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**EASTERN ONTARIO CLIMATE: VARIABILITY AND TRENDS
DURING THE 20TH CENTURY**

Nancy Lemay

A thesis submitted in conformity with the requirements
for a degree of Master of Science
Faculty of Graduate and Postdoctoral Studies
Ottawa-Carleton Geosciences Centre
University of Ottawa



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Abstract

The historical climate record is analyzed to determine trends and variability to develop possible scenarios for future climates. The study area is the Prescott-Russell United Counties and Stormont, Dundas and Glengarry United Counties of Eastern Ontario. Three data sets were used: the Canadian monthly climate data, the Historical Canadian Database Version 2: Monthly Rehabilitated Precipitation and Homogenized Temperature Data Sets and the Eastern Canada daily dataset.

The ten warmest years of the past century occurred at the beginning and at the end of the century. However, the last decade (1990-1998) experienced four of the ten warmest years of the century, including the warmest year on record (1998), which was a full degree warmer than the second warmest (1953). Throughout the record a warm spring and summer typically determined a warm annual temperature. The mean monthly minimum temperatures seem more variable than the maximum temperatures. Unlike the warmest years the ten coldest years occurred in the early part of the century, between 1904-1943. Cold springs and autumns, the transition seasons, determined the cooler years. Thus spring temperatures appear to have a pivotal influence on how extreme a year will be, because both coldest and warmest years are strongly influenced by the spring mean monthly temperature. The diurnal temperature range (DTR) decreased considerably

in the months of January and April, during the 1930s. During the warm period of the 1990s, the daily temperature range decreased in the month of July.

The 1990s, although warm in the mean, had fewer extreme heat waves and fewer cold snaps. There is no clear relation between temperature and precipitation, suggesting that future climates may be wet or dry. Thus this uncertainty should be considered when planning for infrastructure and budgets. However, the last two decades were both warm and wet. In warm decades precipitation tends to fall more as large or small, rather than intermediate-sized events.

From the mid 1960s to the present the growing season has started earlier, and since 1984 has been ending later than the long-term average. The inter-annual variability of the duration of the growing season was high in the 1990s. A comparison of daily values in cold and warm years shows an increase in the mean of winter and summer temperatures with little change in variability. This suggests extreme events will be concentrated in warmer temperatures in both seasons.

Résumé

Le but de ce projet de recherche consiste en une analyse détaillée des données climatiques du 20^{ième} siècle pour des études d'impacts. Les données climatiques historiques ont été analysées pour déterminer les tendances et prédire des scénarios possibles pour des climats futurs. La région d'étude englobe les comtés unis de Prescott-Russell et de Stormont, Dundas et Glengarry, tous situés dans l'est de l'Ontario. Trois banques de données ont été utilisées pour ce projet de recherche : les données climatiques mensuelles canadiennes; la deuxième version de la base de données historiques canadiennes (*historical canadian database Version 2 : monthly rehabilitated*

precipitation and homogenized temperature data sets) ; et les données climatiques quotidiennes canadiennes des températures et précipitations de l'est du Canada (1999).

Les résultats ont démontrés que les dix années les plus chaudes du dernier siècle ont eu lieu au début et à la fin du siècle. Par exemple, quatre des dix années les plus chaudes ont eu lieu au cours de la dernière décennie (1990-2000). Mentionnons également que la température de l'année la plus chaude du dernier siècle (1998) fut d'un degré Celsius supérieur à celle de la seconde année la plus chaude (1953). Les années, dont la température moyenne annuelle est plus chaude que la normale, sont principalement influencées par une température printanière et estivale élevée. De plus, les températures minimales mensuelles semblent varier plus que les températures maximales. Contrairement aux dix années les plus chaudes, les dix années les plus froides ont eu lieu au cours de la première partie du dernier siècle, plus précisément entre 1904-1939. Les saisons de transitions froides, c'est-à-dire les printemps et les automnes où la température est basse, sont les principaux agents responsables d'une année froide. Les températures printanières semblent avoir une influence importante sur les températures extrêmes d'une année, car les années les plus froides et les plus chaudes sont fortement influencées par la température printanière. L'écart entre les températures minimales et maximales a diminué considérablement durant les mois de janvier et d'avril pendant les années 1930 ainsi que lors de la période chaude des années 1990, l'écart de juillet semble aussi avoir diminué.

Bien que la moyenne des températures des années 1990 soit supérieure à la normale, il n'en demeure pas moins qu'il y a eu, au cours de cette période, moins de vagues de chaleur extrême durant l'été et moins de vagues de temps très froid pendant l'hiver. Aucune relation entre la température et la précipitation ne laisse croire que les climats futurs seront humides ou secs.

Cette incertitude doit être construite dans la planification des infrastructures et des politiques. Cependant, la température des deux dernières décennies était chaude et humide et il y a eu de fortes ou de légères précipitations plutôt que des précipitations moyennes. Depuis les années 1960, la période estivale commence plutôt et depuis 1984 elle se termine plus tard que la moyenne. La variabilité inter-annuelle de la durée de la période estivale fut plus élevée lors des années 1990. Une comparaison des valeurs quotidiennes des années froides et chaudes montre que la moyenne des températures hivernales et estivales augmentent, mais cette augmentation se fait avec peu de changement dans la variabilité. Cette affirmation laisse croire que les événements extrêmes surviennent lors des températures plus chaudes dans les deux saisons.

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1. INTRODUCTION

The global climate has warmed during the last century, at a rate that seems to be greater than natural variability (IPCC, 1995). Most researchers believe that the mean global temperature has increased about 0.3 to 0.6°C over the last century (Kelly *et al.*, 1985; Hansen and Lebedeff, 1988; Vinnikov *et al.*, 1990; Jones, 1994; IPCC, 1996). Although the global temperature has been studied in detail, regional climate changes have been less studied and not at all scales. In particular, changes in daily patterns and extremes are less well known (Bonsal *et al.*, 2001).

This study is the analysis of climate change in Eastern Ontario. It is part of a multidisciplinary project, where the impacts of climate change on municipal infrastructure are being analyzed. The project purpose is to ensure that landscape use and societal infrastructure changes do not further increase vulnerability to climate change, as explained in *Easterling et al.*, (2000), by providing a detailed analysis of the climate record for this region.

There are two general approaches used to provide climate scenarios for impact studies: use of the instrument record to investigate the past and suggest possible analogues for future climates (Jones *et al.*, 1999; IPCC, 2001) and use of general circulation model forecasts (IPCC, 1997). This present study is based on an analysis of the historical record to determine trends and tendencies in the climate and to suggest possible scenarios for the future, as will be explained below (Zhang *et al.*, 2000). It assumes that future climates will consist of similar synoptic patterns as in the present, where present refers to the 20th century during which we have instrumental records of the climate, but with different frequencies of these patterns. For example, the Canadian Centre for Climate Modelling and Analysis (CCCma) suggested that for

North America extreme precipitation that occurs on average every 20 years in the present climate would occur every 10 years in a warmer climate (Zwiers and Kharin, 1998).

To understand why we chose to use this analysis for this study we need to define spatial scales. As defined by the IPCC (1997), continental spatial scale is an area that covers 10-100 million square kilometres (km^2), regional scale 100 thousand – 10 million km^2 and local scale less than 100 thousand km^2 . This study is done on a local scale. This determined the methodology that was used.

Historical climatic observations record the natural variability of a region, as well as past trends and tendencies (Jones *et al.*, 1999; Bootsma, 1994; Idso and Balling, 1991b). Experience from past decades can be used as a guide to potential future climates (Jones *et al.*, 1999; IPCC, 2001). For example, the circulation pattern that caused the drought of the 1930s might occur more frequently in the future, and this will therefore have more serious impacts than in the 1930s.

An alternative approach for climate impact scenario development is to use General Circulation Model (GCM) simulations of future conditions and “downscale” these to the region under study (IPCC, 1997). There are several reasons why GCM simulations were not used in this project. First, different models give different results (IPCC, 1998). One model must be chosen and it is not clear which of the currently available simulations is the most accurate (IPCC, 1998). These models must be given “boundary conditions”. Among these are the potential levels of CO_2 in the future and this is not known with certainty (IPCC, 1997). Choice of a particular scenario may thus be controversial. It has been observed that while there is a warming trend in historical

records, the degree of warming is small compared to that simulated by GCMs (Karl *et al.*, 1991; Skinner and Gullet, 1993; Masson, 1995; Akinremi *et al.*, 1999). The most important reason, however, is that these models are designed to simulate the global climate and tend to be poorly resolved at the local level (IPCC, 1995). The results must be “downscaled” to the region in question to obtain data at a high enough resolution to resolve the local differences. It is not clear how best to do this, and this is a major research question at the present time. Although regional models are beginning to provide reliable estimates of mean conditions, variability is not well stimulated (Giorgi and Francisco, 2000). The question of “downscaling” from a global scale to a local scale, while interesting, is beyond the scope of this project and has been considered problematic. The local scale and availability of adequate instrumental data means that the analogue approach will be used to supply relevant information for impact studies at the scale of this project.

In this study the climate records were analyzed at decadal, annual, seasonal, monthly and daily temporal scales. Monthly mean data are frequently used in regional climate change research (Gruza *et al.*, 1999) but daily data have hardly been used to study regional changes in climatic extremes (Plummer *et al.*, 1999). Data dating back to the beginning of the instrumental record - that is, a little more than a century in length - were used to obtain the clearest possible indication of trends, cycles, and regimes (Zhang *et al.*, 2000). Several research projects have used historical data to understand climate patterns of a given area (Zhang *et al.*, 2000; Quereda Sala *et al.*, 2000; Heimann *et al.*, 2000; Sahai, 1998). The weakness of any historical analysis is that the future can be completely different from the past. Therefore, any “forecasts” presented here are done so with the understanding that climatic patterns may be different from those of the past

century. The variability described should therefore be viewed as conservative, and society, governments and infrastructure must at a minimum be prepared to deal with at least this variability. The possibility of “surprises” in the future should always be in the back of our minds as the precautionary principle suggests.

