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

TITLE PAGE should include the full names of author(s), and professional affiliation(s).
The ABSTRACT should be less than 250 words, and typed on a separate page.
The TEXT of longer contributions should be typed double spaced on numbered pages, and divided into sections, each with a separate heading and numbered consecutively. The section heading should be typed on a separate line.
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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.
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Authors should use the International System of units, but may show other units in parentheses. Authors should provide instructions in the margin for any special type required (Greek letters, capitals, bold face, etc.).

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

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

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

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

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

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

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

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Foreword / Avant-Propos

This issue of the *Bulletin* contains three articles of general interest and a review of the 1986 severe local storm season in Canada. The flow of submitted manuscripts has improved greatly, and we continue to receive some from outside the country. The journal clearly has potential for further growth.

Ce numéro du *Bulletin* contient trois articles d'intérêt général aussi qu'une revue du temps violent estival de 1986 au Canada. Le taux de soumission de manuscrits a beaucoup amélioré, y compris un certain nombre de l'extérieur du pays. Le *Bulletin* a vraiment le potentiel de plus de développement dans l'avenir.

Alec Paul
Editor/Rédacteur en chef

Automated Data Collection and Management System for Climatic Data at an Agricultural Research Institution

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ABSTRACT

Automation of climatic data collection and management is invaluable at agricultural research institutions. A Climatic Data Management System implemented at the Lethbridge Research Station utilizes commercially available dataloggers and sensors for data collection. Sufficient flexibility is built into the data collection system to accommodate standard climatic measurements as well as supplementary measurements in support of local research activities. The data collected are processed using a menu-driven computer program to provide quality control checks, to update historical archives, and to produce reports for investigators on station and at external agencies such as Environment Canada. The integration of historical archives with the most current climatic data collected provides a resource to researchers wherein most of the required climatic information is readily available.

RÉSUMÉ

L'informatisation des données climatiques et leur manipulation sont des ressources essentielles à toute station de recherche agricole. Un système de manipulation de données climatiques développé à la Station de recherche de Lethbridge utilise pour l'acquisition de données des collecteurs de données et des capteurs disponibles sur le marché. Le système d'acquisition de données est très flexible puisqu'il peut s'adapter à des observations climatiques standards ainsi que des observations supplémentaires afin d'appuyer des activités locales de recherche. On traite les données acquises par un programme informatique contrôlé par menu afin de vérifier leur qualité, de mettre à jour les archives, et de produire des rapports pour les chercheurs de la Station aussi bien que pour d'autres agences telles Environnement Canada. L'intégration des archives et des données climatiques courantes constitue pour les chercheurs une ressource où la plupart des renseignements climatiques sont faciles d'accès.

1. INTRODUCTION

Although the first automated weather station in Canada was installed over 45 years ago (Douglas, 1981), only in the past 10 years have automated weather stations become common. With recent advances in datalogger and microcomputer technology, an increasing number of organizations and institutions are automating their climatic data collection. It is generally recognized that, with restricted resources, automation is one way of reducing manpower costs (King *et al.*, 1987). However, in some instances, increased quantity and quality of data may be the primary objective in automating climatic data collection. Recently, the Atmospheric Environment Service (AES) has recognized the growing number of autostations and has set data collection standards for such stations (Anon., 1989).

Complete and reliable automated climatic monitoring systems are readily available today. Many are used on an operational basis in climate monitoring networks (Curry *et al.*, 1981; Hubbard *et al.*, 1983; Howell *et al.*, 1984). However, automation of climatic data collection at research institutions specializing in agriculture requires special attention since they are often part of the national climatological network and also function to support local research in many disciplines.

The automation of a weather station at an agricultural research institute requires that a) standard climatic measurements conform to specifications and guidelines of national standards, b) Supplementary Climatological Observations (Anon., 1989) can be made on an operational basis, and c) sufficient flexibility is available to accommodate specific requests for data collection in support of individual research programs.

A data collection system must be integrated with a system for reporting and retrieval of data. Such a system must satisfy reporting requirements of the Canadian Climate Program and other external agencies, as well as serve as a resource to scientists who require a variety of climatic data. A retrieval system that provides accurate, up-to-date, as well as historical, data in a readily usable form will accommodate most user demands. Data from other locations may also be required. For example, in addition to the 500 hectares of research plots at Lethbridge, the Research Station maintains substations at Vauxhall (190 ha), Onefour (17,000 ha), and Stavely (360 ha) for studies in irrigation, range management, and hydrology. To date, only the climatic data collected at the Lethbridge station and the Vauxhall substation are incorporated into the retrieval system.

This article describes a Climatic Data Management System (abbreviated as the CDMS) that includes automated data collecting, reporting and retrieval which was initiated in 1986 (upgraded in 1988) at the Agriculture Canada Research Station at Lethbridge. Research activities conducted by a staff of 270 are divided into forage and cereal crop science, soil science, and livestock science. The CDMS, described here, attempts to provide for the needs of the researcher and the national climatological network.

Several types of commercially available dataloggers are compatible with most meteorological sensors and can provide sufficient flexibility for the required number and type of measurements. At Lethbridge, the Campbell Scientific model CR7 and the Sciemetric Instruments model 8082A dataloggers have been used for data collection since 1986. Both these dataloggers allow maximum flexibility in the type and number of sensors being monitored. The Sciemetric 8082A datalogger requires a low cost microcomputer as support. Although both dataloggers have performed satisfactorily for data collection, the CR7 proved more reliable because of its internal power backup and has been in use since 1988. The Campbell Scientific 21X datalogger with an AM32 Input Multiplexer has provided sufficient flexibility at the Vauxhall Substation. Technical specifications for these dataloggers are available from the manufacturers (Table 1).

The data collection system must have sufficient flexibility to accommodate requests from researchers for Supplementary Climatological

TABLE 1. Dataloggers and sensors for the automated data collection system.

Instrumentation	Source
CR7 datalogger	Campbell Scientific Canada Ltd., Edmonton, Alberta
21X datalogger	Campbell Scientific
8082A datalogger	Sciemetric Instruments Inc., Nepean, Ontario
DC103A Answer Modem	Campbell Scientific
C20 Cassette Interface	Campbell Scientific
Model 207 temperature/RH probe	Campbell Scientific
Models 107 and 107b temperature probes	Campbell Scientific
Relative Humidity, temperature probes	Micromet Systems, Vancouver, B.C.
Met One Heavy Duty Anemometer 013	Met One Inc., Grants Pass, Oregon
Met One Wind Direction Sensor 023	Met One Inc.
Kipp and Zonen CM5 pyranometers	Kipp and Zonen, Delft, Netherlands
Middleton pyrradiometer CN1	Middleton Instruments, Melbourne, Australia
Tipping bucket rain gauge	Environment Canada AES

NOTE: The listing of brand names and suppliers above should not be construed as endorsement of only these specific products. Other commercially available instruments may be equally satisfactory.

Observations for a short period of time. For example, measurements of night-time wind and temperature profiles may be requested to support a study of flight activity of cutworm moths for the months of July and August. The data collection system must be able to respond to such requests and often several such requests simultaneously and without interference to the routine data collection at the Ordinary or Principal Climatological Station (Anon., 1989).

The Campbell Scientific dataloggers were programmed to sample sensor output every 5 seconds in accordance with recommendations by King *et al.*, (1987). Output data were generated each hour, at 0800 and 1600 h, and during a rainfall event at 1-minute intervals. The hourly output consisted of averaged temperature (soil, grass and screen), humidity, radiation, wind, and rainfall data as well as the top-of-the-hour (1 minute) averaged temperatures and humidity. The latter output corresponds to a manual measurement conducted at Principal Climatological Stations. The averaged hourly data may be more relevant for research. The output at 0800 and 1600 h (MST) produces maximum and minimum soil, screen and grass temperatures, which correspond to manual measurements made at Ordinary Climatological Stations. The event output produces rainfall amounts occurring every minute during rainfall events to enable a calculation of rainfall intensity.

Data collected by the dataloggers are recorded on cassette tape (Lethbridge Station) or transferred via modem (Vauxhall Substation) to the mainframe computer (Figure 1) once a week. Although the data transferred via modem are very reliable, cassette tape is used as backup at the Vauxhall Substation.

Commercially available sensors for the measurement of climatological elements are listed in Table 1 and conform to, or exceed, Atmospheric Environment Service (AES) guidelines (Anon., 1983). All sensors are of the "off the shelf" variety and were configured and installed according to manufacturers' specifications. Additional signal cables from the dataloggers were installed and connected to junction boxes positioned at various locations within the weather observing site. Thus, any additional Supplementary Climatological Observation requested by researchers can be collected with a minimum of difficulty.

Calibrations for the anemometers, net pyrradiometers, and pyranometers at all stations are conducted during March (initiated in 1988) by mounting these sensors on a fixed horizontal bar located at the Lethbridge weather station. Anemometers are refitted with new bearings and reed switches prior to calibration against a standard (previously calibrated against a pitot tube anemometer in a wind tunnel). Net pyrradiometers and pyranometers were calibrated against sensors previously calibrated at the National Radiation Centre.

Although the dependability of current dataloggers and sensors appears satisfactory, there continues to be a problem with such measurements as evaporation, daily snowfall, depth of snow on the ground, and sunshine hours. Research to resolve these problems is ongoing (Goodison *et al.*, 1987). In the

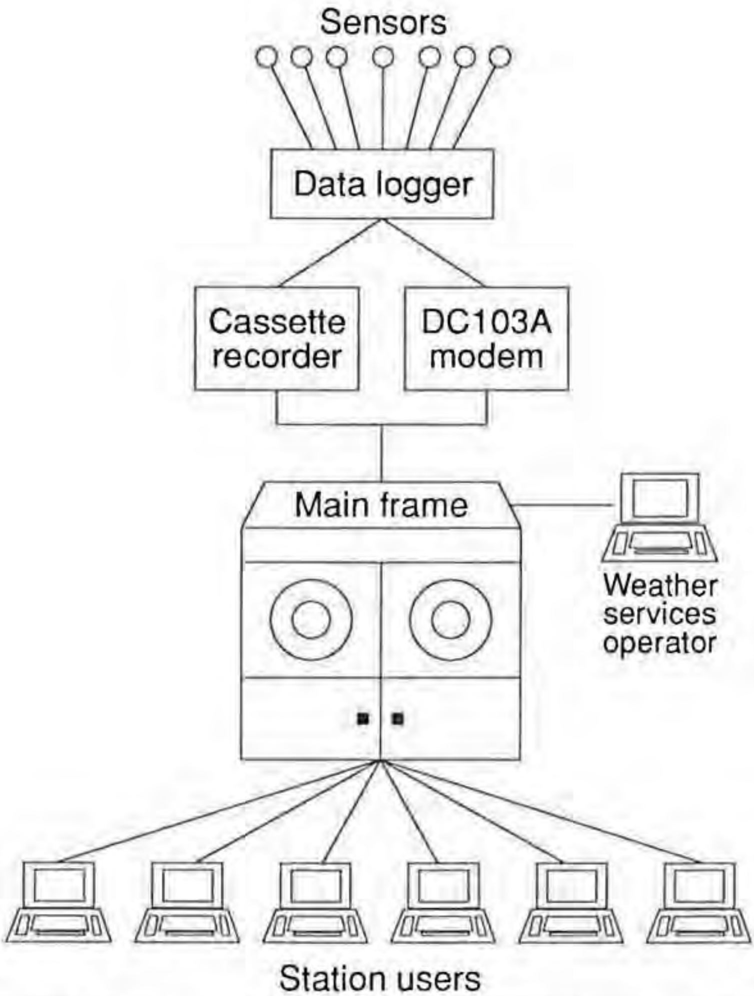

FIGURE 1. Schematic diagram of data collection and information discrimination of the CDMS at the Agriculture Canada Research Station, Lethbridge, Alberta.

interim, daily visits are required at Ordinary Weather Stations if these measurements are incorporated into the measurement program. It is difficult to envision a completely automated, maintenance-free, agroclimatic station. For example, weekly visits to the Lethbridge and Vauxhall weather stations are made to maintain the sensors and to check sensor readings against measurements made using manual methods. More frequent visits may be required to remove ice/frost/dew from net pyrradiometers, although these may be reduced by heating the sensor (McGinn and King, 1988). The weekly visits, in conjunction with the data quality control checks, ensure that the quality of the data from sensors remains optimum.

3. DATA MANAGEMENT

3.1 *Climate Services*

The three main functions of Climate Services at Lethbridge Research Station are as follows:

1) ensure quality of data collected,
2) on a routine basis, produce weekly, monthly, and yearly summaries and reports of climatic data for research scientists on-station and at external agencies such as Environment Canada, and
3) respond to inquiries for specific climatic information from research scientists and the public by preparing specialized or customized data sets upon request.

The CDMS provides an integrated data reporting/retrieval system to accommodate these objectives. Full access to the CDMS is restricted to the Weather Services Operator responsible for the maintenance and operation of the weather stations at Lethbridge and at Vauxhall.

A series of programs written in DATATRIEVE (Anon., 1984) and FORTRAN (execution controlled using a forms management system, FMS), collectively named "WEATHER", has been constructed to meet the data management requirements of CDMS. Included in WEATHER are programs which allow the Weather Services Operator to enter any manual observations including sunshine hours, Class A pan measurements, and snow accumulation. Once data from the datalogger have been loaded into the mainframe (via C20 Cassette Interface or modem), several calculations (e.g., for longwave radiation downward) and quality control (see section 3.2, Quality Control) are automatically performed. The data from the datalogger which pass the quality control are appended to a single DATATRIEVE database. Manual measurements (sunshine, evaporation, and snow depth) are subject to quality control as they are entered by the Weather Services Operator. The DATATRIEVE database, which is archived each month, is used to update five Principal Data Source Files (PDSF) outlined as follows (Figure 2):

1) Rainfall Intensity File, which contains rainfall data (April to October) since August 1988,
2) Daily Data File, which contains a summary of climatic observations for each day (since January 1, 1909 at Lethbridge), and is used to update other files in the PDSF,
3) Monthly Historical Data File, which contains information for each of the 12 months, e.g., mean monthly temperature, total monthly precipitation, total sunshine hours,
4) Daily Summary File, which contains long-term averages and extremes for each parameter for each day of the year,
5) Long-term File, which contains long-term monthly averages and extremes for each parameter for each month of the year, e.g., average June precipitation, average December temperature, average August Class A pan evaporation.

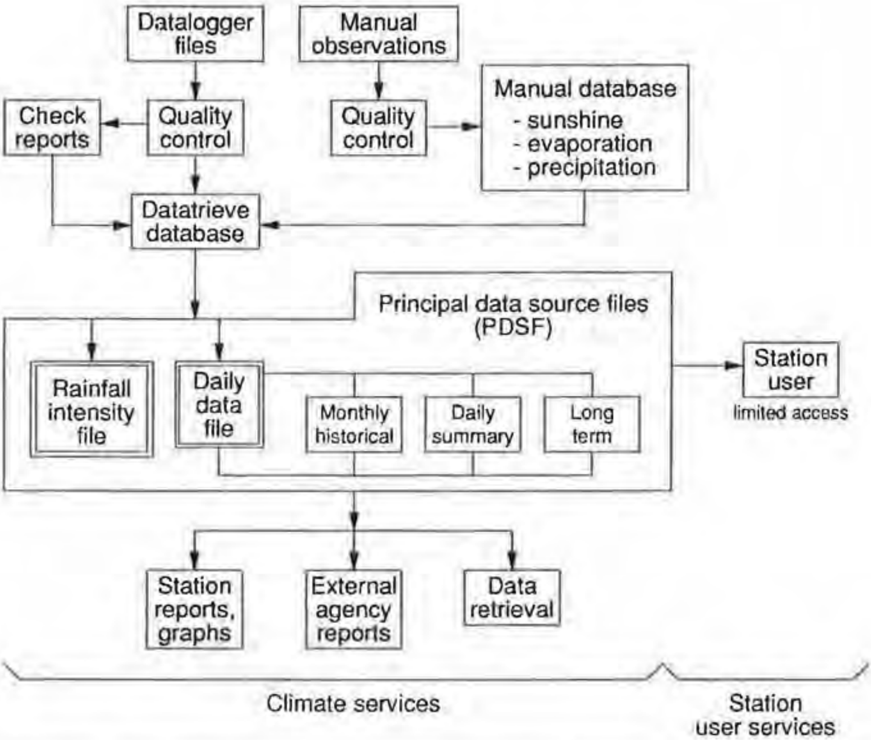

FIGURE 2. Schematic diagram of the flow of data in the CDMS at the Agriculture Canada Research Station, Lethbridge, Alberta.

The PDSF provide the data source to create operational work files. Work files contain the specific data sets required for each of the specified reports, graphs, or retrieval operations.

3.2 *Quality Control*

Quality Control of the data from the datalogger is performed when the data are loaded into the DATATRIEVE database (first step in the CDMS). Data are flagged if they fall outside an inner or outer range or if continuity between time steps is extreme (Table 2). The inner ranges correspond to station extreme high and low values (e.g., temperatures); an inner range failure can alert the Weather Service Operator to a new extreme value. After all data have been transferred to the DATATRIEVE database, the Weather Services Operator is able to scan quickly for flagged data and decides to accept, edit, or reject flagged values. The flags reflect the decision of the Weather Services Operator and accompany the data in the subsequent output.

TABLE 2. Quality control parameters used by Climatic Data Management System.

Measurement	Lower Outer	Lower Inner	Upper Inner	Upper Outer	Continuity (units/h)
Temperature (°C)					
Soil 2 cm	−20	−15.0	38.0	40	3
5 cm	−20	−12.5	31.0	40	2
10 cm	−20	−11.0	27.5	40	2
20 cm	−20	−10.0	26.0	30	2
50 cm	−15	−7.0	23.0	30	1
100 cm	−10	−1.0	17.3	30	1
150 cm	−10	0.6	15.5	30	1
300 cm	−20	1.5	12.2	30	1
Air	−50	−43.0	39.1	50	15
Grass	−65	−45	55	60	20
Pan	−25	−15	35	35	10
BBC†	−65	−45	40	50	15
Radiation (kJ/h)					
Incoming global	0	0	3600	4700	3000
Reflected global	0	0	2200	2400	1500
Diffuse global	0	0	2520	4680	1500
Net allwave	−1440	−720	2650	2880	2500
Net allwave (BBC†)	−1440	−720	2850	3150	2750
Longwave down	−1440	−720	2160	2880	720
Wind speed (m/s)					
0.5 m	0	0	13	20	10
10 m		0	0	28	40
Maximum 10 m	0	0	28	40	
Wind direction frequency		0	0	1	1
Prevailing direction	0	0	360	360	360
Humidity (%)	5	10	100	100	40
Vapor pressure (kPa)	0	0	5	10	1
Precipitation (mm)	0	0	40	90	
Battery voltage (V)	12	12	15	15	1

† BBC = Black Body Cup.

