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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.

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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.

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

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

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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.

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Foreword / Avant-Propos

This issue contains contributions on a variety of topics and regions but this can be achieved only through a continuing flow of manuscripts submitted to the journal. I would like to encourage all climatologists to consider *Climatological Bulletin* as a potential outlet for their work. This certainly includes the area of ocean-climate interactions. Submissions for the News and Comments section are always welcome too.

Dans ce numéro se regroupent des articles variés provenant de diverses régions. Une telle situation se produit seulement d'un taux assez élevé de soumission de manuscrits. J'aimerais encourager tout(e) climatologue à considérer le *Bulletin climatologique* pour la publication de ses recherches, y compris surement le domaine du lien océan-climat. Le *Bulletin* accueil également des nouvelles et des commentaires.

Alec Paul
Editor / Rédacteur en chef

Rainfall Distribution During Extended Periods in Mid-Summer in Southwestern Ontario

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[Original manuscript received 7 June 1991;
in revised form 20 July 1992]

ABSTRACT

This study was conducted to assess the feasibility of combining gauge data and weather radar images to estimate areal distribution of accumulated rainfall during extended periods of the growing season. Two mid-summer periods in southwestern Ontario were studied in the following manner. First, rainfall estimates from radar image pixels surrounding the gauge sites were related to gauge measured amounts. These relationships were used to correct radar image rainfall for comparison with isohyet maps drawn using gauge totals. Visual comparisons of the paired maps indicated that the picture of areal rainfall distribution during extended periods would be much improved using corrected radar images. However, it is apparent that a denser network of gauges would be needed to provide the functional relationships between radar and gauge rainfall based on comparisons in a four-county area of the region used in this study.

RÉSUMÉ

Cette étude a évalué la possibilité de combiner les données pluviométriques et les images radar météorologiques dans le but d'estimer la distribution spatiale des pluies accumulées durant les périodes de la saison croissante prolongée. Deux périodes qui ont eu lieu en mi-été dans le sud-ouest Ontarien ont été étudiées de la manière suivante. On a d'abord utilisé les pixels d'image radar pour estimer les hauteurs de pluie environnant les sites des pluviomètres et on a comparé ces valeurs à celles mesurées par les pluviomètres. Les relations ainsi obtenues ont permis de corriger les hauteurs de pluie calculées à partir des images radar, hauteurs qui sont alors comparées aux cartes d'isohyètes tracées à partir des totaux pluviométriques. Les comparaisons quant à l'apparence visuelle des paires de

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cartes nous ont indiqué que l'apparence de la distribution des hauteurs de pluie durant les périodes prolongées est meilleure lorsque l'on utilise les données radar corrigées. Toutefois, en se basant sur des comparaisons englobant l'étendue de quatre comtés faisant partie de la région à l'étude, il est apparent qu'il faudrait un réseau plus dense de pluviomètres pour fournir la relation fonctionelle entre les hauteurs de précipitations déterminées à l'aide du radar et celles obtenues par des pluviomètres.

1. INTRODUCTION

Knowledge of the areal distribution of rainfall amounts during the growing season in agricultural regions is important for crop assessment, irrigation planning and water management. Conventionally, areal distribution of rainfall is estimated by interpolating between the rain gauges in a network. Even though raingauges provide adequate measurement of rainfall at specific sites, it is difficult to determine the areal extent of many rainfall events due to the sparseness of most gauge networks. This is particularly the case for convective rainfall events that occur more frequently during summer in the high and mid-latitudes and in the tropics (Jackson, 1977 and Raddatz, 1987). By contrast, weather radar images provide reasonable pictures of the areal distribution of rainfall by measuring the volume of rain-size droplets in rain-producing clouds, but do not estimate the amount that actually reaches the surface as accurately as gauges.

According to Gorrie and Kouwen (1977), there are several advantages in using radar to measure precipitation: the areal nature of the data; the high resolution; the capability of assessing rainfall in remote areas; the high frequency of data recording; and the high volume transmission of the data.

Although radar is capable of portraying rainfall distribution continuously in space and time (Wilson, 1976), its use for quantifying precipitation has been limited (Kouwen, 1988). This is mainly due to the frequent disagreement between radar estimates and gauge measurements. There are many reasons for this, including sampling height and droplet size distribution (Hill, *et al.*, 1981), horizontal wind effects, evaporation, beam blockage, rain-rate gradients, vertical air motion, beam attenuation (Doviak and Zrnic, 1984), terrain echoes and anomalous propagation (Wilson, 1976), and beam filling problems (Woodley *et al.* 1975). Even raingauges have limitations, but remain the standard technique for point rainfall measurements (Barnston and Thomas, 1983). Considering the advantages and disadvantages of these two kinds of measurements, it would be advantageous to make use of both to generate a better picture of areal rainfall distribution for periods of interest.

The purpose of this study is to determine if it is feasible to depict the accumulated areal rainfall distribution during the growing season using a combination of radar data and a sparse raingauge network. Although other studies of this nature have been conducted for single rainfall events not related to dry periods (Austin, 1987; Barnston and Thomas, 1983; Brandes, 1975;

Hildebrand *et al.* 1979; Hill *et al.* 1981; Woodley *et al.* 1975), this appears to be the first study for extended periods requiring accumulation of radar data for several rainfall events. Two rain gauge networks and radar map archives for southwestern Ontario were used in this study.

STUDY AREA AND DATA

The weather radar facility located near Exeter (43° 22'N and 87° 23'W) in southwestern Ontario and rain gauges within 150 km of this site (Fig. 1) provided the data for the analyses of rainfall distribution during two extended periods of

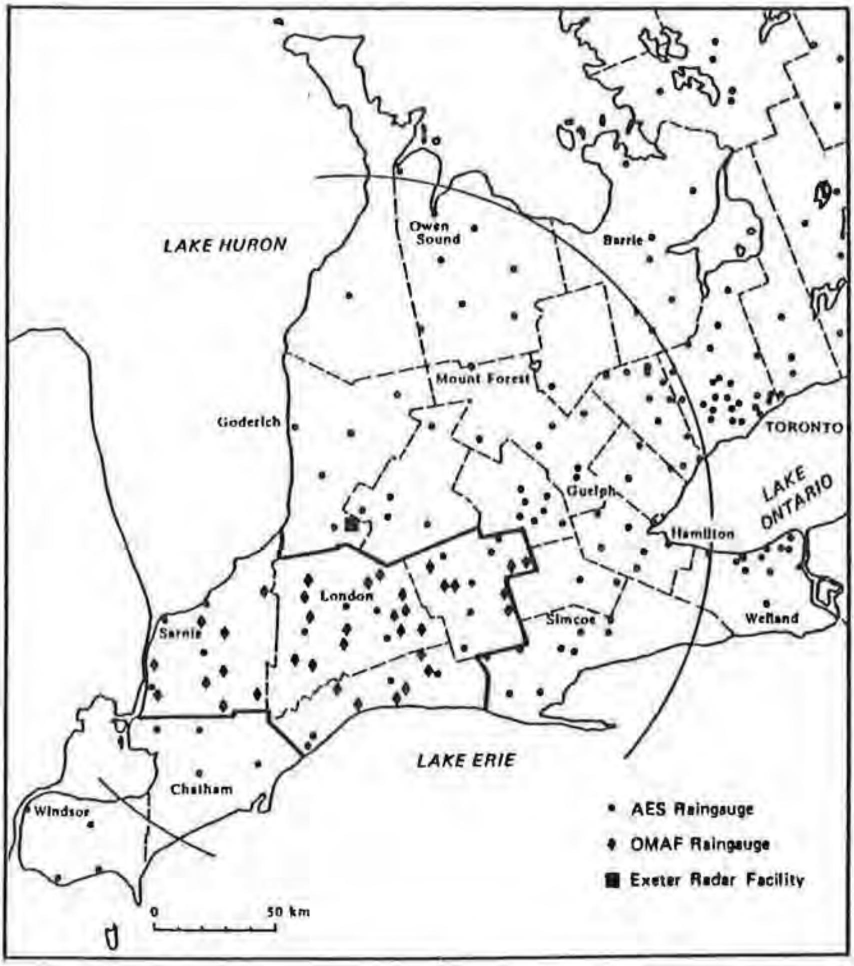

FIGURE 1. Study area in southwestern Ontario showing location of A.E.S. and O.M.A.F. rain gauges and the Exeter radar facility.

the growing season. The characteristics of the radar facility at Exeter are provided in detail by Hogg (1978) and summarized by Sribimawati (1989). It has a wavelength of 5.34 cm and the beam width is 1.08°. Rainfalls measured in three types of gauges were used in this study - the standard and "tipping-bucket" gauges used in the AES network and the wedge-shaped open top gauge used by the SCIAO* volunteers. The area, surrounded by the lower Great Lakes, has a change in altitude from about 175m above mean sea level at lake level in the south and west to over 500m in the northeastern part of the region. It has a modified continental cool, humid climate (Hare & Thomas, 1974) influenced by the lakes on three sides. The growing season starts in early to mid-April and ends in late October or early November. The mean annual precipitation ranges from 710 mm west of Toronto to 1060 mm west of the highest uplands. This difference is mainly due to the extra snowfall received in areas to the lee of Lake Huron. The mean precipitation during the growing season is more uniform averaging 70 to 80 mm per month (Brown *et al.* 1968). Dry periods do occur in some parts of the area with fairly regular frequency (Brown and Wyllie, 1984). The extended periods selected for this study were July 12 to August 17, 1984 and July 17 to August 17, 1985. Rainfall was accumulated in each of the periods for 89 Atmospheric Environment Service (AES) gauge sites in the area (Fig. 1) and from radar images stored on magnetic tape using a computer program developed for the purpose (Hogg, 1978). This program provides radar estimated rainfall in a grid pattern for 4 km^2 pixels over the whole area and uses the Marshall-Palmer relationship (Reflectivity = 200 $Rainrate^{1.6}$) to convert constant altitude reflectivity measurements into rainrate estimates (Battan, 1973).

METHOD OF ANALYSIS

First the radar estimated average rainfall for the nine pixels surrounding each of the 89 gauge sites were correlated with gauge rainfall. A relationship for each study period was determined and used to correct gray-scale maps prepared from accumulated radar rainfall in the 4 km^2 pixels. In the correlation/regression analyses between the two sets of rainfall data, variables for distance from the site of the radar facility and altitude of the gauge site were also considered, but found not to be significant. The STATGRAPHICS statistical software package was used to analyze the data with the stepwise variable selection procedure.

The areal distribution of rainfall for each period was mapped using a subjective approach for the 89 rain gauge sites and the corrected gray-scale maps of radar rainfall using the results of the regression analyses. Both sets of maps were compared visually.

A secondary rain gauge network (OMAF/SCIAO)[1] for a four county area in the southern part of the region (outlined by heavy lines in Fig 1) was used to supplement the AES network in this area for the 1985 period

* See footnote no. 1.

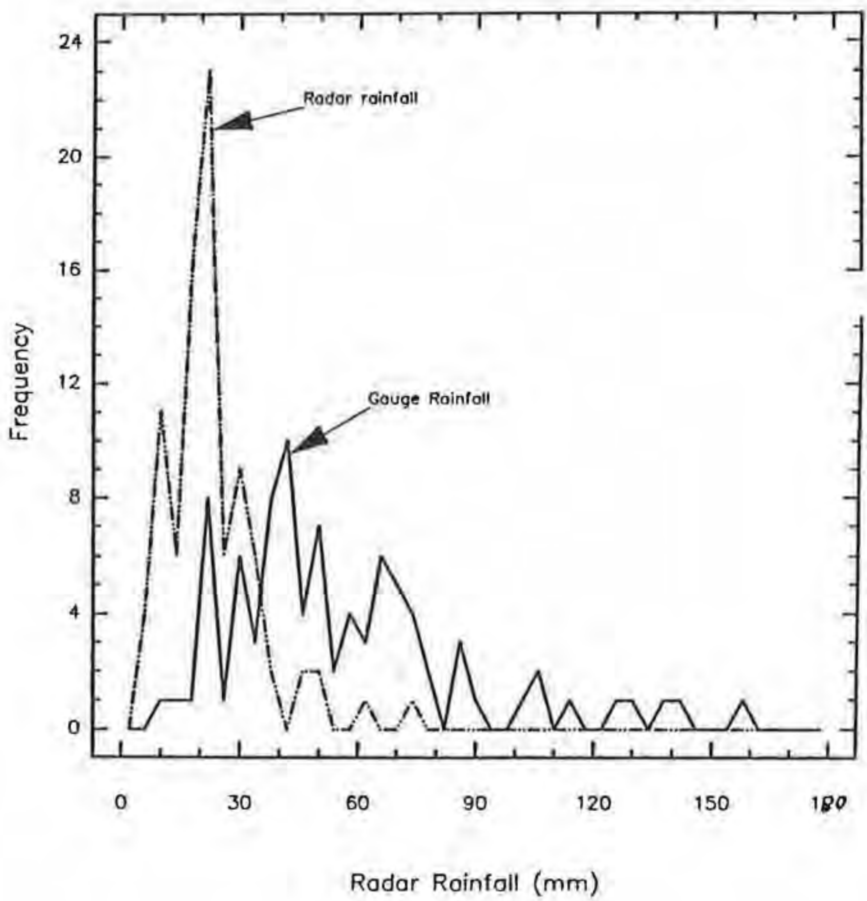

FIGURE 2. Frequency of occurrence of rainfall amounts, as recorded by gauges and by radar (average of nine pixels at gauge site), accumulated from July 17 to August 17, 1985.

rainfall. The areal rainfall distribution based on this denser gauge network was compared with the corrected radar rainfall by overlaying the two maps.

RESULTS AND DISCUSSION

Gauge rainfall accumulations for the 89 sites ranged from 10 to 142 mm with a

1 OMAF/SCIAO gauges are open-topped and wedge-shaped. These are used by members of county Soil and Crop Improvement Associations of Ontario (SCIAO) who voluntarily provide daily rainfall data to the county office of the Ontario Ministry of Agriculture and Food (OMAF) for publication.

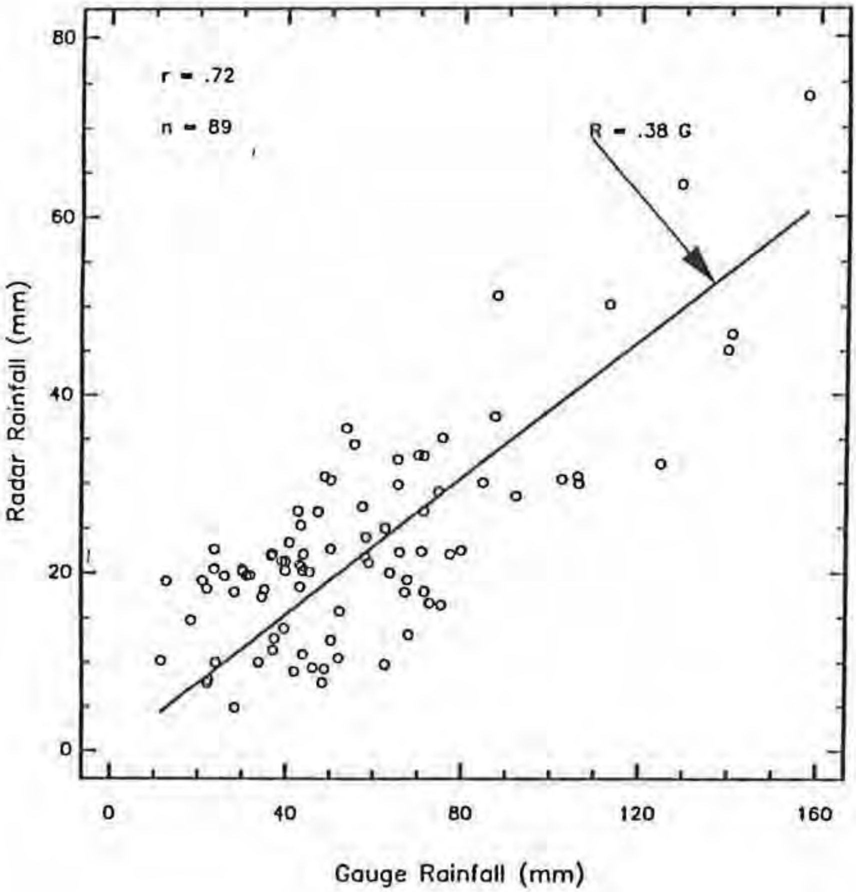

FIGURE 3. Relationship between the July 17 to August 17, 1985 period rainfall as recorded by gauges and radar.

mean of 53 mm for the 37-day period in 1984 and from 11 to 157 (mean 56 mm) for the 32-day period in 1985, whereas radar accumulations (average for nine pixels) for the same sites ranged from 5 to 73 mm in both years. The frequency distribution for both sets of data showed a significant positive skewness as shown for the 1985 gauge and radar data in Fig. 2. The 'normal' rainfall amount in this region would be ≈90 mm for the 37-day dry period in 1984 and ≈80 mm for the 32-day period in 1985.

Regression analyses relating radar rainfall to gauge rainfall, altitude of the gauge site, and distance from the radar indicated that neither altitude nor distance were significant (5% error level). Consequently, a simple regression of radar versus gauge rainfall, with a zero intercept assumed, showed radar rainfall

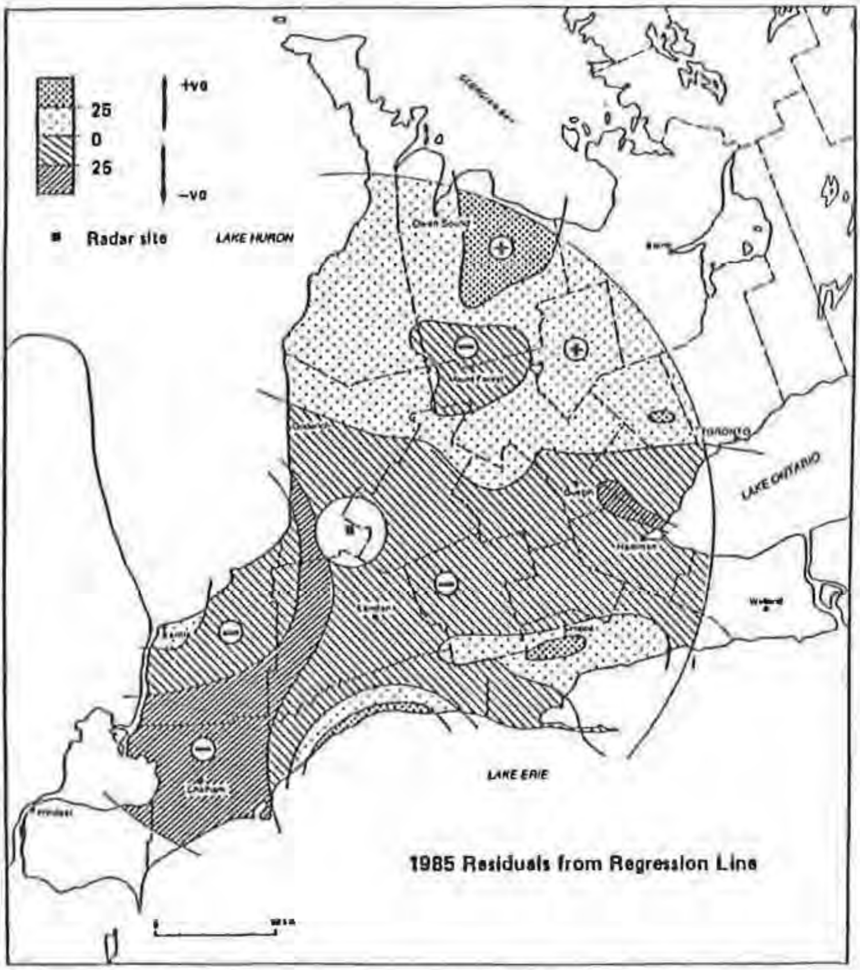

FIGURE 4. Illustration of the magnitude and distribution of departures (residuals) from the linear regression of radar vs gauge rainfall (Fig.3) for the study area in southwestern Ontario in 1985.

from the scans at the 1.5 km CAPPI (Constant Altitude Plan Position Indicator) height to be about 45% of that measured in gauges in 1984 and 38% in 1985. The relationship for 1985 is shown in Fig. 3.

An analysis of the residuals based on the errors from the regression relationships indicated no significant differences. However, when residuals were mapped (Fig.4) there appeared to be a tendency for the residuals to increase with distance from the radar site (Sribimawati, 1989) as found by Hogg, 1978, and to be positive with increase in elevation of the land from radar site and negative with decrease in elevation (Fig.4).

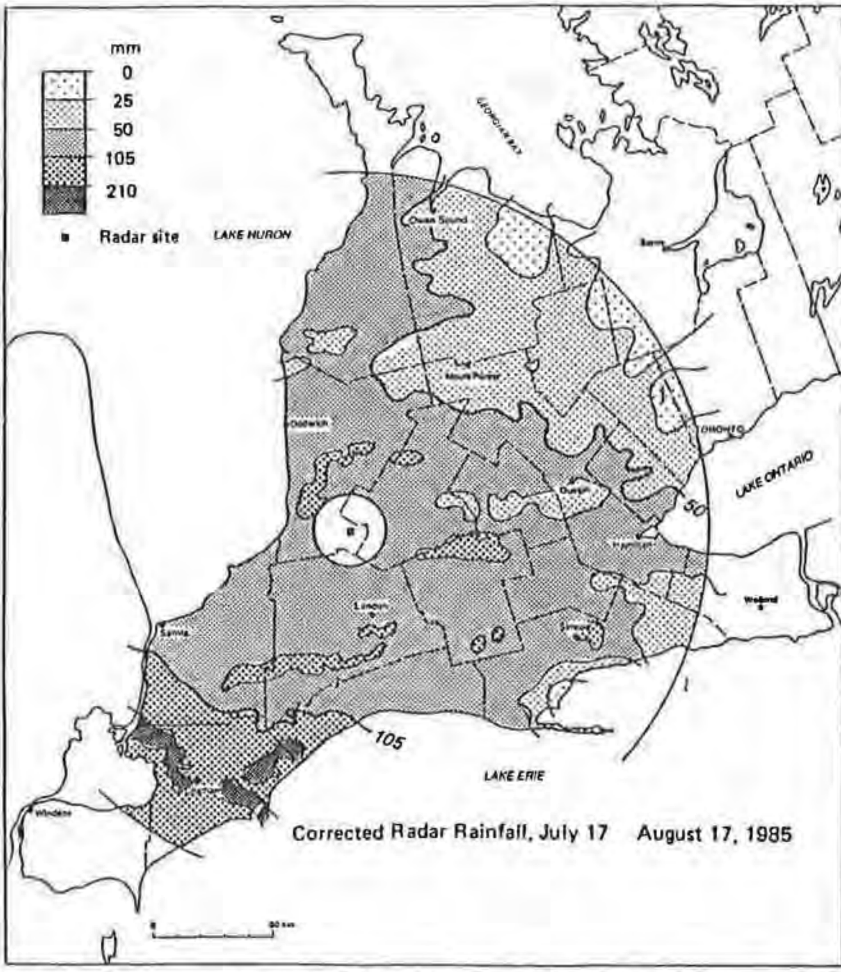

FIGURE 5. Accumulated rainfall for July 17 to August 17, 1991 period, based on corrected radar image maps using relationship in Fig. 3, showing the distribution over the study area based on the CAPPI radar images.