1.1. Climate Change Forecasts

The Intergovernmental Panel on Climate Change (IPCC) has predicted that mean global temperature relative to 1990 will increase by 2°C by 2100 if greenhouse gases and aerosols increase at a moderate pace (IPCC, 1995). Temperatures increase proportionately to the quantity of emissions. IPCC forecasts predict an increase ranging between 1 and 4.5°C by 2100 (IPCC, 1995). All of the models predict that temperatures will rise faster than they have during the past 10,000 years (IPCC, 1995). However, little effect on precipitation is indicated.

The three global climate models analyzed in the IPCC reports predict that December, January and February would increase in temperature between 12 and 4°C if carbon dioxide emissions double (IPCC, 1990, fig. 5.4). The same models predict an increase in temperature of 4 to 8°C for the months of June, July and August (IPCC, 1990, fig. 5.4).

Changes in climate variability may be more significant than change in mean temperature and precipitation (Groisman *et al.*, 1999). Several studies have found that small changes in the mean climate bring noticeable change in the frequency and intensity of extreme events (Katz and Brown, 1992; Wagner, 1996). Models also predict that a climate change will increase the frequency of extreme events, for example, producing more droughts and floods in certain areas but fewer droughts and floods in other areas of the globe (IPCC, 1995; Masson, 1999). Small

differences in mean temperature and precipitation or climate variability can cause changes in the frequency of violent events. Some models predict that we will have an increase in the probability of dry days and long dry periods. As the amount of precipitation decreases, the chances of having droughts increases (IPCC, 1995).

Most studies seem to predict more intense precipitation in a shorter time span, due to more frequent storms (Groisman *et al.*, 1999; IPCC, 1996; Hennessy *et al.*, 1997). A general explanation of why global warming would increase extreme precipitation events is that as the weather gets warmer it accelerates the hydrological cycle. The water cycle is the process by which water from the oceans evaporates into the atmosphere to condense out as precipitation. The water vapor-liquid equilibrium is temperature dependent; therefore, a warmer atmosphere should heat up the oceans faster leading to more evaporation. The increased amount of water, when condensed, more frequently falls from the atmosphere as larger downpours. However, both the land and ocean are heated, so that evapo-transpiration increases on land as well. When large areas of land are dry, severe heating of the air should increase, thereby increasing pressure gradients and leading to more frequent cyclones. Global warming can also shift the distribution of storm tracks and subsequently change the location of floods and droughts to regions that previously were less affected by these phenomena (MacIver, 1997; Epstein, 2000).

Global warming may also bring about an increase in temperature extremes in summer and a decrease in winter temperature extremes (IPCC, 1995). Precipitation should increase in higher latitudes in winter and some models show this trend continuing into mid-latitudes (IPCC, 1995). All models show that soil humidity will increase in northern latitudes, and most models also

predict that soil surfaces will be drier in mid-latitudes in the northern hemisphere in summer (IPCC, 1995).

Precipitation will be affected by carbon dioxide doubling in the atmosphere. For the months of December, January and February, precipitation is predicted to increase (Fig.5.6 in IPCC, 1990). However, June, July and August precipitation is predicted to decrease (Fig. 5.6 in IPCC, 1990).

1.2. Climate of the 20th Century for Southern Canada

The temperature of southern Canada increased by 0.9°C during the 20th century (Bonsal *et al.*, 2000). A major increase in temperature occurred between 1920-1930 with a maximum in 1940 and a slight decrease in the 1970s (Environment Canada, 1999). Since 1980, temperatures have increased to reach the 1940 value, however at a steeper rate (Environment Canada, 1999). Since the 1980s temperatures have remained above the 20th century average, except for 1996 (Environment Canada, 1999). This recent increase in temperature was accompanied by greater precipitation. The increase in mean temperature is generally due to an increase in minimum temperature (Karl *et al.*, 1993; Horton, 1995; Jones, 1999; Smith *et al.*, 1997; Zhang *et al.*, 2000; Balling *et al.*, 1990), suggesting that night-time temperature causes the increase in the mean. This reduces the diurnal temperature range (DTR), between maximum (daytime) temperature and minimum (night-time) temperature. The decrease of the daily temperature range (DTR) is approximately equal to the increase of the mean temperature (Karl *et al.*, 1993). Most of the decline in the DTR occurred before the 1950s, and coincides with an increase in cloud cover during this period (Zhang *et al.*, 2000; Folland *et al.*, 1992). In addition, the type of cloud might have an impact on the decrease in the DTR. Clouds with low bases are most effective in reflecting the sunlight; therefore the DTR reduction by clouds is largest in warm and dry seasons

such as autumns, when latent heat release was limited by the soil moisture content (Dai *et al.*, 1999). Atmosphere aerosol loading can also be responsible for a decrease in DTR (Easterling *et al.*, 1997).

1.3. General description of the climate of the study region

Prescott-Russell United Counties and Stormont, Dundas and Glengarry United Counties are situated within the Great Lakes-St Lawrence climate region that encompasses part of Southern Ontario and the southernmost part of Québec (Hare and Thomas, 1974). Within this climatic region are several important cities, including Toronto, Ottawa, Montréal, and Québec and a large portion of the Canadian population. The region is bounded in the south by the lower Great Lakes (Ontario, Erie and Huron). Here the north-south extent is about 480 km, decreasing to less than 320 km at its eastern edge, near Québec City. The region is composed mainly of relatively flat lowlands with a mean elevation of less than 150 m above mean sea level; however some areas located in the Appalachians south of the St Lawrence River and along the edge of the Laurentian Shield rise to more than 300 m above sea level (Hare and Thomas, 1974; Smith *et al.*, 1997).

1.4. Climate of the Study Region

The Great Lakes-St Lawrence climatic region has a temperate continental climate (Smith *et al.*, 1997). Winter daily and monthly temperatures are more variable than summer temperatures (Smith *et al.*, 1997). Day-to-day alterations of high and low-pressure systems, especially in winter, bring a variety of weather to the region. Precipitation tends to be evenly distributed throughout the year and extended wet or dry spells are rare, as would be expected from a continental climate (Hare and Thomas, 1979). Moist air from the Gulf of Mexico brings hot, humid, and unsettled weather in summer and snow and thaws with rain in winter (MacIver,

1997). Cold air masses (continental arctic) bring dry conditions and clear skies. Winter lows originating in the south or west of the United States frequently cross the continent via the Great Lakes and the St. Lawrence corridor (MacIver, 1997). The following section gives a basic summary of the seasonal climate of the Great Lakes and the St. Lawrence corridor.

1.4.2. Winter in the Great Lakes and the St. Lawrence corridor

Winter mean temperatures range between -15.3°C and -5.4°C with an average of -9.2°C (Environment Canada, 1982). Precipitation ranges between 145.4 and 435.8 mm with an average of 261.0 mm (Environment Canada, 1982).

The Great Lakes have little effect on the temperature of the surrounding area but do affect precipitation downwind (Smith *et al.*, 1997). Air masses moving over the Great Lakes can pick up extra moisture if they are not frozen over; giving localized additional precipitation downwind of the lakes, known as “lake effect” snowfall (Kunkel *et al.*, 1998). This effect does not extend to southern Québec.

In the winter the region usually experiences cold, dry weather as a result of continental arctic (cA) air from Western Canada (MacIver, 1997). Associated with this air mass are low pressures. An air mass that rarely reaches Eastern Ontario in winter is modified maritime tropical air (mT) from the Gulf of Mexico (Hare and Thomas, 1979). When it does arrive in the region, it brings mild temperatures, with a resultant brief thawing of snow and ice surfaces. In the winter the region can be hit with several types of systems, some moving in from west of the Great Lakes or north and eastward into Ontario and Québec from the central United States (Hare and Thomas, 1979). These tend to deliver larger amounts of precipitation.

1.4.3. Spring in the Great Lakes and the St. Lawrence corridor

Spring mean daily temperatures range between 1.8°C and 8.6°C with an average of 5.1°C (Environment Canada, 1982). Precipitation ranges between 90.0 and 427.0 mm with an average of 229.0 mm (Environment Canada, 1982). With increasing intensity of solar radiation, mean daily temperatures usually cross the freezing point early in March in Southern Ontario and later that month in Southern Québec (Hare and Thomas, 1979). Spring, on occasion, may be short; temperatures in the range of 20.0 to 28.0°C have occurred during March, mostly notably in 1945 and 1946 (Environment Canada, 1982). On the other hand, near 0°C temperatures have occurred in April, for example in 1972 (Environment Canada, 1982).

The St-Lawrence Valley usually warms very rapidly in spring. Temperatures average 3.0°C in Montréal in early April, increase to 11.0°C by the end of that month, and to 16.0°C by the end of May (Hare and Thomas, 1979). Snowfall is still common in March, but by May it is rare (Hare and Thomas, 1979). Intense low-pressure systems frequently pass over the region during March and early April with the result that wind speeds are higher on average during these months than during any other time of year (Hare and Thomas, 1979). Thunderstorms again become common during the spring, and a few tornadoes or near-tornadoes are reported each year.