3.3 *Reporting*

Traditional Environment Canada data reporting forms such as Snow Survey Form (0063-2333), Climatological Station Reports (0063-2304), Sunshine Records (0063-2307), Monthly Records of Soil Temperature (0063-2271), and Class A Pan Evaporation Monthly Records (0063-2270) are still in wide use. Some weather stations that have automated their data collection now generate computer printouts with formats identical to the required AES reporting forms. These printouts are now routinely submitted. A further advance in this area has been the recent AES Western Region guidelines (Anon., 1987) for formatting climatic data on magnetic tape or diskettes for submission so that no hard copy is required providing specific formatting criteria are followed.

At Lethbridge, a series of data and graphical summaries is also routinely produced for station investigators (Table 3). The graphs are formatted within WEATHER employing SAS/GRAPH (Anon., 1985) so that they are updated and generated each month on a routine basis with the data summaries and agency reports. Figure 3 displays examples of the graphs currently in use at

TABLE 3. Reports produced by the Climatic Data Management System.

Report Type	Report Name
ATMOSPHERIC ENVIRONMENT SERVICE	
	Monthly Sunshine Record
	Climatological Station Report
	Monthly Record of Soil Temperature
	Class A Pan Evaporation Record
	Rainfall Intensity
AGRICULTURE CANADA	Canadian Weather Review
STATION CLIMATE SERVICES	
Data Summaries	Monthly Climate Summary
	Monthly Wind Summary
	Monthly Radiation Summary
	Station Soil Temperature Report
	Weekly Summary
	Yearly Summary
Graphical Summaries	Historical and Current Precipitation
	Historical and Current Temperatures
	Historical and Current Evaporation
	Seasonal Precipitation and Evaporation
	Historical and Current Wind
	Accumulated Precipitation
	Daily Difference from the Mean
	Current Temperature and Wind
	Current Temperature Trends
CLIMATE SERVICES OPERATOR	
Check Reports	Quality Check
	Missing Data Check
	Radiation (1) Check
	Radiation (2) Check
	Wind Check
	Temperatures Check
	Humidity Check
	Rain/Snow Check
	Evaporation Check
	Sunshine Check

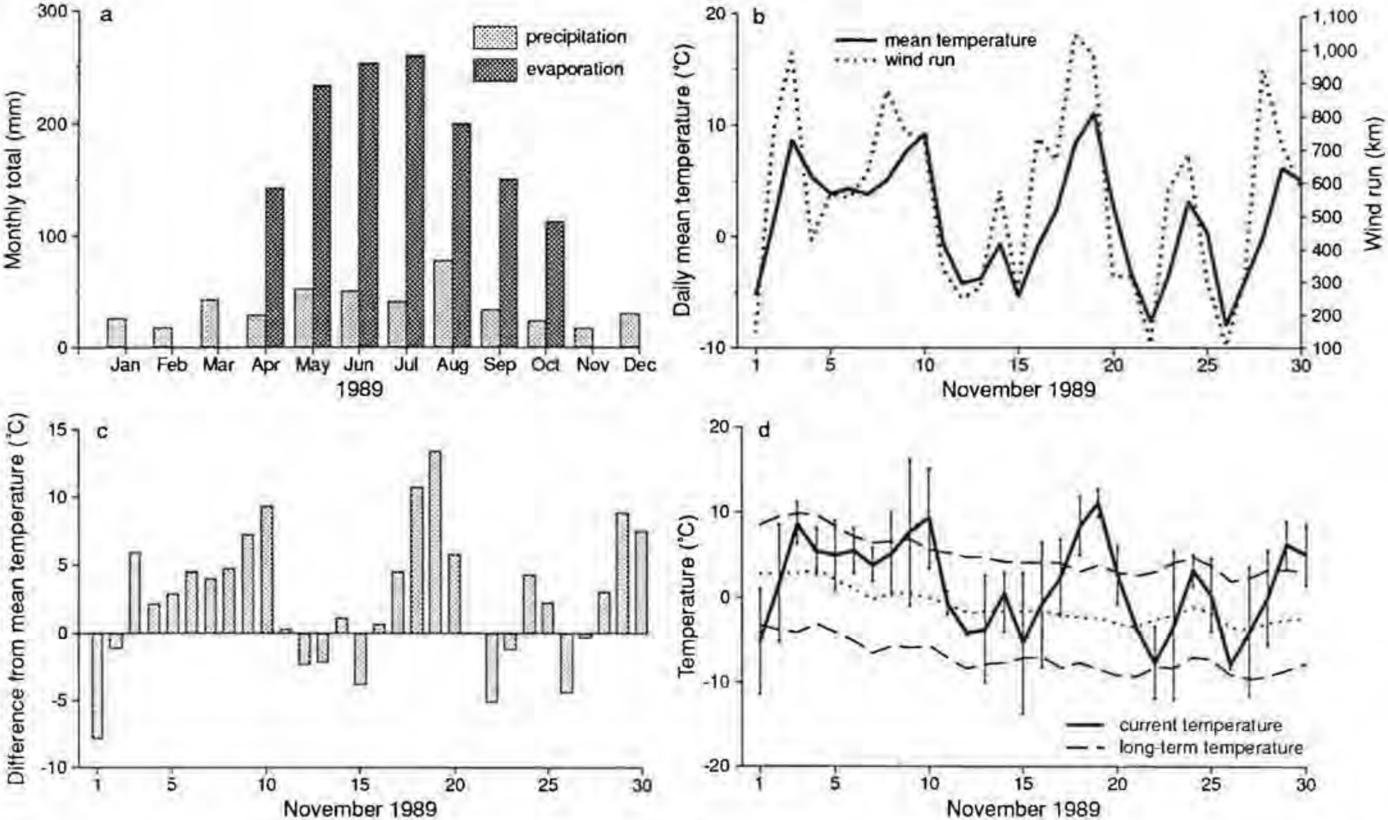

FIGURE 3. Examples of graphical data summaries produced monthly at the Agriculture Canada Research Station, Lethbridge, Alberta.

a) Total monthly precipitation and class A pan evaporation for current year (January to November 1989 inclusive).

b) Daily mean air temperatures and total daily wind run for current month (November 1989).

c) Daily difference from mean temperature for current month (November 1989).

d) Historical daily maximum, minimum and mean air temperatures (shaded area and broken line) and observed daily maximum, minimum and mean air temperatures (vertical bars and solid line) for the current month (November 1989).

Lethbridge; for example, a graph showing mean daily temperature and total daily wind run (Figure 3b) is produced on a regular basis to give an indication of the frequency and intensity of chinook episodes. Such a graph may not provide useful information at other locations.

In one operation, a complete series of operational work files, one file for each of the preprogrammed reports and graphs, is generated. One or more of the PDSF are used as the source of data for the operational work files. Employing a menu, the Weather Services Operator may then produce any one or a complete series of all the required Agency Reports, Station Reports, and Graphical Summaries. The reports and graphs may be displayed, printed, mailed to any other MicroVAX account on-station or merged with mailing lists for dissemination to users off-station.

3.4 *Retrieval*

Agricultural research institutions have requirements in addition to the reporting of recent climatic data. Often climatic data from the past few years or growing seasons are required for accurate analysis of experimental results. Some experiments may be conducted over years, even decades. For example, crop rotation trials initiated at Lethbridge in 1912 are still in progress and are constantly being evaluated (Janzen, 1987). On other occasions it may be necessary to compare recent climatic events with historical data to evaluate the validity of experimental results from the field.

Often climatic data are required from a substation where the mesoclimate or soil type is different from that at Lethbridge. Data from the Vauxhall Substation are currently integrated with the CDMS. In addition to, and in support of, particular research projects, Supplementary Climatological Observations must be made available to investigators. Finally, and again in support of research activities, the CDMS must be capable of real-time data reporting should any research project demonstrate such a need.

The Weather Services Operator has access to all historical data from the Lethbridge and the Vauxhall substations. Requests from station researchers or external agencies for specialized climatic information can be processed quickly. A series of menus allows the Weather Services Operator to select the location, climatic parameters and the time period of requested data. The request for climatic data is submitted in a batch format and compiled from the PDSF; the output is either printed, displayed on screen, or mailed electronically to the client by selection of the appropriate option.

The DATATRIEVE database containing the complete record of all parameters for the current month is readily available upon request. Data for prior months (since 1986) are accessed by the Weather Services Operator through the mainframe's archive retrieval system.

By combining a system for controlling the entry of current climatological observations into a series of data files containing historical databases with a system of data management and manipulation, the major objectives of Climate Services (data quality control, reporting, and retrieval) are fulfilled.

4. USER SERVICES

To alleviate the demands on Climate Services for the most frequently requested data, restricted access to WEATHER is available to all scientists on station through Station User Services. To ensure accuracy of the climatic data base and to safeguard the CDMS from inadvertent alteration, station users do not have access to any of the editorial functions, programming, or preset reports or graphics. Access to these features is limited to the Weather Services Operator only.

Within WEATHER, a menu is presented to the Station User that contains five options for accessing current reports or retrieving data from historical data files. The options are:

1) Query on Daily Data (most current 2 years only)
2) Monthly Data from Historical Records
3) Query on Long-Term Means and Extremes
4) Most Current Monthly Summary
5) Most Current Weekly Summary

Upon selection of one of the above options, subsequent menus prompt the user to select the location, climatic parameters required, and time period of records requested. According to selections made, the user may then display the data, print them, or mail them electronically to a computer account for further processing. In addition, the most current station weekly and monthly climatic summaries are available.

5. CONCLUSIONS

This paper describes a climatic data management system (CDMS) used at the Lethbridge and Vauxhall Weather Stations. The CDMS, because it handles both standard and supplementary climatological observations, has proven invaluable in managing climatic data at our agricultural research institution. The CDMS is written using FMS (forms management system), DATATRIEVE and FORTRAN computer languages and employs some functions of SAS-GRAPH on a MicroVax 3600 computer. The CDMS uses approximately 70,000 blocks which includes the DATATRIEVE and PDSF databases for Lethbridge and Vauxhall. Changes are currently being made to convert from DATATRIEVE to FORTRAN to allow the transfer of the CDMS to other agricultural research institutions that do not use DATATRIEVE. More detailed information on the datalogger and mainframe programs of CDMS is available from the authors.

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Some Impacts on Rice Yield from Changes in the Variance of Precipitation*

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ABSTRACT

The information most commonly made available from the Global Climate Models (GCMs) for use in work on the impact of climate change comprises "long-term" monthly mean temperatures and precipitation estimates from both "BASE" and "2 × CO_2" runs. Variances of these variables about their means (and hence implied changes in variances) are not generally available. However, changes in risk associated with a climate-sensitive enterprise require an assessment of the consequences of such changes in variance.

This paper postulates scenarios of change in precipitation variance which are used, together with a quarter century of BASE climatological data and its associated 2 × CO_2 climate change data as derived from GCM model output, in order to obtain plant process model estimates of changes in the statistical distributions of rice yield and irrigation water demand in northern Thailand. One scenario simply increases the variance about the monthly means by about 20%, which leads to increases in estimates of variance of both rice yield and irrigation water demand. The other scenario redistributes the variance (without changing its total value) in such a manner that the impact on the Southeast Asia study area of the ENSO (El Niño/Southern Oscillation) phenomenon is increased. This leads to decreases in the estimates of variance of both rice yield and irrigation water demand in Chiang Mai province, Thailand.

RÉSUMÉ

Les renseignements disponibles des modèles de climat global (MCG) pour ce qui est du travail sur l'impact du changement climatique sont d'habitude les estimations à long-terme des températures et des précipitations moyennes mensuelles obtenues à partir des modèles "BASE" et "2 × CO_2". Les variances de ces variables autour de leurs moyennes (ce qui inclue les changements de variance) ne sont généralement pas disponibles. Néanmoins, les

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changements de risque des entreprises agricoles sensibles au climat exigent une évaluation des conséquences du changement de la variance.

Cet article propose des scénarios des changements de la variance des précipitations. On utilise ces scenarios, aussi que 25 années de données climatologiques et leurs données associeées au modèle 2 × CO_2 issues d'un MCG, afin d'estimer, par un modèle "plant process", les changements des distributions statistiques des rendements de riz et de la demande en eaux d'irrigation en Thaïlande du nord. Un de ces scénarios augmente la variance des moyennes de précipitations mensuelles d'environ 20 pour cent, ce qui provoque des hausses des estimations de variance des rendements de riz et de la demande en eaux d'irrigation. L'autre scénario redistribue la variance, sans toutefois changer sa valeur totale, de façon à ce que l'impact du phénomène ENSO (El Niño/Southern Oscillation) soit mis en évidence. Ceci provoque des réductions des estimations de variance des rendements de riz et de la demande en eaux d'irrigation dans la province de Chiang Mai en Thaïlande.

INTRODUCTION

One of the factors in the assessment of risk associated with grain farming is the distribution of yields to be expected in the long term. Since both the mean and the variance of yield are required to determine this risk, any change in growing conditions which affects either or both of these parameters significantly is of importance in the estimation of changes in this risk.

The present paper deals with changes in the climatological aspects of the crop's growing conditions, with a particular focus on the impacts of changes in the variance of precipitation on upland rice yields simulated over a quarter of a century. Cooter (1985) and Parry, Carter, and Konijn (1988) stress the fact that, while we deal with crop yield on an annual basis, the within-season variability in the weather has at least as much impact on the yield variance as does the between-season variability in total growing-season precipitation or energy degree days. Cooter (1985) has documented this quantitatively using the CERES-MAIZE plant process model.

For this reason it is vital to use a daily process model as opposed to a regression model to estimate the impacts of weather and climate on crop yield. In the present study we use the CERES-RICE (Upland Version) model (Ritchie, 1988). The model makes explicit use of precipitation, temperature, and solar radiation on a daily basis in estimating changes in biomass and phenological development of the crop. Parry and Read (1988), as well as Eddy and Sladewski (1988), mention the importance of the impact of changes in rainfall variability on changes in the variability of water yield from a catchment basin. In the case of irrigated agriculture, this translates into changes in the uncertainty of irrigation water supply.

Our study area is in Southeast Asia and the rainfall, on which we will impose well-defined and explicit changes for introduction into the plant process model, is monsoonal in character. Our climate change scenarios are developed by modifying the daily rainfall amounts using the basic observed daily rainfall data for the period 1951–1975. The rainfall 'days of occurrence' are not changed. This is a very important constraint because, if an increase in rain were to occur by increasing the number of days of rain instead of by increasing the intensity, then the associated changes in solar radiation reaching the plant could have as much impact on yield as would the changes in water availability. Apart from this, variations in the timing of runs of rainy days can have significant impacts on subsequent yields.

THE CLIMATE SCENARIOS

We define four climate scenarios for use in the study:

i) BASE: this is the 25 years of daily values of observations from 1951 to 1975 (UNDP, 1982). While daily temperatures (maximum and

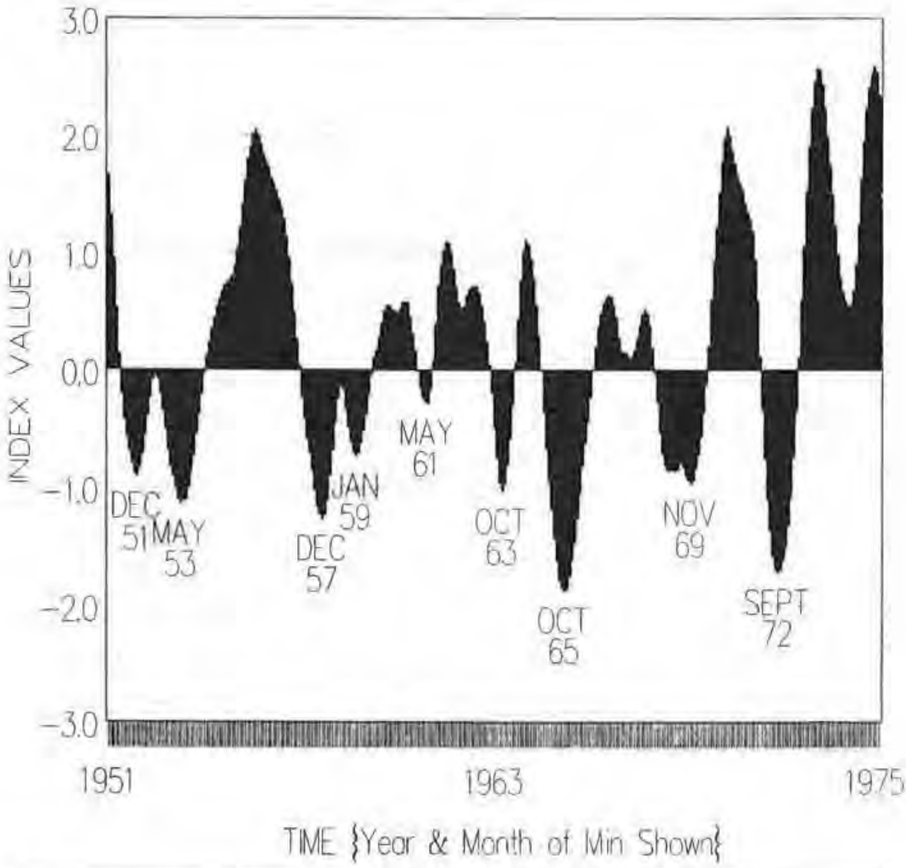

FIGURE 1. Southern Oscillation Index (monthly smoothed values)

minimum) were obtained from observations, daily solar radiation was obtained by regression for wet and dry days separately.

ii) GISS: this is obtained from the BASE scenario by modifying the temperature and precipitation using the output from the particular GCM (Global Climate Model) used by the Goddard Institute of Space Studies. The 25 years of daily data produced for this scenario exhibit a 6.8% decrease in the variance of the daily precipitation about the monthly mean.

iii) BAVA: this is obtained from the BASE scenario by changing the observed variance of precipitation about the monthly means. The total variance is increased by 21% over that of the BASE.

iv) BASO: this is obtained from the BASE scenario by redistributing the (eigenvector components of) variance of the precipitation in order to enhance the ENSO (El Niño/Southern Oscillation) effect (see, for example, Nicholls, 1988). The total variance is left unchanged. Figure 1 shows the large (time) scale events which are enhanced in the case of this scenario. Associated work not reported here shows these events to be reflected in the precipitation regimes of Southeast Asia. The technology for accomplishing this variance redistribution is described and illustrated in some detail by Panturat (1987).

ILLUSTRATIVE IMPACTS OF THE CLIMATE CHANGE SCENARIOS ON RICE YIELD

We chose to illustrate the impacts of the above described climate (variance) change scenarios on upland rice yield at Chiang Mai, Thailand under selected cultural practice constraints. Two of these scenarios (the BASE and the GISS) are illustrated in Figure 2. As implied by Figure 2, the July precipitation shows the only increase from the BASE to the GISS, the other months showing decreases. Maximum and minimum temperatures were predicted by GISS to increase by 3.0–6.5°C depending on the time of year. The BASO and BAVA scenarios have the same daily temperature values as does the BASE scenario. All four have the same daily solar radiation values. For the purpose of this study the upland rice plant process model is considered to be a system transfer function which transforms input random variables (the climate scenarios) into output random variables (rice yield) under a specified set of treatments (parameters) called cultural practice, soils, genetics, etc. The process model used is typical of such system transfer functions; however, the treatments used here were chosen to illustrate the impacts of the four climate scenarios rather than to simulate actual farm practices in northern Thailand.