In order to compare the radar generated rainfall maps with the gauge -based maps it was necessary to correct the radar rainfall isohyets. This was done by using a multiplier of 2.22 in 1984 and 2.62 in 1985, based on the regression analyses. Comparisons of the two sets of maps showed that cells of extreme rainfall appeared on the radar-generated maps that were not found on the AES gauge maps due to the sparsity of rain gauges. For example, the two cells of rainfall greater than 105 mm south and southwest of London appear on the radar-generated map (Fig. 5) for 1985, but do not appear on the AES gauge network map. Other cells were displaced slightly on the radar maps and/or reshaped from their original "cell" location as subjectively drawn using the gauge

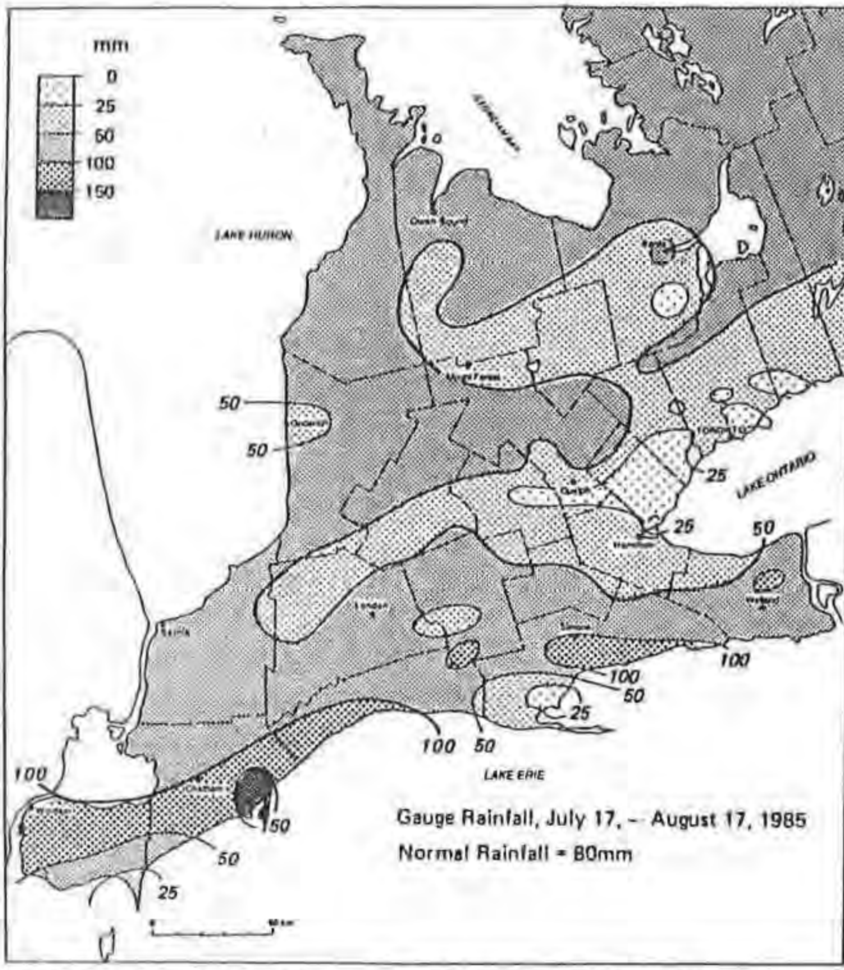

FIGURE 6. Accumulated rainfall for the period of July 17 to August 17, 1985 showing the estimated distribution over southwestern Ontario, based on the A.E.S. gauge network.

rainfall totals. For example, the cell with >105 mm near Simcoe (Fig. 5) is south of Simcoe and was extended south and east to Lake Erie when isohyets were drawn (Fig. 6) based on the AES gauge sites data. Also, the large dry cell (<50mm) that was drawn to cover a large area of four counties from northwest of London to southeast of Hamilton on the gauge map (Fig. 6) appears as two small cells south and west of Guelph on the radar map (Fig. 5). This illustrates that a rain gauge network cannot capture the true spatial variability of growing season rainfall totals for a region as discussed by Huff and Shipp, 1968 and Rudd, 1961.

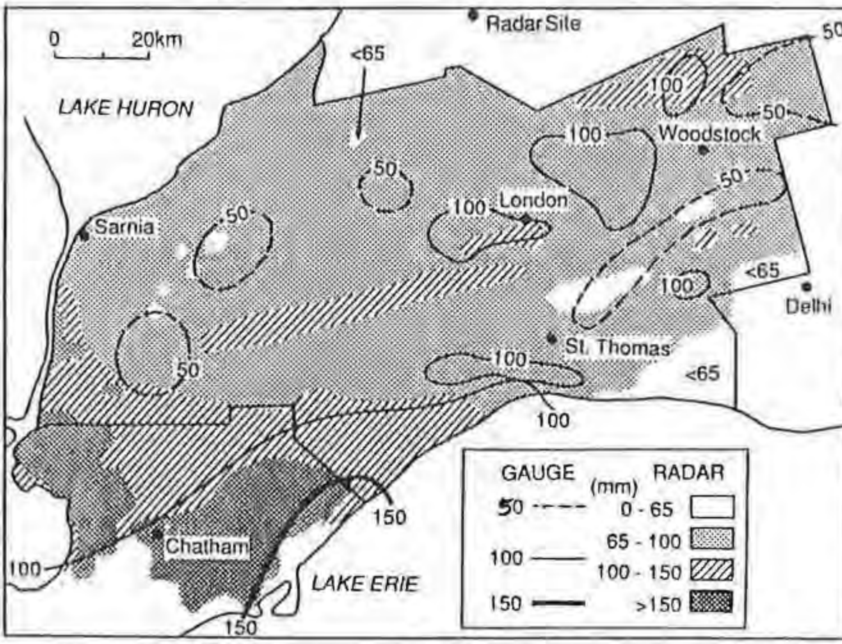

FIGURE 7. Estimated July 17 to August 17, 1985 rainfall distribution based on A.E.S. and O.M.A.F. gauges compared to radar image data for a four-county area plus north Kent in the study region.

The displacement of the extreme rainfall amounts on the radar maps resulted in large residuals (deviations from regression line) for sites where the displacement was the largest (Fig. 4). This emphasizes the need for use of the synoptic situation for each rainfall event so that wind speed and direction can be considered when providing ground level precipitation from radar images.

The four-county area, where a denser network of gauges (AES plus OMAF/SCIAO[1]) was used to draw isohyets for 1985 rainfall, is compared with the corrected radar map (Fig. 7) using the overlay technique. Part of Kent county north and east of Chatham is included with the four county area to depict the cells with >150 mm, although there were only four A.E.S. rain gauge sites in this part of Kent (Fig. 1). One of the rain gauges in southwest Elgin and one in Kent recorded over 150 mm, but the gauge in Chatham and the one in northwest Kent did not record over 150 mm as indicated by the radar data. This difference may have been due to anomalous propagation in the radar echoes or error due to large residuals in the original regression relationship that only accounted for 53% of the variance. In most cases the radar facility generated the vicinity of extreme rainfall occurrences fairly well. Some cells were isolated by the radar that were not recorded by gauges. The cells drawn based on gauge data were usually larger than those isolated by radar in the same vicinity. In a few cases a rain gauge isolated cells with more rainfall than shown by radar.

CONCLUSIONS

The picture of areal distribution of rainfall during extended time periods of the growing season could be improved by using accumulated CAPPI radar images in conjunction with gauge data. It is possible that functional relationships between point radar and gauge data will be required for each rainfall event so that synoptic conditions can be included in the relationship based on the displacement of the cells of extreme rainfall in the last figure. Weighting factors that consider distance from the radar and geographic effects may also improve the relationship between gauge and radar rainfall amounts.

ACKNOWLEDGEMENTS

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Sea-ice anomalies in the western Arctic and Greenland-Iceland Sea and their relation to an interdecadal climate cycle

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ABSTRACT

From an analysis of Arctic sea-ice concentration, sea-level pressure, runoff and salinity data collected during the 1980s, it is found that large sea-ice extents and low salinities observed in the Greenland-Iceland Sea during the late 1980s can be attributed to prior high runoffs into the Beaufort Sea in the mid-1980s. We refer to such ocean climate freshening events in the Greenland-Iceland Sea as '*G*reat *I*ce and *S*alinity *A*nomalies' or GISAs. A lagged cross-correlation study of 36 years of low-pass filtered areal sea-ice extent anomalies from various subregions of the central Arctic Basin and Greenland-Iceland Sea indicates that both positive and negative ice anomalies tend to propagate from the Beaufort Sea through to the Greenland-Iceland Sea via the Beaufort Gyre and the Transpolar Drift Stream. This behaviour of the sea-ice fluctuations is consistent with the interdecadal Arctic climate cycle recently proposed by Mysak, Manak and Marsden (1990). A study of lagged cross-correlations of low-passed filtered ice data from subregions covering the whole Arctic and its marginal seas reveals a complex ice anomaly drift pattern which, however, has a number of similarities with that recently obtained by Chapman and Walsh from an analysis of monthly ice anomalies. A discussion is also given of the possible connections between the decadal-scale GISAs and lower latitude interdecadal climate variations.

RÉSUMÉ

Une analyse des données recueillies durant les années 80 sur la concentration de glace dans l'océan Arctique, la pression au niveau de la mer, l'écoulement des eaux et la salinité nous révèle que les vaste étendues de glace et les faibles taux de salinité observés à la fin des années 80 dans la mer du Groëland—Islande peuvent dépendre de la quantité d'eau douce qui s'est déversée dans la mer de Beaufort au milieu des années 80. Nous parlons de

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cette période de restauration du milieu océanique comme l'époque "d'importantes anomalies de glace et de salinité (GISA-Great Ice and Salinity Anomaly)". Une étude des corrélatives croisées par intervalles sur une période de 36 ans des étendues anormales de la glace de mer de diverses sous-régions de la mer du Groënland-Islande, soumises à un filtre à basse fréquence, démontre qu'elles, aussi bien positives que négatives, on tendance à circuler de la mer de Beaufort vers la mer du Groënland-Islande sous l'action des courants dans la mer de Beaufort et du courant de dérive transpolaire. Ce genre de variation de la masse glaciaire est compatible avec le cycle climatique interdécennal de l'Arctique proposé par Mysak, Manak et Marsden. Une étude des corrélatives croisées par intervalles des données sur les étendues de glace, soumises à un filtre à basse fréquence effectuée dans des sous-régions englobant l'Arctique et les mers avoisinantes révèle l'existence d'un système complexe de dérive d'anomalies de glace. Toutefois, ce modèle possède des caractéristiques semblables à celui qu'ont obtenu récemment, dans leur analyse des anomalies de glace mensuelles, Chapman et Walsh. Nous étudierons également des liens qui peuvent exister entre les variations de GISA calculées sur une décennie et les variations climatiques interdécennales observées aux faibles latitudes.

1. INTRODUCTION

In a recent paper, Mysak *et al.* (1990, hereafter referred to as M) proposed that decadal-scale fluctuations of sea-ice extent in the Greenland-Iceland Sea may be linked to a certain sequence of high-latitude hydrological, oceanic and atmospheric processes in the form of a multi-component feedback loop (Kellogg 1983). Fig. 1 shows a modified (and simplified) form of this loop, which was also used as the basis of a Boolean Delay Equation model of interdecadal Arctic climate variability (Darby and Mysak 1992). Because the loop is negative or reversing, it can, in the absence of other strongly damping factors, give rise to self-sustained climatic oscillations in the Arctic with an estimated period (the time to go around the loop twice) of 15-20 years. For example, the loop implies, among other things, that in northern Canada, there can be alternating states of heavy and light runoff, which are followed a few years later by corresponding states of suppressed convection and convective overturning in the Iceland Sea. We define here the Iceland Sea as the region between Jan Mayen Island (71°N, 8°W - see Fig. 2a) and Iceland. The Greenland Sea, on the other hand, is the region between Jan Mayen and Fram Strait. We shall refer to the two regions collectively as the Greenland-Iceland Sea. In M (and also Mysak and Power 1991) however, the Greenland-Iceland Sea was simply called the Greenland Sea.

The 'Great Salinity Anomaly' or GSA (Dickson *et al.* 1988), a freshening of the North Atlantic subpolar gyre in the late 1960s and 1970s which suppressed convection in the Iceland Sea for several years, was incorporated into the aforementioned feedback loop by M, who argued that it could have been partly formed by large runoffs into the western Arctic during the mid-1960s (see Fig. 17 in M). Therefore, M proposed that the GSA could be regarded as a cyclic event, part and parcel of a sequence of large-scale air-ice-sea interactions

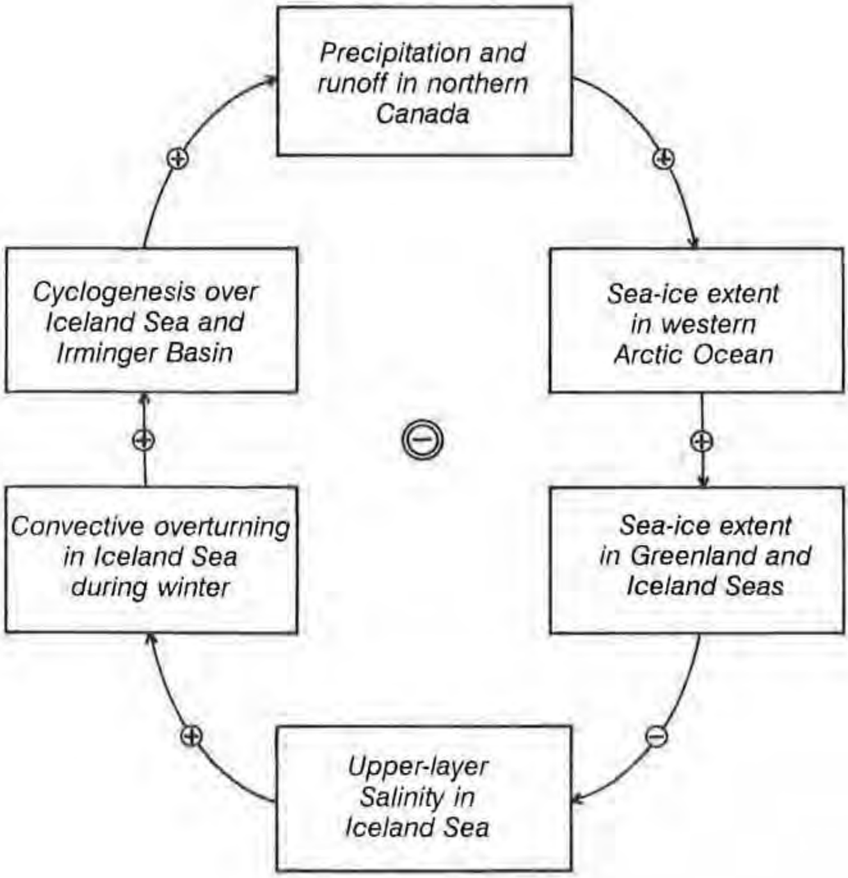


FIGURE 1 Negative (or reversing) feedback loop linking northern Canadian river runoff, Arctic sea-ice extent, Greenland-Iceland Sea ice extent, and salinity, convection and cyclogenesis around Iceland. This is a modified (and simplified) version of the ten-component loop originally proposed by Mysak *et al.* (1990) to account for interdecadal Arctic climate oscillations with a period of about 15-20 years.

in the Arctic. On the basis of this conceptual model, M also gave evidence of the occurrence of earlier GSA-like events during this century. It was also predicted by M that another GSA-like event would have occurred in the Greenland-Iceland Sea in the late 1980s.

Mysak and Power (1991) showed that consistent with the above prediction, large sea-ice extents did indeed occur in the Greenland-Iceland Sea during February 1987 and 1988. (They also found that over a period of several decades, fluctuations of North American runoff into the Arctic significantly lead the ice anomalies in the Greenland-Iceland Sea by 3-5 years.) Coincident with the

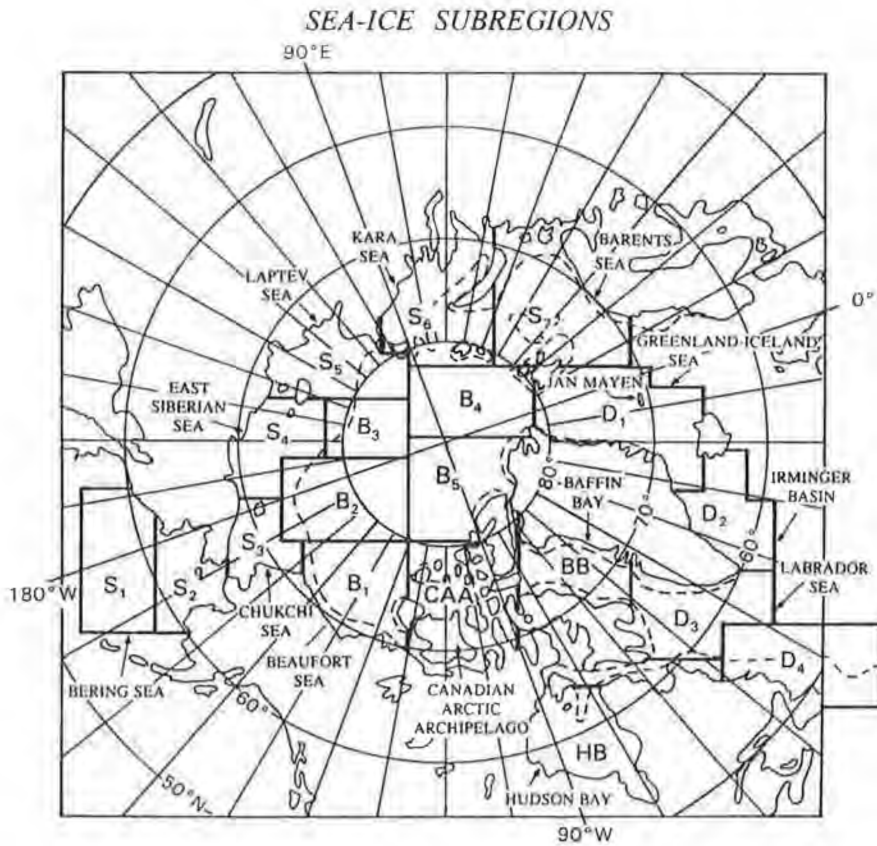


FIGURE 2a Subregions of the Arctic Ocean and marginal seas used in the lagged cross-correlation analysis of low-pass filtered areal sea-ice extent anomalies derived from monthly sea-ice concentration (SIC) data for the period 1953-88. The dashed curve denotes the 200 m isobath.

occurrence of the ice anomalies during the late 1980s was the reduction of convection in the Greenland Sea (Rudels *et al.* 1989; Schlosser *et al.* 1991) and the appearance of upper-ocean low salinity water there during February and March 1989 (GSP Group 1990). If the latter freshwater anomaly advected southward into the Iceland Sea and suppressed convection there, then taken together, these features suggest that a moderately-sized GSA-type event occurred in the Iceland Sea in the late 1980s. As in the case of the late 1960s GSA, the large Greenland-Iceland Sea ice anomalies in the late 1980s appeared to have advected into the Labrador Sea (see Fig. 7 in Chapman and Walsh 1992) and therefore contributed to the extremely heavy ice conditions and cooler air temperatures along the coast of Newfoundland in May 1991 for example (*Globe* *and Mail*, 31 May 1991). (It has also been proposed by J. Elliot (*pers. comm.* 1991) that such large ice anomalies could be partly due to anomalous offshore winds which forced the coastal ice seaward.)

The main purpose of this paper is to present evidence which indicates that this last GSA-type event, which we shall call a GISA, an acronym for 'Great Ice and Salinity Anomaly', may have also originated from large runoffs into the western Arctic during the mid-1980s. However, the possible role of anomalous regional surface winds in creating the GISA is also examined. Dickson *et al.* (1975) and Walsh and Chapman (1990a) (see also Serreze *et al.* 1992) have argued, respectively, that anomalous winds over the Greenland Sea and to the northwest of Fram Strait were important forcing factors in the generation of the late 1960s GSA.

A second purpose of this paper is to present a lagged cross-correlation analysis of 36 years of low-pass filtered sea-ice concentration data from several subregions of the Arctic and marginal seas. The goal here is to show that both positive and negative ice anomalies in the western Arctic propagate out into the Greenland Sea and beyond with the mean ice drift. Also, the low-frequency ice anomaly drift pattern for the whole Arctic and its marginal seas is found and compared with that obtained by Chapman and Walsh (1991) who used *monthly* data from the US Navy/NOAA Joint Ice Center subregions.

Finally, the third purpose of this article is to comment on the possible connections between GISAs and lower latitude interdecadal climatic fluctuations. Evidence accrued so far (see for example references listed in Weaver *et al.* 1991) suggests that many types of natural interdecadal fluctuations occur at middle and high latitudes; thus it is conceivable that they could be triggered by polar climatic variations on this time scale. Alternatively, middle latitude fluctuations could influence (e.g., amplify) the type of climate oscillations described in M. A better understanding of these connections is particularly relevant to one of the central problems associated with potential enhanced greenhouse warming: how to separate natural climate variations on decadal time scales, which tend to be amplified in the north polar region, from those climatic changes due to anthropogenic forcing which occur on the decade-to-century time scale.

The outline of this paper is as follows. In section 2 the data sets that we have analyzed are described, and in section 3 a discussion is given of the 1980s GISA, which is also compared with the generation and evolution of the GSA in the late 1960s. Also in section 3 some new insights are given on what might have caused the large 1960s runoffs into the Arctic, which partly generated the GSA. In section 4 we present a lagged cross-correlation analysis of 36 years of low-frequency areal sea-ice anomalies for various subregions of the Arctic. Finally, in section 5 we suggest how GISAs may be linked with lower latitude interdecadal climate variability.

2. DATA

The sea-ice concentration (SIC) and sea-level pressure (SLP) data that are presented in the next two sections were kindly provided by John Walsh of the University of Illinois. The SIC data consist of end-of-the-month concentrations in tenths given on a square 1° × 1° (latitude) grid centred at the north pole, which was developed by Walsh and Johnson (1979). The positive x and y axes of this grid are along 20° W and 70° E, respectively (see Fig. 2 in M). The data cover the period 1953-88, but according to Chapman and Walsh (1991), the quality prior to 1972 is less reliable because then the data were derived from many sources. After 1972 the routine monitoring of sea ice on the hemispheric scale was made possible by polar-orbiting satellites whose passive microwave sensors had cloud penetraing capabilities, and accordingly, the data became much more homogeneous. Maps of the annual mean and seasonal mean SIC fields for each year during the period 1953-88 are given in the 'quick look' atlas of Mysak and Wang (1991).

From the monthly SIC data, areal sea-ice extent anomalies were calculated as described in Mysak and Manak (1989) to remove the 36-year climatological annual cycle. These anomalies were then subdivided to form areal sea-ice anomaly time series for each of the subregions shown in Fig. 2a, which are similar to the US Navy/NOAA Joint Ice Center standard subregions (see for example Fig. 3 in Chapman and Walsh 1991). To focus on the low-frequency variability of the areal sea-ice extent anomalies, the time series for the subregions were next low-pass filtered to remove all spectral components with periods shorter than 30 months (see Power and Mysak (1992) for details of the filtering procedure). The resulting smoothed areal sea-ice anomaly time series were used in the cross-correlation analysis in section 4. A set of these time series for the five contiguous subregions B_I to D_I is shown in Fig. 2b. Note that the sequence of subregions follows the ice drift pattern which leads to the export of sea ice out of the Arctic Ocean (through Fram Strait) via the Beaufort Gyre (BG) and the Transpolar Drift Stream (TDS) (see Fig. 18b in M).