1.4.4. Summer in the Great Lakes and the St. Lawrence corridor

On average, summer mean daily temperatures range between 17.8°C and 21.8°C (Environment Canada, 1982). The precipitation ranges between 123 and 497 mm (Environment Canada, 1982). Normally, mean daily temperatures exceed 19°C at Windsor from early June until mid-September, while at Québec City the comparable mid-summer period is from mid-June until mid-August (Hare and Thomas, 1979). July mean daily temperatures average slightly above

21°C in the major urban areas and in the southwest of the region, while elsewhere the month is a little cooler (Hare and Thomas, 1979). Daytime temperatures are modified in the immediate area of the Great Lakes, but the lake breeze does not usually extend many miles inland. Night-time temperatures are a few degrees lower in the highland areas than along the Great Lakes and in the cities, but topography does not cause much contrast in summer daytime temperatures (Hare and Thomas, 1979). Temperatures of 38°C or higher have been experienced at a majority of stations in southern Ontario, but only rarely in Southern Québec (Hare and Thomas, 1979). Most summer rainfall comes in showers and thunderstorms, and in July these occur most frequently in the late afternoon (Hare and Thomas, 1979). In the summer there are several air masses that can influence the weather of Eastern Ontario. Air masses, moving in from the Northwest, bring cool dry weather. Maritime Tropical (mT) air from the Gulf of Mexico is responsible for humid weather often associated with afternoon convective thunderstorms (Environment Canada, 1999). Summer precipitation can come from the passage of organized systems of low pressure and by isolated convective storms (Environment Canada, 1999). A normal month of July would have ten days of measurable rainfall in southwestern Ontario and thirteen in the Eastern Townships of Québec (Hare and Thomas, 1979). This precipitation is usually in the form of showers and thunderstorms, which usually occur late in the afternoon (Hare and Thomas, 1974).

1.4.5. Autumn in the Great Lakes and the St. Lawrence corridor

Autumn temperatures range between 5.5°C and 10.3°C, with an average of 8.0°C (Environment Canada, 1982). Precipitation ranges between 114.0 and 402.0 mm, with an average of 245.0 mm (Environment Canada, 1982). Autumn may be considered to begin during the last half of September when mean daily temperatures fail to reach 16.0°C (Hare and Thomas, 1979). Freezing temperatures can be expected on more than half the nights in rural Québec by mid-

November and by the first week of December in Montréal and throughout Southern Ontario (Hare and Thomas, 1979).

Along with shortening of the daylight period during this season, there is a marked increase in cloudiness, so the normal duration of bright sunshine decreases fairly rapidly. In the late summer or early fall the region is often affected by the remnants of tropical hurricanes as they move northeastward along the Atlantic seaboard, or on relatively rare occasions directly over the region.

2. SPATIAL DIFFERENCES: CAN ONE STATION REPRESENT THE AREA?

The first question addressed was the spatial representativeness of one or two stations. Can we choose one or two stations to represent Eastern Ontario? That is, do Prescott-Russell (PR) and Stormont, Dundas and Glengarry (SDG) United Counties act as one climatic unit, or are there significant spatial differences from north to south and east to west?

2.1. Longest Climatic Stations

Five climatic stations possessing the longest time series were selected to investigate this question, including Montréal McGill, Les Cèdres, Maniwaki, Ottawa CDA and Morrisburg (Figure 2-1). For most climate stations, except Ottawa CDA, the monthly data used for this analysis are from the Canadian Monthly Normals CD (Atmospheric Environment Service, 1993). Ottawa CDA climate station data were obtained from the Historical Canadian Database Version 2: Monthly Rehabilitated Precipitation and Homogenized Temperature Data Sets (Atmospheric Environment Service, 2000). The rehabilitated precipitation takes into account the under-sampling of rain and snow by rain gauges prior to 1975 (Karl *et al.*, 1998). In order to compare the similarity of temperature and precipitation between stations scatter plots were prepared which allow rapid visual assessments of the overall similarity of station pairs. A quantitative indication of the linear correlation between the station data, the Pearson product coefficient of correlation, was also calculated. Scatter plot matrices effectively illustrate the relationships among the stations, and correlation coefficients are also displayed on these plots. The correlations were computed on the middle month of every season (January, April, July and October).

As expected, the mean monthly temperatures were more highly correlated than total monthly precipitation (Figure 2-4 and Figure 2-5) (Glaser *et al.*, 1999). Temperature is an advected

property and atmospheric movements tend to equalize temperatures. Both winter temperatures and precipitation were more highly correlated than in summer. The scatter plots for July monthly precipitation show the lowest correlations. Again, this was expected. During the month of July most of the precipitation is convective, which tends to be more localized and less organized than the frontal precipitation that typifies winter. Visual inspection of the plots shows that the relationships are linear and therefore computation of the correlation coefficient is valid.

Not surprisingly, data from stations that are closer together are more highly correlated. The correlation coefficient ranged between 0.63-0.85 for mean monthly minimum temperatures (Figure 2-3), 0.77-0.86 for mean monthly maximum temperatures (Figure 2-2), 0.78-0.91 for mean monthly temperatures and 0.35-0.74 for total monthly precipitation (Figure 2-5).

2.2. Shorter Climatic Stations within Study Area

The above analysis was based on the stations in southern Ontario and Québec possessing the longest record, which were located around the periphery of the study area. Statistical estimates are improved with longer records. Stations within the study area have shorter time series. The scatter plots and correlations were repeated using stations within the study area to ascertain their degree of correlation. To represent the study area we chose five stations, Cornwall, Cornwall Hydro, Dalhousie Mills, Glen Gordon, and Ottawa CDA. Ottawa CDA was again chosen to relate this analysis to the previous one.

The correlation coefficient ranged between 0.80-0.95 for the mean monthly minimum temperatures, between 0.90-0.97 for the mean monthly maximum temperatures, between 0.89-0.98 for the mean monthly temperatures, and between 0.49-0.70 for total monthly precipitation

(not shown). These values are comparable to those found using the longer station records.

The climate stations examined exhibited high correlation. This indicates that the study area falls essentially within one climatic region. Given these results, it is possible to perform analysis on one or two stations and this will represent the whole region. Further analysis will therefore be done on two stations Ottawa CDA and Morrisburg, which have the longest time series.

2.3. Summary

- Mean monthly temperatures were more highly correlated spatially than total monthly precipitation.
- Both winter temperatures and precipitation were more highly correlated than in summer.
- Not surprisingly, stations that are closer together are more highly correlated.
- The correlation coefficient ranged between 0.63-0.85 for mean monthly minimum temperatures, 0.77-0.86 for the mean monthly maximum temperatures, 0.78-0.91 for mean monthly temperatures, and 0.35-0.74 for total monthly precipitation.

APPENDIX A

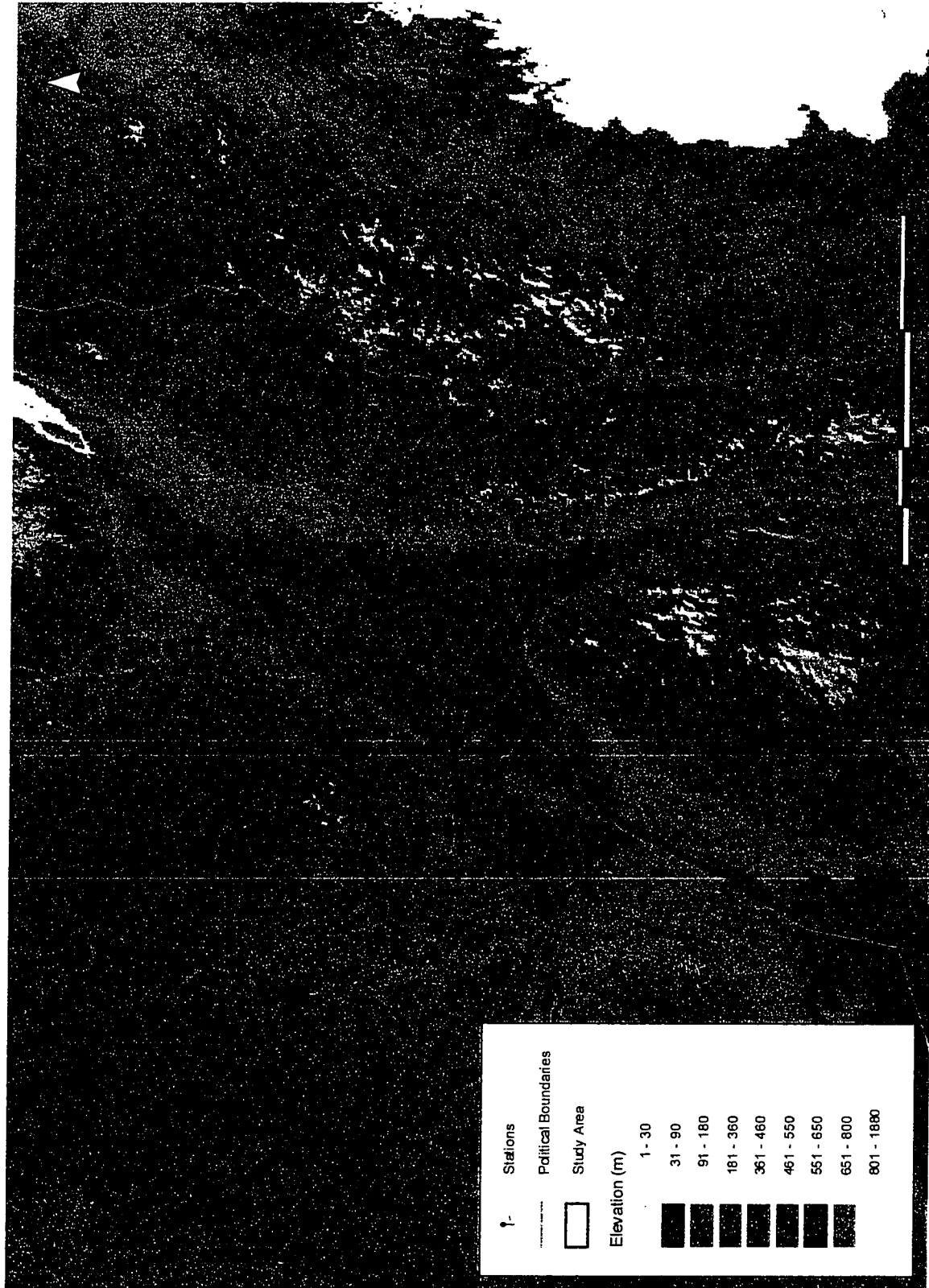


Figure 2-1. Study area showing distribution of climate stations.