A major rice crop was planted in June with its genetic parameters set to a 150-day growing season. Second rice (90-day genetics) was planted in February. When irrigated, the amount of water supplied each day was enough to bring the soil water up to field capacity after the effect of any precipitation had been

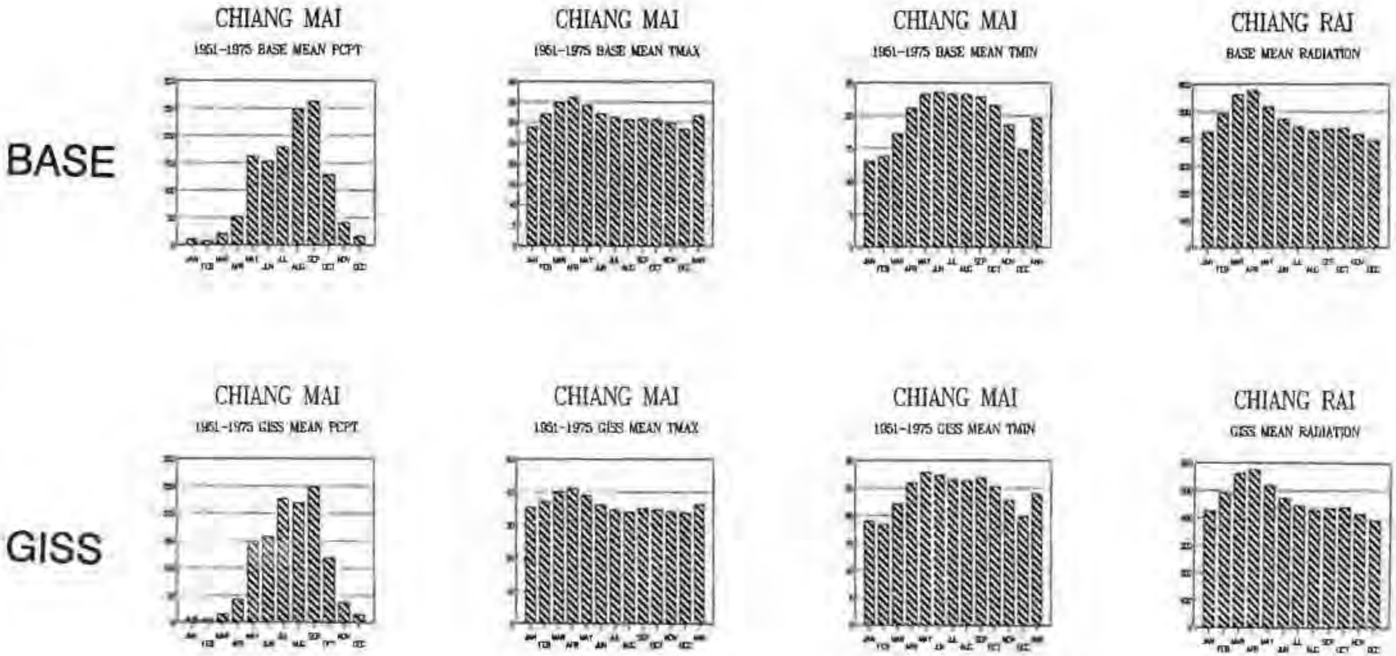

FIGURE 2. 25-year mean statistics used for climate scenarios at Chiang Mai, Thailand

considered: thus there was no water stress on the plant given the irrigation treatment. When fertilizer was applied it was considered to be Urea with 10 Kg/Ha applied at each of three times during the growing season: 1) 300 growing degree days after emergence, 2) about one week before the end of the juvenile period, and 3) one week after the end of the juvenile period. A soil was picked to be typical of the area around Chiang Mai, Thailand, and its characteristics held constant for this study.

Figure 3 shows the 25-year time series of rice yields produced under four climate scenarios given major rice with fertilized, non-irrigated treatments. It can be seen that the BAVA scenario made the bad years (1959, 1966) worse and the good (1966) better, while the GISS had the opposite effect. Table 1 summarizes this effect.

With respect to the BASE scenario; in this case:

i) BASO increases the mean yield and decreases the variance,

ii) BAVA decreases the mean yield and increases the variance,

and, iii) GISS decreases the mean yield and decreases the variance.

Figure 4 shows these effects in terms of cumulative frequency distributions.

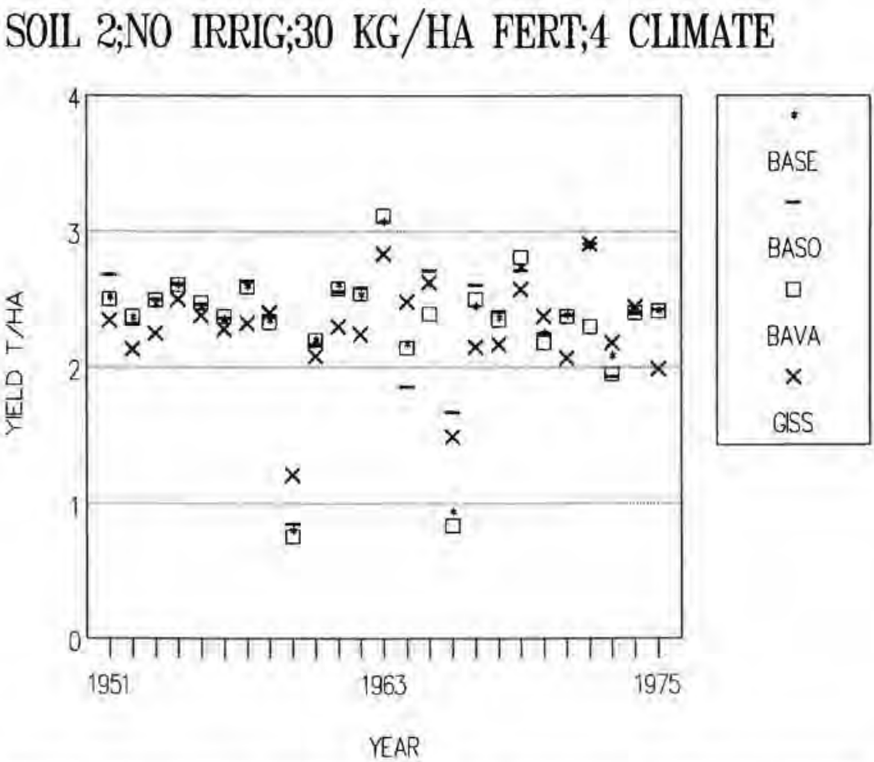

FIGURE 3. Non-irrigated Major Rice model output time series for Chiang Mai, Thailand

TABLE 1. Chiang Mai Statistics on Grain Yield and Irrigation Water Demand for 25 Year (1951–1975) Upland Rice Model Runs Using Four Climate Scenarios with Differing Variances in Precipitation Inputs; Grain = 25-Year Mean in T/Ha; Water = 25-Year Mean Irrigation Demand (mm/growing season).

				BASE		BASO		BAVA		GISS	
CROP	SOIL	IRRIG	FERT	GRAIN	VAR	GRAIN	VAR	GRAIN	VAR	GRAIN	VAR
MAJOR	2	NO	NO	1.16	.0469	1.19	.0483	1.16	.0577	1.15	.0416
MAJOR	2	NO	YES	2.34	.2423	2.38	.1960	2.30	.2546	1.27	.1270
MAJOR	2	YES	YES	2.59	.0076	2.59	.0075	2.59	.0082	2.40	.0069
SECOND	2	YES	NO	1.08	.0061	1.08	.0060	1.08	.0061	1.07	.0081
	SOIL	IRRIG	FERT	WATER	VAR	WATER	VAR	WATER	VAR	WATER	VAR
MAJOR	2	YES	YES	394	3756	392	3482	397	4315	382	5028
SECOND	2	YES	NO	568	5281	569	5595	571	5559	742	10000

TABLE 2. Percent Changes Associated with Table 1.
Definitions: BASO/BASE = 100 * (BASO-BASE)/BASE
: Grain = 25-Year Mean Grain Yield
: Water = 25-Year Mean Irrigation Used

				BASO/BASE		BAVA/BASE		GISS/BASE	
CROP	SOIL	IRRIG	FERT	GRAIN	VAR	GRAIN	VAR	GRAIN	VAR
MAJOR	2	NO	NO	2.6%	3%	0%	23%	−.86%	−11%
MAJOR	2	NO	YES	1.71%	−19%	−1.7%	4.3%	−46%	−48%
MAJOR	2	YES	YES	0%	−1.8%	0%	8%	−7.3%	−8.8%
SECOND	2	YES	NO	0%	−1.6%	0%	0%	−.9%	33%
	SOIL	IRRIG	FERT	WATER	VAR	WATER	VAR	WATER	VAR
MAJOR	2	YES	YES	−.5%	−7.3%	.8%	15%	−3%	34%
SECOND	2	YES	NO	−.18%	5.9%	.53%	5.3%	31%	82%

Figures 5 and 6 present results from another set of treatments: major rice, irrigated, and fertilized. Since the crop has been irrigated, the changes in precipitation imposed by the BASO and BAVA scenarios have not affected the yields (Figure 5) significantly, but rather the effects show up in the demand for irrigation water (Figure 6). As can be seen in Table 1, whereas there has been an increase in mean yield for the GISS scenario (major rice, irrigated, fertilized) over that of the first case (major rice, non-irrigated, fertilized) described above, this increase has been greater than the cases in the other three scenarios. This is a rather complicated consequence of the fact the GISS has a hotter growing season and a wetter July than do the other three scenarios. For example, the higher temperatures decrease the amount of time the plant spends in the grain filling stage in general for this type of cultivar.

To summarize this case, with respect to the BASE:

i) the BASO produced no change in mean grain yield and a slight decrease in mean water demand, while it produced decreases in the variances of both the mean yield and the water demand,

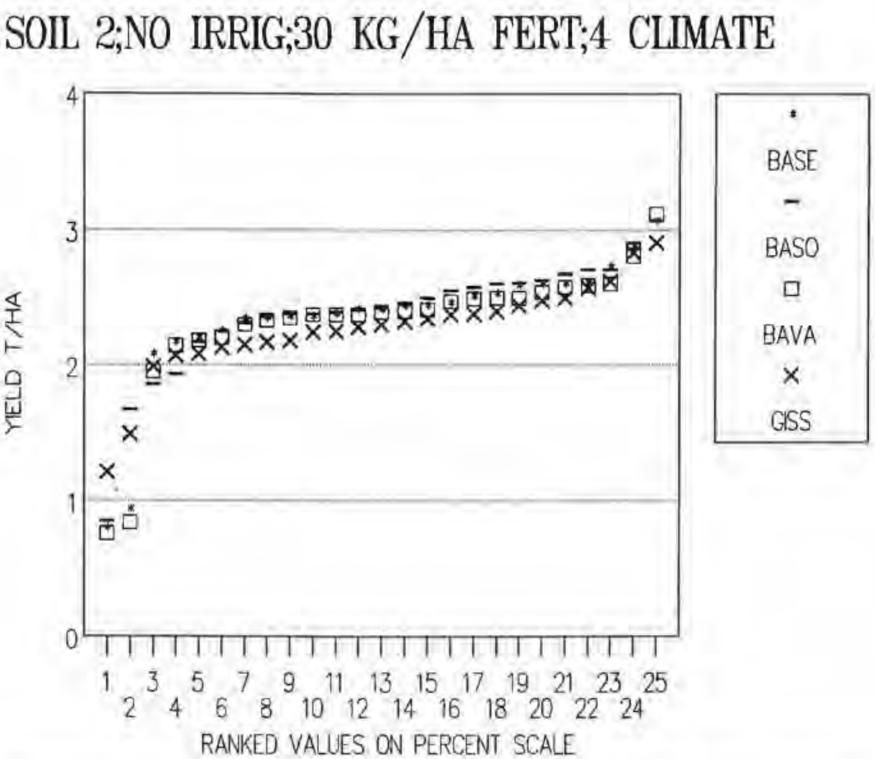

FIGURE 4. Ogive of non-irrigated Major Rice model output (from figure 3 data)

ii) the BAVA produced no change in mean grain yield and a slight increase in the mean water demand, while it produced an increase in the variance in both variables,

iii) the GISS produced decreases in both the mean grain yield and in mean water demand, while it decreased the variance of the yield and increased the variance of the water demand.

Tables 1 and 2 show that in the case of Second Rice, which was always irrigated, the four scenarios produced essentially the same mean yield, although the BASO scenario tended to decrease the yield variance slightly from that of the BASE, while the GISS scenario increased the yield variance considerably.

However, in the case of the Second Rice demand for irrigation water: with respect to the BASE, all these climate change scenarios showed increases in both the mean water demand and its variance. The increased dry-season temperatures associated with the GISS scenario produced rather dramatic increases in irrigation water demand and in its variance.

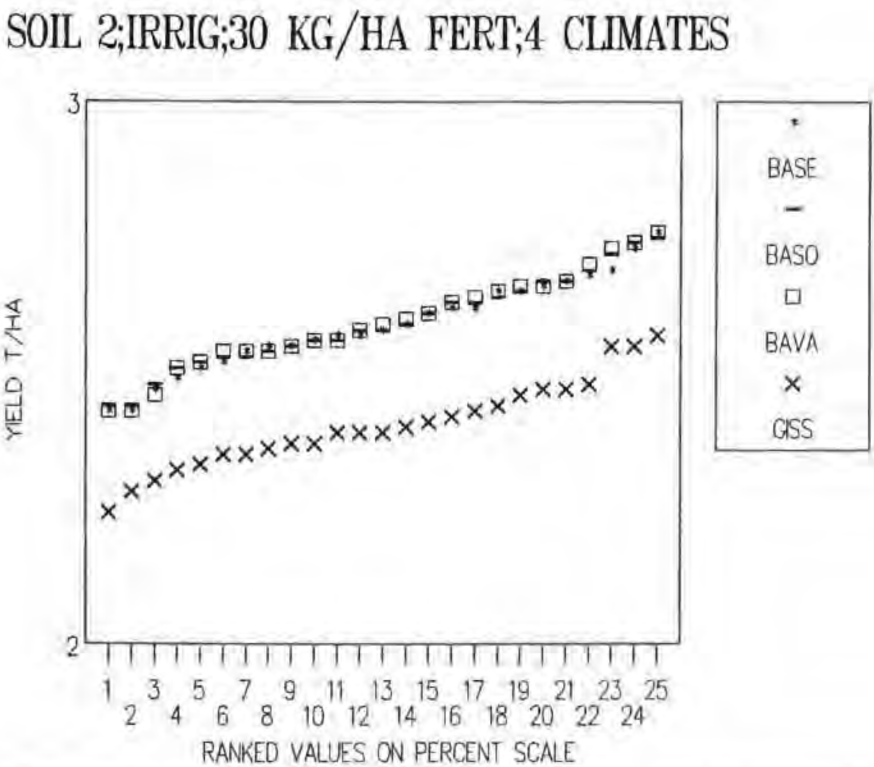

FIGURE 5. Ogive of irrigated Major Rice model – estimated yield for Chiang Mai, Thailand

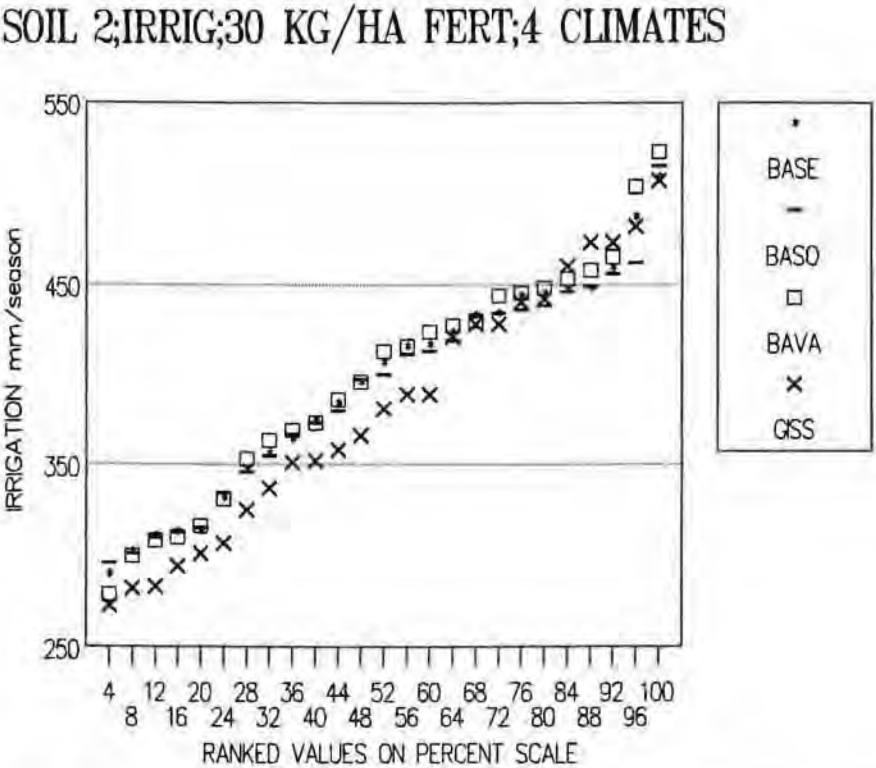

FIGURE 6. Ogive of irrigated Major Rice model – estimated irrigation (for figure 5 yields)

SUMMARY

Four climate scenarios were generated and tested to discover the impact on upland rice production of differences among the four series of 25 years of daily precipitation values. With respect to the BASE scenario of observed variables, the variances of the daily precipitation about its 25-year monthly mean values of these climate change scenarios were:

i) increased by 21% for the BAVA scenario (the standard deviation was increased by 10%),
ii) left unchanged but redistributed (to enhance the longer (time) scale events) for the BASO scenario, and
iii) decreased by 6.8% for the GISS scenario (which also was endowed with significant temperature increases).

With respect to grain yields produced by the BASE scenario, the three climate change scenarios produced no startling changes in the 25-year average yields; however, the variances of the non-irrigated crop yields generally were i) decreased by the BASO and by the GISS and ii) increased by the BAVA, while the variances of the irrigated crop yields were left unchanged by the BASO and BAVA and increased by the GISS. The impacts of the changes in precipitation variances on irrigated crops showed up in the demand for irrigation water as a function of growing season. In the case of Second Rice the variance of the irrigation water applied increased for all these climate change scenarios; whereas, in the case of Major Rice this irrigation demand variance decreased for the BASO and increased for the BAVA and GISS.

It has been demonstrated that changes in precipitation variance will show up as changes in risk (in terms of changes in variance) associated with crop production: directly in the case of rain-fed crops, and indirectly in the form of changes in water demand in the case of irrigated crops. However, these changes in risk are a function of both cultural practice and climate change. This implies that some portion of an increase in risk could be mitigated by changes in cultural practice which might require an increase in irrigation water supply to be most effective.