The monthly mean SLP data provided by Walsh originate from NCAR and are given on a 5° × 5° latitude-longitude grid which covers most of the Northern Hemisphere from January 1899 to January 1988. However, because of missing data in the Arctic prior to the 1950s and the limited record of SIC data, only the data from 1953-87 were used in this paper. Maps of the seasonal mean and annual mean SLP fields for each year are displayed in the 'quick-look' atlas of Mysak and Wang (1991), who also included the SLP anomaly fields (departures from the 1953-87 climatology). For a further discussion of the SLP data, we refer the reader to Walsh and Chapman (1990b) who used this data set to study short-term Arctic climate variability. The low-pass filtered SLP data have been analyzed by Power and Mysak (1992).

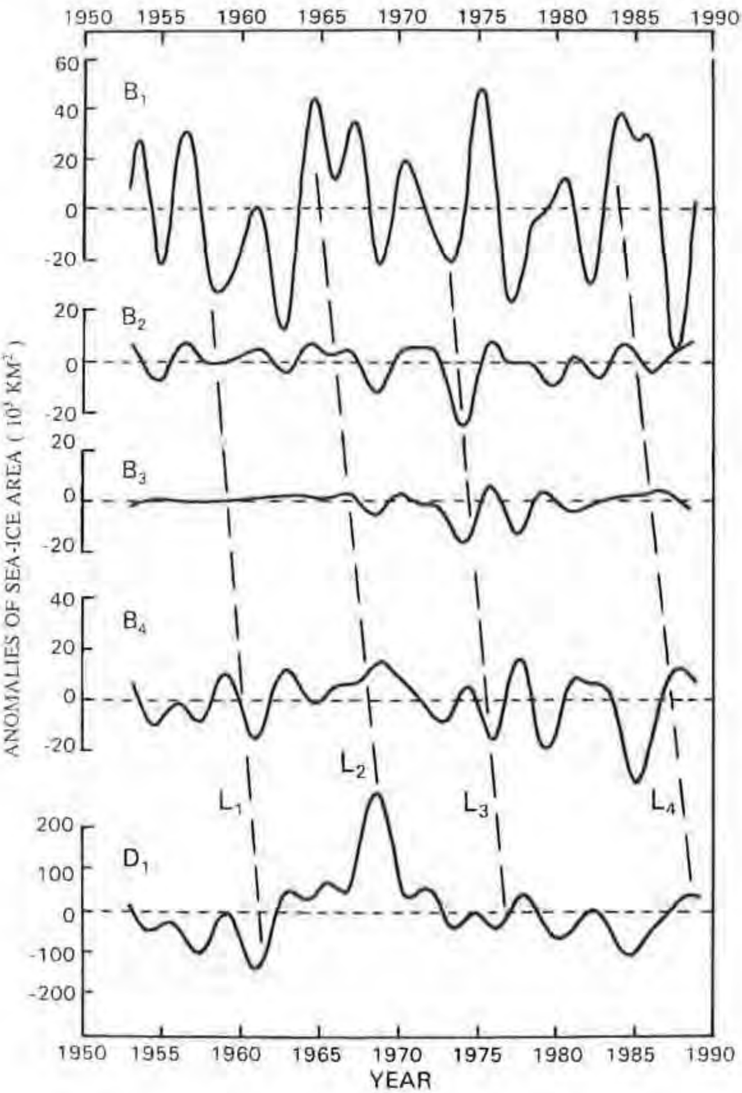


FIGURE 2b Low-pass filtered anomalies of areal sea-ice extent for subregions $B_1, \ldots, D_1$ in the Arctic Ocean and Greenland-Iceland Sea (see Fig. 2a); note that the vertical scale in the bottom time series (for subregion D_1) has been compressed by a factor of five. The distances between the zero-means of adjacent pairs of time series are proportional to the corresponding distances between the centres of the adjacent subregions shown in a). The dashed lines with negative slope (L_i) indicate the propagation of ice anomalies from the Beaufort Sea (subregion B_1) through to the Greenland-Iceland Sea (subregion D_1). In particular, the line L_4 shows that the origin of the GISA in the Greenland-Iceland Sea in the late 1980s could have been due to the large anomaly in subregions B_1 in the mid-1980s.

The large Greenland-Iceland Sea ice extents shown in Mysak and Power (1991) for February 1987 and 1988 are also clearly visible in the winter (the mean of December, January and February) SIC maps for 1987 and 1988 (see pp. 152 and 155 in Mysak and Wang (1991)). A characteristic magnitude of the associated low-pass filtered areal sea-ice anomalies in the late 1980s is 6×10^4 km^2 (see the D_1 time series in Fig. 2b) which, when multiplied by the typical ice thickness for this region (1 m - see Bourke and Garrett 1987), gives a characteristic ice volume anomaly magnitude of 60 km^3. If this 1980s GISA is an integral part of the interdecadal cycle illustrated in Fig. 1, then conceivably, as in the case of the GSA, it too could have been generated partly by large runoffs into the western Arctic during the mid-1980s.

Figure 3a shows that during 1984-86 the Mackenzie River discharge was indeed above average, a situation which presumably caused the simultaneous below-average salinities on the Beaufort shelf to the north of the Mackenzie delta (Fig. 3b) and also the positive areal sea-ice anomalies in the western Arctic subregion B_1 (Fig. 3c). The runoff-ice cover relationship is consistent with the findings of Manak and Mysak (1989) who showed, among other things, that the Mackenzie River discharge is positively correlated with ice extent on the Beaufort Sea shelf, with discharge leading by about one year. The basic mechanism believed operative here is that fresher upper-ocean water resulting from higher runoff tends to freeze more easily and hence produce more sea ice the following winter and spring. The ice anomaly in the Beaufort Sea has a magnitude of about 3×10^4 km^2 (Fig. 3c), and since the ice thickness is typically 2-3 m here (Bourke and Garrett 1987), the corresponding ice volume anomaly is 60-90 km^3, which is comparable to that in the Greenland-Iceland Sea, as estimated in the previous paragraph.

From Fig. 3c it is also interesting to note the large ice anomaly peak in 1975, which is most likely due to the very high runoff (Fig. 3a) and low shelf salinities (Fig. 3b) in 1974. On the other hand, the largely negative ice anomalies during 1978-82 appear to have been caused by the low runoffs and high salinities which occurred at about that time. Finally, in the earlier part of the ice anomaly time series in Fig. 3c, we observe the large positive anomalies during 1964-67, which M proposed were caused by the anomalously large runoffs from North America into the Arctic (Fig. 17 in M).

It is instructive at this point to compare particular annual mean SIC maps with corresponding SLP maps in order to determine, in a crude way, the possible role of atmospheric forcing in creating the ice anomalies, first in the western Arctic and then in the Greenland Sea a few years later. Upon comparing Figs. 4a and 4b, we first note that in the Beaufort Sea region the ice coverage during 1985 was above average, which is consistent with Fig. 3c. Upon comparing Figs. 4d and 4e we observe that during 1985 there was a high

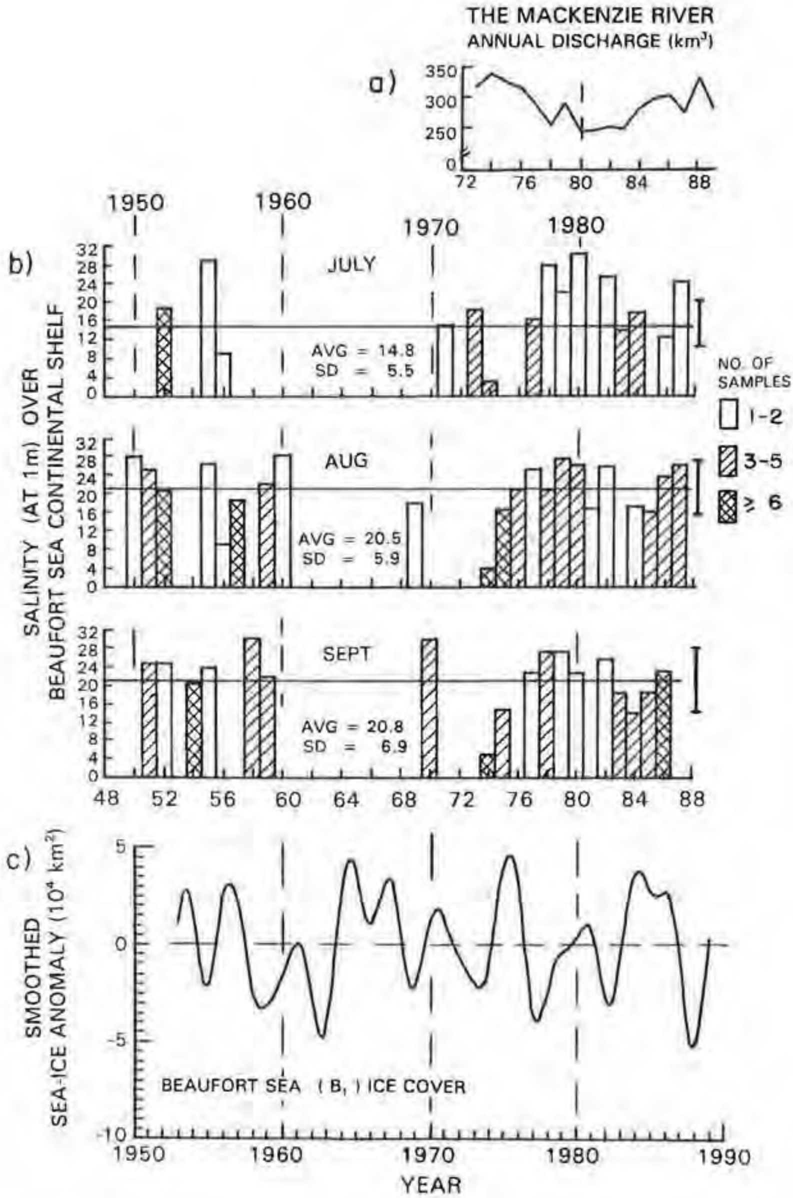
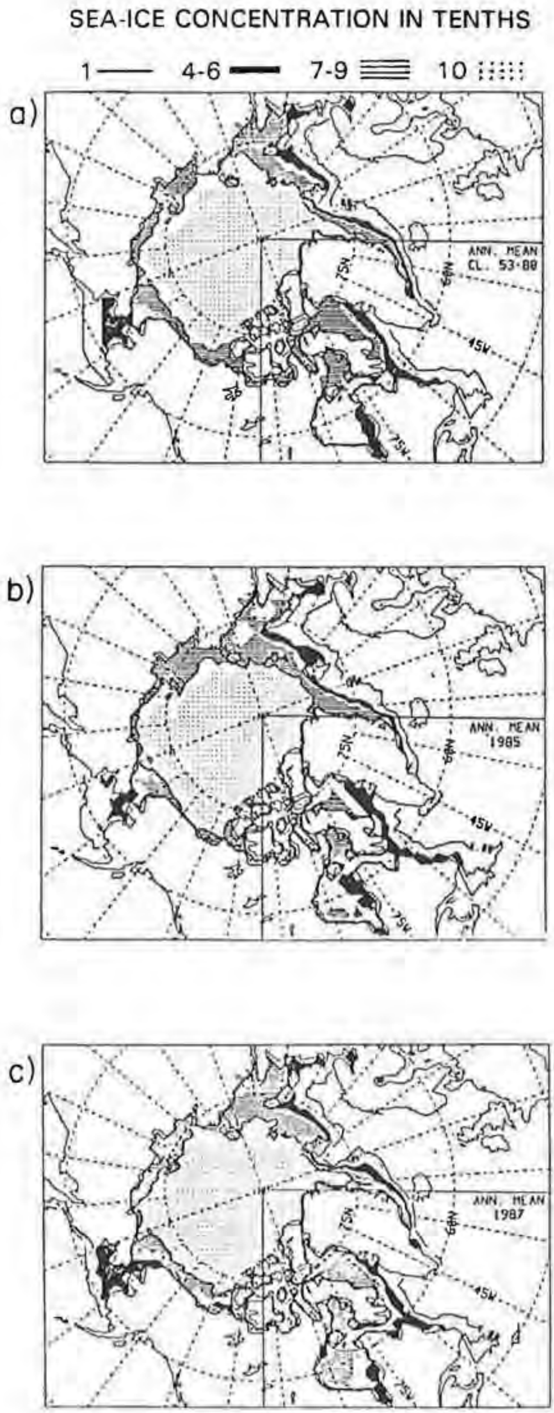


FIGURE 3 a) Annual Mackenzie River runoff during 1973-89 at Arctic Red River (a city on the Mackenzie R.). (Data courtesy of R. Lawford.) b) Salinities at 1 m over the southeastern Beaufort Sea continental shelf (in subregion B_1) for July, August and September during 1950-87 (from Fissel and Melling 1990). c) Low-pass filtered ice anomalies in the Beaufort Sea.


SEA-ICE CONCENTRATION IN TENTHS
1
4-6
7-9
10
a)
ANN. MEAN
CL. 53-88
75N
60N
45W
75W
b)
ANN. MEAN
1985
75N
60N
45W
75W
c)
ANN. MEAN
1987
75N
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45W
75W

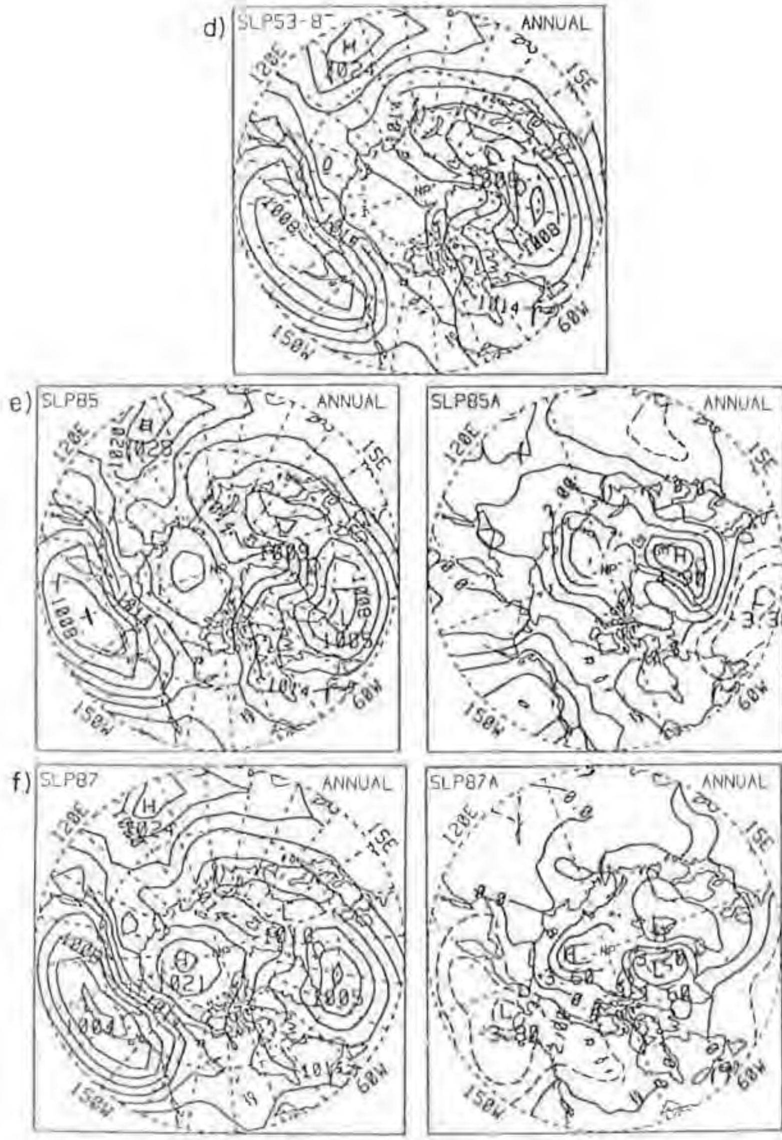


FIGURE 4 a) Annual mean climatology of sea-ice coverage in the Arctic Ocean and marginal seas for 1953-88 (from Mysak and Wang 1991). The centre of the black band to the east of Greenland, say, is regarded as the position of the 'ice edge' in the Greenland-Iceland Sea. b) As in a) but for 1985 (ie, average of monthly SIC data for Jan. 1985 to Dec. 1985). c) As in b) but for 1987. d) Annual mean climatology of sea-level pressure (SLP) field poleward of 45°N for 1953-87 (from Mysak and Wang 1991). Contour interval is 2 mb. e) Left, as in d) but for 1985. Right, anomaly field of the 1985 SLP shown at left expressed as departures from the climatology in d). Contour interval is 1 mb. f) As in e) but for 1987.

pressure anomaly cell over the western Arctic, whose associated (anomaly) winds, in the absence of other factors, would have tended to produce ice convergence, resulting in lower ice concentrations in the coastal region of the Beaufort Sea since the ice motion would tend to be a few degrees to the right of the local wind vectors. However, in reality the SIC was above average along the coast, which signifies that runoff-induced ice formation (Manak and Mysak 1989) dominated the aforementioned wind-driven effect.

From a comparison of Fig. 4c and 4a we see that during 1987, two years after the positive anomalies in the western Arctic could have been advected into the Greenland-Iceland Sea via the BG and TDS (see line L_4 Fig. 2b and section 4), the ice edge in the Greenland Sea (i.e., north of Jan Mayen) is much further south than in climatology. We also note that the SIC is considerably reduced in the Beaufort Sea. During 1987 there was also a high pressure anomaly cell over the Greenland-Iceland Sea (Fig. 4f), whose associated winds would have tended to drive the ice edge *toward* the east Greenland coast. Remarkably, however, this process did not create a negative ice-extent anomaly in the Greenland-Iceland Sea. Thus we conclude that the ice enhancement processes in the Arctic basin (especially that due to runoff) were sufficiently strong to produce enough ice there which when exported into the Greenland-Iceland Sea, dominated the wind-driven effects.

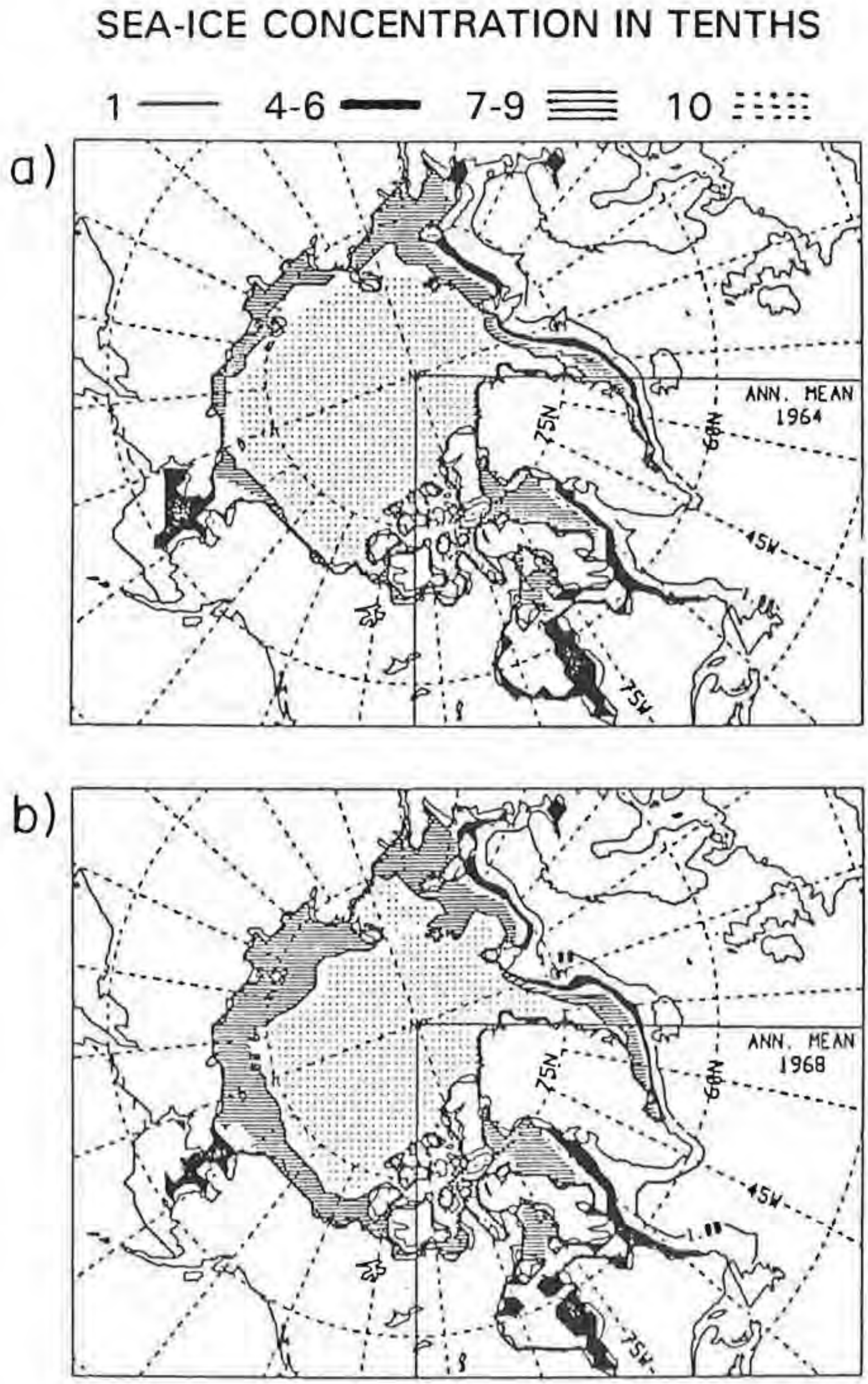
In the case of the late 1960s GSA, runoff and wind-driven effects appeared to have worked together in creating the large ice anomalies, first in the western Arctic and then in the Greenland-Iceland Sea. Fig. 5a shows a nearly solid ice cover in the western Arctic during 1964 (a very large runoff year) which could, however, also have been partly caused by the weak low pressure anomaly cell over this region (see Fig. 5c, right) because the associated anomaly winds in this case would have produced ice divergence, i.e., driven the thick, multi-year ice in the central Beaufort Sea toward the coast. Similarly, during 1968 the extensive sea-ice cover in the Greenland-Iceland Sea could have been partly created by the anomaly winds associated with the high pressure anomaly cell whose centre is to the west of Iceland (Fig. 5d, right), as originally proposed by Dickson *et al.* (1975). We also note here that the winds associated with the mean annual SLP field for 1967 (Mysak and Wang 1991) would have driven the thick multi-year ice north of Greenland into the TDS which could have added to the large sea-ice extent seen in Fig. 5b (as first suggested by Walsh and Chapman (1990a)). The fact that the 1968 ice volume anomaly in the Greenland-Iceland Sea is at least 200 km^3 (versus about 100 km^3 for the Beaufort Sea ice anomaly - see Fig. 2b) further confirms that the regional winds were an important contributor to the large sea-ice anomalies seen in subregion D_1 at that time.

Clearly, further research is required to sort out the relative importance of the different mechanisms that generate GISAs. Also, the fact that the atmospheric circulation over the Greenland-Iceland Sea during the peak of the late 1960s GSA was different than that during the 1980s GISA indicates the possible importance of lower latitude influences. Work on this problem is currently in progress at McGill University (D. Holland, *pers. comm.*, 1992) where an atmospherically driven coupled ice-ocean model of the Arctic and North Atlantic is being run to test the efficacy of the different ice generation and forcing mechanisms described above.