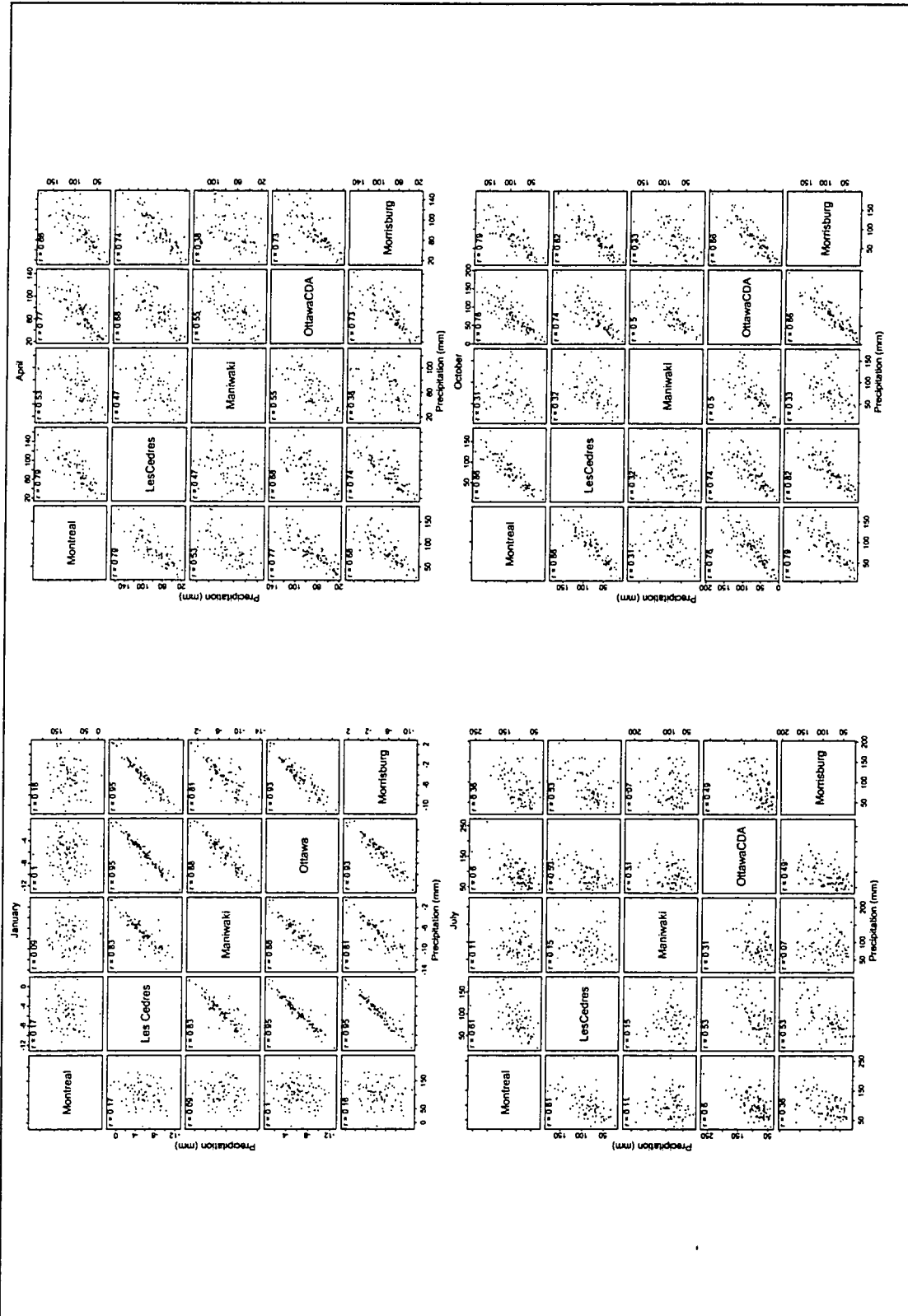


Figure 2-5. Scatter plot matrices for monthly total precipitation

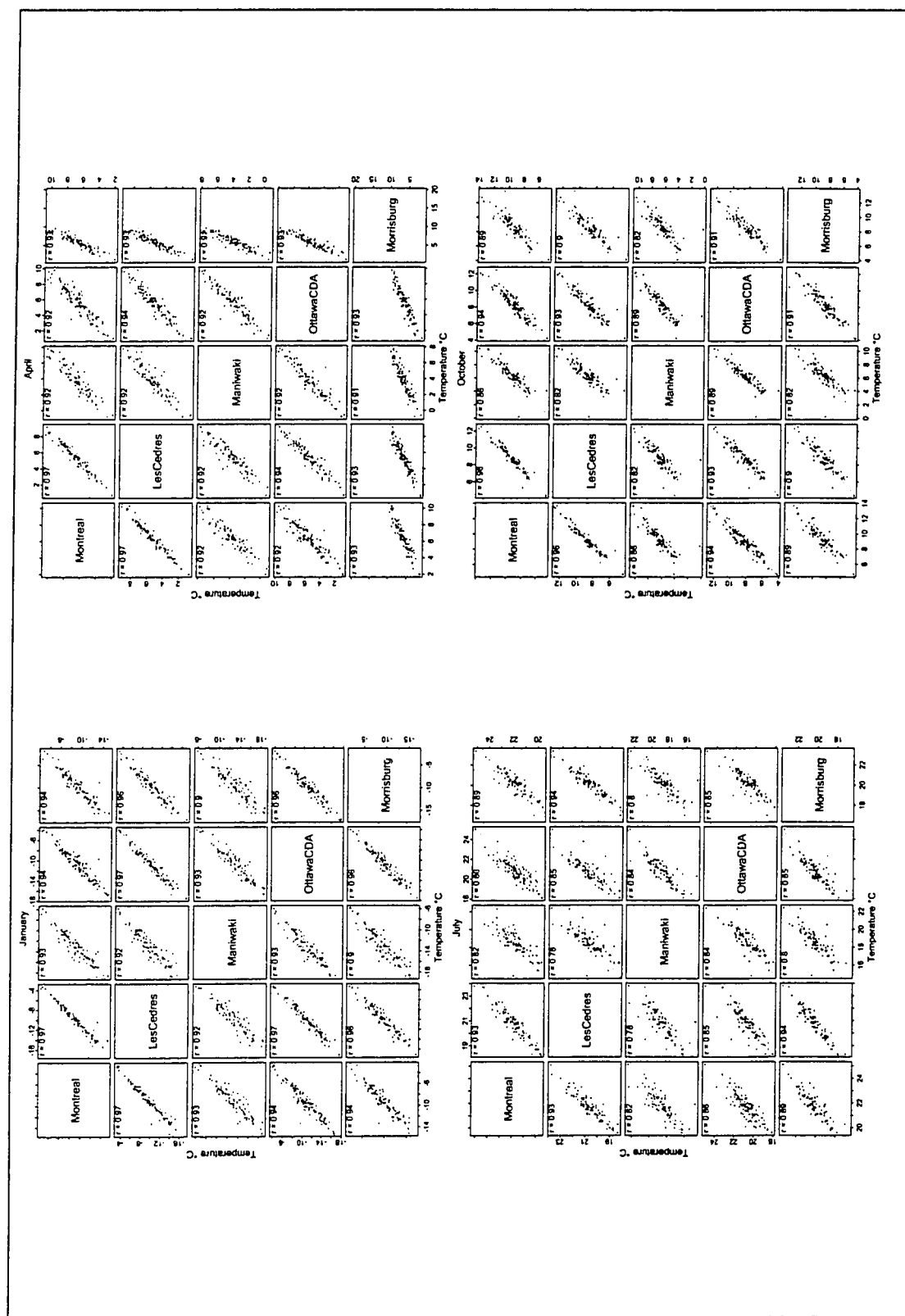


Figure 2-4 Scatter plot matrices for mean monthly temperature

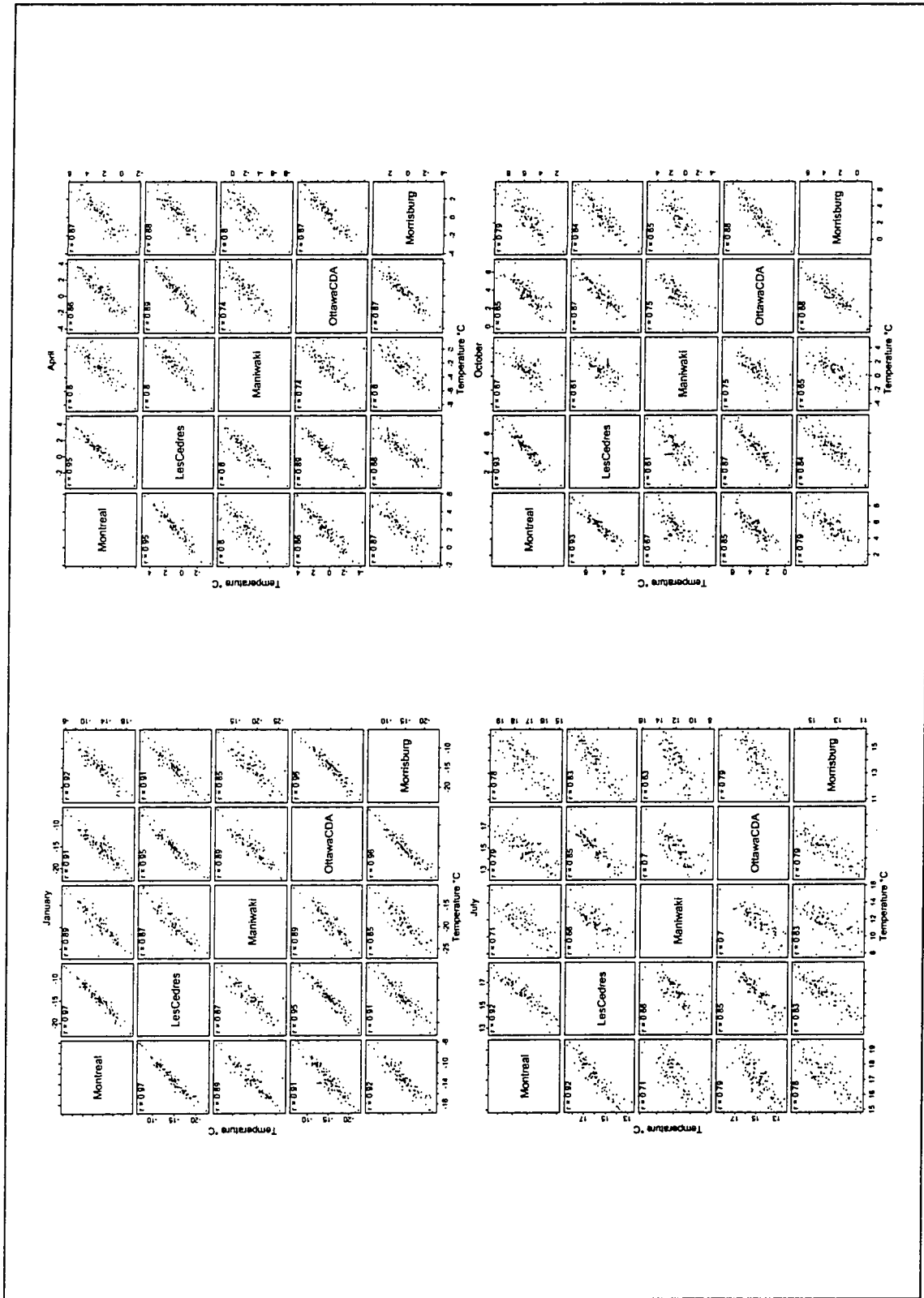


Figure 2-3 Scatter plot matrices for monthly mean minimum temperature

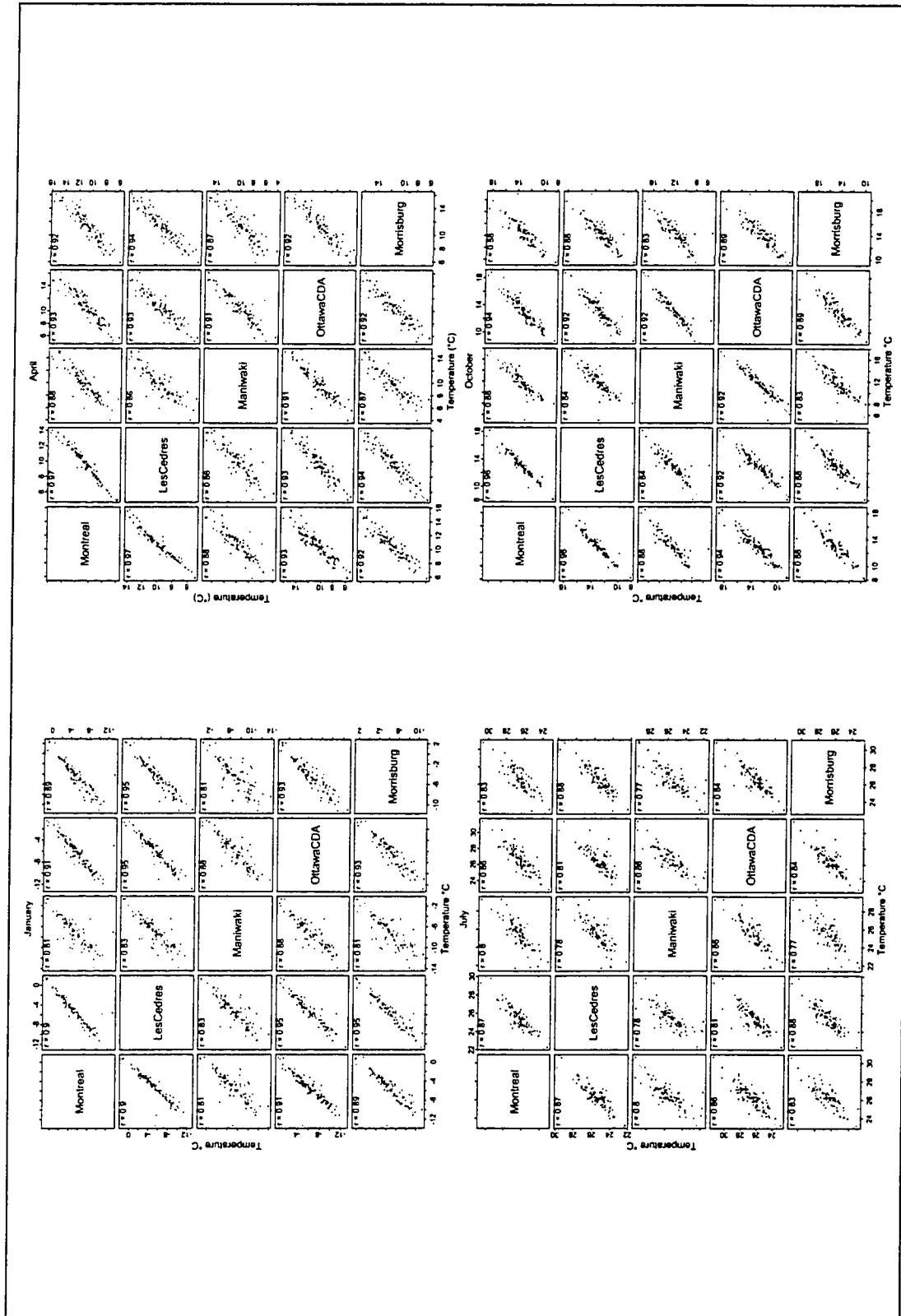


Figure 2-2 Scatter plot matrices for monthly mean maximum temperature

3. DECADEAL ANALYSIS: WHAT PERIODS OF THE 20TH CENTURY ARE WARMER, COLDER, DRIER AND WETTER?

In this section we analyze decadal means of Ottawa CDA to quantify inter-decadal variability. Decadal means and standard deviations of temperature and precipitation of Ottawa CDA are analyzed. We also computed the mean and standard deviation (STD) of 10-year running overlapping periods. The number of days above or below a certain threshold was calculated. A gamma distribution was fitted to the precipitation data in order to analyze the patterns of precipitation at a decadal scale. Only annual values were analyzed.

3.1. Temperature

The warmest decades in terms of mean air temperature were the 1990s followed by the 1980s and 1890s (Table 3-1). The coldest decades were the 1930s, followed by the 1910s. Contrary to several other analyses (Diaz and Quayle, 1980; Jones *et al.*, 1986; Diaz, 1986; Yamamoto *et al.*, 1986; Trenberth, 1990; Miller *et al.*, 1994), the 1930s were relatively cold in Eastern Ontario. The 1890s, 1950s, 1980s and 1990s had mean air temperatures above the 5.9°C overall average. Decades with below average mean temperatures (1900s, 1910s, 1920s and 1930s) had higher than average standard deviation of 0.7°C, suggesting that the inter-annual variability is greater in colder decades. The 1990s resemble the 1950s because their standard deviations were both greater than the mean of 0.7°C and their mean temperature was above 5.9°C (Table 3-1).