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Reconstruction of Toronto Temperatures 1778–1840 Using Various United States and Other Data

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ABSTRACT

Records of daily maximum and minimum temperatures for Toronto City exist and are archived from March 1, 1840 to the present day. This lengthy time series has been extended back to 1778 in this article by using standard differences in mean monthly temperatures between Toronto and a number of United States stations. Temperature data taken three times a day from another station in Toronto in the decade of the 1830s are also available and were used in this process too.

RÉSUMÉ

Les données des températures maximales et minimales quotidiennes de la ville de Toronto ont été préservées à partir du 1er mars 1840 et cela jusqu'à aujourd'hui. On peut étendre de beaucoup cette longue série temporelle, en utilisant les écarts-types de températures mensuelles moyennes entre la station de Toronto et plusieurs stations des Etats-Unis, la date la plus ancienne étant juillet 1778. En outre, de 1830 à 1840, un nombre considérable de données sur la température ont été amassées à partir de relevées trois fois par jour, à une autre station de Toronto. On a utilisé ces données aussi dans le processus décrit plus haut.

INTRODUCTION

In December 1839, the British government established a meteorological and magnetic observatory at Toronto, Ontario. Some sporadic observations began late in the month at Fort York, on the shore of Lake Ontario just west of the town, then called York. Fixed hourly observations of temperature commenced in the new year, but it was not until March 1, 1840 that regular daily maximum and minimum values were recorded, and on this date daily digital archive readings begin. On September 5, 1840, the observation site was moved to the University of King's College, now the University of Toronto, about two kilometres north of the lakefront. Although a number of small changes in location occurred in later years, a relatively homogeneous, high-quality data set extends from September 1840 to the present day. However, the rather large urban heat-island effect, which influences the records of all such large cities, is evident.

The Toronto record from 1840 to the present comprises the longest continuous temperature time-series in the Canadian Climatological Archive, and thus it is frequently used in the analyses of long-term temperature trends. The purpose of this paper is to present a method of extrapolating the Toronto temperature time-series backwards from 1840, using various United States and other data. The earliest American data used in the analysis were taken in 1778. The extension of this time-series by sixty years is of significant interest to those who are studying the variability of historical climates, and the methodology may be applicable to other studies of past climate.

SOURCES OF EARLY CLIMATE DATA USED FOR COMPARATIVE PURPOSES

Toronto Area

The first fragmentary climate data for Toronto were taken in the year 1801. These are contained in the Hodgins Papers in the Archives of Ontario, Toronto. The data are identical to those published in the *Upper Canada Gazette* at the time the observations were taken; so it may be presumed that Dr. Hodgins merely copied long-hand this original source. The data include the temperature and weather or sky conditions at three fixed times a day. Similar data were published for a number of months in the same newspaper around 1820. Neither data set was lengthy enough to be used in this study.

Later a longer, more useful data set was taken by Charles Dade (1831–1841) from January 1831 to April 1841. Rev. Dade was the headmaster of Upper Canada College, then situated close to the centre of the town on the lake shore, not far from the later Fort York station. The thermometer was read two or three times a day at fixed times, but slight changes in the reporting hours occurred during the decade and occasionally only one observation was taken in a day. Only a few months were incomplete, except for an extended period from October 1838 to June 1839 when Rev. Dade returned to England for the winter.

The periods of record for the various early Toronto stations used for the purpose of comparison are shown in Figure 1. Data from Fort York are combined in the Archive with the University station and identified as "Toronto" (no modifier), but are unofficially called "Toronto City." Data later than 1855 were not considered.

Remainder of Southern Ontario

Data for Ancaster, about 65 km southwest of Toronto, were taken by Craigie (1835) from January 1835 to December 1845 and proved to be only of limited use in the Toronto data extension. William Craigie was a surgeon who apparently

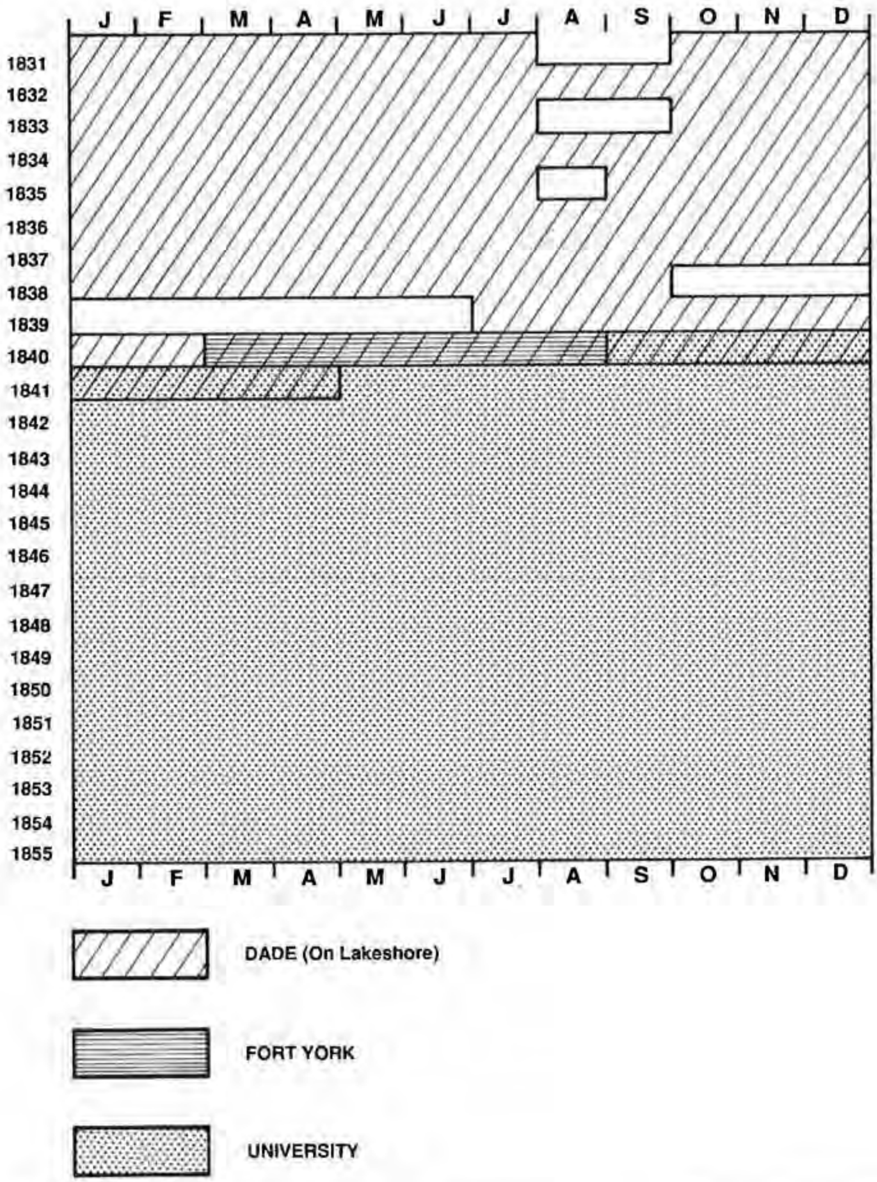


FIGURE 1. Early Toronto climatological records

tabulated daily maximum and minimum temperatures as well as fixed-hour readings. His thermometers "were in a northern exposure, five feet from the ground, and shaded from the effects of direct insolation and radiation from the sky." However, only newspaper tabulations of monthly means of the 9 a.m. and 9 p.m. observations survive.

American Stations

Mean monthly temperature data were abstracted from the Smithsonian Institute (1927) for Albany, New Haven and New York City and from the United States Weather Bureau (1932–1937) for Albany, Baltimore and Rochester. Considerable monthly data were also available from grammar schools in New York State. These were published by Hough (1855, 1872). Data for Auburn, Buffalo, Cortland, Fairfield, Fredonia, Hamilton, Lewiston, Lowville, Oneida, Rochester (College) and Utica were used. Other stations listed in the above publications did not have sufficient useful data.

All stations actually used in the study are shown in Figure 2. In the case of the New York State grammar school records, there were many missing months and years for most stations, and only the first and last years of data are shown. In all cases, data later than 1855 were not used.

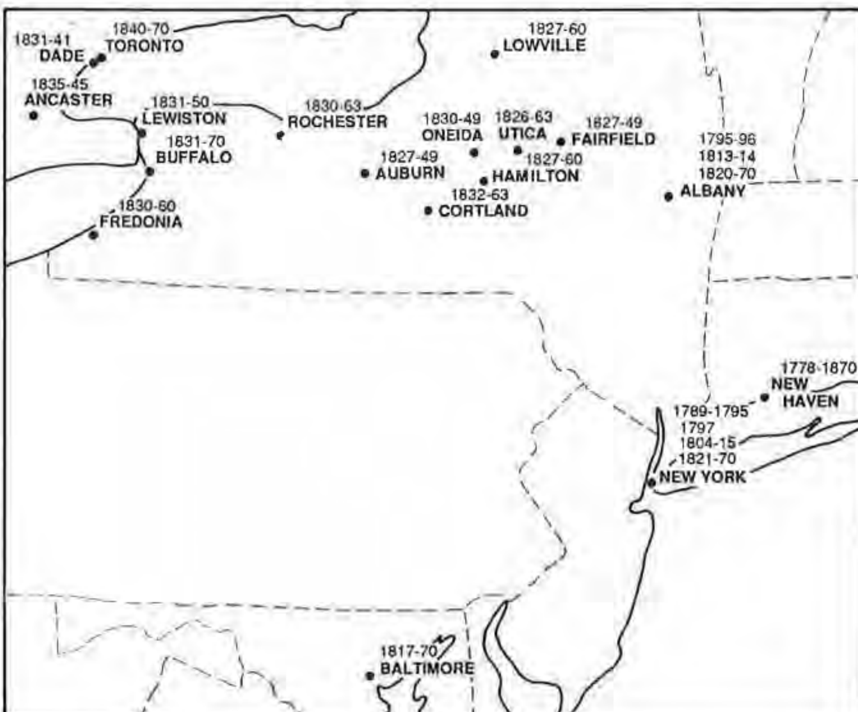


FIGURE 2. Early eastern North America climatic data

As seen in Figure 2, the only data available for the study are from stations to the southeast of Toronto. In order to estimate any possible bias introduced by not using data from all quadrants, mean temperatures for each month for the 30-year period 1951–1980, at Bridgeport CT (near New Haven), Huntington WV, Green Bay WI and Val d'Or PQ, were each correlated with Toronto's monthly means. These stations are approximately the same distance from Toronto and represent each of the four quadrants (see Figure 3). A principal component analysis averaged for the twelve months showed that 26.0% of the variance in the Toronto means was represented by the Bridgeport means, 23.7% by Huntington, 25.8% by Green Bay and 24.5% by Val d'Or. Individual monthly values ranged from 20% to 29%.

In the case of most of the data prior to 1840, observations were taken with the thermometer attached to the north wall of a building. Recording maximum and minimum thermometers were not generally used. Monthly means were computed from two, three or more observations a day, and the time and number of daily observations frequently changed and were not consistent, either at a site or from one station to another. In addition, the thermometers may not have

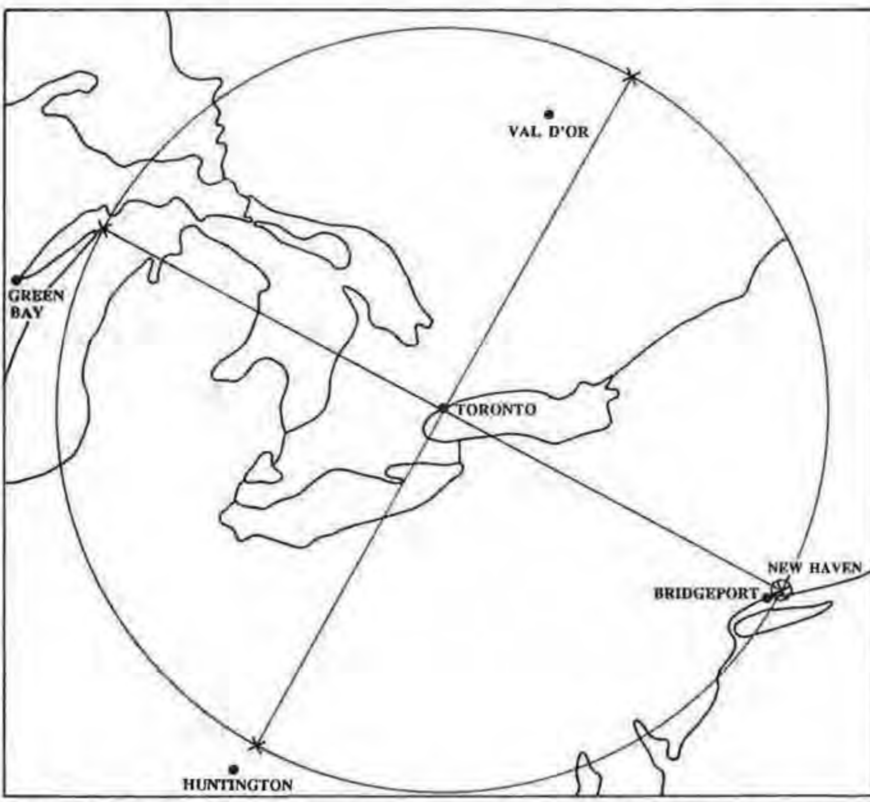


FIGURE 3. Stations chosen from each quadrant for data correlation with Toronto, 1951–1980

been calibrated accurately or sufficiently shielded from insolation, and changes in exposure or siting may not have been recorded.

METHOD OF ESTIMATION OF TORONTO MEAN TEMPERATURES

Three distinct methods (Crowe, 1989) were employed in the calculation of Toronto mean temperatures, due to significant differences in the form of the source data: monthly means at the American stations (calculated by a variety of methods depending on the station); several observations each day for Dade; and monthly means for 9 a.m. and 9 p.m. in the case of Ancaster. These were labelled Method "S", Method "D", and Method "A", respectively.

All three methods were employed whenever data permitted. In deriving the final Toronto estimates, however, Method "D" was chosen whenever Dade data were available. Thus, Method "S" was used up to December 1830, but Method "D" from January 1831 to February 1840. For missing Dade months, Method "S" was substituted before 1835, but from this year on, a linear regression equation was used based on the 52 months when the calculated American data could be compared with both Dade and Ancaster calculations.

$$T = -0.126 + 0.6045\,T_A + 0.4108\,T_S,$$

where T is the estimated Toronto monthly mean
T_A is the estimated Toronto mean using Method "A", and
T_S is the estimated Toronto mean using Method "S", all in °F.

Method "S"

Method "S" is outlined in Figure 4. There are five distinct steps:

1. Difference calculations. Mean monthly temperature data for Toronto (City), 1840 (March–December) – 1870, and for all available American stations within about 400 miles of Toronto having significant data before 1870 were tabulated. Sixteen distinct U.S. stations were available. Most stations did not have data before 1820, but New Haven CT had data as early as 1778 (Figure 2). In order to facilitate comparison of data from all stations, for each individual month, differences were calculated for all possible pairs of stations, for example, Toronto minus Rochester, Toronto minus Albany, Toronto minus New Haven, . . . Rochester minus Albany, etc.

2. Correction and deletion of bad data. The differences for each station pair were tabulated by month and year and the overall monthly mean differences calculated. Also, standard deviations of the mean monthly temperatures for each station were calculated. Then, for each station pair for each of the twelve months, an average standard deviation was calculated, and all differences greater or less than one standard deviation were identified. For example, the s.d. of the August means at Toronto is 1.8°F, Albany 2.2°F, for an average of 2.0°F. The mean

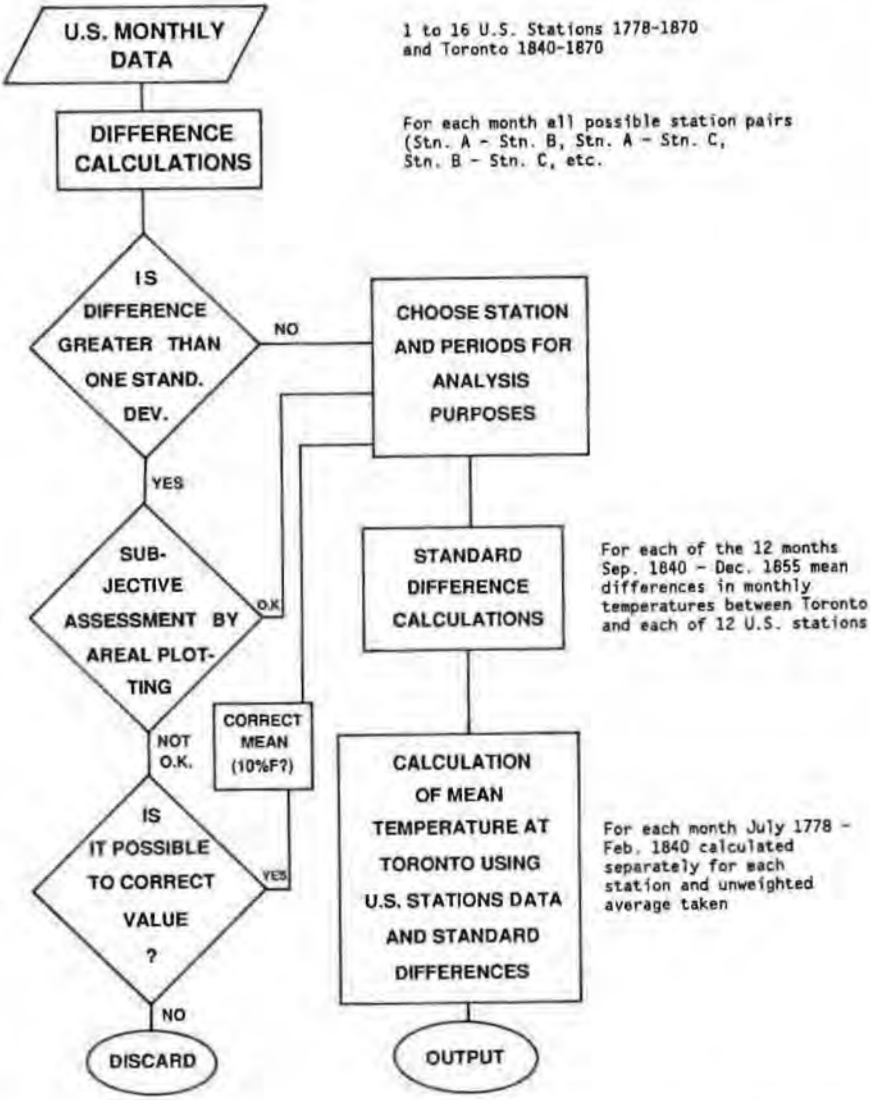


FIGURE 4. Method "S"

difference for the month, Toronto-Albany, is −4.5°F, so that the 1 s.d. range is −2.5°F to −6.5°F. By identifying differences outside the 1 s.d. range, it was easy to spot unusual months or questionable data. For any month for which no station pair differences lay outside the 1 s.d. range, the data were assumed to be good. Otherwise, a subjective assessment was made by the areal plotting of the means and departures from normal. In a few cases, it was possible to correct a value when it was obvious that a typographical error of 10°F had been made in the printed source. Most questionable data, however, were discarded.