Critics of the interdecadal Arctic cycle theory proposed by M and now embodied in Fig. 1 often argue that anomalies in the runoff from the Siberian rivers, whose total climatological discharge is four to five times that of the Mackenzie (Aagaard and Carmack 1989), should contribute substantially to the formation of GISAs. It is countered here that, because of the very wide and shallow Eurasian shelf, any anomalies from this runoff get well mixed on the shelf with central Arctic Ocean waters that flow up onto the shelf. After mixing due to eddies and convective overturning, the waters near the edge of the shelf then tend to slide down into the intermediate Atlantic layer of the Arctic (Coachman and Barnes 1962) and hence do not directly affect ice formation at the surface. Also, as pointed out in M, during the years of peak runoff from North America in the mid-1960s, the Siberian runoff was near normal or below normal (Cattle 1985), and hence could not have added to the fresh water anomalies that made up the GSA.

Other possible weaknesses of the feedback loop in Fig. 1 are the following two links. First, that strong convective overturning during winter in the Iceland Sea (a process which would create positive SST anomalies because of the warm Atlantic water being brought to the surface, and hence cause increased heat fluxes to the atmosphere in this region and, because of ocean advection of the SST anomalies, also cause increased heat fluxes in the Irminger Basin) would produce strong cyclogenesis around Iceland (see left side of Fig. 1). Secondly, that such cyclogenesis would contribute to increased precipitation and runoff in northern Canada (see upper left and top part of Fig. 1). At this stage we cannot easily verify the first link; however, an examination of winter SLP maps for the years just before the GSA suggests how greater precipitation (and hence runoff) in northern Canada could have resulted from a change in the position and structure of the Icelandic Low. We also suggest that the occurrence of this latter link is consistent with the recent 'teleconnection' results of Walsh and Chapman (1990b). They showed that the winter SLP anomalies in the Iceland Sea and Irminger basin are highly correlated ($0.6 \leq r \leq 0.8$) with those at the 'base point' 75° N, 90° W in the Canadian Arctic Archipelago (CAA) (see their Fig. 12b).

From the orientation of the isobars on the northern side of the climatological Icelandic Low (Fig. 6a), we observe that cold dry air would tend to flow southward from the eastern Arctic into the Greenland Sea, then westward across Greenland and finally southward over the CAA and Hudson Bay. (Although the Greenland ice sheet is about 2 km above sea level, since the troposphere is over 10 km thick in this region one would expect at least some of the low-level flow around the Icelandic Low to pass over the ice sheet.) Similarly, on the western side of the CAA there would tend to be a northerly flow of cold


SEA-ICE CONCENTRATION IN TENTHS
1
4-6
7-9
10
a)
ANN. MEAN
1964
75N
60N
45W
75W
b)
ANN. MEAN
1968
75N
60N
45W
75W

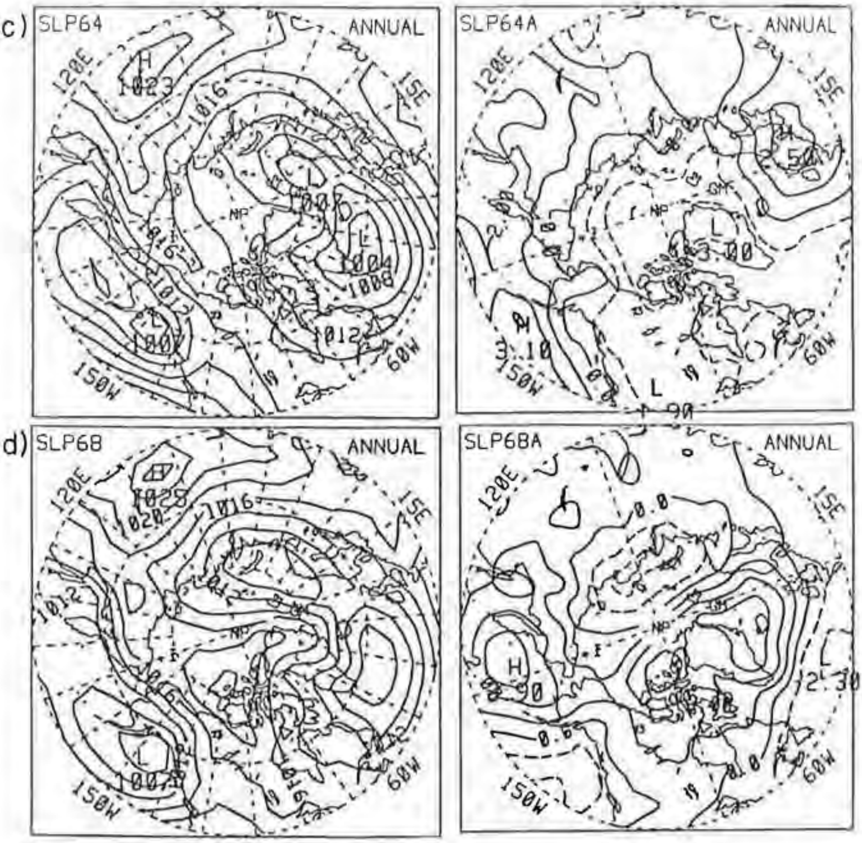


FIGURE 5 a) As in Fig. 4b but for 1964. b) As in Fig. 4b but for 1968. c) As in Fig. 4e but for 1964. d) As in Fig. 4e but for 1968.

dry air from the Arctic High region in the western Arctic. Taken together we would thus expect fairly low precipitation and runoff in northern Canada. During winter 1961 the Icelandic Low and the Arctic High both intensified, but there was little change in their positions or in the orientation of their isobars (see Fig. 6b). Thus we would have expected even more cold dry air over northern Canada and consequently, very low precipitation and runoff into the Arctic Ocean and Hudson Bay. The latter was indeed observed during 1961 - see Fig. 17 in M.

Figure 6c on the other hand shows that quite a different situation occurred with respect to the SLP pattern during winter 1964 (the year of maximum runoff), presumably because of changes in the ocean-to-atmosphere heat fluxes around Iceland. The Icelandic Low broke up into two lows (see Fig.

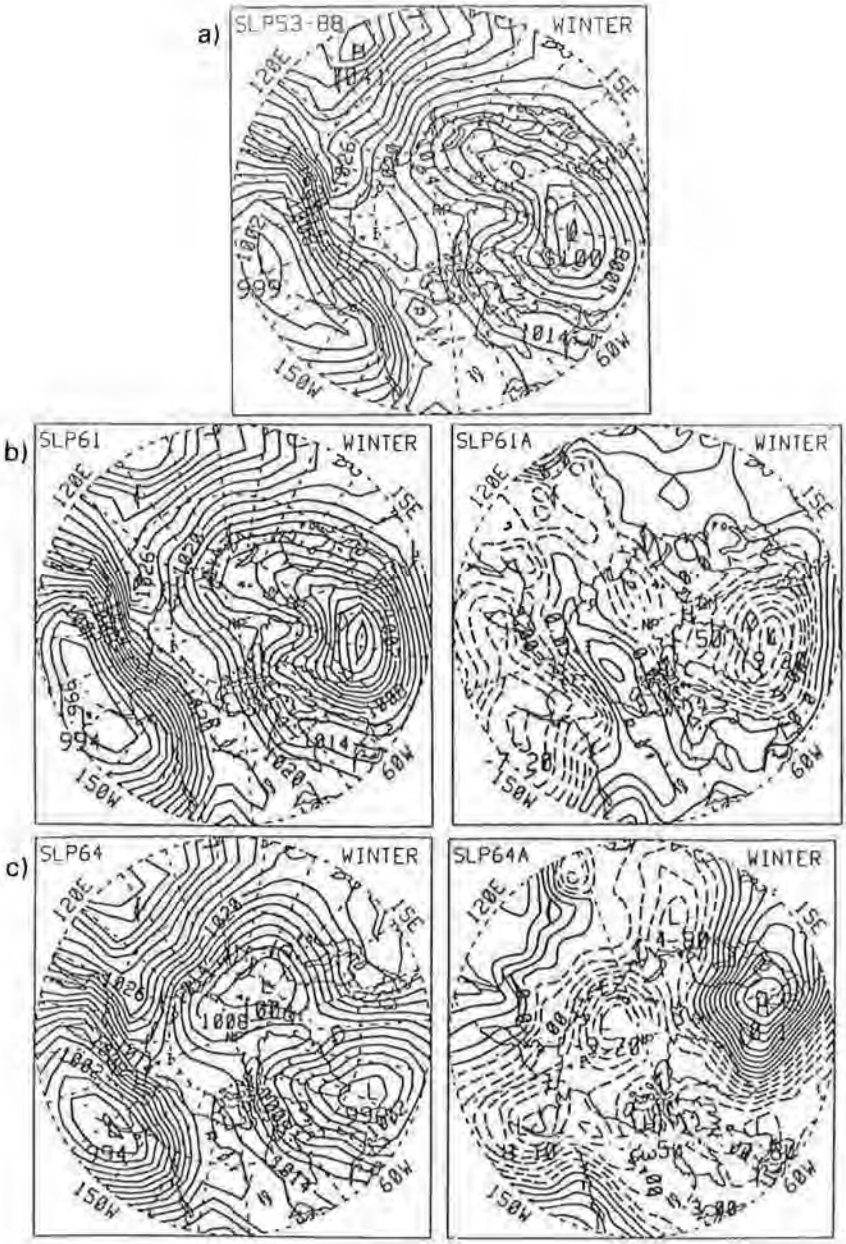


FIGURE 6 a) Winter (Dec., Jan., Feb.) mean climatology of SLP field poleward of 45°N for 1953-88 (from Mysak and Wang 1991). Contour interval is 2 mb. b) Left, as in a) but for 1961. Right, anomaly of winter 1961 SLP field shown at left expressed as departures from the climatology in a). Contour interval is 1 mb. c) As in b), but for 1964.

6c, left), with the centre of the main (southern) low being located south of Greenland. Also the orientation of the isobars south of Iceland implies that warm moist air from west of the United Kingdom, where the sea-surface temperatures (SSTs) are typically 10°C, would have been transported across and around southern Greenland and over to the CAA and Hudson Bay, and hence would have caused heavy precipitation and large runoffs there, as observed (Fig. 17 in M). The existence of such easterly anomaly winds around the southern end of Greenland when the main centre of the Icelandic Low shifts southward has also been noted by Dunbar and Thomson (1979). At the same time, it is interesting to note that the Aleutian Low intensified and its centre shifted westward during winter 1964, which would have also brought warm moist air from the Pacific into the western part of northern Canada (see Fig. 6c, right) and hence contributed to the large runoff. Remarkably, a similar situation regarding the SLP pattern also occurred during winter 1965 (Mysak and Wang 1991), which was another year of high runoff (see Fig. 17 in M).

It is now instructive to compare the above SLP patterns with those that occurred during the winters of 1968-70, the peak GSA years when convective overturning was suppressed in the Iceland Sea and the SST anomalies were negative (see Fig. 6 in M). During these winters, there were strong northerly flows of cold dry air along the east coast of Greenland (Dickson *et al.* 1988; Mysak and Wang 1991) *and* a high pressure anomaly cell over the CAA (this can also be seen in Fig. 5d, which shows the annual SLP field and its anomalies for 1968). As a consequence, a higher incidence of *anticyclones* over the CAA would have been expected, and indeed this was the case (Serreze *et al.* 1992). Also, this would imply lower runoffs in northern Canada at that time; this was certainly the case for the Mackenzie River in 1969 and 1970 (see Fig. 21 in Tyler 1992).

Just before the time of the most recent GISA, a sequence of SLP patterns similar to those in the mid-1960s also occurred. The patterns of the winter 1985 and 1986 SLP maps (Mysak and Wang 1991) imply that warm moist air from the southeast of Greenland would have been transported across southern Greenland and into northern Canada, causing heavy precipitation and large runoffs, as observed (Fig. 3a). As more data becomes available it will be interesting to examine the evolution of the SLP fields and runoffs during the late 1980s (peak GISA years), to see if that was also a period of more anticyclones and lower runoffs in northern Canada.

4. LAGGED CROSS-CORRELATION ANALYSIS OF SUBREGION ANOMALIES

From the sloping lines L_i in Fig. 2b, we note several cases in which both positive and negative ice anomalies appear to propagate from the Beaufort Sea through to the Greenland Sea, with a travel time of the order of 2-3 years. It thus is worthwhile to perform a lagged cross-correlation analysis of the ice anomalies in the subregions linking these two seas. The procedure we follow is similar to that

TABLE 1: Maximum lagged cross-correlation coefficients (r) for smoothed areal sea-ice anomalies in subregion B_1 (see Fig. 2a) versus those in subregions B_2, B_3, B_4, D_1, D_2 and D_3 (first line). The lag at each maximum correlation is given in the second line. The 95% significance level is estimated to be approximately $r = 0.3$ for simultaneously correlated data, rising to 0.36 for data sets lagged up to 120 months.

	B_2	B_3	B_4	D_1	D_2	D_3
r_{max} (with B_1 leading)	0.27	0.33	0.53	0.40	0.27	0.21
lag (months) at r_{max}	2	5	28	27	36	39

used by M, who studied the movement of smoothed Greenland-Iceland Sea ice anomalies into the Labrador Sea via five subregions (see their Figs. 2 and 3). Later in this section we shall also present the results of cross-correlation calculations for other subregions which yield a picture of the ice anomaly advection pattern for the whole Arctic Ocean and its marginal seas. However, it should be pointed out that not all anomalies are created in the western Arctic and then propagate out into the Greenland-Iceland Sea. For example, the large negative ice anomalies centred around 1984 in subregions B_4 and D_1 were likely caused by the anomalous winds associated with the 1984 SLP pattern over the eastern Arctic (see Fig. 14 in Chapman and Walsh 1991) which would have tended to push ice in the TDS over towards the north of Greenland.

In the first phase of the analysis, the lagged cross-correlation functions were computed for the low-pass areal ice anomalies in subregion B_1 versus those in the subregions B_2, B_3, . . . D_3, a sequence which follows the mean ice drift from the Beaufort Sea through to the Labrador Sea. These functions were next examined for asymmetries about the zero-lag to determine direction of anomaly advection (Chapman and Walsh 1991; see also Fig. 4 in M). The maximum lagged correlation coefficients obtained from this analysis are given in Table 1. To find the 95% significance level for the correlations, the number of degrees of freedom (for simultaneously correlated data) was first estimated to be $2N/30 = 29$, where $N = 432$ (total number of months of data) and 30 is the high-frequency cutoff. Then from Table 13 in Pearson and Hartley (1966), we obtained, using a one-tailed test for normally distributed data, a 95% significance level of approximately $r = 0.3$. This simple method for determining the significance level was deemed to be satisfactory when compared with results using the more sophisticated approach adopted by Power and Mysak (1992). For lagged cross-correlations, the number of degrees of freedom decreases with lag and the significance level for r slowly increases to 0.36 for a lag of 120 months. This is due to the fact that as the lag increases, less data are used in the calculation of the cross-correlations.

The results of Table 1 show that the low-frequency ice anomalies in B_1 lead those in the Greenland Sea (subregion D_1) by just over two years, which is consistent with the phase lines shown in Fig. 2b. Moreover, there appears to be a continuous advection of ice anomalies by the BG, the TDS and the EGC (East

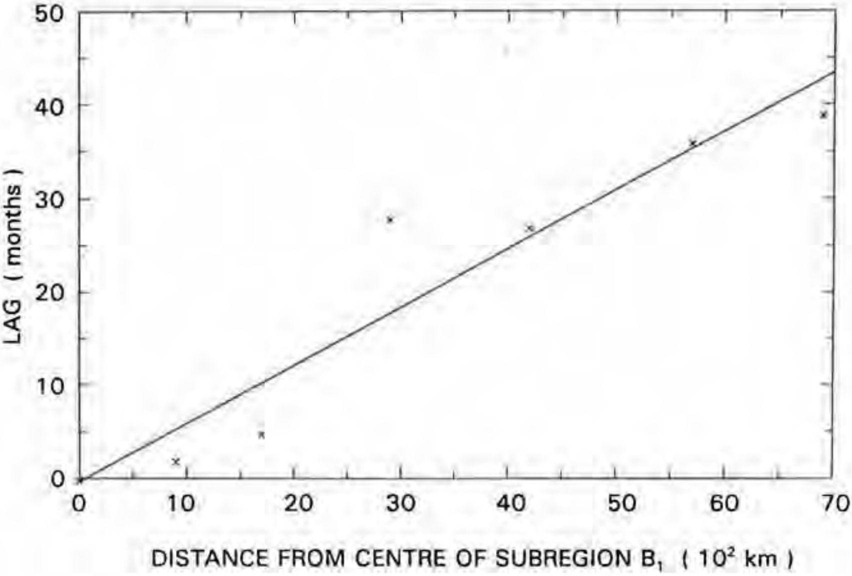


FIGURE 7 Best linear fit to the lag at maximum correlation (data from Table 1) versus distance from the centre of subregion B_1 to centre of subregion D_3 via the centres of subregions B_2, B_3, B_4, D_1 and D_2 (see Fig. 2a).

Greenland Current) all the way into the Labrador Sea. Although the maximum cross-correlations for data from B_1 versus D_2 and D_3 are not significant, the cross-correlations between the data from adjacent regions are significant (see Fig. 8b below) and thus support the above conclusion.

To estimate the average speed of advection of the ice anomalies from the Beaufort Sea into the Greenland Sea and beyond, a cumulative lag plot was constructed (Fig. 7). From the best linear fit to the data, we find an average advection speed of about 2000 km/yr, or roughly 5 km/day, which lies well within the range of typical drift speeds for sea ice, namely 1 - 10 km/day (Chapman and Walsh 1991).

Chapman and Walsh (1991) determined the monthly ice anomaly drift pattern for the whole Arctic (Fig. 8a) by computing the lagged cross-correlation functions for data from adjacent US Navy/NOAA Arctic subregions (indicated by the heavy lines in Fig. 8a). These differ from those defined in Fig. 2a as follows: The Navy/NOAA Arctic Ocean subregion approximately consists of the union of B_1 to B_5; their Southern Baffin Bay subregion consists of D_3 and D_4; and their Bering Sea consists of S_1 and S_2. On the other hand, the CAA subregion in Fig. 2a has been subdivided into West Canada and East Canada in the Navy/NOAA scheme. However, even with these differences it is possible to make a comparison of the Chapman and Walsh ice anomaly drift pattern with

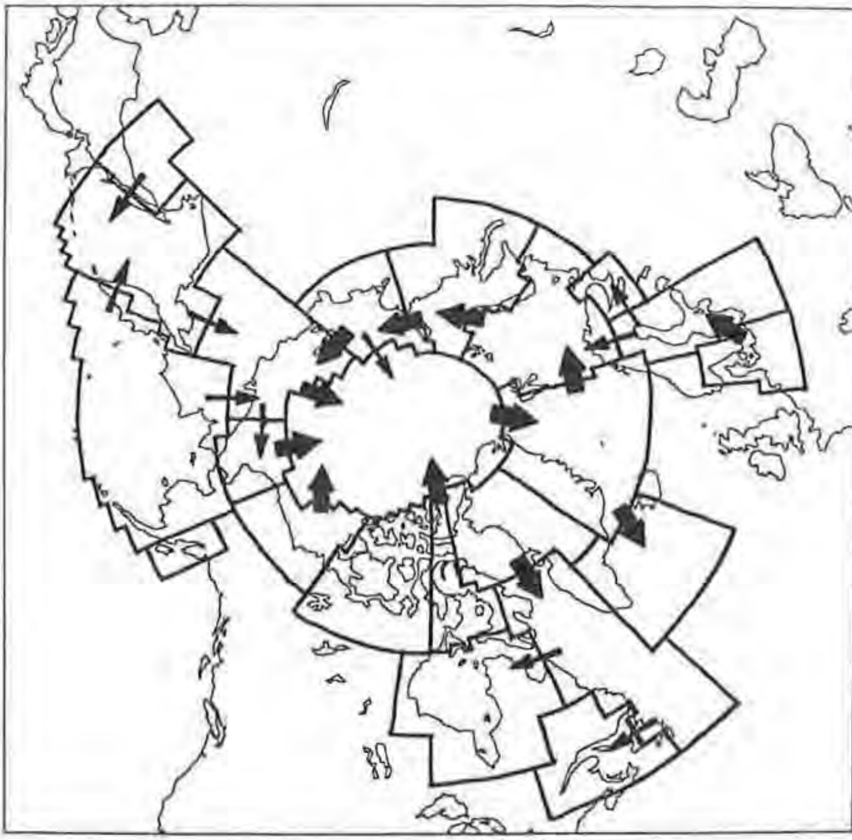


FIGURE 8a Ice anomaly advection pattern derived from asymmetries about zero-lag of cross-correlation functions computed using monthly data from adjacent US Navy/NOAA Joint Ice Center standard subregions (from Chapman and Walsh 1991). Large (small) arrows connect adjacent subregions for which cross-correlations at lags +1 (month) and −1 differ by more than 0.12 (0.06). Arrows point in direction of advection implied by asymmetry.

that obtained here (Fig. 8b), which is based on the cross-correlations between the low-pass filtered time series from the subregions in Fig. 2a.

First, we note from Fig. 8a that the monthly ice anomalies in the Beaufort Sea also appear to propagate all the way to the Irminger Basin (subregion D_2), as was found for the low-pass anomalies (Figs. 7 and 8b). However, the lack of resolution for the Labrador Sea region in the Navy/NOAA scheme probably accounts for the absence of anomaly propagation from the Irminger Basin into this region. In both patterns we observe an eastward drift of the anomalies along the Eurasian shelf; however, we note that the subregion S_3 (Chukchi Sea) appears to be a *source* region for the low-frequency anomalies (see Fig. 8b). Other notable differences are the propagation of low-pass filtered

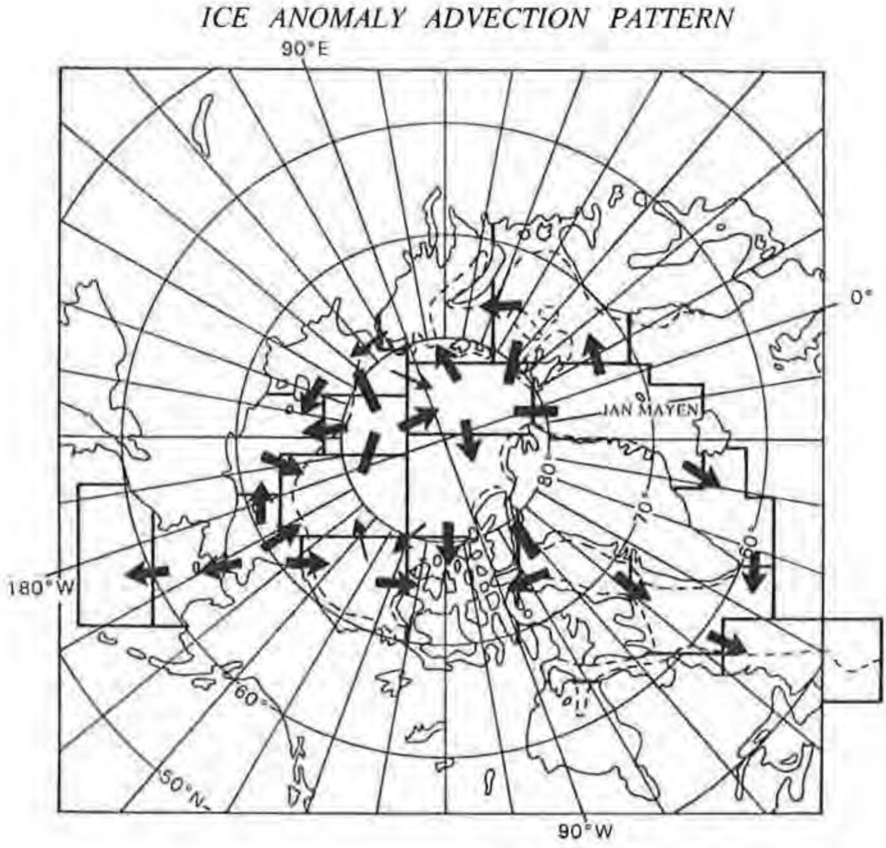


FIGURE 8b As in a) except based on cross-correlation functions using low-pass filtered data from subregions in Fig. 2a. However, in this figure a large arrow connects two subregions for which the maximum of the (asymmetric) lagged cross-correlation is significant at the 95% level. A large bar connects two subregions for which the cross-correlation function is symmetric about zero-lag, at which, however, the anomalies are significantly correlated. A small arrow connects two subregions for which the maximum of the lagged cross-correlation coefficient $r \geq 0.15$, but is not significant.

anomalies from the Chukchi Sea into the Bering Sea; from the Beaufort Sea into the CAA; and from the subregions B_5 and BB into the CAA. No significant such correlations were found by Chapman and Walsh, which suggests that at relatively low frequencies there may be important 'teleconnections' between these subregions. The Chukchi-Bering Sea connection is reminiscent of the results of Power and Mysak (1992) who found that the teleconnection between the western Arctic SLP anomalies and those in the Pacific became more pronounced at longer periods (greater than five years).