The warmest decades in terms of maximum air temperature were the 1890s and the 1990s (Table 3-1). The coldest maximum air temperatures occurred in the 1930s followed by the 1970s. The 1890s, 1910s, 1950s, 1980s and 1990s had an average maximum air temperature above the 10.8°C overall average. The 1900s, 1920s, 1930s, 1940s, 1960s and 1970s had an average

maximum air temperature below the 10.8°C overall average. The 1910s, 1950s and 1990s had standard deviations greater than the mean standard deviation of 0.8°C. The maximum air temperatures of the 1910s, 1950s and 1990s had higher than average inter-annual variability. The coldest decades in terms of minimum air temperature were the 1910s followed by the 1920s (Table 3-1). The warmest were the 1990s followed by the 1980s. The 1890s, 1950s, 1960s, 1970s, 1980s and 1990s had average minimum air temperatures above the 1.0°C average. Most decades with below average minimum temperatures (1900s, 1910s, 1920s and 1930s) had standard deviations higher than the average of 0.7°C, suggesting that the inter-annual variability was greater in colder decades. However, the 1970s and 1990s had higher than average minimum air temperature and with standard deviations greater than the mean of 0.7°C (Table 3-1).

3.1.2. Extreme Mean Temperatures

An important question this section will answer is, are the warmer decades warmer than average because they have more days above a certain threshold or is every day generally warmer? In fact, the answer is not straightforward. Some decades are warmer because the overall mean is increasing without having an increase of extreme warm days, for example the 1990s and 1980s and others are warmer due to more days above a certain threshold, for example the 1890s (Table 3-1 and Table 3-3).

