.J. Middleton
D.R. Miller
D.S. Munro

S:E. Nicholson

T.R. Oke
S. Orvig

A.H. Paul
A.H. Perry
J.M. Powell

E.A. Ripley
P. Robinson
J.C. Rogers

B. Sanderson
T. Singh
T.W. Schmidlin
P.J. Smith
D.L. Spittlehouse
P.W. Suckling

P. Taylor
S.E. Tuller

E.E. Wheaton
C.J. Willmott
L. Wojtiw

B. Yarnal