Another interesting relationship found in the cross-correlation analysis of the low-pass filtered anomalies is that the fluctuations in Hudson Bay significantly lead those in the Labrador Sea. (Since these two regions are separated by Hudson Strait, no connecting arrow is shown in Fig. 8b.) Chapman and Walsh, however, found that the monthly ice anomalies in the Labrador Sea slightly lead those in the Hudson Strait-Hudson Bay region (see Fig. 8a).

5. POSSIBLE CONNECTIONS OF GISAs WITH LOWER LATITUDE INTERDECADAL VARIABLITY

In reality it is quite likely that the interdecadal Arctic climate cycle depicted in Fig. 1 may be connected to lower latitude decadal-scale fluctuations in the atmosphere and oceans. This idea is in part supported by the findings of Power and Mysak (1992) who showed that statistically significant associations exist between Arctic and extratropical SLP fluctuations, especially at periods of several years. In the way of connections there are at least three possibilities: 1) The Arctic cycle triggers lower latitude fluctuations. 2) Lower latitude variations influence or excite some of the processes involved in the feedback loop shown in Fig. 1. 3) There are lower latitude decadal-scale fluctuations that co-exist with the interdecadal Arctic climate cycle. We now expand on each of these cases.

5.1 The Arctic as a trigger for lower latitude fluctuations

Because the Greenland Sea is weakly stratified, the waters there are "delicately poised with respect to their ability to sustain convection" (Aagaard and Carmack 1989). Hence these authors have argued that a modest increase in the supply of fresh water from the Arctic could reduce convection in the Greenland Sea. However, it is not believed (R. Dickson, *pers. comm.* 1992) that this occurred during the time of the GSA. It was only in the Iceland Sea to the south that convection was suppressed during the early years of the GSA.

However, it is conceivable that alternating periods of extensive and reduced ice cover in the Greenland-Iceland Sea, which are respectively accompanied by relatively cold and warm upper-ocean temperatures (see Fig. 6 in M), could result (via advection) in decadal-scale SST anomalies in the southwestern part of the subpolar gyre (Mysak 1991). It is important to determine the origin of such SST anomalies since they generate significant large-scale disturbances in the overlying atmosphere (Palmer and Sun 1985) and also appear to influence runoff in western Siberia (Peng and Mysak 1992).

From Fig. 9, which depicts the time-longitude evolution of SST anomalies averaged over a mid-latitude band in the North Atlantic, we clearly see the existence of alternating cold and warm periods in the northwestern Atlantic, i.e., at around 30° W. Along the time axis, the sequence of solid and dotted lines indicates respectively, large and small (or near-normal) sea-ice extents in the Greenland and Iceland Seas. In several cases, we observe that heavy ice conditions (large sea-ice extents) precede negative SST anomalies in the

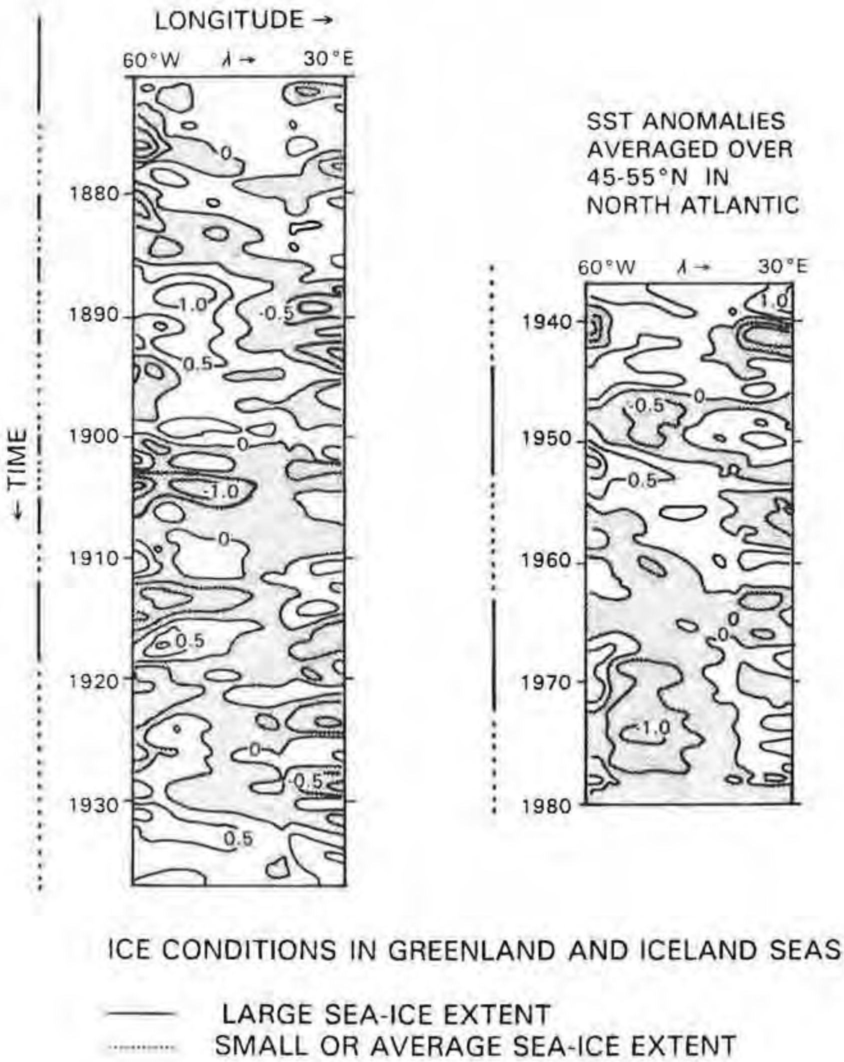


FIGURE 9 Low-pass filtered and de-trended SST anomalies in the latitude band 45-55°N as a function of time and latitude in the North Atlantic and Baltic Sea (from Bryan and Stouffer 1991). Solid and dotted lines next to the time axis indicate, respectively, periods of relatively large and small (or near normal) sea-ice extents in the Greenland and Iceland Seas as estimated from data shown in Figs. 3, 10 and 15 in Mysak *et al.* (1990).

northwestern Atlantic by approximately 5 years (the advection time from the Greenland-Iceland Sea to this region via the subpolar gyre), and similarly, light ice conditions in the Greenland-Iceland Sea precede positive SST anomalies, also by about 5 years. While the correspondence between heavy (light) ice conditions and relatively cold (warm) SSTs in the northwestern Atlantic is not completely one-to-one, the relationship is sufficiently encouraging to warrant further investigation. It is also relevant to point out here that the most prominent interdecadal periodicity associated with the ice anomalies in the Greenland-Iceland Sea, as determined from the spectrum of the 375-year Koch ice index for Iceland, is 27 years (Stocker and Mysak 1992).

Another way in which Arctic sea-ice changes could cause lower latitude climate variability is via the surface albedo: anomalously large sea-ice extents increase the albedo and *vice versa*. However, the changes in ice area on decadal time scales, as opposed to those due to the seasonal cycle, are only of the order of a few percent (Mysak and Manak 1989), and therefore are unlikely to induce very large changes in the Arctic energy budget, which impacts upon the energy budget of the middle latitudes via the circulation in the troposphere. On the other hand, the southern hemisphere sea-ice cover, because it is thinner and closer to the equator, may show larger changes on the decadal time scale. Thus the discussion of decadal-scale Arctic albedo changes should be done in concert with studies of the natural variability of the south polar region.

5.2 Forcing from the lower latitudes

The second possibility, that lower latitude interdecadal fluctuations excite similar-scale Arctic climate changes, is the more traditional and widely accepted viewpoint. There have recently been many observations of interdecadal variability at middle and tropical latitudes in the climate system (for a list of references, see Weaver *et al.* 1991). Many investigators believe that these fluctuations may be due to internal oscillations in the thermohaline circulation (THC), an idea that goes back to Bjerknes (1964). Remarkably, climate modellers have shown that these THC oscillations can occur even in the presence of steady atmospheric forcing (for example, see Weaver *et al.* (1991) and the references therein). Such oscillations would produce fluctuations in the oceanic poleward heat transport and hence cause changes in surface air temperature at locations where the THC 'ventilates' - in the northern North Atlantic and in the Southern Ocean. Such poleward heat transport changes in the North Atlantic, which could also have contributed to the SST anomalies seen in Fig. 9, have recently been observed by Greatbatch and Xu (1992). They found increased transports at 54.5°N in the 1950s and reduced transports in the 1970s, which correspond the warm and cold SSTs seen at these times in Fig. 9.

In the recent study of Higuchi *et al.* (1991), it was shown that the standing eddy poleward heat transport in the lower troposphere in the northern hemisphere exhibits strong decadal-scale variability. In particular, in years of very large (weak) transports, they found that the ice margin in the Greenland Sea is substantially reduced (expanded). Thus the atmosphere in this case is the medium which can transmit lower latitude decadal-scale signals into the Arctic region and possibly alter the circulation there. This concept is certainly consistent with the aforementioned fact (section 3) that the SLP anomalies over the Greenland Sea in 1968 (peak GSA year) and in 1987 (peak GISA year) were quite different and hence could have been due to lower latitude variabilities, independent of air-sea interactions around Iceland (see also Dickson and Namias 1976).

5.3 Co-existing Arctic and lower latitude fluctuations

The third possibility, that polar and lower latitude decadal-scale climate fluctuations may simply 'co-exist', is suggested by the spatial structure of the third empirical orthogonal function (EOF) of SST anomalies that has been computed by Folland *et al.* (1986a) (see bottom of Fig. 10, which also shows for comparison the first 'global warming' EOF and the second 'ENSO' EOF - see Bryan and Stouffer, 1991). Note that the largest amplitudes of the third EOF, whose temporal fluctuations have an interdecadal time scale, are in the northeast Pacific, the northwest Atlantic and in a broad band over the South Atlantic and South Indian oceans. This high-latitude amplification suggests as well, perhaps, that the global THC (the 'conveyor belt') may be a connecting link since the latter is driven by deep water formation in both the North Atlantic and the Southern Ocean. As an aside, Folland *et al.* (1986b) found that such decadal-scale SST fluctuations were closely linked with rainfall changes in the Sahel.

The particularly large gradients in the northeast Pacific and northwest Atlantic seen in the third EOF of Fig. 10 also indicate that these areas could be closely tied in with interdecadal variability in the Arctic. Walsh and Chapman (1990b) showed that monthly Arctic SLP fluctuations in winter are associated or 'teleconnected' with SLP changes in the northern North Atlantic. In a continuation of this study using data from all seasons, Power and Mysak (1992) found that at low frequencies (periods longer than five years), this teleconnection pattern persists. But they also discovered a new teleconnection pattern between centres in the Arctic and the North Pacific. However, neither of these statistical studies can address the question of cause and effect, and therefore, these patterns have to be taken as starting points for further research on the global connections of interdecadal climate variability in various regions.

6 SUMMARY AND CONCLUDING REMARKS

We have shown that during the late 1980s a Great Ice and Salinity Anomaly (GISA) in the Greenland-Iceland Sea was most likely generated remotely by prior above-average runoffs into the western Arctic Ocean. Similarly, large runoffs also occurred from North America into the Arctic a few years prior to the late 1960s peak of the GSA. However, unlike in the case of the GSA, when regional atmospheric forcing also contributed to its generation, the wind anomalies associated with the SLP fields during the 1980s GISA would have tended to *oppose* the formation of large sea-ice extents in the Greenland-Iceland Sea.

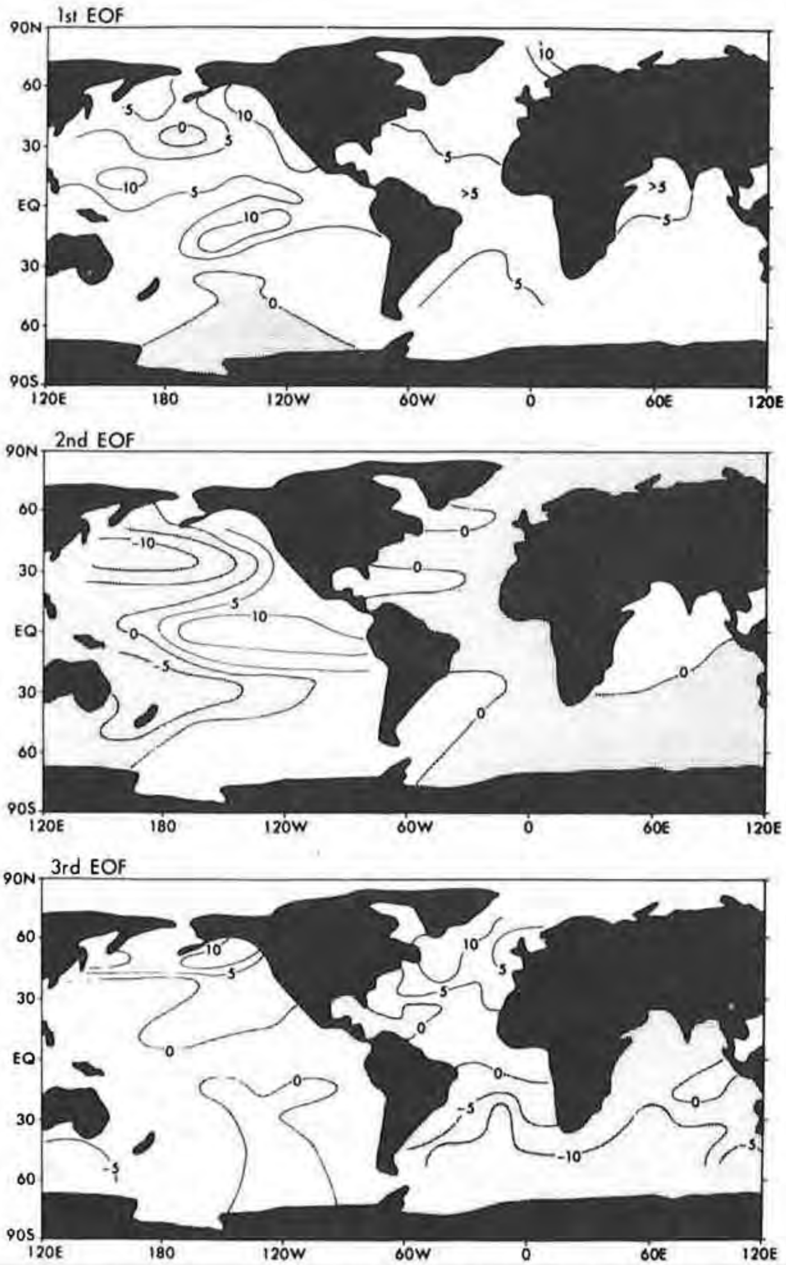


FIGURE 10 The first three empirical orthogonal function (EOF) patterns of SST calculated for the period 1901-80 from the British Meteorological Office file (from Bryan and Stouffer 1991, who contoured and re-plotted the 10° × 10° EOF values originally computed by Folland *et al.* (1986a)).

A lagged cross-correlation analysis of 36 years of low-pass filtered SIC data from various subregions in the Arctic and marginal seas revealed that ice anomalies are advected in a manner similar to that found by Chapman and Walsh (1991) who used monthly (unsmoothed) data. However, some differences were found; for example, we showed that the Chukchi Sea appears to be a source region (a 'factory') for low-frequency ice anomalies.

While many of the above results are encouraging in so far as they lend further support for the existence of the interdecadal Arctic climate cycle proposed by M and now described in Fig. 1, more work is required. For example, we have undoubtedly invoked an oversimplified view of runoff-shelf water-ice interactions in the Beaufort Sea. Macdonald and Carmack (1991) have recently examined these interactions in some detail, and certain aspects of their results could be incorporated into the feedback loop shown in Fig. 1. Secondly, with only 36 years of SIC data available at the time this research work was done, there are some concerns regarding the statistical significance of the cross-correlation results using low-pass filtered data. In a few years, more than 40 years of SIC and SLP data will be available and thus it would be of considerable interest at that time to update the analysis described in section 4. Recently, Chapman and Walsh (1992) have analyzed 38 years of SIC data up to 1990 and showed, among other things, that the recent GISA definitely had its peak in 1987-88 (see their Fig. 7a).

Finally, we have made a number of speculative comments regarding the possible connections between a) cyclogenesis around Iceland and runoff in northern Canada (section 3), and b) GISAs and lower latitude interdecadal climate variability (section 5). While these remarks should be treated as tentative, it is nevertheless hoped that they will serve as a guide for further studies of regional and global interdecadal variability in the climate system. It is clear, however, that to derive statistically significant results from such studies, we shall need long records of various climate or proxy climate variables, and hence it is important that we develop and support long-term observational climate projects in the Arctic.

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Climatic Variability and Air Quality in the Great Plains of North America

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ABSTRACT

Drought and dust are common companions in the Great Plains, with elevated dust levels occurring during dry periods. Measurements of total suspended particulates (TSP) at Canadian and U.S. sites during the 1970's and 1980's show the extent of particulate increases during several dry periods.

Dry periods are more common than wet periods in this region. Furthermore, past experience shows that warmer periods tend to be drier. As many climatologists predict warmer temperatures in the next fifty years, there is a concern about increasing dryness as well. This study considers the potential for increased dust levels in the Great Plains, including possibly unhealthy values of respirable particulates. By analyzing past TSP records associated with dry periods, a range of potential dust level increases is estimated for a warmer Great Plains region.

RÉSUMÉ

La sécheresse et la poussière visitent souvent les Grandes plaines; le taux de poussière dans l'air y est élevé durant les périodes de sécheresse. Le calcul du nombre de particules suspendues (TSP) dans diverses stations du Canada et des États-Unis durant les années 70 et 80 démontre que le nombre de particules augmente en période de sécheresse. Les périodes de sécheresse sont plus fréquentes que les périodes d'humidité dans cette région. De plus, des observations antérieures démontrent que les périodes de chaleur ont tendance à être plus sèches. Et, comme plusieurs climatologues prévoient une élévation des températures dans les cinquante prochaines années, il y a lieu de s'inquiéter également de l'augmentation du nombre de périodes de sécheresse. Cette étude envisage la possibilité d'une augmentation du taux de poussière dans l'air des Grandes plaines et, peut-être, un coefficient plus élevé de particules qui présentent un danger pour la santé. A partir de l'analyse des données sur les TSP durant les périodes de sécheresse, nous avons calculé une échelle de variations du taux de poussières advenant un réchauffement des Grandes plaines.

INTRODUCTION

One aspect of the global-warming issue of concern to both Canada and the United States is the question of how air quality responds to rising temperatures.

The air quality of the Great Plains of North America has always been thought to be good. Clear skies are considered typical, except for the occasional duststorm, from Texas through the prairie provinces of Canada. This study suggests, however, that global warming may lead to more frequent droughts, duststorms, and unhealthy levels of particulate air pollution over the Canadian prairies and the Great Plains.

The U.S. Great Plains have often been described as a region of unreliable precipitation and highly variable climate, and even as a desert by some early settlers heading further west (Lawson, 1971). The Plains have suffered from numerous droughts and choking duststorms. Bark (1978) lists major drought periods in Nebraska from the thirteenth century to the 1950s, as derived from studies of tree rings. Other tree ring analyses from four areas of the Great Plains were used to reconstruct drought histories from 1700 to 1977 (Stockton and Meko, 1983). Droughts were estimated to last up to 38 years, with a mean periodicity of 16-19 years for the region.

Droughts have also plagued the Canadian prairies, the most drought-susceptible region in Canada. Early records of serious droughts go back to the early 1800's. Droughts in the Red River Settlement of Manitoba are mentioned in 1820 and 1868 (Jones, 1991). Numerous accounts of drought were also recorded in the late 1880's and 1890's. Serious precipitation deficiencies varied widely both in areal extent and in time over the agricultural area of the prairie provinces from the 1920's to 1970 (Chakravarti, 1976). A description of agricultural drought years from 1928 to 1980 by the Canadian Climate Centre (1986) similarly shows both the high temporal and spatial variability of these droughts, and their widely differing severities and impacts across the prairies. Louie (1986) reported that Palmer Drought Index values for the period 1951-1984 for Winnipeg and Regina show a high frequency of moderate to severe droughts.

PAST IMPACTS OF DROUGHT ON AIR QUALITY

Particulate air pollution is measured as the total suspended particulates (TSP) by the National Air Pollution Surveillance Network (NAPSN) in Canada, and by state and local networks in the U.S., under the guidelines of the Environmental Protection Agency (EPA), with 24-hour samples being taken every six days. TSP samples are taken using a High-Volume air sampler, which acts like a vacuum cleaner, pulling roughly 2 cubic meters of ambient air per minute through a fiberglass filter paper. The filter paper is weighed and concentrations of particulates are calculated by dividing the weight of particles by the volume of air sampled.

For the Canadian portion of this study, monitoring stations in 11 prairie cities were initially selected. However, only seven of these had a sufficiently long and continuous record for the study period, 1970-1989. These monitoring stations are all located in urban, commercial settings (Figure 1). The

FIGURE 1. The Great Plains of North America study area and locations of air quality monitoring stations.

TSP values for the 1970-1989 period demonstrate that dust levels vary from year to year (Table 1), but many locations show a peak in spring, in either April or May (Figure 2). Wheaton and Chakravarti (1990) found the same pattern for duststorms on the prairies. They comment that at this time of year plant cover is limited, and mean wind speeds are greatest; and since precipitation does not usually peak until June, soils can be dry in spring in years with low snowmelt. Tillage of the farm fields can further loosen soil particles and decrease vegetative cover.

U.S. Great Plains TSP data cover only the 1980-1989 years, as

Table 1: Average Dust Levels (TSP, $\mu g/m^3$) for Canadian Prairies Cities, 1970-1989*

	Winnipeg	Brandon	Regina	Saskatoon	Moose Jaw	Edmonton	Calgary
1970-79	80		67	94	80	111	120
1980-89	71	42	48	44		74	92
MAX(YR)**	95(81)	83(74)	84(77)	130(77)	99(76)	159(76)	159(80)
MIN(YR)**	57(86)	28(86)	38(85)	35(85)	36(86)	52(85)	59(85)
1980	78	58	62	53	66	100	159
1981	95	55	64	64	70	102	149
1982	64	40	48	54	56	75	117
1983	66	43	42	-	51	64	81
1984	82	41	41	46		71	71
1985	71	30	38	35	40	52	59
1986	57	28	—	36	36	84	77
1987	69	39	53	41	43	72	85
1988	73	38	44	41	-	60	75
1989	56	42	39	39	—	63	69

*Data from the Environment Canada, National Air Pollution Surveillance, Annual Summaries, 1970-1989, Air Pollution Control Directorate, Ottawa Samplers located at urban, commercial locations.