As discussed in a paper from a workshop on indices and indicators for climate extremes, temperature extremes must be defined to enable the study of changes through time (Folland *et al.*, 1999). These fixed thresholds, where extremes are defined as days with temperatures higher than a certain temperature, are called absolute extremes (Bonsal *et al.*, 2001). The decades having the greatest number of days with mean temperatures above 20°C were the 1970s followed

by the 1950s (Table 3-2). The decades having the lowest number of days with a mean temperature above 20°C were the 1900s followed by the 1890s (Table 3-2). In general, the second half of the century had more days with a mean temperature above 20°C. The decades having the greatest number of days with a mean temperature above 15°C were the 1970s followed by the 1980s (Table 3-2). The decades having the lowest number of days with a mean temperature above 15°C were the 1900s followed by the 1920s. Again, the second half of the century had more days with a mean temperature above 15°C.

3.1.3. Extreme Maximum Temperatures

Daily afternoon temperatures greater than 30°C can produce health problems as well as requiring large amounts of energy for air conditioning. Decades having the greatest number of days with a maximum temperature above 30°C were the 1910s followed by the 1940s (Table 3-3). The decades having the lowest number of days with maximum temperatures above 30°C were the 1960s and 1990s. Note that throughout this study, the 1990s are based on data only through 1998 and therefore any conclusion based on analysis of this decade will be slightly biased. This result goes against what has been generally thought, where a general warming would tend to lead to an increase in extremely high temperature events (Karl and Nicholls, 1999). The number of days per decade having a maximum temperature above 30°C was greatest in the 1890s, 1900s, 1910s, 1930s and 1940s. In other words, the coldest decades, except for the 1890s, have more days with a maximum temperature above 30°C compared to the warmest decades. The decades having the greatest number of days with a maximum temperature above 25°C were the 1890s followed by the 1940s (Table 3-3). The decades having the lowest number of days with a maximum temperature above 25°C are the 1980s followed by the 1970s. Decades with the largest number of days with maximum temperature above 25°C were the same as those with a

temperature above 30°C, with the addition of the 1950s. It is worth noting that the 1990s is the period with fewest days above 30°C and 25°C.

3.1.4. Extreme Minimum Temperatures

The decades having a greater number of days with a minimum temperature below -30°C were the 1930s followed by the 1940s (Table 3-4). Note that the 1940s had the largest number of days with maximum temperatures above 30°C. The decades having the lowest number of days with a minimum temperature below -30°C were the 1990s followed by the 1980s. Again, the 1990s had fewer days with maximum temperatures above 30°C. The number of days per decade having a minimum temperature below -30°C and -25°C was greater for the first half of the century, which is between 1890-1950 (Table 3-4). The decades having the greatest number of days with a minimum temperature below -25°C were the 1930s followed by the 1940s. The decades having the lowest number of days with a minimum temperature below -25°C were the 1980s followed by the 1990s. Most of these decades have standard deviations greater than the average. The second half of the century had the least number of days below -30°C. Therefore, to answer the question raised at the beginning of this section, warm decades are warmer because the overall mean increases and not because of an increase in the frequency of extreme warm days.

3.2. Precipitation

The number of days with precipitation is an important index to be calculated (Nicholls, 1999). The number of days with measurable precipitation has varied through time. The decades with the greatest number of precipitation events were the 1970s followed by the 1980s (Table 3-5). The decades with the fewest precipitation events were the 1890s followed by the 1920s. The total number of precipitation events during the 20th century (through 1998) was 1392 events,

with a mean annual value of 143. Since the 1970s every decade has had a mean number of events per year above the average. A similar increase in the number of precipitation days has also been noted in the prairies since the 1960s (Akinremi, 2001). The annual precipitation by decade has varied through time. The same has been seen in United States data (Kunkel *et al.*, 1999). The wettest decades were the 1970s followed by the 1990s (Table 3-5). An increase in precipitation may be the consequence of an intensified hydrological cycle in a warmer atmosphere (Førland *et al.*, 2000; Trenberth, 1998). The driest decades were the 1960s followed by the 1950s. The mean annual precipitation amount per decade was 876.7 mm with a standard deviation of 44.7 mm (Table 3-5). The most variable decades, in terms of the annual precipitation, were the 1890s, followed by the 1990s and 1940s.

3.2.2. Frequency Distribution of Precipitation Events

The effects of precipitation distribution have been studied by Kunkel *et al.* (1998); they noted that an increase in precipitation variability could cause substantial water management problems, even if mean values did not change. In order to enable water resource management in the study region and to better quantify changes in the frequency distribution of precipitation events, the gamma distribution was fitted to the daily precipitation amounts of the ten warmest, coldest, wettest and driest years. Most studies have looked only at changes in the total amount of precipitation over a long averaging period, such as at the annual, seasonal and monthly scale (Karl *et al.*, 1993; Groisman and Easterling, 1994; IPCC, 1996). These studies, although quite useful, cannot determine how precipitation changes within these periods of time (Karl and Knight, 1998). The gamma distribution is frequently used to describe daily precipitation events (Nicholls, 1999).

The probability density function of the gamma distribution is defined as (Wilks, 1995):

$$f(x) = \frac{1}{b\Gamma(c)} x^{c-1} \exp\left(-\frac{x}{b}\right)$$

$$0 \leq x, b > 0, c > 0$$

where

Γ is the Gamma function

b is the scale parameter

c is the shape parameter

e is the base of the natural logarithm.

The Gamma distribution cannot be fitted to data containing a 0, therefore the analysis was done only on days with measured precipitation (Nicholls, 1999). Figure 3-1 shows the theoretical distributions based on different combinations of scale and shape.

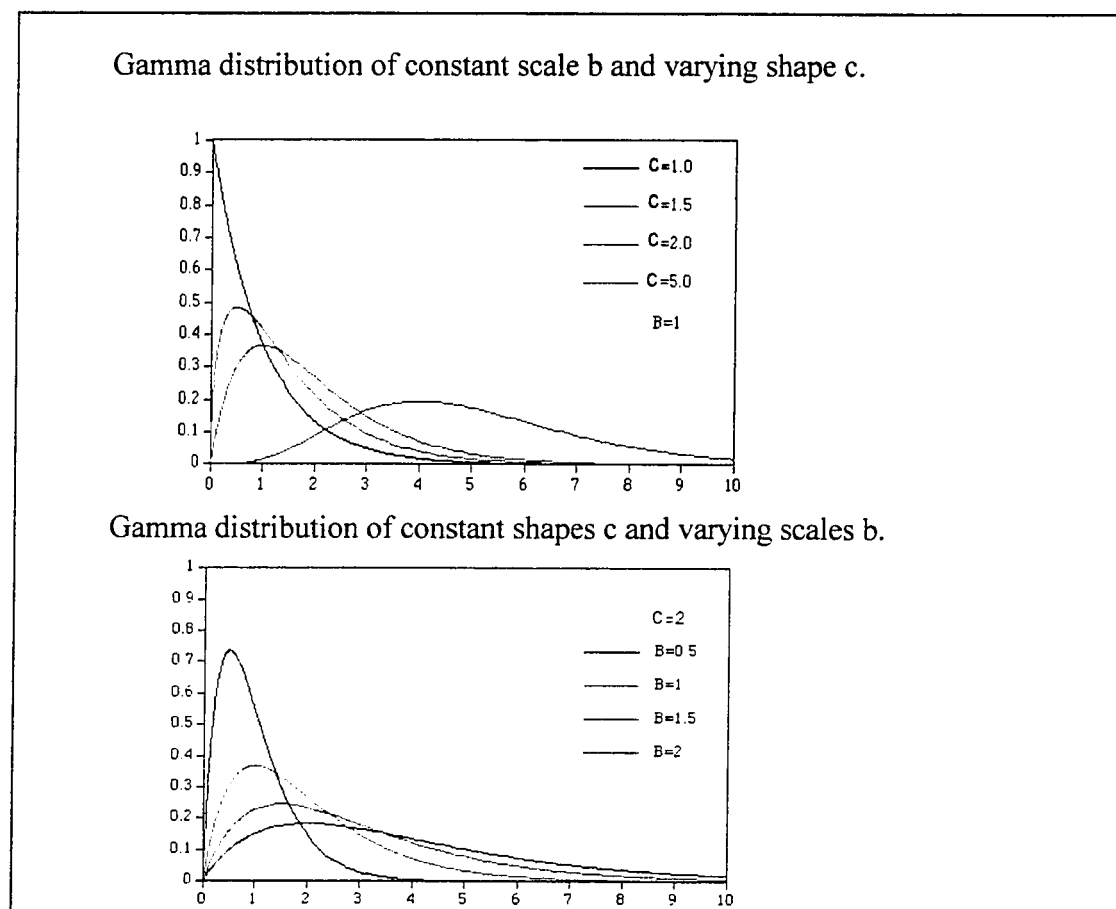


Figure 3-1. Gamma distributions based on different combinations of scale and shape.

The scale coefficient of the gamma distribution is largest for the three warmest decades, the 1890s, 1980s and 1990s. In other words, three out of the ten warmest decades have more precipitation events compared to colder decades (Table 3-5). The smallest scale parameter was in the 1930s followed by the 1910s; that is, they had the fewest precipitation events. The mean scale parameter is 6.91 with a standard deviation of 0.98. The average standard deviation for every decade shows that the warmest decades have more variability in their scale coefficient. In other words, from one year to the next in these decades, the number of precipitation events fluctuates greatly. The largest shape parameter was found in the 1920s followed by the 1930s; these decades had precipitation occurring in small, medium and large events. The smallest shape parameter was found in the 1980s followed by the 1990s. In other words, these decades tended to have very small events and some large events. The mean shape parameter is 0.91 with a standard deviation of 0.09. The average standard deviation for every decade shows that the coldest decades seem to have more variability in their shape parameter.