3. Choosing of stations and periods for analysis purposes. Following the corrections and the discarding of questionable months, a new data set for each of the 16 American stations was prepared. The Toronto data were assumed to be "good" and the aim was to choose as many of the 16 U.S. stations as possible for 1840–1870 for the purposes of comparison. Many of the stations had missing or discarded data in the last half of this period, and so it was necessary to use only the 1840–1855 record. Within this record, not enough data were available for the computation of reasonable monthly means at Auburn or Buffalo, and the data for Rochester College were identical to or varied by only a small constant from the Rochester data and hence were suspect. The number of U.S. stations for the purposes of comparative analysis was therefore reduced to 13.

4. Standard difference calculations. For each of the 12 months, mean differences in monthly temperatures between Toronto and each of the 13 American stations were calculated. The calculations were based on all months, September 1840 to December 1855, inclusive. It was felt that the early data for Toronto, March to August, 1840, taken near the lake shore at Fort York, were not homogeneous with the later University site observations. Because of some missing months for most U.S. stations, the availability of data varied from month to month and from station to station. The standard differences were calculated from means based on 10 to 15 years in most cases. Those between Baltimore and Toronto ranged between 10.0°F and 13.5°F, depending upon the month. Because of its great distance from Toronto and the resulting high and variable differences in the monthly mean temperatures, it was decided to eliminate Baltimore. Thus, only 12 stations were left for further analysis.

5. Calculation of Toronto means. For each month, July 1778 to February 1840, an estimated mean temperature for Toronto was calculated separately based on each American station for which a mean monthly temperature was available. Thus, in June 1831, the mean monthly temperature at Albany was 72.8°F, and since the standard difference, Toronto-Albany (based on 1840–1855) is −6.8°F, the resulting estimate of the Toronto mean is 66.0°F. The overall Toronto mean for a particular month was calculated as the unweighted average of all the individual estimates from the U.S. stations with available data; the number of such estimates for any month varied from 1 to 12. The estimated Toronto means then were checked against the actual means from September 1840 to December 1855.

Although errors for some months were as great as 4.0°F, the standard deviations of the errors varied from 0.94°F to 1.75°F for individual months, averaging 1.17°F.

Method "D"

Method "D" is outlined in Figures 5 and 6. There are eleven distinct steps:

1. Estimation of daily maximum and minimum temperatures. Rev. Dade took one, two or three observations a day, often but not always at 9 a.m., 3 p.m. and 6 p.m. It was necessary to estimate daily maximum and minimum readings. This was done by using mean hourly temperatures in comparison with mean daily maxima and minima for each month at Toronto's Pearson International Airport (Atmospheric Environment Service, 1978). Thus, a correction factor was calculated to be subtracted from the morning reading to estimate the daily minimum and to be added to the mid-day and evening observations to estimate the daily maximum. These applied to Pearson Airport, so corrections for Dade were computed by multiplying the Pearson corrections by the ratio of the monthly mean daily range at Toronto (City) to that at Pearson. These figures were rounded to the nearest whole Fahrenheit degree.

2. Calculation of mean monthly temperatures. For each month, the mean daily maximum and mean daily minimum were calculated from the daily values. The mean monthly temperatures were then simply the mean of the mean daily maximum and the mean daily minimum.

3. Standard difference calculations, Dade minus U.S. stations. In order to estimate Toronto mean temperatures by using Dade data, it was necessary to compare Dade monthly means as computed above to those of as many American stations as possible. For each of the 12 months for the period January 1831 to April 1841, mean differences in monthly temperature were calculated between Dade and each of 9 U.S. stations: Albany, Cortland, Fredonia, Lewiston, New Haven, New York, Oneida, Rochester, and Utica. Data for Fairfield, Hamilton and Lowville were not used in this analysis due to many missing months during the decade.

4. Standard difference calculations, Toronto minus U.S. stations. Similarly, for each of the 12 months for the period March 1840 to December 1855, mean differences in monthly temperatures were calculated between Toronto and each of the 9 U.S. stations used in the Dade standard differences above.

5. First approximation of Toronto-Dade differences. Since both Toronto and Dade means are compared to the same 9 American stations, the first approximation of Toronto-Dade differences was obtained by subtracting the Toronto standard differences above from the Dade standard differences above. These were calculated separately for each of the 9 U.S. stations and the overall mean taken each month. This analysis indicated that for every month of the year Dade values were high, and that correction values ranging from −0.6°F (February) to −4.0°F

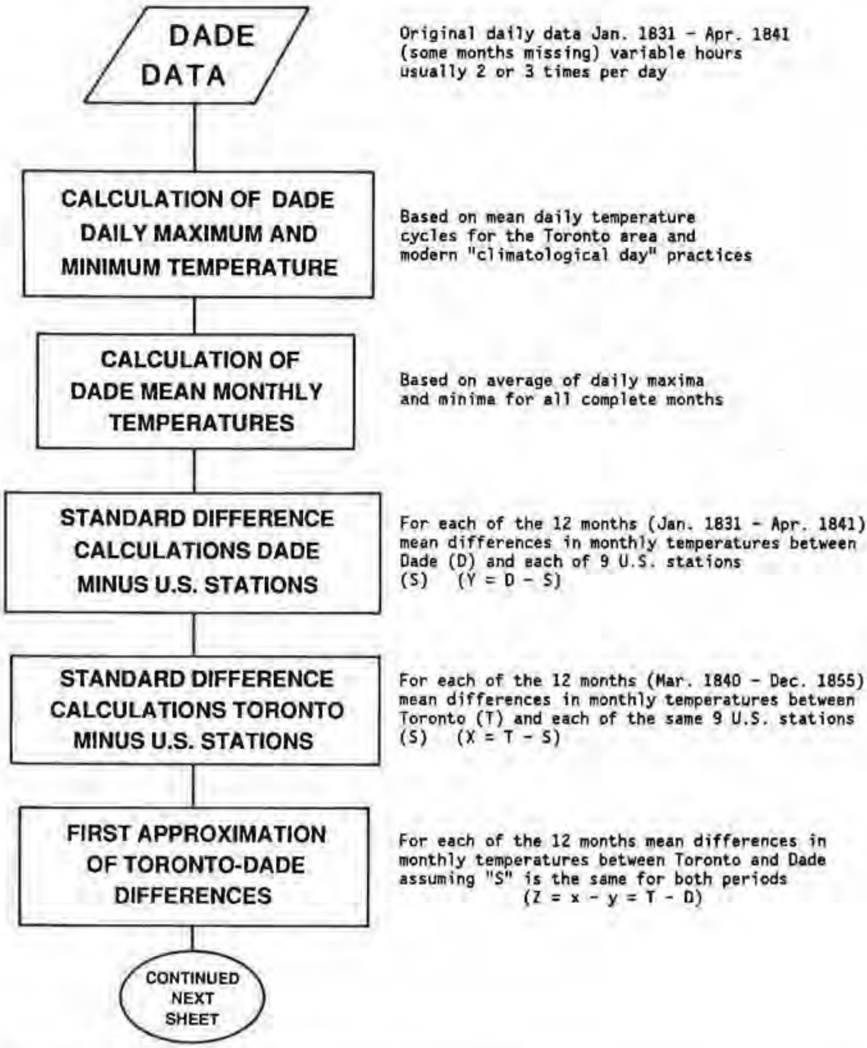
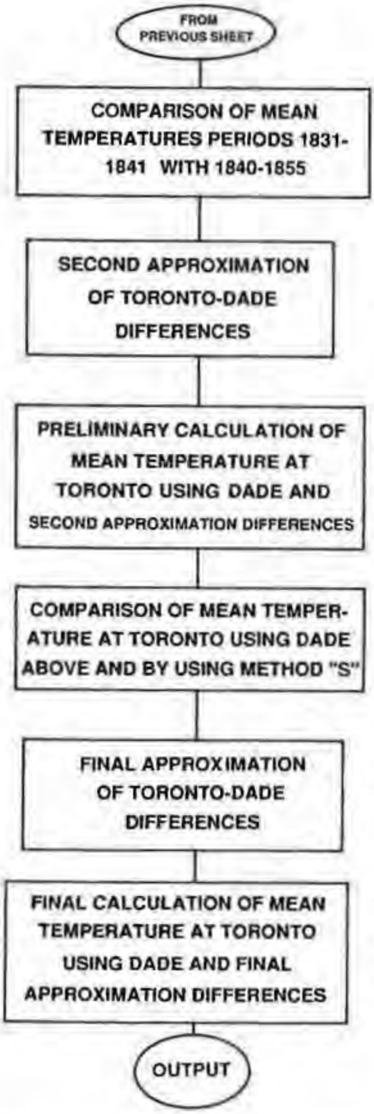


FIGURE 5. Method "D"



For each of the 12 months mean differences (C) in monthly mean temperatures at 3 U.S. stations Period A(1831-1841) from Period B(1840-1855) (C=B-A)

For each of the 12 months difference C substracted from first approximation differences ($Z_1 = Z - C$) (Z_1 12-month Fourier smoothed)

For each month, Jan. 1831 - Apr. 1841, Toronto mean (T_D) calculated using Dade mean (D) and Fourier smoothed 2nd approximation difference (Z_1) ($T_D = D + Z_1$)

For each month Jan. 1831 - Apr. 1841 difference calculated using Dade (T_D) from Method "S" (T_S) ($C_1 = T_S - T_D$)

For each of the 12 months difference C_1 substracted from Fourier smoothed Z_1 ($Z_2 = Z_1 - C_1$) (Z_2 12-month Fourier smoothed)

For each month Jan. 1831 - Feb. 1840 Toronto mean (T_D) calculated using Dade mean (D) and Fourier smoothed final approximation differences (Z_2) ($T_D = D + Z_2$)

FIGURE 6. Method "D" – continued

(July) had to be applied to Dade means to give a reasonable estimate of Toronto means.

6. Comparison of mean temperatures for 1831–1841 and for 1840–1855. There was no reason to assume that 1831 to 1855 was climatically homogeneous. In order to obtain a measure of the differences in mean temperature between the early period of the Dade observations (1831–1841) and the later period of the Toronto observations (1840–1855), calculations were performed for the three U.S. stations with the best and most continuous observations, Albany, New Haven and New York. Means for both periods were calculated for each of the 12 months separately for each of the three stations, allowing for those months during which Dade observations were missing. For each month, an overall mean difference (unweighted average of the three stations) between the means of the two periods was obtained. The earlier period was colder than the later at each of the three stations for each of the 12 months. The overall monthly differences ranged from 0.4°F for April to 2.5°F for December.

7. Second approximation of Toronto-Dade differences. The second approximation takes into consideration the fact that the earlier 1831–1841 period was significantly colder than the later 1840–1855 period. The first approximation Toronto-Dade differences were increased by the overall mean differences between the two decades. Because of the variability from month to month, Fourier smoothing was applied to the monthly values. As a result, the second approximation of Toronto-Dade differences ranged from −2.7°F in September and October to −4.1°F in December.

8. Preliminary calculation of mean Toronto temperatures using Dade and second approximation differences. For each month for which Dade means were available in the period January 1831 to April 1841, a Toronto mean was calculated using the second approximation differences (Fourier smoothed) above.

9. Comparison of mean temperatures at Toronto by using Dade calculations above and by using Method "S". For each month for which Dade means were available in the period January 1831 to April 1841, the Toronto mean using the Fourier smoothed second approximation differences with Dade were compared with means as calculated by Method "S", which uses all available American data. The overall mean differences in the two methods were compiled for each month and it was found that Method "S" gave higher values than the Dade method in the case of all months, ranging from 0.4°F in March to 2.6°F in February. The standard deviation of the monthly differences between the two methods ranged from 0.6°F in June to 1.7°F in January.

10. Final approximation of Toronto-Dade differences. Since Method "S" indicated somewhat higher means for Toronto for every month of the year than those by using the preliminary Dade calculations, it would appear that the second approximation allowing for the mean temperature differences between the two periods was based on differences that were too great, Consequently, the final approximation of Toronto-Dade differences was calculated by reducing the second approximation differences by the differences indicated between Method "S" and the preliminary Dade calculations above. Again, because of the month-to-month variation in the correction values, a Fourier smoothing was applied. The final approximation of Toronto-Dade differences then ranged from −1.1°F in October to −3.2°F in June.

11. Final calculation of Toronto means. For each month for which Dade means were available in the period January 1831 to February 1840, a Toronto mean was calculated using the final approximation differences (Fourier smoothed) above.

Method "A"

Method "A" is outlined in Figure 7. There are three distinct steps:

1. Correction of mean monthly temperatures. No daily observations are available for Ancaster, only published monthly means of 9 a.m. and 9 p.m. observations, from which a simple average was computed to produce a monthly mean. Correction values were calculated for each month in order to provide monthly means based on the modern practice of using daily maxima and minima. These were done by comparing means produced by averaging 9 a.m. and 9 p.m. monthly means at Toronto's Pearson International Airport (Atmospheric Environment Service, 1978) with the monthly means at the same station, which are calculated by the usual mean of daily maximum and minimum values.

2. Standard difference calculations. Ancaster and Toronto data overlap for the period March 1840 to December 1845. For each of the 12 months during this period, mean differences were calculated between the corrected Ancaster monthly means and the official Toronto means.

3. Calculation of Toronto means. For each month January 1835 to February 1840, a mean temperature was calculated for Toronto using the corrected Ancaster mean and the standard differences above.

THE RECONSTRUCTED TORONTO TEMPERATURE TIME SERIES

By using Method "S", "D", or "A" as appropriate, monthly mean temperatures were estimated for Toronto from July 1778 to February 1840. No American data were available for September 1778 or February, July, August, October, November and December 1779, so that no means could be estimated for these months. Beginning with January 1780, a complete set of monthly values was obtained. All calculations were done using the Fahrenheit scale, and then the whole set was converted to Celsius and combined with Atmospheric Environment Service Archive values that begin March 1840 and continue with no breaks until the present day.

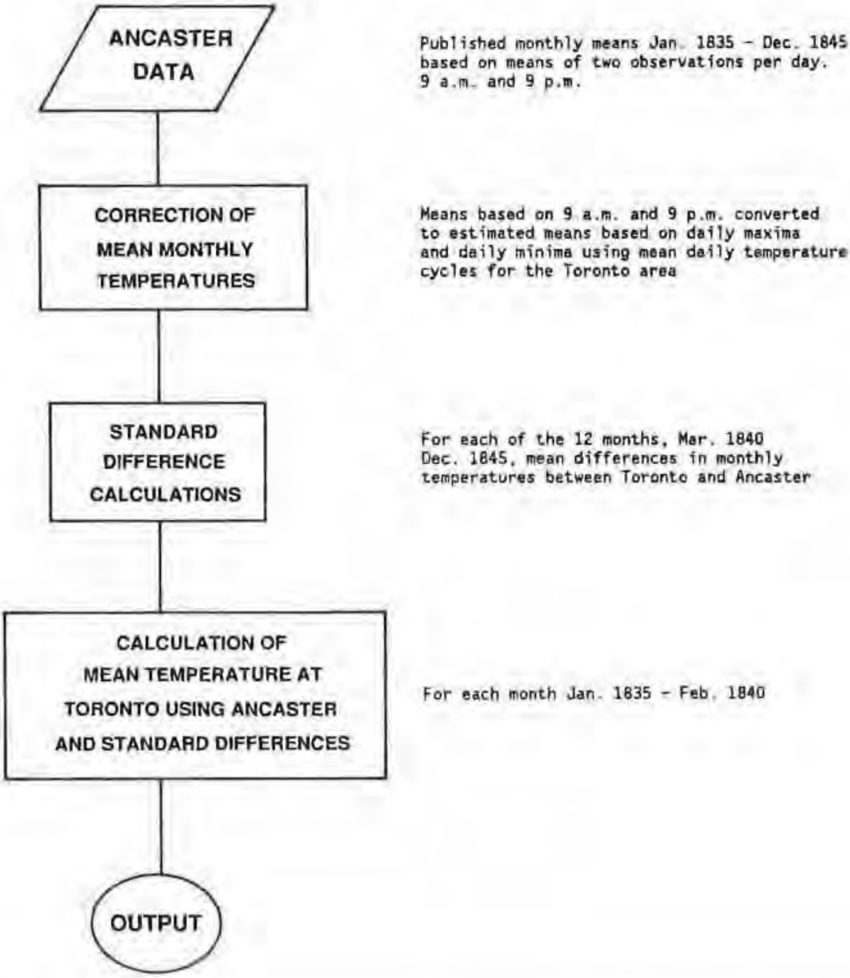


FIGURE 7. Method "A"

Statistical F tests were applied to monthly and seasonal values to test the homogeneity of variance between various time periods. In the first instance, three 30-year time periods were chosen: (A) 1780–1809; (B) 1810–1839; and (C) 1840–1869. Period A involves only Method "S" and through much of this period only one, two or three American stations had data available for comparative purposes. Period B involves Dade data as well as an increasing number of U.S. stations. Period C involves the early instrumental record at Toronto before urban warming was significant. Only June temperature variances are significantly different at the 99% level between periods A and B and between A and C. In the second instance, two 40-year time periods were chosen: (A) 1801–1840 and

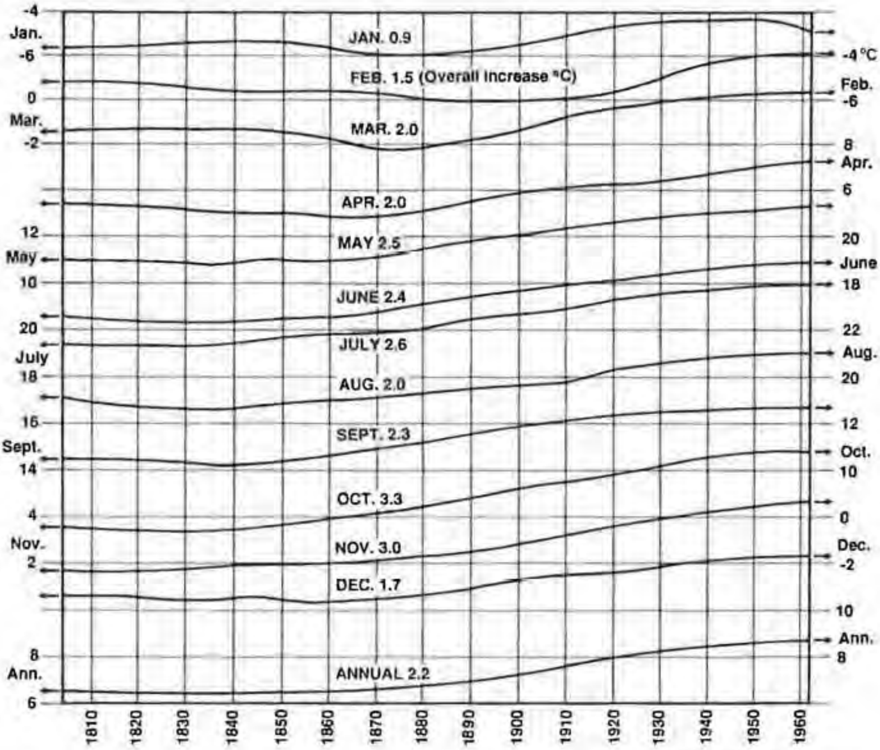


FIGURE 8. Trend lines based on 50-year running means of mean monthly and annual temperatures at Toronto

(B) 1841–1880. Period A represents the 40 years of reconstruction prior to the official observations beginning in March 1840, while Period B contains the first full 40 years of instrumental data. Only January variances are significantly different at the 99% level.