**The highest (MAX) and lowest (MIN) annual average TSP values for the entire 1970-1989 period.

relatively few monitoring sites had a long enough record to use for comparative analyses. Data was made available for the Plains states, Kansas through North Dakota, though most reliable records come from larger Plains cities. Consequently, only seven U.S. locations are included in the comparative statistics: Kansas City, Missouri; Omaha, Lincoln and N. Platte, Nebraska; Sioux Falls, South Dakota; Bismark and Fargo, North Dakota (Figure 1).

The 1976-1977 drought was the driest period for the eastern prairies since the 1930's. From July 1976 to April 1977, a dominant high pressure ridge along the west coast led to less than 50 per cent of normal precipitation and extremely low soil moisture (Figure 3) across the southern Canadian prairies, before heavy rains relieved the situation in Manitoba in May. However, Saskatchewan and Alberta remained dry through 1977. LaDochy and Annett (1982) studied TSP records from 1974-78 at the University of Winnipeg, where 24-hour samples were taken every three days, and found this ten-month period of 1976-77 to have the highest dust levels. TSP also were found to be lowest on days with precipitation and snow cover (47% of the 5-year average), and highest (135% of average) with no snow cover and no precipitation.

In 1980, severe drought struck the Plains and the prairies. In the central U.S., Kansas City experienced extreme drought and scorching temperatures from June to August. Many heat-related deaths occurred as temperatures reached 50 C in the central city (Wagner, 1980). TSP are measured at ten monitors throughout Kansas City, Missouri, though only nine had a long enough record for use in this study. Monthly TSP readings were significantly higher in 1980 than in 1977-79 or 1981 (Annett and LaDochy, 1983). TSP values

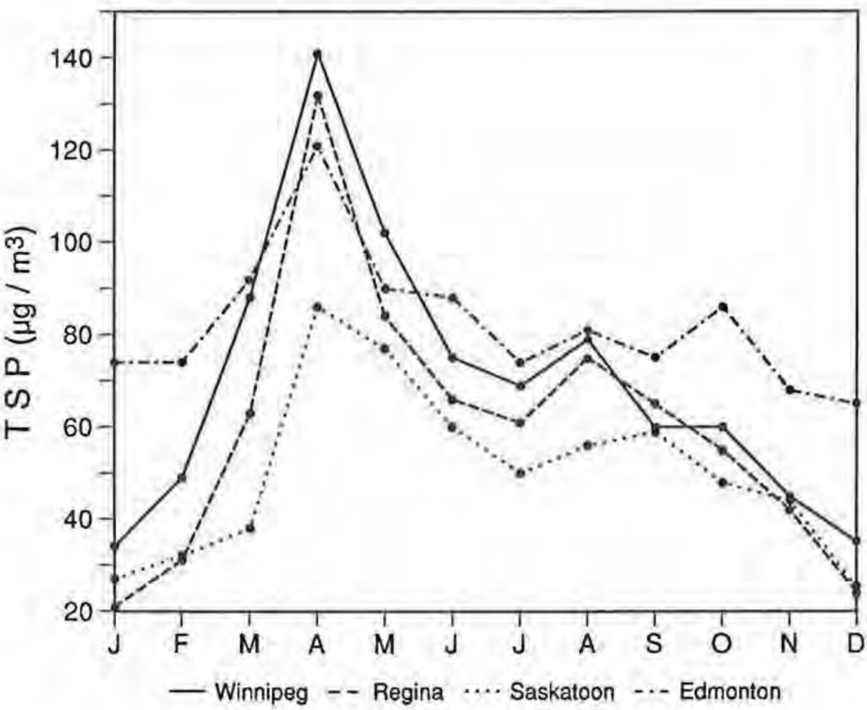

FIGURE 2. Monthly average dust levels (TSP, ug/m^3) for four Canadian prairie cities, 1980-1990. Source of data: Environment Canada, 1971-1989.

in Kansas City for the 1980s as a whole have also shown a clear relationship with precipitation (Annett, 1990). Wet periods had lower TSP, but snow cover did not produce as much dust reduction as in Winnipeg. Perhaps this is due to Kansas City's shorter snow season and higher levels of industrial activity. Omaha, Nebraska's 1980 annual average TSP was the highest for the 1980's at 147% of the decadal average, while other Great Plains cities also had elevated averages that year (Table 2).

In the Canadian prairies, drought continued from fall of 1979 through summer 1980 (LeCompte, 1981), with record heat in April and May leading to record losses from forest fires. Soil moisture reserves by May 1980 were at record low values in most places across the prairie provinces (Edey, 1980).

The year 1981 was dry again on the Canadian prairies and the northern U.S. Plains. Wheaton and Chakravarti(1990) studied 1977-85 on the Canadian prairies and found 1981 to be the peak year of the period in all three provinces, with 174 reports of duststorm conditions at the 31 stations which they reviewed. Many of these were massive storms that were reported at several of the

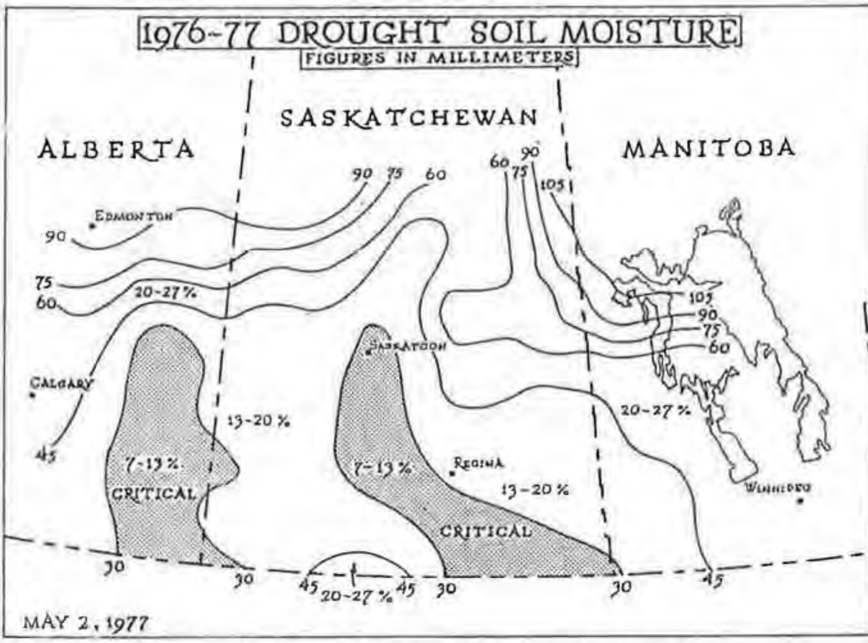

FIGURE 3. Soil moisture during the 1976-77 prairie drought in millimeters and per cent of capacity. From Edey (1977).

Table 2. Average Dust Levels (TSP, $\mu g/m^3$) for U.S. Great Plains Cities, 1980-1989.*

	K.C.[1]	Omaha, NE[2]	N. Platte, NE[3]	Lincoln, NE[3]	Sioux Falls, SD[3]	Bismarck, ND[3]	Fargo, ND[3]
80-89	58.4	53.6	46	-	-	-	-
80	81.9	77.8	62	93	65	56	59
81	67.8	66.2	45	67	57	54	53
82	52.8	58.7	47	61	49	46	39
83	58.8	47.7	39	58	50	50	41
84	58.1	50.0	49	57	-	-	-
85	60.9	45.3	42	58	-	-	-
86	61.8	43.3	41	54	-	-	-
87	67.1	46.3	40	-	-	-	-
88	76.7	55.2	38	-	-	51	37
89	64.7	53.0	55	-	-	-	-

*Source: EPA (1992) Air Quality Standards: TSP, 1980-1989, EPA, National Air Data Branch, RTP, NC. Maximum values bold.
[1]Arithmetic mean of 9 stations 1981-85; 7 stations 1985-87; 4 stations 1988-89. From Air Quality section, Health Dept., K.C., MO.
[2]Arithmetic mean of 6 stations.
[3]Urban, commercial locations

stations, thus the high number. Winnipeg recorded its highest annual average TSP in 1981 (95 ug/m3). The 24-hour average on April 16 exceeded 900 ug/m3 (Environment Canada, 1982). Williston, North Dakota recorded a 1089 ug/m3 reading, while other stations in the state reached extreme values as well on the 16th of April (EPA, 1981). The U.S. federal primary standard is 150 ug/m3 for a 24-hour sample and 75 ug/m3 for an annual average (EPA, 1979).

Duststorms and droughts returned to the central prairies in force in 1984 (Hopkinson, 1984), to southwestern Saskatchewan and Alberta in summer 1985 (Shabbir, 1985), and in 1986-89. In the fall of 1987, record dry periods were experienced in parts of the Canadian prairies. Calgary, hosting the February 1988 Winter Olympics, had experienced only two drier November-April periods in the previous 103 years (LeCompte, 1989). TSP values in Calgary and Edmonton were unusually high at the start of 1988. On May 1, a duststorm brought Winnipeg a 1075 ug/m3 reading at a residential site.

Record heat, including a reading of 44 C in eastern Saskatchewan, dominated the prairie summer of 1988, and the U.S. northern Plains and Corn Belt also suffered extreme drought. Sixty-two climatic divisions recorded their driest April-June period in 58 years, while 104 others had one of their top five driest April-June periods (NOAA, 1988).

Spring rains in 1989 ended dry conditions over the western Canadian prairies, but parts of eastern Saskatchewan and Manitoba were as dry as or drier than 1988. More than 150 forest fires were raging in Manitoba in May, when there was warm, dry, windy weather (Raddatz and Guezen, 1989). However, summer rains alleviated the situation considerably. Figure 4 shows the improved soil moisture conditions in July 1989 compared with the year before.

Farther south, the Central Plains drought continued into 1989, with Kansas having one of the worst cold season droughts in the last fifty years (Namias, 1989); Salina recorded 41 C in April. By May, severe to extreme drought covered the region from eastern Colorado to southern Wisconsin. Conditions remained worst in Kansas. Summer rains helped the central region, while the northern Plains continued dry into 1990. North Dakota soils were bare of snow in January, and dust began flying again.

CLIMATIC CHANGE AND THE PLAINS

The record of global temperature shows definite warming since the 1880's, but the temperature increase has not been continuous. The greatest warming was from about 1920 to 1940, with a slight cooling from 1940 to the mid-1970's, followed by warming again into the 1980's (Karl, 1990). Guezen and Raddatz (1988) found the 1930's and 1980's in North America to be comparable with respect to frequency and intensity of droughts, and the extent of area affected.

But do rising temperatures necessarily mean lower precipitation for the Plains? Researchers using global climate models have tried to predict not only the amount of warming with a doubling of atmospheric carbon dioxide, but

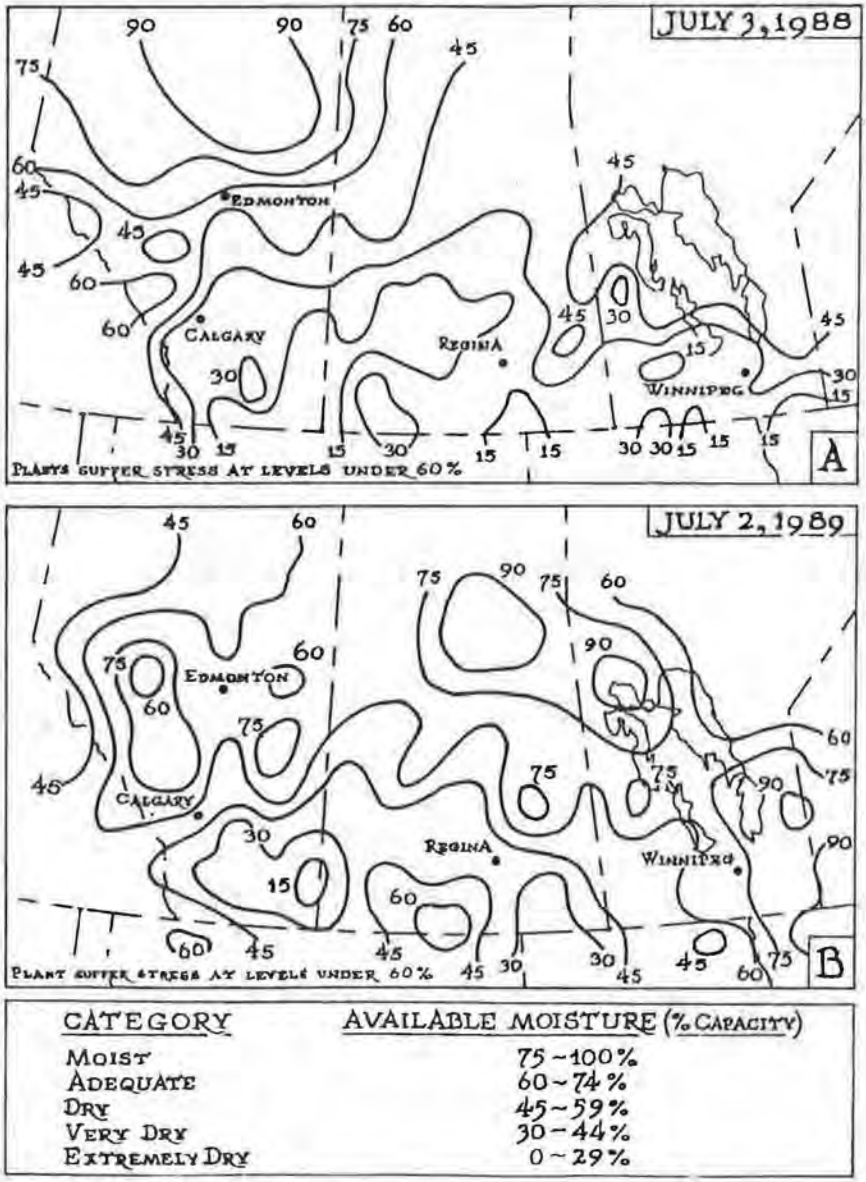

FIGURE 4. Soil moisture improved over the Canadian Prairies in 1989 after severe drought in 1988. From Raddatz and Guezen (1989).

also the regional distribution of warming, and, more importantly, the distribution of accompanying changes in precipitation. Several models, such as Manabe and Wetherald's (1987) at Princeton, have indicated that the largest warming would occur in the higher latitudes of North America. Jager and Kellogg (1983), using the analogue method based on the ten warmest Arctic summers from the past, concluded that drier conditions in the Central Plains would result from warming.

Not all models concur. While the consensus among climatologists is that global warming is taking place, and most agree that warming in the polar regions will be amplified in winter, accompanied by increased evapotranspiration and precipitation, there is less agreement about the magnitude of regional warming and especially about regional changes in precipitation and evaporation (Hengevelt, 1990). Williams et al. (1987) studied the possible effects of carbon dioxide doubling on Saskatchewan agriculture using four different global climate models. With no increase in precipitation over the 1951-80 normals, the models predicted increased wind erosion potential and droughts, with more duststorm occurences.

While most climatologists believe that the Great Plains will experience warming and more frequent dry periods in the near future, year to year conditions continue to be highly variable and elusively unpredictable in the spatial and temporal patterns of wet and dry spells. If the drier conditions of the 1980's continue into the 1990's, particulate air quality will undoubtedly deteriorate. Repetition of the 1976-77 and 1980 droughts will cause TSP values to increase significantly, with more violations of federal standards, which are set to protect the health of the public.

CONCLUSIONS

While particulate air pollution emissions have been decreasing (EPA, 1987), TSP levels and duststorm frequencies have not, as measured at various locations in the Central Plains. Agricultural practices are believed to be the primary cause of increased duststorms in the U.S. (McCauley, et. al., 1981; Changnon, 1983).

In light of recent predictions of a warmer, drier Central Plains in the future, we may anticipate continuing duststorms and unhealthy TSP levels in coming years. Dustier skies over the Central Plains may lead to abrasion of crops and property, accidents due to reduced visibility, atmospheric electrification, interference with communications, human health problems, changes in solar radiation and possible weather modification (Pye, 1987). It seems imperative that steps be taken to protect soil from dessication and erosion, thus sustaining a valuable resource, while at the same time cleansing the Plains atmosphere.

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THE PRAIRIE DROUGHT OF 1988

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1. INTRODUCTION AND OBJECTIVES

Climatic extremes have severe effects on the environment and on weather sensitive sectors of the economy and society. During and following 1988, a number of the effects of a severe drought were evident on the Canadian prairies. Analysis of these effects is useful to determine how vulnerable the environment, economy and society are to drought. If more is known about how sectors respond to a drought, then strategies can be developed and prioritized to avoid or mitigate the effects of future droughts.

This paper is an executive summary of "Environmental and Economic Impacts of the 1988 Drought, with Emphasis on Saskatchewan and Manitoba" (Wheaton and Arthur 1989). The overall objective of this project was to assess the environmental and economic impacts of the 1988 drought on the provinces of Saskatchewan and Manitoba, including:

1) a description of the drought climate of 1988;

2) an overview of the effects of drought on various economic sectors in Canada with emphasis on Manitoba and Saskatchewan;

3) testing of impact models; and

4) provision of recommendations for future work.

The physical and economic impacts of the 1988 drought are addressed by sectors or issues including agriculture, land degradation, forestry, water resources, waterfowl, fisheries, outdoor recreation and tourism, transportation, energy and other industries. Both physical and economic impacts can linger and show up in the year(s) following a drought. Although these lingering effects were beyond the scope of the project, they should be monitored to provide a more complete understanding of the drought effects.

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2. DROUGHT CLIMATE OF 1988

The 1988 drought was significant by many standards including its intensity, duration, area and effects. The drought had significant impacts on agriculture, forestry, wetlands, waterfowl, water supplies, and many others.

The antecedent climate set the stage for the development of the 1988 drought. The warm dry, fall weather persisted into the winter of 1987-88 with much of the agricultural region of Alberta and Saskatchewan receiving less than 50% of normal precipitation. The sparse snow cover and high spring temperatures resulted in little or no spring runoff from prairie watersheds in 1988. Mean temperatures were 2 to 4° C above normal for most of Western Canada during March, April and May. Few water bodies recovered to 1987 levels and many were dry by June, 1988.

Hot, dry, and often dusty conditions prevailed over much of the agricultural prairies in the summer of 1988. The hottest June on record was experienced over the southern agricultural area of the three prairie provinces with mean temperatures 4 to 7° C above normal. Several temperature records were broken at southern climate stations, especially during June. At least seven Saskatchewan stations recorded daily temperatures of 42° C or higher and Kincaid experienced the highest temperature at 43.5° C. Many stations in southern Saskatchewan and Alberta as well as many in western agricultural Manitoba had less than half of their normal June rainfall.

This combination of record heat and dry weather resulted in extreme drought conditions. A wedge of severe drought, as designated by Palmer Drought Index (PDI) values of less than -6, had moved northward almost to the boreal forest fringe in Saskatchewan in June, 1988 and covered approximately 20% of the Saskatchewan agricultural area (Figure 1). Temperatures fell to generally near normal values by July, 1988. However, southern Alberta as well as southwestern and northeastern agricultural Saskatchewan continued to be dry, receiving less than 50 to 75% of normal rainfall. By August, 1988 the surface drought conditions had weakened somewhat, except for the southern prairies. Soil moisture still remained in a deficit situation at the end of September across the southern part of Western Canada. The end of the drought was still not evident by the end of December, 1988. Consequently, there was good evidence that indicated the occurrence of an intense, large and rare drought in 1988, one of the worst in this century.

Comparisons with other prairie droughts also show that 1988 was certainly a major drought event. The droughts of 1987 and 1988 appeared to be more widespread than those of 1937 and 1938. The years 1986 to 1988 were much warmer than 1936 to 1938, indicating that evaporation losses were greater during those years of the 1980s. The 1988 drought was also severe because of its timing following the other droughts of the 1980s.

The 1988 drought conditions also affected other areas of Canada. Ontario had a warm dry spring in 1988 which continued into the summer. The

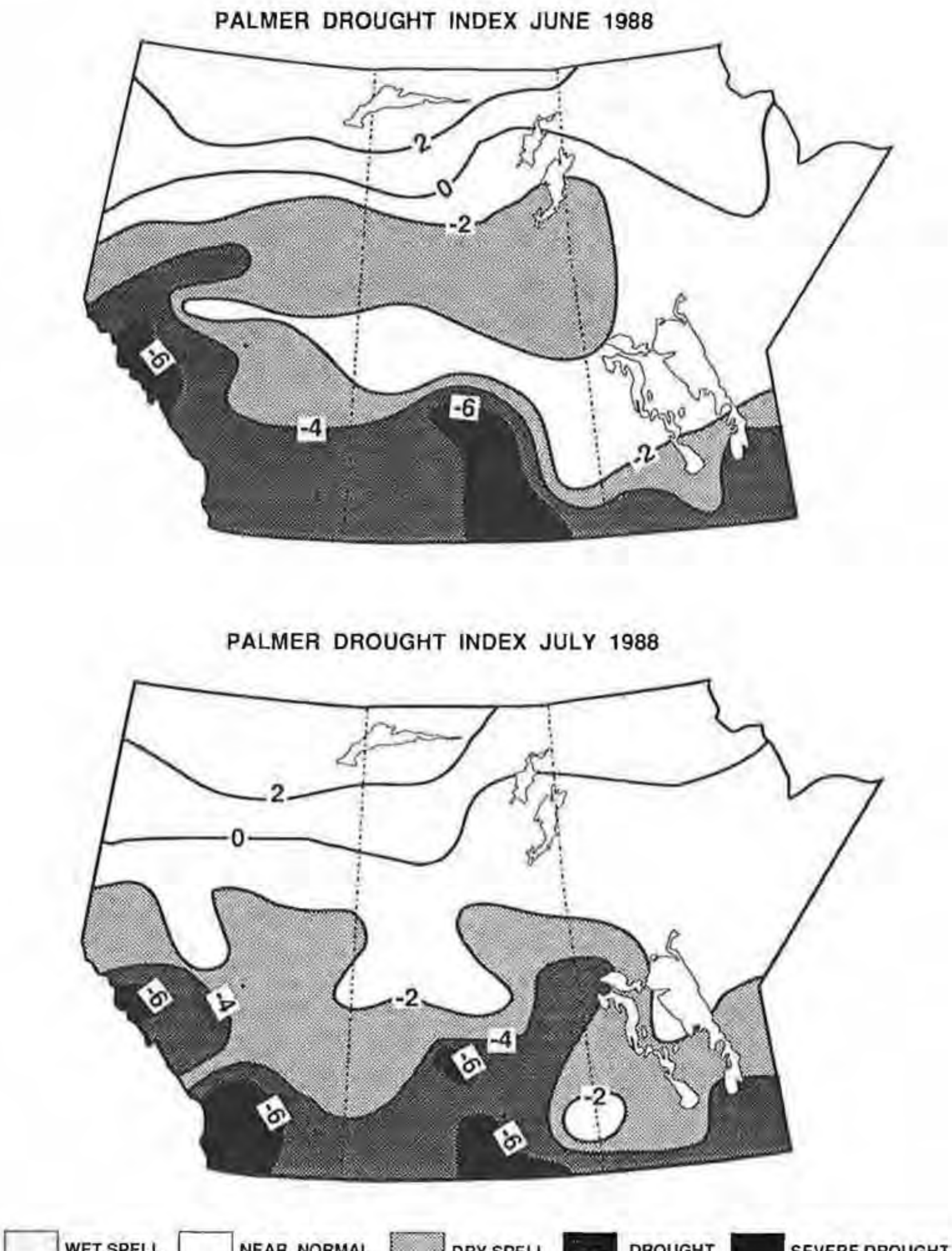

FIGURE 1. Palmer drought index for June and July, 1988. Data source: Jones (1988 p. comm.)