3.3. Summary

- The warmest decades in terms of mean air temperature were the 1990s followed by the 1980s and the 1890s. The coldest were the 1930s followed by the 1910s.
- The warmest decades in terms of maximum air temperature were the 1890s followed by the 1990s. The coldest were the 1930s followed by the 1970s.
- The warmest decades in terms of minimum air temperature were the 1990s followed by the 1980s. The coldest were the 1910s followed by the 1920s.
- The second half of the century had more days with a mean temperature above 20°C and 15°C.
- The decades with the greatest number of days with maximum temperature above 30°C

were the 1910s followed by the 1940s. The decade with the lowest was the 1990s.

- The decades with the greatest number of days with maximum temperature above 25°C were the 1890s followed by the 1940s. The decades with the lowest were 1980s followed by the 1970s.
- The decades with the greatest number of days with minimum temperature below -30°C were the 1930s followed by the 1940s. The decades with the lowest were the 1990s followed by the 1980s.
- The number of days per decade having with minimum temperature below -30°C and -25°C was greater for the first half of the century, between 1890-1950.
- Since the 1970s, every decade has had a greater than average mean number of precipitation events per year.
- The wettest decades were the 1970s followed by the 1990s. The driest decades were the 1960s followed by the 1950s.
- The scale parameter of the gamma distribution was largest for the warmer decades (the 1890s and the 1990s) and smallest for the coldest decades (the 1930s and the 1910s).
- The shape parameter of the gamma distribution was largest in the 1920s followed by the 1930s, and smallest in the 1980s followed by the 1990s.

APPENDIX B

Table 3-1. Decadal mean, maximum, minimum temperature and total precipitation

Decade	Mean	STD	Maximum	STD	Minimum	STD	Precipitation	STD
1891-1900	6.3	0.5	11.2	0.5	1.5	0.5	1015.7	101.0
1901-1910	5.7	0.7	10.8	0.8	0.7	0.8	989.0	122.1
1911-1920	5.5	0.9	10.8	1.0	0.1	0.9	987.2	127.9
1921-1930	5.6	0.8	10.8	0.9	0.5	0.8	1033.9	131.4
1931-1940	5.4	0.9	10.3	0.8	0.5	1.1	966.3	117.5
1941-1950	5.8	0.6	10.8	0.7	0.7	0.5	1035.3	145.7
1951-1960	6.1	0.7	11.0	0.8	1.1	0.7	944.1	100.7
1961-1970	5.8	0.4	10.6	0.4	1.0	0.4	932.3	85.8
1971-1980	5.8	0.7	10.5	0.7	1.1	0.8	1088.1	140.1
1981-1990	6.4	0.6	11.1	0.5	1.6	0.7	1007.1	100.1
1991-1998	6.4	1.1	11.2	1.1	1.7	1.0	1034.8	92.8
Century Median	5.8	0.7	10.8	0.8	1	0.8	1007.1	117.5
Century STD	0.4	0.2	0.3	0.2	0.5	0.2	45.5	20.0

Table 3-2. Number of days per decade having a mean temperature above 20 and 15°C

Decade	Days ≥ 20	STD	Mean	Days ≥ 15	STD	Mean
1891-1900	21	2.02	2	378	7.07	38
1901-1910	18	1.32	2	323	8.63	32
1911-1920	49	3.48	5	382	7.44	38
1921-1930	24	3.92	2	327	10.80	33
1931-1940	39	2.02	4	373	5.33	37
1941-1950	45	3.41	4	412	8.40	41
1951-1960	62	5.71	6	401	11.99	40
1961-1970	54	2.99	5	433	7.73	43
1971-1980	71	4.77	7	503	8.54	50
1981-1990	55	3.10	5	458	9.55	46
1991-1998	40	2.62	5	394	9.22	49
Century median	45	3.1	5	394	8.54	40
Century STD	17.1	1.27	2	52.93	1.81	6

Table 3-3. Number of days per decade having a mean maximum daily temperature above or equal 30 and 25°C

Decade	Days ≥ 30	STD	Mean	Days ≥ 25	STD	Mean
1891-1900	171	2.18	17.10	666	9.02	66.60
1901-1910	181	9.52	18.10	673	13.43	67.30
1911-1920	225	8.03	22.50	661	11.46	66.10
1921-1930	131	10.35	13.10	609	16.42	60.90
1931-1940	158	4.92	15.80	672	8.42	67.20
1941-1950	182	8.99	18.20	676	10.33	67.60
1951-1960	144	12.52	14.40	633	17.81	63.30
1961-1970	118	4.87	11.80	592	5.41	59.20
1971-1980	120	6.55	12.00	590	10.18	59.00
1981-1990	120	7.64	12.00	572	9.92	57.20
1991-1998	89	7.32	11.13	484	13.78	60.50
Century Median	144	7.64	14.4	633	10.33	63.3
Century STD	38	2.88	3.58	59	3.62	3.93

Table 3-4. Number of days per decade having a mean minimum daily temperature below or equal -30 and -25°C

Decade	Days ≤ -30	STD	Mean	Days ≤ -25	STD	Mean
1891-1900	27	1.57	2.70	102	4.98	10.20
1901-1910	29	3.11	2.90	131	6.10	13.10
1911-1920	30	3.23	3.00	121	5.95	12.10
1921-1930	27	1.25	2.70	104	2.84	10.40
1931-1940	48	6.18	4.80	140	8.29	14.00
1941-1950	37	2.58	3.70	119	5.02	11.90
1951-1960	19	1.73	1.90	75	3.89	7.50
1961-1970	12	1.03	1.20	77	4.24	7.70
1971-1980	13	1.34	1.30	72	3.68	7.20
1981-1990	9	1.37	0.90	56	4.40	5.60
1991-1998	6	1.39	0.75	52	3.93	6.50
Century Median	27	1.57	2.7	102	4.4	10.2
Century STD	13	1.51	1.27	31	1.50	2.89

Table 3-5 Decadal analysis of number of precipitation events and total annual amounts of precipitation

Years	Total Number of Events	Mean Number of Events per year	Amounts Per Year (mm)	Standard Deviation	Shape	Standard Deviation	Scale	Standard Deviation
1891-1900	1239	123	1015.7	6.1	0.99	0.10	7.66	1.37
1901-1910	1335	135	989.0	5.6	0.96	0.03	6.65	0.62
1911-1920	1339	133	987.2	5.4	1.02	0.09	6.29	0.77
1921-1930	1333	135	1033.9	5.5	1.05	0.11	6.43	0.80
1931-1940	1387	137	966.3	5.4	1.03	0.16	6.16	0.96
1941-1950	1450	143	1035.3	6.1	0.87	0.10	7.43	1.45
1951-1960	1391	141	944.1	5.4	0.91	0.08	6.59	0.93
1961-1970	1398	138	932.3	5.0	0.89	0.08	6.36	0.57
1971-1980	1707	169	1088.1	5.7	0.79	0.10	7.04	0.84
1981-1990	1631	164	1007.1	5.8	0.74	0.07	7.55	1.01
1991-1998	1102	158	1034.8	5.9	0.75	0.06	7.84	1.42

4. ANNUAL ANALYSIS: WHICH YEARS DETERMINED THE WARMEST, COLDEST, WETTEST AND DRIEST DECADES?

In this chapter, we will analyze the annual temperature and precipitation records from Ottawa CDA to identify the warmest, coldest, driest and wettest years for further analysis. Data from Morrisburg will be included in some analyses to ensure the conclusions are representative of the region and not due to local factors such as urban effects. The underlying premise of this study is that the warm years will be considered analogues of future warming. Conditions such as occurred during these years are expected to become more frequent in the future.

4.1. Temperature

Ottawa mean annual temperature averaged over the 20th century is 5.9°C. The mean annual maximum temperature was 10.8°C and the mean annual minimum temperature was 0.9°C. Morrisburg mean annual temperature averaged over the 20th century was 6.0°C. The mean annual maximum temperature is 11.6°C and the mean annual minimum temperature is 0.4°C. Although the means of the two stations are comparable, the daily temperature range (DTR) was less in Ottawa. Differences in land use and land cover influence the DTR (Gallo, 1996). For example, stations that are located in areas with predominantly rural land use/land cover usually display the greatest observed DTR (Gallo, 1996). Sala *et al.* (2000) found that in the Spanish Mediterranean region, an increase in the minimum daily temperature was associated with an increase in urban development. As Morrisburg is a rural climate station, we would expect it to have a greater DTR than Ottawa CDA, located in a urban area. Morrisburg tends to have warmer daytime temperatures, however, Ottawa tends to have warmer night-time temperatures.

At Ottawa CDA, the warmest year of the century was 1998, with an annual average air

temperature of 8.6°C; the coldest year of the century was 1917, with an annual average air temperature of 3.7°C (Table 4-2).

The warmest year on record was 1998, which in many ways was one of the worst weather years on record. Many regions of the world were hit with several heat waves and air pollution episodes, and Hurricane Mitch caused more than 11,000 deaths in several Central America countries (Trenberth, 1999).