In Figure 8 trend lines based upon 50-year running means plotted for the middle year are shown for all months. Fifty-year means over the period 1780 to 1987 can be plotted only from 1805 to 1962. The overall rise in temperature during the period ranges from 0.9°C in January to 3.3°C in October, with an annual average of 2.2°C. A significant amount of this increase is no doubt due to the urban heat-island effect, which became increasingly significant from the 1880s on.

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TORONTO CITY MEAN TEMPERATURE 1778–1989

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1778	M	M	M	M	M	M	20.5	20.9	M	9.3	-.4	-4.8	M
1779	-4.7	M	-.4	7.2	12.8	18.1	M	M	13.9	M	M	M	M
1780	-5.5	-4.9	-2.2	4.1	12.1	16.2	21.4	21.8	13.6	8.8	.6	-2.7	6.9
1781	-1.6	-2.6	-.8	4.7	11.1	15.7	20.7	20.1	14.4	8.6	.2	-3.2	7.3
1782	-6.6	-6.3	-2.7	7.2	12.0	17.7	18.3	20.4	16.0	5.7	.4	-3.4	6.6
1783	-5.9	-3.2	-2.2	5.3	11.5	17.7	18.8	19.2	11.8	5.9	-.6	-4.2	6.2
1784	-8.6	-9.8	-3.1	2.2	10.6	16.6	19.1	20.0	14.3	6.4	3.4	-4.5	5.6
1785	-7.1	-6.1	-4.9	3.9	9.0	17.4	19.2	19.1	13.0	7.6	1.7	-3.3	5.8
1786	-6.8	-4.6	.7	4.6	10.3	17.5	19.4	17.5	14.3	8.9	-.6	-6.2	6.3
1787	-5.0	-5.6	-.4	5.8	9.9	15.6	18.1	18.4	13.2	5.1	3.0	-3.3	6.2
1788	-6.4	-6.5	-1.5	6.3	11.1	16.4	20.3	19.7	15.1	11.2	5.2	-4.3	7.2
1789	-5.0	-8.0	-1.3	5.3	9.3	17.3	19.8	19.9	14.6	5.3	2.7	-1.2	6.6
1790	-2.8	-4.7	-1.6	3.9	11.3	16.7	18.5	19.4	14.7	7.7	1.8	-7.4	6.5
1791	-4.9	-6.5	.7	6.2	12.7	17.2	19.3	19.6	13.8	6.4	1.7	-3.6	6.9
1792	-8.8	-6.2	.3	6.4	12.4	15.6	18.7	18.8	12.3	8.5	2.7	-4.2	6.4
1793	-3.0	-4.4	.7	7.2	12.6	17.3	20.3	20.1	15.2	7.3	1.9	-3.6	7.6
1794	-4.2	-5.5	.9	6.7	12.8	16.2	18.8	19.7	15.9	6.5	2.3	1.6	7.6
1795	-5.4	-5.1	-1.1	6.1	13.2	15.3	20.3	20.9	14.9	8.2	.8	-.4	7.3
1796	-4.5	-5.6	-3.4	6.1	9.8	16.4	19.4	18.4	14.4	6.9	1.3	-7.3	6.0
1797	-6.7	-2.2	-1.0	5.2	9.8	16.0	20.6	19.1	13.9	6.1	-.8	-7.1	6.1
1798	-5.1	-7.1	-1.6	6.1	13.0	17.6	19.4	21.8	15.8	9.0	-.8	-7.6	6.7
1799	-5.6	-7.3	-5.2	3.6	10.6	17.4	20.3	20.2	14.6	7.8	2.0	-3.9	6.2
1800	-5.7	-5.1	-1.4	6.7	11.2	17.8	21.0	19.2	15.1	8.6	.6	-1.8	7.2
1801	-4.4	-4.7	1.2	5.7	12.5	15.9	20.2	18.8	17.0	8.4	2.3	-1.3	7.6
1802	-1.0	-5.3	-.3	5.9	10.7	17.2	20.3	20.7	16.4	10.0	2.7	-3.3	7.8
1803	-4.7	-3.1	-1.4	6.4	9.3	17.3	20.9	20.2	14.8	9.7	.9	-.3	7.5
1804	-6.7	-4.5	-1.7	5.7	12.7	17.9	19.1	19.4	16.3	7.8	3.0	-4.9	7.0
1805	-7.5	-3.9	1.3	7.7	11.8	16.9	20.6	21.3	16.7	6.2	2.7	1.3	7.9
1806	-5.0	-1.2	-3.3	3.4	11.9	17.6	18.9	18.1	15.1	7.7	2.5	-3.6	6.8
1807	-6.2	-5.3	-2.9	4.7	10.1	15.2	19.7	19.1	13.1	8.2	.3	-.3	6.3

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1808	−5.7	−3.1	.6	5.8	10.0	17.1	19.8	17.7	14.4	7.2	2.6	−1.9	7.0
1809	−6.9	−6.9	−2.3	5.1	10.4	15.6	17.1	18.1	12.9	11.2	−.3	−.9	6.1
1810	−5.0	−3.3	−1.8	5.2	12.2	17.1	18.2	18.1	14.8	6.3	.9	−3.7	6.6
1811	−5.3	−5.9	.8	5.2	10.5	16.8	19.1	18.5	14.3	10.0	2.2	−3.9	6.9
1812	−6.9	−5.9	−4.0	4.3	7.4	15.4	17.6	17.7	12.3	7.1	1.2	−3.7	5.2
1813	−6.7	−5.7	−3.2	5.9	9.6	16.6	18.8	20.1	16.0	6.8	2.2	−4.1	6.4
1814	−6.4	−3.8	−2.4	6.2	13.1	15.9	18.3	18.8	14.3	7.0	1.7	−5.0	6.5
1815	−6.6	−7.1	−1.0	5.1	8.9	15.4	19.9	17.8	13.1	6.6	2.3	−4.8	5.8
1816	−7.6	−5.1	−3.4	3.1	8.5	13.3	16.1	17.9	12.1	7.8	3.4	−3.7	5.2
1817	−6.4	−9.9	−3.4	4.3	8.4	13.9	17.3	18.2	14.8	5.6	2.4	−3.7	5.1
1818	−6.3	−9.4	−2.4	2.4	9.2	16.9	19.3	17.4	12.9	6.7	3.2	−6.5	5.3
1819	−3.4	−3.4	−4.8	4.1	9.4	16.4	19.0	18.7	16.4	6.8	2.9	−3.8	6.5
1820	−7.2	−3.2	−2.4	6.0	10.2	17.2	21.3	18.7	15.9	6.8	−.4	−5.7	6.4
1821	−9.3	−2.9	−2.5	2.8	10.9	17.1	18.1	19.9	15.4	7.2	1.7	−4.5	6.2
1822	−7.7	−5.4	.7	5.7	12.7	16.8	19.8	19.2	16.5	8.4	4.1	−3.3	7.3
1823	−4.9	−8.3	−2.4	5.9	10.5	16.4	19.9	19.3	13.3	6.2	−.8	−2.6	6.0
1824	−2.7	−4.4	−1.7	5.5	9.4	15.3	18.6	17.6	14.1	7.7	1.4	−.9	6.7
1825	−4.1	−3.8	1.6	6.5	11.4	18.2	21.7	19.4	13.8	9.2	1.6	−3.7	7.7
1826	−4.4	−3.0	−.6	3.2	15.2	17.3	20.1	19.9	16.0	8.8	2.2	−3.2	7.6
1827	−7.9	−3.8	−.2	7.4	10.8	15.9	19.6	18.5	14.8	8.4	−.8	−2.3	6.7
1828	−2.4	.7	.7	4.1	12.2	19.8	19.8	20.4	15.2	7.2	3.0	.0	8.4
1829	−6.1	−8.2	−2.6	5.6	13.4	16.1	17.7	18.5	12.1	7.7	1.5	.8	6.4
1830	−6.4	−5.8	.2	9.1	10.7	15.1	20.8	18.6	13.5	8.9	6.1	−1.3	7.5
1831	−6.9	−8.6	2.4	5.7	10.8	18.9	18.9	19.8	14.6	8.2	1.8	−10.1	6.3
1832	−5.8	−6.9	−.7	4.0	9.2	17.1	19.4	17.9	14.3	8.7	1.9	−1.5	6.5
1833	−2.9	−7.3	−1.8	7.7	13.3	15.2	19.6	17.9	14.8	7.2	.2	−1.7	6.9
1834	−7.5	−1.7	−.2	7.0	11.2	15.9	21.4	19.2	14.0	6.1	1.3	−4.5	6.9
1835	−4.8	−8.4	−1.1	4.6	12.4	16.4	19.1	17.4	11.6	9.1	1.6	−5.6	6.0
1836	−4.9	−9.4	−4.2	3.6	11.0	15.1	19.9	16.8	14.2	3.9	.3	−4.6	5.1
1837	−7.8	−5.8	−3.4	3.4	8.6	16.1	18.2	16.7	13.5	6.0	2.4	−3.3	5.4
1838	−2.8	−10.3	1.8	1.8	8.4	18.2	21.4	19.1	14.9	6.4	−.9	−6.4	6.0
1839	−4.8	−3.6	−.9	8.2	10.9	14.2	18.7	17.0	12.3	9.8	1.2	−2.3	6.7

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1840	−7.8	−1.9	1.2	6.7	12.4	15.7	19.5	19.0	12.6	7.4	2.1	−4.9	6.8
1841	−4.5	−5.5	−2.3	4.3	10.9	19.4	19.2	18.7	16.1	5.7	1.3	−2.0	6.8
1842	−2.9	−2.2	2.7	7.0	10.2	14.5	18.6	19.5	13.8	7.8	1.1	−3.8	7.2
1843	−2.1	−8.5	−5.8	5.1	10.8	14.8	19.0	19.4	16.4	6.4	.7	−.7	6.3
1844	−6.5	−3.6	.2	9.3	13.2	16.1	19.5	18.4	15.3	6.6	1.9	−2.1	7.4
1845	−3.2	−3.5	1.6	5.8	10.3	15.9	19.3	19.4	12.8	7.5	2.6	−6.3	6.9
1846	−3.8	−7.5	−.3	6.5	13.1	17.3	20.4	19.9	17.3	7.2	5.1	−2.8	7.7
1847	−5.3	−5.6	−3.3	3.3	11.5	14.4	19.9	17.8	13.0	6.8	3.5	−2.0	6.2
1848	−2.7	−3.0	−2.2	4.9	12.1	16.4	18.0	19.6	12.2	7.6	.9	−1.5	6.9
1849	−7.3	−7.6	.4	3.3	8.9	16.7	19.3	18.2	14.2	7.7	5.6	−3.6	6.3
1850	−1.9	−4.0	−1.7	3.3	9.8	17.4	20.8	19.0	12.8	6.5	2.9	−5.6	6.6
1851	−4.5	−2.6	.4	5.0	10.7	15.0	18.4	17.3	14.9	8.7	−.1	−6.3	6.4
1852	−8.1	−5.2	−3.5	3.0	10.6	15.8	18.8	18.2	13.4	8.8	1.6	−.2	6.1
1853	−5.6	−5.3	−1.5	5.0	9.8	17.9	18.5	20.0	14.9	6.2	3.1	−4.3	6.6
1854	−5.9	−7.0	−1.3	4.1	10.0	16.8	22.0	20.1	16.1	10.1	1.8	−5.6	6.8
1855	−3.9	−10.1	−2.2	5.9	11.9	15.5	20.2	18.0	15.2	6.5	2.9	−3.4	6.4
1856	−9.8	−10.2	−5.7	5.6	10.1	16.7	21.0	17.5	13.5	7.0	2.2	−5.5	5.2
1857	−12.1	−2.2	−3.0	1.9	9.4	14.1	20.1	18.2	14.4	7.1	.7	−1.1	5.6
1858	−1.4	−8.1	−1.4	5.2	9.3	18.5	19.9	19.6	15.2	9.9	1.2	−2.6	7.1
1859	−4.1	−3.5	2.4	4.4	12.9	14.7	19.4	19.6	13.4	6.6	3.6	−7.2	6.9
1860	−4.6	−5.3	1.5	4.3	13.3	17.8	18.1	18.4	12.9	8.7	3.6	−4.5	7.0
1861	−6.9	−3.7	−2.8	5.9	8.9	16.1	18.6	19.0	15.1	9.2	2.9	−.8	6.8
1862	−5.9	−5.7	−1.7	4.4	11.0	15.6	19.7	19.6	15.8	9.0	2.0	−1.7	6.8
1863	−2.1	−5.2	−3.3	5.4	12.7	16.0	19.7	19.4	13.3	8.2	4.0	−2.6	7.1
1864	−4.8	−3.8	−1.7	5.1	12.5	17.2	21.1	20.8	13.6	7.7	2.9	−3.3	7.3
1865	−8.1	−5.5	.2	6.0	11.4	18.6	18.3	18.5	18.7	7.4	3.9	−1.7	7.3
1866	−7.0	−5.5	−2.6	6.9	9.3	15.9	21.2	16.2	13.6	10.4	3.7	−3.6	6.5
1867	−8.1	−2.2	−2.5	4.9	8.5	18.1	20.1	20.5	15.1	10.4	3.9	−5.3	7.0
1868	−7.8	−8.1	−.3	3.4	11.2	16.4	24.4	19.8	14.1	6.2	2.6	−4.9	6.4
1869	−2.1	−4.5	−4.7	4.6	10.4	14.8	18.6	17.7	16.5	6.1	.3	−1.6	6.3
1870	−4.0	−5.9	−2.9	7.3	13.9	19.4	20.5	19.5	16.5	10.5	2.9	−3.2	7.9

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1871	−6.2	−4.8	1.6	6.8	12.0	16.6	19.0	19.9	13.2	9.7	−.4	−5.4	6.8
1872	−6.2	−6.2	−6.1	4.8	11.0	17.1	21.2	21.0	15.4	7.6	.8	−8.2	6.0
1873	−8.3	−7.5	−3.3	4.2	11.0	17.3	20.0	19.1	13.7	7.6	−2.4	−2.0	5.8
1874	−4.4	−5.6	−1.4	.8	11.5	17.1	19.5	19.3	17.4	8.5	1.7	−3.9	6.7
1875	−9.2	−12.6	−4.9	2.5	10.9	16.1	19.2	18.7	13.3	6.4	−.1	−3.0	4.8
1876	−1.3	−5.0	−3.3	3.6	10.7	18.6	20.3	21.2	14.3	5.8	2.9	−8.3	6.6
1877	−8.8	−2.0	−3.6	6.5	12.0	16.7	21.2	20.9	16.6	9.9	3.0	1.2	7.8
1878	−4.5	−3.0	3.1	9.6	11.5	17.0	22.4	20.5	16.4	9.6	2.5	−4.2	8.4
1879	−7.0	−8.1	−1.8	4.2	12.0	16.6	20.5	18.5	13.2	12.7	2.0	−3.2	6.6
1880	.4	−2.6	−1.7	5.3	14.7	18.7	19.7	19.3	15.8	7.3	−1.2	−6.1	7.5
1881	−9.0	−7.1	−1.1	4.3	14.5	15.3	21.5	21.2	20.2	9.8	2.8	1.0	7.8
1882	−5.1	−1.0	−.2	4.6	9.5	16.3	19.4	19.8	16.4	10.9	2.0	−3.7	7.4
1883	−8.2	−7.1	−5.9	3.5	9.6	16.7	18.5	17.6	12.5	7.2	2.8	−3.5	5.3
1884	−9.2	−4.9	−2.3	5.0	10.6	18.2	17.8	18.6	16.5	9.1	1.1	−3.8	6.4
1885	−8.3	−11.9	−8.2	2.9	11.0	15.6	19.9	17.3	13.8	7.6	3.5	−2.6	5.1
1886	−7.4	−7.7	−1.2	7.2	11.7	16.2	19.0	18.7	14.9	9.1	1.9	−6.2	6.4
1887	−8.0	−6.0	−4.1	4.2	14.7	17.5	22.9	19.0	13.7	6.5	1.6	−2.3	6.6
1888	−9.6	−6.0	−5.4	4.0	10.6	18.1	19.0	19.1	13.7	6.3	3.1	−1.5	6.0
1889	−2.5	−8.3	.5	6.3	12.2	15.7	20.6	18.7	15.6	6.0	3.7	1.2	7.5
1890	−1.4	−2.4	−2.4	5.7	10.1	18.7	19.8	18.1	14.2	9.2	2.8	−5.3	7.3
1891	−4.9	−2.4	−1.9	6.3	10.8	18.0	17.9	18.9	17.3	8.7	2.6	.8	7.7
1892	−7.0	−4.4	−2.3	5.3	10.9	18.6	20.1	19.8	15.6	8.7	1.7	−3.6	7.0
1893	−10.0	−7.6	−1.7	4.4	11.1	19.3	20.2	19.3	14.1	9.2	2.9	−4.7	6.4
1894	−2.1	−6.5	2.1	7.0	11.3	19.3	20.6	18.6	17.1	10.2	1.2	−.4	8.2
1895	−6.1	−8.7	−4.4	6.3	13.1	19.9	19.1	18.8	16.0	6.1	2.8	−1.4	6.8
1896	−5.8	−5.6	−4.8	8.0	15.7	18.1	20.7	19.8	14.1	7.2	4.3	−2.4	7.4
1897	−5.1	−4.1	−.1	6.3	11.6	16.4	22.5	18.6	16.3	10.5	3.7	−2.2	7.9
1898	−3.8	−4.2	2.8	6.5	13.2	18.8	21.7	21.4	17.8	10.3	2.0	−3.1	8.6
1899	−5.0	−7.1	−2.1	7.2	13.0	18.6	20.5	21.1	14.0	10.4	4.7	−1.8	7.8
1900	−3.4	−6.7	−4.8	7.5	12.9	18.4	20.6	22.5	18.0	13.5	3.7	−1.7	8.4
1901	−4.7	−8.5	−1.2	8.0	12.5	18.5	22.9	20.7	16.6	9.4	1.4	−3.0	7.7
1902	−4.8	−6.0	3.1	6.7	11.9	15.6	20.5	18.6	15.8	9.3	6.1	−4.3	7.7