1987 conditions also contributed to the 1988 drought. The hottest July since 1955 was experienced in southern Ontario with temperatures in the mid 30s being recorded in many areas of the province. Lack of rainfall also predominated in southern Ontario and cumulative rainfalls from May 1 to mid July were less than 40% of normal in southwestern Ontario. Except for areas such as Windsor and Toronto, significant rainfalls had effectively ended the drought by about early August, 1988. However summer continued to be hot into August, in general.

The 1988 drought in the U.S. was also the worst in many years. The driest April, May and June since 1895 were recorded for many districts in Wisconsin, Illinois, Indiana, Ohio and some areas of Iowa, Missouri and Michigan. Stations throughout a large portion of North America received less than 30% of normal precipitation in April, May and June, 1988.

Several steps are recommended to further document the drought of 1988. They include undertaking further analyses regarding the drought coverage, heat waves, evaporation amounts, drought origins and return periods. Such research concerning the sequence of droughts of the 1980s would be useful. Without an improved understanding of the nature and origin of droughts, the analyses of their relationships with the economy and society are not complete.

3. GENERAL OVERVIEW OF THE ECONOMIC IMPACTS OF THE 1988 DROUGHT

Canada's Real Gross Domestic Product (GDP) at Factor Cost (1981 dollars) showed a 4.4% increase for the 1988 calendar year, which is an average rate of growth compared to growth rates since the 1982 recession. Agricultural output, however, decreased by 12.7% in 1988. The drought of 1988 was estimated to have caused a direct production loss of $1.8 billion in 1981 dollars, or 0.4% of real GDP.

In 1988, Manitoba's economy showed real GDP growth of only about 0.4%, according to the Conference Board of Canada. The drought reduced agricultural output by 18.5% and was also considered instrumental in reducing hydroelectric power generation in the province (output decreased by 13.2% in 1988).

In April, 1989, the Conference Board of Canada estimated that Saskatchewan's economic output had fallen by 5% in 1988. The 1988 GDP for Saskatchewan's agricultural sector was 38.6% below the 1987 GDP. Alberta's economic output grew by an estimated 6.8% in 1988, despite a decline in the agricultural sector of 1.2%. Although Ontario's annual economic growth was 4.8% in 1988, agricultural output declined by 4.6% in 1988. However, Ontario's farm cash receipts actually rose in 1988 (to nearly $2 billion from $1.7 billion in 1987), primarily as a result of increased prices and the draw down of 1987 stocks.

In the U.S. 1988 real GNP growth was expected to be over 3.5%, despite the expected agricultural production loss of $13 billion from the $4 trillion U.S. economy. However, regional effects were more severe, particularly in the northern plains and midwestern regions.

4. IMPACTS OF THE 1988 DROUGHT ON AGRICULTURE

A wide range of impacts of the 1988 drought on the agricultural sectors of Canada (with an emphasis on Manitoba and Saskatchewan) were documented, including wind erosion, production, grain quality, inventories, marketing, livestock, incomes, farm management, global production and inventories, and prices.

Dust Storms and Wind Erosion–Saskatchewan and Manitoba, 1988. Dust storms and wind erosion of soil were frequent in 1988, causing serious problems especially in the prairies. Dust storms affected many areas and had numerous effects which can linger into the future.

Dust storm frequencies equalled or exceeded previous record maxima for two stations in each province and were above average at a number of other locations. The monitoring network consisted of nine stations in Saskatchewan and five stations in Manitoba. The total number of dust storm days ranged from as low as one for Dauphin, Manitoba to a maximum of 15 at Kindersley in west central agricultural Saskatchewan. The area of the secondary maximum dust storm days was around Winnipeg, Manitoba. The most extensive spatial coverage of dust storms in 1988 occurred during June.

Further work should be done to characterize dust storms, including their areal extent, relationship with climatic and crop residue parameters, dust amounts, as well as the on and off farm costs of dust storms.

Production. In general, the conditions of 1988 reduced production of Canada's seven major grains to 39.1 million tonnes, a drop of 29% from 1987, representing the lowest production since 1979. Production of western Canada's four major specialty crops (mustard seed, dry peas, lentils and canary seed) declined by 40% in 1988 from 1987. Tame hay production in Canada in 1988 was 94% of 1987's production. Vegetable production also declined substantially.

The estimation and prediction of crop production in extreme weather years is an important capability. In order to test one widely accepted modelling tool, the Crop Environment Resource Synthesis (CERES) model was used to estimate the spring wheat yields of 1988 for the Saskatoon Crop District, as a case study. Modelled yields were lower than actual average yields. The reasons for this discrepancy should be determined and used to improve the simulation of growth and yield as affected by drought conditions.

Quality. The drought also affected crop quality, producing higher than average grades of grains. The reasons for this are complex; in general, hot dry conditions result in higher grain protein levels and reduce after swathing sprouting and bleaching. Furthermore, the dry spring conditions of 1988 allowed for earlier seeding and a longer harvest window, reducing harvest damage and shrivelling.

Inventories. Opening crop inventories (August, 1988) were 30% lower than the previous 10 year average (1978 to 1987) of 10.4 million tonnes. Combined with the lower production in 1988, primarily as a result of the drought, supplies (opening stocks plus production) for the crop year totalled 23.3 million tonnes; a 32% reduction from the 10 year average of 34.2 million tonnes. On-farm closing stocks (July 31, 1989) of the seven major grains for all of Canada were 3.5 million tonnes; a 50% reduction from the previous year.

Marketing. Western producers' marketing volumes of all grains were relatively high during this period in 1988 due to the favourable prices; farmers depleted older stock (some of which had been held for speculative reasons). The 1988/89 wheat sales for all of Canada totalled 14.7 million tonnes, close to two-thirds of sales volumes in each of the previous years. Sales of all grains totalled 25.5 million tonnes in 1988/89, a reduction of 26% from the 34.3 million tonnes marketed in 1987/88.

Livestock. The 1988 drought resulted in dry pastures, poor hay and feed production and shortages of water for stock in some areas, particularly the southern Canadian prairies and northern Great Plains. On the Canadian prairies there was some movement of cattle to more northern areas where moisture conditions were more favourable.

Canadian beef prices are strongly affected by U.S. market influences and remained low in 1988 (partially due to the strength of the Canadian dollar). When combined with high domestic feed costs brought on by the drought, these low prices resulted in lower profits to producers. However, it appears that the various government drought programs helped ameliorate some of the effects of drought on the cattle sector.[1]

Feed costs for hog producers also rose, but stabilization plans helped offset some of the losses. Hog numbers were maintained throughout 1988. Feed costs for supply managed commodities (poultry, dairy) were passed on to consumers in higher prices, so these sectors were not significantly affected.

Incomes. Despite the increases in gross receipts for the crops sector, particularly in Saskatchewan, much of the increase came out of 1987 production, resulting in decreases in provincial net income (calculation based on production, rather than sales) in 1988. If provincial net incomes are calculated with government program payments included, Manitoba showed net farm income losses of 50% and Saskatchewan 78% (over 1987 figures). Crop farm bankruptcies increased slightly in 1988, but partial blame can be attributed to low crop prices of years preceding 1988.

Adjusted Farm Management. Farmers were surveyed to determine what information they needed to make adjustments to drought conditions. Information concerning herbicide effectiveness in dry conditions was rated most

1 For complete review of drought program impacts, contact Agriculture Canada in Ottawa.

important, with interest in new tillage, seeding and fertilization practices also being important.

Global production and inventories. World wheat production in 1988/89 was estimated at 501.2 million tonnes, similar to the estimated 501.7 million tonnes produced in 1987/88. The less than three month world supply of wheat[2] indicated the tightest world wheat carryover since the early 1970s.

The 1988/89 wheat production by the five main exporters, Canada, Australia, Argentina, the United States and the European Economic Community (EEC) declined by 8% from the previous year to 162 million tonnes, due mainly to the North American drought. Production by the other wheat producing countries increased.

Prices. As the effects of drought became apparent early in the summer of 1988, prices responded to low production and inventories with sharp increases. However, the agricultural program competition between the U.S. and EEC may have prevented prices from reaching truer "market values."

5. IMPACTS OF THE 1988 DROUGHT ON FORESTRY–SASKATCHEWAN AND MANITOBA

Although forestry contributes less than 1% to the total gross domestic product for Manitoba and Saskatchewan, it is an important sector economically and socially in localized areas in northern (boreal) regions which depend on employment and business opportunities from forestry. The drought of 1988 occurred less uniformly across the commercial forest region of Saskatchewan and Manitoba than in the agricultural region; western Saskatchewan forests were little affected, while the Saskatchewan-Manitoba border and southeastern Manitoba had the worst drought conditions.

A crude estimate of growth losses, based on comparison with inter-regional differences in climate and productivity, pointed to a total loss of timber production on the order of millions of cubic meters. This loss would be concentrated on well drained sites, with wetter sites being buffered against the effects of below average precipitation by the presence of the water table. The economic impact of the loss of timber production may not be obvious in the shorter run, as final harvests depend on growth over many years, not on the growth of any one year.

Mortality due to drought is more likely in seedlings than in established stands. In Manitoba, mortality rates in plantations were 20% above normal in 1988, and damage to nursery seedlings also occurred. In Saskatchewan, overall mortality rates were about average, although elevated mortality could have occurred in specific regions.

Damage by stress from heat and/or lack of moisture is difficult to separate from other factors, such as disease or insect damage, especially since

2 A three month world supply of wheat is considered adequate in terms of food security.

some disease and insect damage could be drought-induced. Outbreaks of forest tent caterpillar and spruce budworm involved timber losses of millions of cubic metres and may have been fostered in part by the warm, dry conditions of the late 1980s.

Forest fires are the most visible effect of dry weather on forests. Forest fire incidence was high in Manitoba in 1988, with 982 fires reported. The area of burn was also high in 1988 at almost 0.5 million ha, and fire management costs reached $24 million in 1988. Fire conditions actually worsened in 1989 because of the lingering drought conditions in the fall and winter of 1988 (3.0 million ha burned in 1,119 fires leading to fire management expenses of $60-65 million in 1989).

Saskatchewan experienced 980 forest fires in 1988. The total number of forest fires was higher in 1988 than at any time (since 1918), except 1987. However, the area burned (81,000 ha) was less than the long-term average of 130,000 ha per year. The 1988 volume of burn at 2.2 million m^3 was much lower than the 7.5 million m^3 burned in 1987. Fire fighting costs were high in both 1987 and 1988 at $33.9 million and $31.8 million.

6. IMPACTS OF THE 1988 DROUGHT ON WATER RESOURCES SASKATCHEWAN AND MANITOBA

Surface Hydrology. All water supply sectors ranging from farm supply to hydroelectric reservoirs were affected by the 1988 drought. The drought affected the entire prairie drainage basin except an area from the Quill Lakes to Lake Manitoba. More than 50% of the boreal forest region was also affected. These impacts included inflow to the provinces and the flow of water within Saskatchewan and Manitoba.

Two large areas of Saskatchewan were heavily affected by drought in 1988. Much of the agricultural area of Saskatchewan had annual water flow volumes less than 50% of normal (Figure 2). The second drought zone covered the area from Shell Lake to Prince Albert along a line north of the Saskatchewan River to Winnipegosis in Manitoba and north to Reindeer Lake in Saskatchewan and then over to just include Lac La Ronge. Three areas of Saskatchewan had moderately affected stream flow (51-100% of normal): areas around Esterhazy/Welwyn, Lloydminster/Saskatoon/Prince Albert, and Cumberland House.

Approximately 75% of Saskatchewan (by area, south of 58°N) was affected by drought. Thirty-seven percent of the hydrometric stations broke a record for lowest flows. The mean volume was 60 to 70% of normal volume.

Three zones of Manitoba were heavily affected by drought in 1988 (Figure 2). In the south, the drought zone included most of agricultural Manitoba, extending north of 52° N in the east. The second drought area extended from northern Saskatchewan along a line from Prince Albert to La

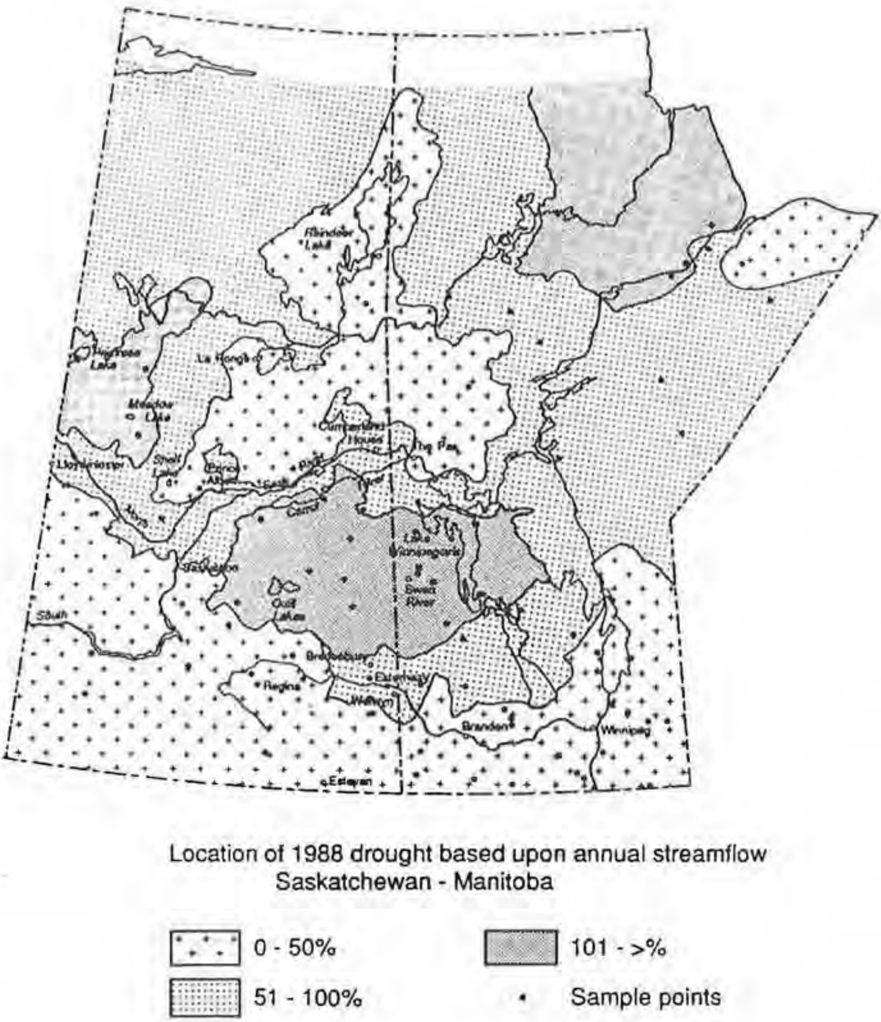

FIGURE 2. Annual stream flow volumes, Saskatchewan and Manitoba, 1988 (expressed as a percentage of normal). Data source: Inland Waters Directorate 1989

Ronge into Manitoba about the third of the way across the province and northward past Reindeer Lake. The third area was south of Hudson Bay close to the Ontario border.

About 25% of Manitoba's area had stream flows less than 50% of normal. About 35% of Manitoba was affected by water flows of 51 to 100% of normal. Twenty-five percent of the stations broke a record for lowest flows. The mean flow volume was between 50 to 60% of normal.

Recommendations for further work included developing mechanisms to incorporate long-term issues, such as drought and sustainable development, into water management decisions and policy development.

Groundwater. Groundwater is a critically important resource for Saskatchewan and Manitoba residents. Several aquifers in Saskatchewan have been declining during the 1980s. This decline is partly in response to the dry climatic conditions that have occurred throughout much of the 1980s. The wells at shallow depths in southern Saskatchewan exhibited decreasing trends since the early to mid 1970s and record low values for 1988. Wells at intermediate depths show varying trends. Wells that are completed at a deeper level (greater than or equal to 100 m) show some signs of slow declines in water levels.

Groundwater levels in most of Manitoba remained fairly stable over the period of record. The only area with a continuous downward trend is the southeastern corner, with a drop of three metres over 15 years. Some record low levels were recorded by November, 1988.

Some groundwater supply problems continued into 1989 in both provinces. However, the degree to which the 1988 drought is related to these problems is questionable. Several recommendations are made including–an improvement of the understanding of the relationship between climatic factors and groundwater levels; investigation of the nature, direction and causes of trends of levels; and further investigation of the relationship between wetland drainage and groundwater levels.

The year, 1988, and indeed, the 1980s have provided an excellent test case to assess the relationship between severe drought and drought sequences on groundwater quantity and quality. This "natural experiment" of 1988 and indeed the 1980s should be taken advantage of in further work to improve the understanding of the groundwater resource.

Economic Aspects. This discussion covers aggregate water supply issues and primary non-industrial uses such as home (domestic) consumption. Many rural water supply problems occurred on the prairies during 1988, some of which were critical. The Saskatchewan government increased funding to the Saskatchewan Water Corporation by $8.5 million for drought relief projects. The Saskatchewan Water Corporation received record requests for assistance in 1988. Test drilling increased to 1,246 in 1988 from 663 in 1987; recipients of well assistance for deep and shallow wells numbered 2,855. Community well assistance increased to 29 in 1988 from 20 in 1987. Recipients of dugouts and small storage reservoirs increased almost ten-fold to 4,169. Assistance for farm dugout pumping almost doubled in 1988 over 1987 levels. Assistance for individual irrigation projects also increased. Programs receiving additional funds were intended to address short-term water supply problems as well as to meet requirements for long-term drought mitigation measures.

The Manitoba Water Services Board's long-term drought mitigation funds in 1988/89 were increased from the initial allocation of $650,000 to $2.25 million. Requests for assistance in dugout filling in Manitoba increased from 62 in 1986, to 109 in 1987, and to 504 in 1988 (compared to 4,169 in Saskatchewan in 1988 for dugouts and small storage reservoirs).

The hot, dry weather in spring and early summer of 1988 led to increased water consumption rates for many prairie cities. For example, the water consumption rates of the City of Winnipeg increased to a point that voluntary restrictions were imposed for lawn watering. While the increased consumption prompted some additional operating expenses, these were considerably less than the $3.155 million of additional revenues generated from user fees. A number of complaints were received by the city regarding water quality.

Funding for the Rural Water Development Program of the Prairie Farm Rehabilitation Administration was $24 million in 1988/89 (versus $7 million in 1987). This included $18.87 million for on-farm projects and $5.11 million for rural community and group projects. The largest proportion of federal funding for on-farm projects went to Alberta (52.8%) and Saskatchewan (38.2%); the remaining 9% was dispensed to Manitobans.

7. IMPACTS OF THE 1988 DROUGHT WATERFOWL-SASKATCHEWAN AND MANITOBA

Waterfowl and their habitat suffered extreme losses because of the dry climate of the 1980s. Droughts decreased the number of wetlands: for July, 1988 the number of ponds counted in Saskatchewan and Manitoba was below 50% of normal. A 16% decrease (from the 1955-87 average) in the overall number of ducks was also documented during the 1980s. The increased incidence of waterfowl disease may have been related to dry conditions and resultant crowding.

The drought of 1988 was one of several factors producing a cumulative negative impact on the habitat of many migratory bird species. Similarly, habitat availability is one of many factors responsible for the continual reductions in migratory bird permit sales since the mid-1970s. While this trend in reduced permit sales decreases hunting pressure on declining bird populations, it also results in less revenue from permit sales and from the substantial expenditures related to hunting.

Losses in hunting expenditures during 1988 were estimated at $2.0 million in Manitoba and $2.3 million in Saskatchewan (1987 dollars) for resident hunters only. However, these losses in permit sales and/or hunting expenditures cannot be attributed to the drought alone (other contributing factors include income and price levels, employment, changing preferences, demographic trends, *etc.*).

Finally, the 1988 drought had an indirect effect of reducing the level of waterfowl damage on crops by enabling an early, short harvest in Manitoba and Saskatchewan.

8. IMPACTS OF THE 1988 DROUGHT ON FISHERIES-SASKATCHEWAN AND MANITOBA

Drought can affect fish populations by reducing habitat availability and quality, affecting not only fish survival but also their reproductive capability and growth rates. In both sport fisheries and commercial fisheries, the potential impact of a drought would not likely appear until the year when the class spawned in 1988 reaches harvestable size, unless fish kills are significant.

Fish kills in the southern lakes of the two provinces occur almost annually. Therefore, both provinces have "drought proofing" programs in place. The programs generally include yearly restocking, aeration programs and snow removal. Neither Saskatchewan nor Manitoba appeared to have experienced above normal expenditures for winterkill prevention or for water body restocking during 1988.

The 1988 resident license sales in Saskatchewan were 146,494 and non-resident sales were 20,145. Resident recreational fishing license sales in Saskatchewan have been decreasing since the early 1980s, while non-resident sales have been increasing. The reduced sales of the former are possibly linked to the depressed farm economy that prevailed even prior to the 1988 drought. Angler license sales were also down in Manitoba in 1988/89. Non-resident license sales at 32,441, were thought to have declined because drought in the United States reduced fishing trips by U.S. residents to Manitoba fishing lodges. The precise reduction due to drought could not be established for non-resident licenses, and it could not be established whether reduced resident sales could be attributed to the drought.

Commercial fish in Saskatchewan and Manitoba, as well as Alberta, Northwest Territories and Northwestern Ontario are marketed by the federal crown corporation, the Freshwater Fish Marketing Corporation (FFMC), situated in Winnipeg, Manitoba. Total commercial production in this area in 1988/89 increased by a small factor of 4% over 1987/88. Preliminary estimates indicated reduced profits in 1988/89 in comparison to the previous year's record, but these losses were not directly related to the drought.

9. IMPACTS OF THE 1988 DROUGHT ON RECREATION/TOURISM -SASKATCHEWAN AND MANITOBA

As in many of the sectors, many other factors as well as weather and climate affect tourism and recreation participation and performance. For example, both Manitoba and Saskatchewan, as well as surrounding regions, suffered from slow economic growth prior to the 1988 drought, which could have negatively affected tourism and recreation.

Canada experienced a record travel deficit in 1988 as the result of increased Canadian visits to the U.S. and decreased U.S. visits to Canada, with the strengthening Canadian dollar playing a major role. The drought in Manitoba and Saskatchewan may have also reduced the attraction of these provinces to U.S. residents. The drought in the north central U.S. also may have reduced demand for travel.

Summer travel patterns in 1988 were comparable to those in 1986 in both Manitoba and Saskatchewan. In Manitoba, both resident travel within province and visits from out of province increased slightly in 1988. In Saskatchewan, resident travel also increased slightly while visits from other parts of Canada increased significantly between 1986 and 1988. Numbers of United States residents entering both Manitoba and Saskatchewan declined in 1988 from 1987, but numbers of visits from residents of other countries increased.

The Canadian Tourism Research Institute blamed the drought and its effects on the economies of Manitoba and Saskatchewan for the close to zero or negative growth in the gross domestic product of the tourism industry in both provinces. The decline in sales of sporting goods and in some types of construction work related to recreation, is an indication of the effect of the depressed economy on some aspects of recreation.