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1903	−5.0	−3.5	4.3	6.6	13.3	16.6	20.7	17.7	16.2	10.5	1.7	−5.1	7.8
1904	−8.9	−10.4	−1.9	4.0	13.2	17.3	19.7	18.2	14.8	7.8	2.2	−5.4	5.9
1905	−7.8	−8.6	−.8	5.7	11.5	17.6	21.0	19.7	16.8	9.3	2.7	−.5	7.2
1906	−.6	−5.4	−2.8	7.1	12.4	18.7	21.2	22.1	18.3	9.6	3.0	−4.9	8.2
1907	−5.5	−7.5	1.0	3.6	9.0	17.7	20.7	18.6	16.5	7.2	2.8	−1.4	6.9
1908	−4.2	−7.1	−.3	5.5	13.5	19.0	21.6	19.5	17.7	10.8	4.3	−1.6	8.2
1909	−3.1	−3.0	−1.1	5.0	12.1	18.6	19.9	20.7	15.7	7.9	4.8	−3.3	7.9
1910	−3.6	−6.1	3.8	8.3	11.5	18.2	21.8	19.8	15.6	10.7	2.3	−6.0	8.0
1911	−3.4	−3.7	−1.1	6.3	16.3	18.6	22.0	20.8	15.9	9.7	2.2	1.1	8.7
1912	−10.0	−7.3	−3.5	5.5	12.9	16.8	21.0	17.8	17.1	10.4	4.7	.4	7.2
1913	−.4	−6.5	.8	8.0	12.4	18.2	21.3	20.4	15.3	11.0	5.7	.8	8.9
1914	−3.6	−9.2	−.7	5.3	14.8	18.0	21.4	20.1	16.2	11.6	3.4	−3.5	7.8
1915	−4.6	−3.3	−1.2	10.0	11.2	16.9	20.3	19.1	17.5	11.1	4.8	−2.5	8.3
1916	−1.0	−7.3	−3.7	7.0	12.4	15.7	24.5	22.3	16.2	9.8	3.2	−2.8	8.0
1917	−5.2	−8.3	.1	5.1	9.7	16.0	21.4	19.9	14.8	7.0	1.4	−7.0	6.2
1918	−10.4	−6.0	.9	6.5	14.0	16.4	21.0	21.7	13.6	10.8	5.6	−.4	7.8
1919	−1.6	−2.1	1.0	5.9	13.0	22.5	23.0	20.0	17.5	11.7	3.5	−5.2	9.1
1920	−10.6	−6.6	1.1	4.6	12.5	18.8	19.2	21.1	17.7	12.8	2.7	−.3	7.8
1921	−2.3	−2.0	3.7	9.6	14.6	20.4	25.5	20.1	19.9	10.2	2.4	−2.0	10.0
1922	−4.8	−3.1	1.3	7.5	15.4	19.3	20.9	20.6	17.6	9.9	4.9	−2.0	9.0
1923	−5.7	−7.4	−2.7	5.8	10.9	19.2	20.6	18.8	16.0	9.4	3.9	2.4	7.6
1924	−4.8	−6.5	−.2	6.0	10.0	17.2	19.6	19.4	13.9	10.4	3.9	−4.5	7.0
1925	−6.5	−2.6	1.7	7.4	10.5	19.3	19.8	20.5	16.5	5.8	3.2	−3.1	7.7
1926	−4.1	−6.1	−3.3	3.0	11.6	15.4	19.9	20.3	15.1	8.4	3.1	−4.5	6.6
1927	−6.0	−2.8	1.8	6.4	11.6	16.5	20.5	18.2	17.4	11.7	5.0	−1.6	8.2
1928	−3.8	−4.3	−.8	5.4	12.3	16.4	21.1	21.5	14.3	10.5	4.3	.5	8.1
1929	−5.0	−5.6	2.7	7.6	11.7	17.7	20.4	18.6	16.8	9.2	3.3	−3.7	7.8
1930	−5.1	−2.9	−.6	6.1	14.2	19.4	21.2	20.7	17.3	9.5	4.9	−1.8	8.6
1931	−4.0	−3.0	.8	7.1	13.3	18.9	23.1	20.8	18.9	11.8	7.7	.8	9.7
1932	1.9	−1.3	−1.6	5.0	13.0	19.2	19.9	21.0	16.7	10.8	2.1	−.9	8.8
1933	.9	−3.3	−.2	7.3	14.2	19.8	22.8	20.7	17.1	8.9	−.2	−4.3	8.6
1934	−3.4	−12.1	−2.2	5.6	14.3	19.9	22.0	18.7	17.2	9.3	5.7	−3.6	7.6

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1935	−6.3	−5.4	2.0	6.5	11.1	17.7	23.3	21.1	14.9	10.1	4.4	−5.2	7.9
1936	−5.3	−8.1	1.4	4.3	14.9	18.3	22.9	20.6	17.1	9.5	1.3	−.3	8.1
1937	−.5	−2.3	−1.9	6.3	13.7	18.9	21.9	22.6	15.7	8.7	3.7	−2.6	8.7
1938	−5.4	−2.7	−2.1	8.0	12.9	18.8	22.2	22.8	15.0	11.2	5.1	−.6	9.1
1939	−4.6	−4.0	−1.8	4.8	14.4	18.7	22.2	22.4	16.5	10.1	2.8	−.4	8.4
1940	−7.5	−4.2	−3.2	5.2	12.3	17.4	21.6	20.5	16.3	8.9	3.4	−1.2	7.5
1941	−5.3	−4.5	−2.7	10.4	14.8	20.5	22.3	20.1	17.5	11.1	5.7	.2	9.2
1942	−4.0	−6.2	2.4	9.9	13.7	19.0	21.3	20.8	16.4	10.8	4.4	−4.0	8.7
1943	−6.9	−3.5	−1.1	4.0	12.8	20.8	21.9	20.5	15.6	9.4	3.3	−2.9	7.8
1944	−1.1	−3.7	−1.9	4.8	15.6	19.1	22.0	22.3	16.8	10.3	4.5	−3.5	8.8
1945	−9.4	−3.4	6.2	8.7	10.3	17.4	20.6	21.0	16.8	9.2	4.4	−4.2	8.1
1946	−3.4	−5.2	6.1	7.1	12.5	18.2	21.4	19.1	17.2	12.3	5.9	−1.5	9.1
1947	−2.9	−5.3	−.6	5.8	11.3	18.1	21.0	23.0	17.5	14.5	3.8	−2.7	8.6
1948	−7.3	−5.0	.1	8.5	11.9	18.8	22.0	21.7	19.0	9.4	7.5	−.4	8.9
1949	−1.6	−1.4	.4	7.7	14.7	22.2	23.3	22.9	15.1	13.1	3.0	.2	10.0
1950	−.1	−4.6	−2.2	4.6	13.2	18.3	20.8	20.4	15.5	12.2	3.7	−1.9	8.3
1951	−2.6	−2.5	1.7	7.6	14.8	18.7	21.9	20.6	16.7	11.4	1.7	−1.7	9.0
1952	−2.6	−1.8	.1	9.8	12.7	19.7	23.5	20.8	18.0	8.5	5.7	1.0	9.6
1953	−1.3	−.8	2.5	7.1	13.8	19.5	22.3	22.0	17.4	12.0	6.8	1.1	10.2
1954	−6.0	.5	.0	7.9	12.5	19.9	21.5	20.1	16.5	12.0	5.3	−1.8	9.0
1955	−3.9	−3.1	.2	10.5	15.5	20.2	24.6	23.5	16.8	12.2	3.7	−3.8	9.7
1956	−3.9	−2.2	−.9	5.5	11.2	19.2	20.5	20.2	14.4	12.2	5.2	.1	8.5
1957	−6.5	−1.4	2.2	8.6	12.6	20.0	21.5	20.2	16.8	10.4	5.6	1.1	9.3
1958	−3.8	−6.2	2.6	9.1	12.7	16.4	21.6	20.8	17.1	10.8	5.4	−5.2	8.4
1959	−5.8	−5.7	−.6	8.0	14.5	20.3	22.9	24.2	19.3	10.4	3.0	−.2	9.2
1960	−3.5	−2.9	−3.7	8.1	13.9	18.6	20.9	21.1	18.6	11.0	6.5	−3.9	8.7
1961	−6.4	−1.2	1.1	5.4	12.4	18.1	21.8	21.4	20.3	13.0	4.8	−1.2	9.1
1962	−5.5	−6.2	1.4	7.9	16.4	19.6	20.6	21.3	15.6	11.4	4.1	−2.7	8.7
1963	−6.9	−7.5	2.0	7.9	12.6	19.8	22.3	19.7	15.0	14.6	7.3	−5.3	8.5
1964	−1.8	−3.2	.7	7.0	15.6	18.7	23.0	18.6	16.3	10.0	5.8	−1.1	9.1
1965	−5.1	−4.2	−.8	5.4	15.3	18.5	19.6	19.9	16.9	9.3	4.5	1.2	8.4

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1966	−5.9	−3.0	2.1	6.4	11.0	20.1	23.2	21.0	15.9	9.9	5.6	−1.6	8.7
1967	−1.1	−6.7	−.6	7.3	10.2	20.9	20.9	19.9	16.1	10.5	2.6	−.1	8.3
1968	−6.2	−5.9	2.1	9.3	11.5	18.0	21.5	20.9	18.6	12.2	4.3	−3.0	8.6
1969	−4.1	−2.6	−.2	8.4	13.1	17.5	22.2	23.0	17.8	10.6	4.9	−3.4	8.9
1970	−7.4	−4.5	−.3	8.4	13.6	19.6	22.5	22.2	17.6	12.3	6.3	−2.9	9.0
1971	−6.8	−2.8	−.7	6.2	13.5	19.7	21.4	20.8	19.2	14.5	4.4	.9	9.2
1972	−3.6	−4.9	−1.8	5.3	15.4	17.5	22.3	20.6	17.9	8.8	3.4	−.7	8.4
1973	−2.2	−4.9	4.9	7.8	12.1	20.0	22.9	23.7	18.0	12.7	5.6	−1.9	9.9
1974	−3.0	−5.3	.5	8.7	11.8	18.2	22.4	22.1	15.8	9.1	5.0	1.3	8.9
1975	−1.0	−1.8	−.6	4.4	17.0	20.1	23.3	21.8	15.4	12.0	8.5	−2.3	9.7
1976	−6.4	−.1	2.1	9.3	12.4	20.9	20.6	20.6	16.5	8.4	2.2	−5.0	8.5
1977	−9.1	−3.8	4.1	8.9	16.5	18.6	22.3	20.4	17.2	10.3	5.9	−2.0	9.1
1978	−6.7	−6.8	−1.3	5.9	14.4	18.5	21.5	21.1	16.5	10.1	4.6	−.9	8.1
1979	−6.0	−8.8	2.9	6.6	12.7	18.3	21.9	19.9	16.7	9.5	5.4	.3	8.3
1980	−3.6	−5.7	−.1	7.8	15.5	16.1	21.9	22.5	16.9	8.6	3.5	−4.3	8.3
1981	−7.9	−.4	1.9	8.3	13.4	18.9	22.2	20.8	16.1	8.3	5.1	−1.1	8.8
1982	−7.8	−4.7	.2	5.9	15.2	16.6	22.2	18.8	16.1	11.3	5.6	2.3	8.5
1983	−2.3	−1.5	2.2	6.9	11.3	20.0	23.4	22.4	18.2	10.9	4.5	−4.2	9.3
1984	−6.6	.5	−2.6	8.2	11.7	19.7	21.2	22.3	15.6	12.0	4.8	1.7	9.0
1985	−6.2	−3.4	2.1	8.6	14.7	17.1	21.0	20.5	18.4	11.4	4.8	−3.2	8.8
1986	−3.9	−4.4	2.2	9.3	15.7	17.9	22.0	20.0	16.0	10.6	3.5	.4	9.1
1987	−2.5	−3.2	3.6	10.3	15.8	20.8	23.7	21.1	17.0	8.8	4.9	1.2	10.1
1988	−3.1	−4.1	.9	7.3	15.3	19.7	24.2	22.7	16.6	8.7	6.0	−1.0	9.4
1989	−.4	−4.5	−.7	6.2	14.2	19.4	23.1	21.2	17.2	11.1	3.7	−7.8	8.6

M = Missing

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Climate Services Division
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Downsview, Ontario M3H 5T4
(416) 739-4331/4328

NECROLOGY – V.P. SUBRAHMANYAM

Professor V.P. Subrahmanyam of Andhra University, Visakhapatnam, India died on July 18, 1989. He was an internationally known worker in the field of drought research and an important member of the Indian climatological community. Prof. Subrahmanyam visited North America on several occasions and his most recent visit to Canada was in 1986. He will be greatly missed.

G.A. McKay

ALBERTA CLIMATOLOGICAL ASSOCIATION

The Proceedings of the Thirteenth Annual General Meeting of the ACA, held on March 2, 1989 on the theme of *Climate Change – Is It Here?* are now available. The Fourteenth AGM was held on February 22, 1990 on the topic of *Severe Weather*. For information, write:

Teja Singh
Chairman, ACA
Canadian Forestry Service
5320 – 122 Street
Edmonton, Alberta
T6H 3S5

Climate Review / Revue du climat

SUMMARY AND HIGHLIGHTS OF THE 1986 SEVERE LOCAL STORM SEASON

M.J. Newark[1], *L. Coldwells*[2], *M. Leduc*[3], *G. Machnee*[4], *T. Noga*[3], *B. Paruk*[2], *S. Siok*[5], and *D. Waugh*[2]

[Original manuscript received 5 January 1990]

ABSTRACT

This report provides an overview and summary of the 1986 severe local storm season in the broad region from the Rocky Mountains to Québec. Storm statistics were compiled from the seasonal report prepared by each of four Atmospheric Environment Service regions, and are summarized in tabular form. Highlights of the seàson are presented from an overall point of view and also by region.

RÉSUMÉ

Ce rapport donne un perspective global et un sommaire du temps violent estival de 1986 dans la vaste région du Canada des montagnes rocheuses jusqu'au Québec. On a compilé les statistiques des orages du rapport saisonnier qu'on a préparé à chacune des quatre régions du Service de l'environnement atmosphérique (SEA), et on les a disposées en tableaux. On présente généralement les clous de la saison et on les présente aussi par région du SEA.

[1] Canadian Climate Centre, Downsview, Ontario
[2] Alberta Weather Centre, Edmonton, Alberta
[3] Ontario Weather Centre, Toronto, Ontario
[4] Prairie Weather Centre, Winnipeg, Manitoba
[5] Centre Météorologique du Québec, Montréal, Québec

1. INTRODUCTION

This report has been compiled mainly from information contained in the annual reports of the 1986 severe local storm season prepared by the Atmospheric Environment Service weather centres in 4 regions (Western, Central, Ontario, and Québec) and is the third of a series published in Climatological Bulletin. The purpose is to summarize the statistics of the season and place them in an overall perspective, and to present seasonal highlights in narrative form.

The statistics should be interpreted with care because the definition (Table 1) of what constitutes a convective severe local storm varies from region to region and because some changes in the definitions have been made over time. Strictly speaking the statistics are not comparable from one region to another; however, because the definitions are similar, it can be considered that the numbers approximate the picture across part of the country. Counting the number of events

TABLE 1. Regional Definitions of a Severe Convective Weather Event

Western Region

1) tornado, waterspout, or funnel cloud;
2) hail ≥ walnut-size (21 mm), (note: changed from the previous definition of ≥ 12 mm);
3) wind gusts ≥ 100km/h;
4) rainfall amounts ≥ 25 mm in one hour.

The observation of any of the above conditions, singly or together, is necessary for an event to be labelled severe. Some subjective screening is required to eliminate synoptic-scale wind events.

Central Region

1) tornadoes or waterspouts;
2) hail ≥ 20 mm;
3) wind speeds or gusts ≥ 100 km/h;
4) rain amounts ≥ 50 mm within one hour, or ≥ 75 mm within 3 hours.
   (Note: changed from previous definitions)

Ontario Region

1) tornado;
2) hail ≥ 10 mm diameter;
3) damaging thunderstorm wind gusts or, if winds measured, gusts ≥ 80 km/h (44 kts);
4) flooding downpours.

Québec Region

Objective criteria:

1) tornado;
2) hail ≥ 15 mm diameter;
3) strong gusts ≥ 83 km/h (45 kts);
4) heavy downpour ≥ 25 mm/h or, ≥ 50 mm/24 h.

Subjective criteria:

Report of material damage or loss of life or injury caused by strong winds or heavy downpours.

TABLE 2. Severe Local Storm Summary for 1986

AES REGION	WESTERN		CENTRAL			ONTARIO	QUÉBEC		NATIONAL
PROVINCE	NERN BC	ALTA	SASK	MAN	NWRN ONT	ONT	SERN ONT	QUÉ	
SEVERE LOCAL STORMS *									
Number of events	0	80	71	58	3	71	5	83	371
number of days	0	30	28	23	3	25	5	35	84
number of deaths	0	0	0	0	0	1	0	0	1
number of injuries	0	0	0	0	0	0	0	0	0
date season started		May 21	May 04	May 04	May 05	May 06	Jun 16	May 06	May 04
date season ended		Aug 14	Sep 02	Sep 26	Aug 01	Sep 29	Sep 29	Sep 29	Sep 29
length of season (days)		86	121	146	89	147	106	147	149
TORNADOES									
Number of events	0	21	31	9	0	9	1	4	75
number of days	0	10	14	7	0	8	1	2	33
number of deaths	0	0	0	0	0	0	0	0	0
number of injuries	0	0	0	0	0	0	0	0	0
date season started		May 21	May 04	May 11		May 16	Jun 16	Jun 16	May 04
date season ended		Jul 26	Sep 02	Aug 24		Sep 29	Jun 16	Aug 15	Sep 29
length of season (days)		67	121	106		137	1	61	149
HAIL									
Number of events	0	24	28	24	2	16	1	22	117
number of days	0	16	16	13	2	10	1	11	48
date season started		May 21	May 22	May 04	May 05	Jun 16	Aug 06	May 06	May 04
date season ended		Aug 14	Aug 24	Aug 24	Aug 01	Sep 29	Aug 06	Aug 21	Sep 29
length of season (days)		86	95	113	89	106	1	108	149
WIND									
Number of events	0	11	16	23	0	39	2	27	118
number of days	0	9	9	10	0	18	2	13	44
RAIN									
Number of events	0	18	9	9	0	13	1	49	99
number of days	0	15	6	9	0	6	2	23	48
WATERSPOUTS									
Number of events	0	0	0	1	0	4	M	4	M
FUNNEL CLOUDS									
Number of events	0	24	4	1	0	16	M	M	M
LIGHTNING									
Number of deaths	0	1	0	0	1	2	M	M	M

NOTES: (1) Statistics in the "National" column are not truly representative due to regional differences in definitions (see Table 1).
(2) M = not known.
(3) a = not including waterspouts or funnel clouds.

is also a problem which is approached differently from region to region (see Section 2). Although a "national" summary is provided (Table 2), it does not include information from Canada's north, from much of British Columbia, nor from the Atlantic provinces. Some severe local storms are known to occur each year in these regions, but a systematic record of them is not maintained, and indeed, in some areas is impossible to compile due to lack of information. A map of the four regions is given in Figure 1 of Newark *et al.* (February 1987), and it can be seen that they cover the part of Canada most susceptible to such storms.

2. RECORDING AND COUNTING EVENTS

From a climatological point of view one would like to know the number of severe local storms obtained by treating each observation of a phenomenon as a distinct event. These have been referred to as "proper-events" (Legal, 1984 p. 22). In practice, difficulties arise when this is attempted because often there is not enough information available to distinguish each unique event. Even when there is sufficient information, it is not always possible to determine whether a series of damage incidents very closely related in time and space was the result of one intermittent storm, or a succession of independent storms.

The Québec region circumvents this problem by recording severe local storms in terms of "region-events" (Siok, 1987 p. 14). According to this scheme, weather occurrences which take place within a given forecast region are counted as one region-event provided they occur with an hour or so of each other. The remaining regions attempt to record proper-events. With resources that vary from year to year, and from region to region, and without a clear definition of what constitutes a proper-event, the numbers of events shown in Table 2 should be treated with great caution because it is not known how well they represent the true numbers. The number of tornadoes is perhaps an exception because a greater effort is expended on collecting information about them and identifying each one.

For an excellent summary of the problems related to identifying single storm events, and the non-meteorological factors which cloud the issue of interpreting severe thunderstorm data, the reader is referred to Kelly and Schaefer (1985).

3. DATA SOURCES

Reports of severe local storms in 1986 were gathered as follows: (a) from the primary observing network of AES; (b) from volunteer weather watchers in each region; (c) from newspaper clippings; (d) from field surveys of storm damage; (e) from contacts with the media, private individuals, provincial agencies, insurance companies, etc. More detailed information concerning sources can be found in the individual regional reports (Leduc and Noga, 1986; Machnee, 1986; Paruk *et al.*, 1986; and Siok, 1987). It should be noted that the information is gathered primarily from populated areas (approximately shown by the shaded areas in Figure 1 of Newark *et al.*, February 1987).

4. SEASONAL HIGHLIGHTS

4.1 *"National"*

Severe local storms (as defined in Table 1) occurred on 84 days during a season which began on May 4th, and ended on September 29th, and which lasted 149 days. During this season there were 44 days with severe wind storms and 48 days

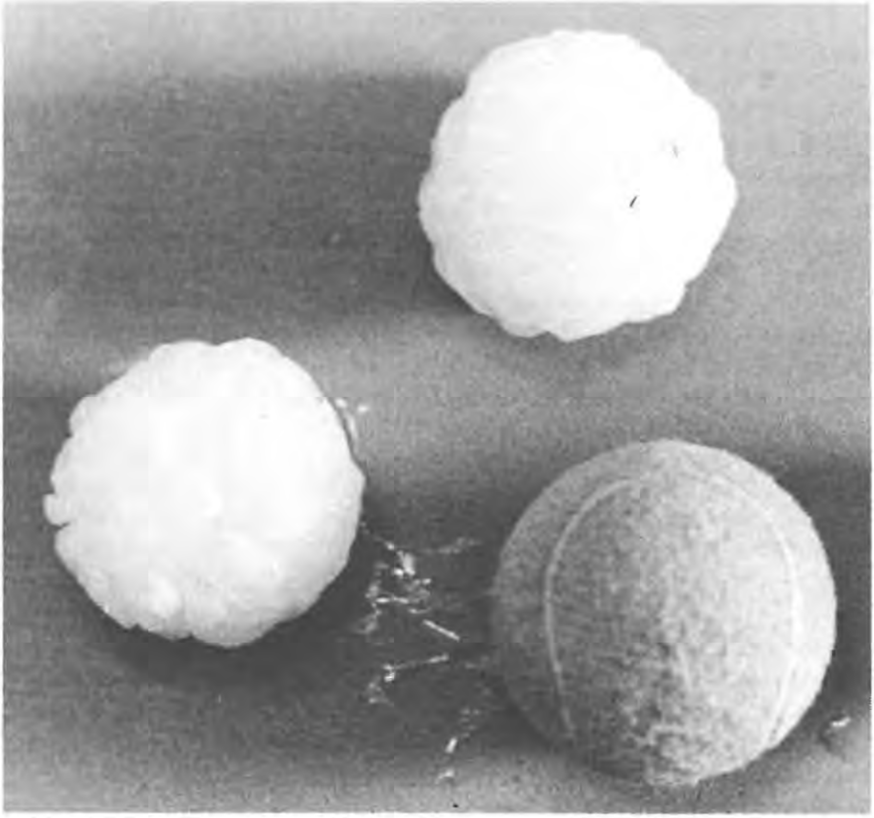

FIGURE 1. Hailstones up to the size of tennis balls fell in the vicinity of Montréal on May 29, 1986. Photograph by Marc A. Gélinas. [Readers will find the photographs of hailstones from storms in the 1970s on the Prairies included in Wojtiw and Lozowski (1975) most interesting also. One of them is considered to be a record for Canada. – *Ed.*]

with severe rain storms. The storms were responsible for at least 1 death. Lightning claimed at least 4 other lives.

One of the more notable events occurred in Montréal, Québec on May 29th, when damage from hail the size of tennis balls (Figure 1) resulted in automobile insurance claims totalling $64 million. On June 16th, many damaging wind storms (with gusts as high as 150 km/h), and 6 tornadoes (3 of which were strong) occurred over a large area from southwestern Ontario to the Eastern Townships of Québec. June 18th was a particularly bad day in Alberta and Saskatchewan, when there were downpours of 70 mm in 2 hours, hailstorms and an outbreak of 9 tornadoes.

The tornado season also began on May 4th and ended on September 29th, a total of 149 days. There were at least 75 tornadoes on a total of 33 days during the season.

Severe hail occurred on 48 days during a 149-day season which also began on May 4th and ended on September 29th.

There were at least 9 waterspouts reported and 45 funnel clouds.

A summary of these statistics is provided in Table 2. Table 3 compares the statistics on a yearly basis. It can be seen that severe storms have been experienced every 2 or 3 days during the season, with tornadoes every 5 days on average, and severe hail every 2 or 3 days. Tables 4 to 8 show the days when various types of storms occurred in the four regions.

4.2 *The Western Region (Northeastern B.C. and Alberta)*

In 1986 no reports of severe local storms were received from northeastern British Columbia. Although the average occurrence of thunder at a point in the region (between 85% and 90% of normal) was nearly the same in both 1986 and 1985,

TABLE 3. Yearly Comparison of "National" Severe Storm Statistics.

The return period is the rounded value of the length of the season divided by the number of days on which the phenomenon occurred. (a = statistics unavailable prior to 1984, but values for 1980 from Newark, 1981; b = excluding 7 in the Maritime provinces; c = from Newark *et al.* February 1987; d = from Newark *et al.*, October 1987; M = not available).

	1980[a]	1984[c]	1985[d]	1986
SEVERE LOCAL STORMS				
Date season began (Julian number)	Apr 06 (097)	Apr 27 (118)	Apr 04 (094)	May 04 (125)
Date season ended (Julian number)	Oct 11 (285)	Oct 03 (277)	Oct 04 (277)	Sep 29 (273)
Length of season in days	189	160	184	149
Number of storm days (return period)	64 (3.0)	81 (2.0)	78 (2.4)	84 (1.8)
Number of wind days (return period)	M	48 (3.3)	27 (6.8)	44 (3.4)
Number of rain days (return period)	M	37 (4.3)	23 (8.0)	48 (3.1)
Number of deaths (not by lightning)	7	4	13	1
Number of injuries	21	45	170	0
TORNADOES				
Date season began (Julian number)	Apr 06 (097)	Apr 27 (118)	May 07 (127)	May 04 (125)
Date season ended (Julian number)	Sep 28 (272)	Oct 03 (277)	Oct 04 (277)	Sep 29 (273)
Length of season in days	176	160	151	149
Number of tornado days (return period)	39 (4.5)	31 (5.2)	28 (5.4)	33 (4.5)
Number of tornadoes (at least)	72[b]	74	51	75
SEVERE HAIL				
Date season began (Julian number)	M	May 12 (133)	Apr 18 (108)	May 04 (125)
Date season ended (Julian number)	M	Sep 02 (246)	Sep 19 (262)	Sep 29 (273)
Length of season in days	M	114	155	149
Number of hail days (return period)	M	50 (2.3)	48 (3.2)	48 (3.1)

there was a major increase in severe weather reports in 1986 as compared to the previous year. The 1986 severe storm season began on May 21st, ended on August 14th, and lasted for 86 days. A total of 80 events occurred on 30 severe weather days during the season. As was also the case in Saskatchewan, nearly 90% of the total number of severe weather days were during May, June and July. With rainfall amounting to only 25% to 50% of normal, August was a very dry month.

The most active period was from June 17th to 18th with a total of 15 severe storm events, including 7 tornadoes and 4 hailstorms. Wind gusts from non-tornadic storms reached 130 km/h. During the season there were 21 tornadoes, 24 severe hail events, 11 severe wind storms, and 18 severe rain storms.

4.3 *The Central Region (Saskatchewan, Manitoba, Northwestern Ontario)*

The 1986 severe weather season was very active with a record high number of 132 events reported. There were 39 tornadoes (also a record high), 31 of which were in Saskatchewan. The number of severe weather days (41) was near average. The season started on May 4th, and ended on September 26th, lasting a total of 146 days, but these statistics are a little misleading because the severe weather was virtually finished by the end of July, with only 2 events reported in August and September. July 1986 was excessively wet on the Prairies, and one of the wettest on record in central Saskatchewan, and was followed by a very dry August.

Saskatchewan experienced several significant outbreaks of tornadoes in June and July. On June 18th, June 30th, and again on July 29th, there were outbreaks of 4 tornadoes each day. Of the 31 tornadoes in Saskatchewan, 13 occurred at night, after 2100 CST. In contrast, only 8 small and weak tornadoes were reported all season in Manitoba. No tornadoes were reported in northwestern Ontario.

Hail the size of baseballs was reported twice, first at Thornhill, Manitoba on May 11th, and again at Oxbow, Saskatchewan on June 26th. Severe rain events occurred in both Saskatchewan and Manitoba, and there were several cases where 100 to 125 mm of rainfall was reported to have fallen in a few hours causing local flooding. However, there were no reports of amounts greater than 200 mm as there were in 1984 and 1985.

On June 20th, there was one lightning fatality near Atikokan, Ontario. One waterspout was reported on August 2nd, over Lake Manitoba.

4.4 *The Ontario Region (excluding northwestern and extreme southeastern sections of Ontario)*

The 1986 summer severe storm season had about an average number of severe weather days (25) but the number of confirmed or probable tornadoes (9) was significantly below the 1978–1985 annual average of 27. An important ingredient in tornado production is the presence of dry air at mid-levels of the atmosphere, but record rainfalls indicate the contrary during the summer of 1986 (which was the

TABLE 4. Severe Local Storm Days, 1986
1 – NERN BC; 2 – ALTA; 3 – SASK; 4 – MAN; 5 – NWRN ONT; 6 – ONT;
7 – SERN ONT; 8 – QUE; 9 – NATIONAL

DATE	1	2	3	4	5	6	7	8	9	DATE	1	2	3	4	5	6	7	8	9
May 4			*	*						Jul 13		*	*	*		*			
5			*	*	*					14		*						*	
6						*		*		15			*					*	
7								*		16								*	
11				*						17						*			
16						*				18				*		*			
18						*		*		20		*						*	
20			*							22			*					*	
21		*	*							23			*	*					
22			*							24		*						*	
28		*								25		*	*	*		*		*	
29								*		26		*		*		*		*	
Jun 1			*							27			*						
2			*	*						28						*			
3			*							29			*				*	*	
4		*								31			*						
6		*								Aug 1				*	*	*			
7		*								2		*				*		*	
9		*								3		*						*	
11			*			*				5								*	
15		*								6		*		*		*	*	*	
16						*	*	*		7								*	
17		*	*							8				*		*			
18		*	*							9						*		*	
19		*	*	*		*				10								*	
20					*					11		*							
21				*						13				*					
22						*				14		*							
23		*								15				*		*	*	*	
24		*	*	*				*		19				*					
25		*	*							21								*	
26			*	*						23								*	
27						*		*		24			*	*				*	
28								*		Sep 2			*						
29		*				*		*		4						*			
30			*							10						*			
Jul 3		*		*						11								*	
6								*		12								*	
7		*						*		13								*	
8		*		*		*				26				*					
9		*								29						*	*	*	
11			*																
12		*	*							TOTAL	0	30	28	23	3	25	5	35	84

wettest in almost 60 years at some southern locations). Hail and flooding rains were the most predominant events, causing damage estimated at $100 million to crops in southern Ontario.

The season began on May 6th and ended September 29th, lasting a total of 147 days. June 16th was the single most active day, producing 18 severe storm events (mostly damaging wind gusts exceeding 100 km/h), including an outbreak of 3 tornadoes. Major damage was caused by an F3 tornado which travelled from Brady Lake to Maynooth. The two days of August 1st and 2nd were also very active with widespread hail up to the size of golf balls, resulting in

TABLE 5. Tornado Days, 1986
1 – NERN BC; 2 – ALTA; 3 – SASK;
4 – MAN; 5 – NWRN ONT; 6 – ONT;
7 – SERN ONT; 8 – QUE; 9 – NATIONAL

DATE		1	2	3	4	5	6	7	8	9
May	4			*						
	5			*						
	11				*					
	16						*			
	21		*							
Jun	1			*						
	3			*						
	6		*							
	16						*	*	*	
	17		*							
	18		*	*						
	19			*	*					
	22						*			
	25		*	*						
	26			*						
	29		*							
	30			*						
Jul	8		*		*		*			
	9		*							
	11			*						
	13		*							
	17						*			
	23				*					
	25			*	*					
	26		*							
	27			*						
	28						*			
	29			*						
Aug	15						*		*	
	19				*					
	24				*					
Sep	2			*						
	29						*			
TOTAL		0	10	14	7	0	8	1	2	33

damage to fruit and vegetable crops estimated at $20 million. Although a number of funnel clouds were reported both days, no actual tornadoes were confirmed. On August 15th, during the afternoon and evening, hail, strong winds, and flooding downpours occurred throughout the lower Great Lakes region. As much as 100 mm of rain in 2 hours was reported. There was one death in Toronto due to the winds.

On June 29th, two children were killed by lightning near Niagara Falls.

4.5 *The Québec Region (southeastern Ontario, Québec)*

Despite a cool summer with above-normal cloud cover and up to 150% of normal precipitation, 88 severe weather events (about 55% of which were severe rain events) on 35 days were recorded in a season stretching from May 6th to September 29th, and lasting 149 days. During the first two months of the season,

TABLE 6. Severe Hail Days, 1986

1 – NERN BC; 2 – ALTA; 3 – SASK; 4 – MAN; 5 – NWRN ONT; 6 – ONT; 7 – SERN ONT; 8 – QUE; 9 – NATIONAL

DATE	1	2	3	4	5	6	7	8	9	DATE	1	2	3	4	5	6	7	8	9
May 4				*						Jul 15			*						
5				*	*					17						*			
6								*		18				*		*			
7								*		22			*						
11				*						23			*						
21		*								24		*							
22			*							25		*	*	*					
29								*		27			*						
Jun 2			*	*						29			*						
3			*							Aug 1					*	*			
15		*								2		*				*		*	
16						*		*		3								*	
17		*	*							6						*	*	*	
18		*								8				*					
19		*	*			*				9								*	
24		*						*		11		*							
25		*	*							13				*					
26			*	*						14		*							
29								*		15				*		*			
Jul 3		*								19				*					
7		*								21								*	
8		*								24			*	*					
11			*							Sep 4						*			
13		*	*	*						29						*			
										TOTAL	0	16	16	13	2	10	1	11	48

TABLE 7. Days with Severe Local Wind, 1986

1 – NERN BC; 2 – ALTA; 3 – SASK; 4 – MAN; 5 – NWRN ONT; 6 – ONT; 7 – SERN ONT; 8 – QUE; 9 – NATIONAL

DATE	1	2	3	4	5	6	7	8	9	DATE	1	2	3	4	5	6	7	8	9
May 5				*						Jun 29						*		*	
16						*				Jul 3				*					
18						*		*		13						*			
21		*								15			*					*	
22										16								*	
28		*								18				*		*			
29								*		20		*							
Jun 1			*							25				*		*			
2				*						27			*						
9		*								28						*			
11			*			*				29			*						
16						*		*		31			*						
17		*								Aug 2						*		*	
18			*							3								*	
19		*	*	*		*				5								*	
21				*						6				*		*	*		
22						*				8						*			
23		*								9						*		*	
24		*		*				*		15						*	*		
25		*	*							21								*	
26				*						Sep 10						*			
27						*													
28								*		TOTAL	0	9	9	10	0	18	2	13	44

TABLE 8. Days with Heavy Local Rain, 1986
1 – NERN BC; 2 – ALTA; 3 – SASK; 4 – MAN; 5 – NWRN ONT; 6 – ONT;
7 – SERN ONT; 8 – QUE; 9 – NATIONAL

DATE	1	2	3	4	5	6	7	8	9	DATE	1	2	3	4	5	6	7	8	9
May 5				*						Jul 22								*	
7								*		24								*	
20			*							25								*	
21		*	*							26				*		*		*/	
28		*								27			*						
Jun 1			*							29							*	*	
2				*						Aug 1						*			
4		*								2								*	
7		*								3		*						*	
16						*				6		*		*					
17		*								7								*	
18		*								8						*			
24			*	*				*		9								*	
25		*								10								*	
26				*						13				*					
27								*		15						*			
29		*								23								*	
Jul 3				*						24								*	
6								*		Sep 11								*	
7		*						*		12								*	
9		*								13								*	
12		*	*							26				*					
14		*						*		29							*	*	
18						*													
20		*						*		TOTAL	0	15	6	9	0	6	2	23	48

wind and hail storms were the most common, but from July to September heavy downpours repeatedly caused flooding in many areas.

Major storms occurred on May 29th, with widespread hail along the St. Lawrence valley between Trois-Rivières and Montréal. Hail the size of tennis balls battered the south shore and east end of Montréal resulting in automobile damage claims of $64 million. On June 16th, severe storms moved in from Ontario, and extensive wind damage occurred over much of southwestern Québec. An F3 tornado struck Lac Gareau (near Maniwaki) severely damaging several summer chalets and overturning a truck. Two other weaker tornadoes occurred further east. From September 11th to 13th, a widespread heavy rain of more than 100 mm resulted in floods in many localities. A dam was damaged at Lachute, roads washed out in Ste-Agathe, and a marina wharf swept away by rising water in Nicolet.

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