Camping and park entry revenues increased by a small amount in Manitoba in 1988. The largest increase was in camping revenue in the Whiteshell region (situated close to Winnipeg). The early spring and warm dry weather over the summer gave greater opportunities for participating in camping and park-based activities, including swimming, hiking, *etc.* Also local travel may be substituted for longer distance travel (tourism) when economies enter downturns.

Total entry permits to the Saskatchewan parks system also increased by a small amount in 1988. The number of camping permits and permits days issued has, however, been declining since 1984.

10. IMPACTS OF THE 1988 DROUGHT ON TRANSPORTATION

While the quantity of water available in rivers and lakes affects navigability, the 1988 drought did not seriously affect the navigation of any major waterways in Canada. Therefore, this section discusses only transportation issues related to changes in shipping volumes as a consequence of drought.

Tonnage of the six principal grains loaded at all ports declined by 24.2% in the first half of the 1988/89 crop year, compared to the previous year, and then by 49.4% in the second half of the year. Total loads for 1988/89 of 20.109 million tonnes were 36.8% lower than the 31.8 million tonnes the year before. Thunder Bay experienced the largest load reduction, of 46.5%, to 7.927 million tonnes. West Coast ports showed a 28.3% reduction in 1988/89, to

12.183 million tonnes. Canadian Pacific Railway's 1988/89 grain car loads were only 55.3% of the previous period's loads. Canadian National Railway's loads were 70.9% of those for 1987.

Grain shipments through the Ports Canada system were reduced by 18% in 1988 from 1987 down to 26 million tonnes. Increased shipment of other commodities enabled a small increase in overall tonnage.

Divisional ports administered by the Canadian Ports Corporation, experienced a 41% decline in grain shipments in 1988, with a total of 1.6 million tonnes. Both grain shipments and total volumes declined at Thunder Bay in 1988, by 16% and 24%, respectively. The lack of grain was expected to affect from 600 to 900 workers, and also added to the concerns of the long-term future of the Thunder Bay/Seaway route for grain transportation.

11. IMPACTS OF THE 1988 DROUGHT ON ENERGY–SASKATCHEWAN AND MANITOBA

In 1988 hydroelectrical power generation comprised 62% of all power generation in Canada, and 94% and 18% of power generation in Manitoba and Saskatchewan, respectively. In more "normal" years hydroelectric power comprises up to 98% of Manitoba's power generation. Manitoba Hydro began experiencing the effects of drought in 1987. By the end of the 1987/88 fiscal year the corporation had accumulated a net expense of $18.5 million, with drought considered as the major contributing factor. Costs of increased fossil fuel consumption and power purchases from other sources accounted for almost 50% of the increase in expenses (before finance expenses). Hydroelectrical generation dropped from a record 24 billion kWh in 1986/87 to 18 billion kWh in 1987/88 and then to 15.2 billion kWh in 1988/89 (a 36.7% reduction between 1986 and 1988). Surplus energy available for export declined, with the consequence that export sales revenue dropped to $31.1 million in 1988/89, a 72.6% reduction from 1986/87. Revenue from Manitoba customers increased from $508 million in 1987/88 to $569 million in 1988/89. A net income loss of $26.4 million was registered. Reserves were reduced from the 1986/87 high of $137.3 million to $92.4 million in 1988/89.

The majority of Saskatchewan's electrical energy is thermal generated. The drought increased the proportion of thermal generation as well as the volume of energy imports. Fuel, water and purchased electricity costs increased by 28.9% from 1987, to $125 million in 1988, primarily due to the decline in hydroelectric energy production and to an increase in total system energy. Net income before finance charges was $272 million, a 13.8% increase from 1987. While the drought caused a reduction in SaskPower hydroelectrical generation, as well as operational problems at the Boundary Dam thermal power station, SaskPower did not appear to suffer the same magnitude of economic repercussions as Manitoba Hydro.

The gas utility of SaskPower experienced a 2.6% reduction in revenue between 1987 and 1988, to $298 million. While this revenue loss was not related to the drought itself, it was however, primarily associated with the mild 1987/1988 winter.

Saskoil's 1988 net revenue increased to $92.9 million, a 4% increase from 1987 net revenues. More substantial growth in net revenue was constrained primarily by lower selling prices of crude oil in 1988, and not by drought.

12. IMPACTS OF THE 1988 DROUGHT ON OTHER INDUSTRIES-SASKATCHEWAN AND MANITOBA

Drought impacts are presented in three parts: impacts on those industries that are water-based; those which may have been affected by input availability and/or cost of production changes; and those which may have experienced changes in demand for their product. Data restrictions prevented a complete analysis, so only specific cases were examined. Case studies, which revealed some increased costs of production, included Labatts (filtration costs rose 20%), J.E. Seagrams and Sons, Ltd. (increased grain costs), McCains and Carnation Foods (disrupted vegetable sources).

Industries experiencing reduced product demand include Inland Cement's and Lafarge Canada's rural cement sales, and agribusinesses dealing in herbicide sales (*e.g.*, Chipman's, although Monsanto showed an increase in sales of pre-emergents) and farm machinery. Industries which were not affected negatively include Saskoil, Campbell's Soup, Manitoba Sugar, and Potash Corporation of Saskatchewan (other fertilizer producers may have suffered losses).

13. ECONOMIC IMPACT ANALYSIS

The economic trends outlined above can be used to develop measures of direct and indirect economic impacts on the various regions of Saskatchewan and Manitoba and on the entire Canadian economy. Input-output (I-O) models were used to estimate the provincial multiplier effects of changes in consumer and government expenditures and product exports (direct impacts only) related to the 1988 drought.

The multipliers were 1.3 for Manitoba and 1.6 for Saskatchewan; in the case of Saskatchewan, for example, every $1 of direct expenditure in the region (due to direct responses to drought) generates an additional $.60 of activity in the other sectors in the region.

These multipliers are quite low for a "closed" model, but reflect the open nature of the resource sectors affected by drought; that is, much of the product (*e.g.*, agricultural commodities, hydroelectrical power, potash) is exported, so further spin-offs are not substantial.

More surprising than the low multipliers is the positive direction of drought effects on the economy. The only sectors with net negative effects are fishing/hunting and potash manufacturing in Saskatchewan and hogs, vegetables, forestry, and fishing in Manitoba. In the drought-stricken crops sectors, production losses were tremendous, but these were offset by increased prices and government compensation. Similarly, cattle producers were compensated through special drought programming and stabilization packages. Sectors like hydroelectrical power generation showed increased purchases of power to meet contracts, but also showed net increases in sales.

The high level of aggregation in the models is somewhat problematic in that some losers are not highlighted (*e.g.*, farm equipment salespeople). Also complicating interpretation of the results are the unquantified losses,.such as the loss in forest productivity (particularly in Saskatchewan) due to the large number of forest fires.

While these results must be presented with serious reservations attached, the results do illustrate that many of the multiplier effects of losses to the agricultural sector were attenuated by higher commodity prices and government programming. Much of this programming is relatively permanently in place, *e.g.*, stabilization and insurance programs, supply management. Furthermore, some sectors benefit from drought and related weather events; while fishing revenues may decline, recreational expenditures (*e.g.*, for water-based recreation, where the water is plentiful) may increase; as farmers cull herds, slaughtering facilities benefit; as crop inventories are depleted (in response to high prices) transportation facilities benefit (in the short-run; in the following crop year, inventories will be low).

14. NEWSPAPER ARTICLES AND THE DROUGHT OF 1988

Newspaper articles indicate the level of public awareness regarding adverse conditions such as those related to the 1988 drought. The newspapers started to run articles about the dry conditions in the late spring of 1987. The peak of drought-related articles occurred in June, 1988 when the prairie region experienced the extreme hot spell. The articles were numerous and frequent.

The majority of these reports covered the agricultural concerns. A fewer number of reports carried information on effects on fish, wildlife and industries. The articles reflected the diverse nature of the numerous drought impacts and the high level of concern regarding the drought.

15. CONCLUSIONS

Recurrent droughts are a major source of risk and uncertainty, especially for agriculture and other water dependent sectors. The 1988 drought reaffirmed this statement. Recurrent droughts are a characteristic of the prairie climate. The consequences of the 1988 drought were numerous, severe, and far ranging.

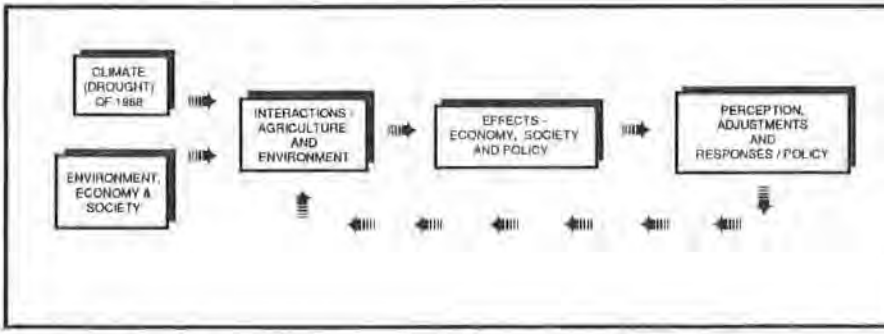

FIGURE 3. Climate, environment and socioeconomic interactions, 1988 drought.

While agriculture is one of the most drought sensitive areas of human activity, such climatic anomalies have wider environmental implications. This study has documented many aspects of the climate-environment-socioeconomic interactions of the 1988 drought, making use of a natural 'experiment' to explore these relationships.

Interaction models are used to portray impacts as joint products of the relationship between climate and society; similar climatic variations can produce different impacts under different sets of social conditions. In turn, a given social condition can determine the level of vulnerability of a society to climatic anomalies (Figure 3).

The 1988 drought's potential effects were attenuated by socioeconomic conditions. Many of these conditions arose from past experiences with drought; for example, current crop varieties and cropping technologies result in higher yields during drought than could be achieved in previous decades. Other socioeconomic conditions stem from past adversities of other kinds; grain and livestock stabilization programs, crop insurance, and ad hoc interventions such as the drought relief programs all reflect society's current willingness to assist adversely affected industries.

Nevertheless, the 1988 drought still caused considerable stress in subsectors of the Saskatchewan and Manitoba economies. As for the 1930s droughts, the 1988 drought struck agriculturally dependent economies that were already weakened by years of low commodity prices. Unfortunately, this also resulted in stress to the very programs and policies that helped mitigate the effects of the 1988 drought; on-going programs continued to run deficits and the will to provide more ad hoc compensation was weakened. The stresses of 1988 should lead us to the design of even better mitigation and adaptation strategies for the next climatic disaster.

ACKNOWLEDGEMENTS

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REPLY TO COMMENTS ON THE APPLICABILITY OF GCM ESTIMATES TO SCENARIOS OF GLOBAL WARMING IN THE MACKENZIE VALLEY AREA

In a recent issue of the Climatological Bulletin, two researchers from the Canadian Climate Centre (Cohen, 1992; Etkin, 1992) have commented upon certain portions of Stuart and Judge (1991). We are grateful to them for their interest in our work and grateful to the editor of this journal for the opportunity to respond.

We would first point out that neither response to our paper seems to be questioning the scientific results of our study. We are all apparently agreed that the application of these GCM's to the Mackenzie Valley area will result in large errors. What seems to be at issue is whether or not these errors are sufficient to disqualify these GCM simulations as scientific tools for regional impact studies in the Mackenzie Valley area. In responding to this question it is our hope that those who use scientific tools such as GCM's to address socio-economic or policy questions will better understand the concern of the scientific community that these tools be used with appropriate consideration of their strengths and weaknesses.

In response to Cohen's question "Should impacts research wait for certainty?" we would point out that certainty is *never* achieved - either in GCM development or in any other scientific area for that matter. Our knowledge of the physical world is encapsulated in hypotheses or theories which are always subject to verification by observations. Any scientific theory may be rejected if measurements show that it is not in agreement with those aspects of the physical world that the theory is attempting to explain. Consequently, all hypotheses can only be tentatively and conditionally accepted. New observations may always come to light in future studies which will overturn even the most widely accepted theories.

Progress in science is achieved by the development of theories or hypotheses and their subsequent testing by experiment. Observations show where a theory is inadequate and often suggest how the theory might be improved. Theories, on the other hand, often result in the design of observational procedures that have not been tried before. A theory gains a considerable degree of credibility if it anticipates experimental results that are subsequently corroborated by independent observations. In this context, the comparison of theory and observations, which was the aim of our paper, is part of a fundamental scientific process.

General Circulation Models are scientific tools of great complexity. Their value lies in their ability to simulate many large-scale features of the global climate system as demonstrated by a comparison of actual and simulated climates. The formulation of the model equations represents the scientific hypothesis which is compared with the observed climate through the $1xCO_2$ scenario run of the model. Based on the results of these comparisons, the hypothesis is modified, and more comparison tests are run. As a result of this iterative process, the model is made to more closely resemble the actual climate as determined by observations. Hansen *et al.* (1983) provide a detailed description of this process of testing and correction that went into the development of their model. In the context of our paper, it must be emphasized that these procedures are applied to the *global* climate and its *large scale* features. Smaller scales such as the Mackenzie Basin are not included in the fine tuning process of GCM development. Therefore, even if the model is successful in simulating large scale features of the global climate, it does not necessarily follow that the model can be used for smaller scales.

It should also be noted that many of the "downstream" models that apply GCM output to specialized impact studies are also well regarded scientific tools that have been developed with a similar degree of rigour and precision. For example, we are aware that many permafrost models are based on heat transfer algorithms that have been subjected to detailed verification and sensitivity tests based on high quality observational programs. In their application to climate change studies, however, these models are only as good as the hypothetical climates employed - climates that are drawn largely from the output of GCM's.

In order to retain their scientific credibility, GCM's should be applied within the rigorous scientific principles that have served as the basis for their development. As we have previously argued, these principles insist that two complementary elements must always be present in any scientific acitivity. First, there must be the development of a theory or hypothesis which encapsulates our understanding of some aspect of the physical universe; and secondly, there must be objective testing of this hypothesis which is based on quantitative observations of whatever it is that we are attempting to explain. GCM's serve as the scientific hypothesis and provide the context in which observations may be understood and explained, as well as the philosophical springboard from which scientists attempt to extend our knowledge. Independent observations provide the only legitimate check on these speculations. Hypotheses which are inconsistent with observations must be rejected and modified hypotheses advanced.

Because of the exhaustive tests and calibrations that have gone into GCM development, we believe that these models qualify as legitimate scientific tools insofar as *large* features of the global climate are concerned, although it should be noted in passing that this view is not unanimously held within the scientific community. If these tools are now to be applied to smaller scales, similar comparisons with actual climate conditions must be carried out. Our paper, which represents only the first step in this process, simply places maps of the $1 \times CO_2$ climate and actual climate norms for the Mackenzie Valley in the same figure. A more complete study would include a quantitative error analysis of the model climates from which one could make an estimate of the uncertainty levels of model projections for this region. Without such studies there is no scientific basis to use GCM's at these scales since the essential comparison between the actual climate and its simulation is absent. Our study, while admittedly insufficient, is useful since it shows the very large errors of these models at regional scales. We believe that if a careful, rigorous error analysis of the control climates were carried out, the magnitude of the errors might well be comparable with the magnitude of the climate signal from doubled concentrations of carbon-dioxide that the model is intended to simulate. Under such circumstances, GCM projections of climate change could only be used in regional scale impact studies if these projections were accompanied by the very large confidence intervals that these regional scale errors would imply. We believe that the recognition of these uncertainties in climate change projections would render regional scale impact studies of little value since, at this scale, the confidence interval associated with the new climate would span current climate conditions as well as a wide range of other alternative climatic conditions. It is for this reason that we believe that the regional application of the models tested in our paper is premature.

Even if our views are seen as too restrictive, however, it is a clear violation of basic scientific principles to apply these models as if regional scale errors did not exist or were of little consequence. We are firmly of the view that the errors need to be acknowledged and their implications for any downstream impact studies quantitatively estimated as a mandatory part of these impact studies. This is essential if the scientific credibility of both GCM's and various impact models is to be maintained.

The absolute requirement that all scientific hypotheses be tested by a comparison with the observational record does not seem to be appreciated by either Cohen or Etkin, and this is a matter of some concern, particularly given the significance attached to the Mackenzie Basin Impact Study within the Government's Green Plan. In his letter Cohen states that "it is important to remind ourselves that global warming exists as an issue because of the GCM simulations of future climates". We agree, but would contend that so long as the implications of global warming are *only* based on GCM hypotheses without reference to appropriate scientific accuracy tests of their validity, then his and other similar impact studies will not be based on science at all. GCM's represent one class of hypotheses of global warming science. In their simulations of large scale climate features, GCM's have now advanced to the point that they have been verified by observations, which thus corroborates their value as scientific tools at these scales. At the regional scale, however, model and observations vary widely, and basic scientific principles require that the hypothesis for this particular application must be rejected and improved hypotheses sought.

There is no substitute for hypothesis testing by careful observations. One cannot, for example, replace a comparison of theory and observation with an intercomparison of various theories as Cohen is apparently doing ("Studies should use more than one global warming scenario . . . "). Furthermore, one cannot avoid the regional scale discrepancies between theory and observation simply by calling an hypothesis a "scenario" instead of a "prediction" as Etkin suggests. We reject his contention that "it is not possible to provide meaningful quantitative error bounds on climate predictions", and would argue instead that unless/until the necessary error analyses are carried out, climate change studies that employ these hypotheses will have no scientific basis. We note that in the following sentence of his letter Etkin goes on to say that "mankind is altering the climate system of the planet". How could he know that this is true if, as he has just stated, we cannot test the accuracy of the models that we have previously agreed are the basis for this assertion?

None of our views on this matter should be surprising to the scientific community, many of whom are now actively involved in studies to reduce the uncertainties in climatic projections on the regional scale. In particular, the Canadian portion of the Global Energy and Water Cycle Experiment (GEWEX) project has selected the Mackenzie Basin as the focus for its studies, and may be expected to make many important scientific contributions over the next several years. These achievements may be expected to reduce the uncertainties associated with GCM's for this particular area, but these uncertainties will never be completely removed, and they must always be carefully considered in any impacts application. It should go without saying that impacts studies that proceed before these uncertainties are reduced should not ignore these errors either.

Unfortunately, it would appear that many impact studies are going forward without much regard for these important scientific principles. Impacts research in the Mackenzie Valley and elsewhere is supported because society has recognized that such studies are necessary and useful. Impacts researchers must use and carefully justify whatever GCM output or other information they think appropriate in these studies. They can neither ignore the large errors inherent in GCM simulation of regional scale climates nor assume, without scientific justification, that one may "cancel out" these errors by subtracting/dividing $2xCO_2$ and $1xCO_2$ grid point values of temperature/precipitation. Unless the error levels of the models are explicitly acknowledged throughout the impact studies, no one may claim that these impact studies have any scientific basis since the fundamental requirements of scientific investigations have been ignored. Policy makers should understand that the results of regional scale studies which do not consider the limitations of the scientific tools used must be regarded as untested and speculative theoretical constructs which may or may not be representative of what changes in climate might actually occur. Furthermore, by failing to acknowledge the large errors inherent in applying curent GCM simulations to regional scales such as the Mackenzie Basin, we can have no idea of the likely errors inherent in impact studies that base their projections on these simulations.

This is the dilemma faced by scientists and engineers in disciplines other than climatology who are fearful that global warming will cause major changes in the landscape, the hydrology or the biota, and result in significant impacts on engineered structures. At present we are conducting what are largely sensitivity studies using hypothesized changes in regional climates that are known to be highly uncertain. While these studies enable scientists to identify sensitive components of natural systems, based on rigorous scientific principles, it remains clear that unless the uncertainties associated with the input climate data are greatly reduced, the value of their results to policy makers will remain limited in terms of regional planning. We are confronted by potentially serious societal impacts as a result of global warming, but lack sufficient scientific understanding of the relevant processes to adequately assess their implications on important and critical regional scales. We need to improve our understanding, and this will be accomplished by standard scientific procedures - test the model, recognize its shortcomings and improve it. Nothing is gained by ignoring the limitations of our present knowledge.

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R.A. Stuart and A.S. Judge

INTERNATIONAL CONGRESS ON MODELLING AND SIMULATION

THEME: Modelling Change in Environmental and Socioeconomic Systems

University of Western Australia, 6–10 December 1993

The Congress incorporates the 10th Biennial Conference of the **Modelling and Simulation Society of Australia, Inc. MSSA Inc.** (formerly SSA Inc.) is an affiliate of the **International Association for Mathematics and Computers in Simulation (IMACS)**.

The MSSA Inc. is an interdisciplinary society which aims to promote, develop and assist in the study and practice of all areas of modelling and simulation in Australia.

There is an emphasis on applied problems. Many of its members work on environmental, agricultural and socio-economic methods and applications. Hence it is natural that the Congress be a joint meeting with the **International Society for Ecological Modelling (ISEM)** and **The International Environmetrics Society (TIES)**, as well as with **IMACS**.

There will be four Presidential and five Keynote Addresses. These and many of the parallel sessions of contributed papers will focus on areas of common interest to the international societies and participating Australian societies.

Abstracts due March 8, 1993. Full papers due August 2, 1993. For further information and registration forms, contact Tony Jakeman, CRES, Institute of Advanced Studies, Australian National University, Canberra ACT 2601, Australia. Phone: 61 6 249 4742, Fax: 249 0757, Email: tony@cres.anu.edu.au.

THIRTEENTH INTERNATIONAL CONGRESS
OF BIOMETEOROLOGY

THEME: Adaptations to Global Atmospheric Change and Variability

The Convention Centre, Calgary, Alberta, September 12–18, 1993.

The International Society of Biometeorology announces its 13th Congress, which will address issues of humans, animals, plants, invertebrates, and microorganisms in relation to climatic change and variability. Interactions related to health and disease, production and performance, dwellings, architecture, clothing, energy and transport will all be within the scope of the congress.

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C^{2}GCR STUDENT DAY

The Second Annual C^{2}GCR (Centre for Climate and Global Change Research) Student Day was held May 4, 1992 at McGill University. At the peak, over 50 students, Centre faculty and visitors were in attendance listening to the presentations from 26 graduate students (17 Ph.D., 9 M.Sc.) who are being supervised by C^{2}GCR faculty members. The success and widespread interest of this event can be measured by the fact that this year there were 9 more presentations than at last year's inaugural C^{2}GCR Student Day.

Papers were presented in four broad categories: Ocean studies and the thermohaline circulation; Clouds and the climate system; Fluxes at the air-land interface; and General atmosphere and ocean modelling. Thus the papers ranged over the air, ocean, ice and land components of the earth associated with the Centre. The Department of Atmospheric and Oceanic Sciences was particularly well represented, with 18 of their students giving papers. Four students from the Department of Geography and four from the Department of Renewable Resources completed the program. The abstracts are available as C^{2}GCR Report No. 92-7, May 1992.

We were particularly fortunate to have with us as special guests Brian Bornhold, Monique Leclerc, and Doug Lightfoot. Dr. Bornhold, a paleoclimatologist and marine earth scientist, has recently been appointed Director of the Canadian Global Change Program, which is run under the auspices of the Royal Society of Canada. Dr. Leclerc, an expert in land surface processes and boundary layer meteorology, is a faculty member in the atmospheric physics group at the Université du Québec à Montréal. She co-supervises (with Dr. P. Schuepp) one of the Centre students (Mr. James Rowland). Finally, Mr. Lightfoot, formerly with Domtar Research and now an engineering consultant, is currently working with Centre member Dr. Chris Green on a project which is evaluating the use of energy sources other than fossil fuels as a means of reducing global warming. Judging from their questions and interactions with the students, they thoroughly enjoyed the day, and we hope that they will be able to join us at such future events.

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