4.1.2. Annual Mean Temperature

The ten warmest years of the past century occurred at the beginning and at the end of the century (Table 4-2). However, in the last decade (1990-2000) Ottawa experienced four of the ten warmest years of the century, including the warmest year on record (1998), which was a full degree warmer than the second warmest, 1953. The next three warmest years occurred in 1990, 1991 and 1995. There has been a steady increase in the mean annual air temperature since the 1970s (Figure 4-1). Several peaks of low and high mean annual air temperature marked the century (Figure 4-1). The relative highs are centered around 1921, followed by 1953 and 1998 (Figure 4-1). The relative lows are centered around 1917, followed by 1934 and 1904 (Figure 4-1). The ten coldest years occurred in the early part of the century, between 1904-1939 (Figure 4-1). As stated in the chapter 3, the warmest decades were the 1990s, 1980s, 1950s and 1890s. These decades were warmest because more than half of the years had mean annual air temperatures above average. The coldest decades were the 1930s, 1920s, 1910s and 1900s. These decades were colder for a variety of reasons. The 1900s were colder than average because two very cold years occurred (1904 and 1907). The 1910s and 1930s were colder than average

because 5 out 10 years were colder than average. The 1920s were colder because most of the years in the decade were below average.

4.1.3. Annual Mean Maximum Temperature

The ten years with the warmest annual maximum temperatures occurred mainly in the first half of the century and during the last decade (Table 4-3). The ten years with coldest annual maximum temperatures were concentrated before the middle of the century, between 1926-1943. The coldest decades of the century were the 1900s, 1920s, 1930s, 1940s, 1960s and 1970s. These decades were colder for different reasons. The 1900s were colder than average because two years were very cold (1904 and 1907). The 1920s were colder than average because five out of ten years were below average. The 1930s and 1960s were colder than average because six out of ten years were below average. The 1940s were colder than average because four out of ten years were below average and two out of the four were very cold, 1943 and 1940. The 1970s were colder than average because eight out of ten years were below average. The warmest decades of the century were the 1890s, 1910s, 1950s, 1980s and 1990s. These decades were warmer for different reasons. The 1890s were warmer because most of the years were above average. The 1910s were warmer because five out of ten were above average but this decade had a very warm year (1913) and a very cold year (1917). The 1950s were warmer because five out of ten years were above average and this decade had the second warmest year (1953). The 1980s were warmer because five out of ten years were above average. The 1990s were warmer because of four very warm years (1990, 1991, 1995 and 1998).

4.1.4. Annual Mean Minimum Temperature

The ten years with the coldest annual minimum temperatures occurred at the beginning of the

century between 1904 and 1940 (Table 4-4). Conversely, the ten years with annual minimum temperatures above average occurred at the end of the century, between 1973 and 1998. The 1890s, 1950s, 1960s, 1970s, 1980s and 1990s had minimum air temperatures above average. These decades had higher than average minimum air temperatures for a variety of reasons. The 1890s, 1960s, 1980s and 1990s had above average minimum temperatures because most of the years were above average. The 1950s and 1970s had above average minimum temperatures because both had four years above average and the years 1953 and 1973 were very warm. The 1900s, 1910s, 1920s, 1930s and 1940s had below average minimum temperatures because most of the years in the decade had below average minimum air temperatures.

4.1.5. Diurnal Temperature Range

Diurnal temperature range (DTR) over land as defined by the difference between average daily maximum and minimum temperatures are the variations in the DTR (Karl *et al.*, 1993; Easterling *et al.*, 1999). There has been a steady decrease in the DTR since the 1920s (Figure 4-2). The cause of this has been an overall increasing trend in minimum temperature. Changes in maximum (daytime) temperatures were more varied, with maximum temperatures occurring in the 1940s, 1980s and 1990s (Gallo, 1996). While the range between night-time and daytime temperatures is larger at Morrisburg than at Ottawa, at both stations the long-term trend in the range is a decrease. A comparison of annual mean monthly maximum and minimum temperatures (Figure 4-3) shows that night-time temperatures were lower at the beginning of the century compared to the second half of the century. There was a significant increase in the minimum temperature at Morrisburg in the 1990s; however this was not seen at Ottawa.

4.1.6. Running Standard Deviations of the Annual Data

A moving standard deviation of the mean annual minimum and maximum temperatures was computed using a 5-year period Figure 4-4. This indicates how inter-annual variability changed through time. Except for some differences in the magnitude of the variability, mean, minimum and maximum monthly temperatures all demonstrate the same tendencies (Figure 4-1 and Figure 4-4). Since the mean temperature is computed from the minimum and maximum temperatures, it is not surprising that it parallels the other two variables. However minimum and maximum temperatures respond to different meteorological factors and need not be highly correlated. The 5-year running standard deviation of the mean annual temperature can be divided into five main periods. The inter-annual temperature variation was high in the 1910s, 1930s, 1950s and 1970s, and low during the 1920s, 1940s and 1960s (Figure 4-1). During the 1930s, the inter-annual variability of minimum temperatures was high, but that of maximum temperatures was low (Figure 4-4).

4.2. Precipitation

The mean total annual precipitation was 1045.6 mm at Morrisburg and 1002.4 mm at Ottawa (Table 4-1). The wettest year of the century was 1972 with an annual total precipitation of 1418.6 mm, and the driest year of the century was 1931 with 713.8 mm (Table 4-5). The driest year had only half of the amount of precipitation of the wettest year. In contrast to temperature, precipitation does not show any significant long-term trend dating back to the beginning of the instrumental record in the 1890s (Figure 4-1). The period since the 1970s had a significantly higher precipitation than the 1930s-1950s period (Figure 4-1). There were large variations through time in inter-annual variability. There was high inter-annual variability around the 1930s, in the mid 1940s, in the mid 1950s, and in the later 1970s. The relationship between

inter-annual variability and mean values is not clear. The 1920s had low variability with high precipitation, while the 1950s had high variability and were relatively dry.

In general, most decades had approximately the same amount of precipitation, except for the 1960s, which had about 1000 mm less. There is no apparent relationship between temperature and precipitation at the decadal scale. Some decades had high temperature variability and high precipitation variability as well; while in other decades they are inversely related. However, the declining temperature range has been attributed to increasing cloud cover (Akinremi *et al.*, 1999). Increased cloud formation may also be associated with more precipitation days or events (Akinremi *et al.*, 1999).

4.3. Summary

- The ten warmest years of the past century were distributed at the beginning and at the end of the century. The ten coldest years occurred in the early part of the century, between 1904-1939.
- In the last decade, (1990-2000) we have experienced the four warmest years of the century, including the warmest year on record (1998), which was a full degree warmer than the second warmest (1953). There has been an overall increase in the mean annual air temperature since the 1970s.
- The ten years with warmest annual maximum temperatures occurred mainly at the beginning of the century and at the end. The coldest years were concentrated before the middle of the century, between 1926-1943.
- The ten years with coldest annual minimum temperatures occurred at the beginning of the century between 1904-1940. The warmest years occurred at the end of the century, between

1973-1998.

- There has been an overall decreasing trend in the diurnal temperature range since the 1920s. The cause of this has been an increase in minimum temperature. The DTR was larger at Morrisburg than at Ottawa, attributed to the rural vs. urban setting respectively. From 1920 to 1930 and 1950 to 1960, night-time temperatures were more variable than daytime temperatures.
- The inter-annual temperature variation was high in the 1910s, 1950s, 1970s and 1990s and low around the 1920s, 1940s and 1960s. The difference in the variability of minimum and maximum temperature was greatest in 1930s.
- The dataset ends in 1998. However, if the trend of the first 8 years of the 1990s persists, that decade as well as the 1980s and 1970s were wetter than average.
- There is no apparent relationship between temperature and precipitation variation at the decadal scale. While some decades have high temperature variability and high precipitation variability as well, in other decades they are inversely related.
- Warmest decades were warm because more than half of the years were above average. Cold decades, however, were below average for various reasons, some because one or two years were greatly below average and others because five or more years were below average.

APPENDIX C

Table 4-1. 20th Century mean annual averages for temperature and total precipitation

Stations	Mean	Maximum	Minimum	Total Precipitation
Ottawa	5.9	10.8	0.9	1002.4
Morrisburg	6.0	11.6	0.4	1045.6

Table 4-2. Ottawa CDA ten warmest and coldest years based on mean annual temperatures

Warmest	Temperature °C	Coldest	Temperature °C
1998	8.6	1917	3.7
1953	7.6	1904	4.2
1990	7.3	1934	4.2
1991	7.3	1926	4.3
1921	7.2	1940	4.6
1898	7.2	1943	4.6
1987	7.0	1912	4.7
1931	7.0	1907	4.8
1973	6.9	1935	4.8
1995	6.7	1939	4.8

Table 4-3. Ottawa CDA ten warmest and coldest based on mean annual maximum temperatures

Coldest	Temperature °C	Warmest	Temperature °C
1917	8.8	1998	13.3
1904	9.2	1921	12.7
1943	9.4	1953	12.6
1972	9.4	1991	12.4
1926	9.5	1913	12.3
1940	9.5	1898	12.0
1929	9.6	1931	12.0
1934	9.6	1990	12.0
1935	9.8	1949	11.9
1936	9.8	1906	11.8

Table 4-4 Ottawa CDA ten warmest and coldest based on mean annual minimum temperatures

Coldest	Temperature °C	Warmest	Temperature °C
1917	-1.4	1998	3.8
1934	-1.2	1953	2.6
1926	-1.0	1990	2.5
1904	-0.7	1898	2.4
1914	-0.7	1973	2.4
1912	-0.5	1991	2.3
1907	-0.3	1987	2.2
1940	-0.3	1931	2.1
1923	-0.2	1981	2.1
1935	-0.2	1979	1.9

Table 4-5 Ottawa CDA ten wettest and driest years based on total annual precipitation

Driest	Precipitation (mm)	Wettest	Precipitation (mm)
1931	713.8	1972	1418.6
1914	744.2	1928	1230.0
1906	771.7	1943	1218.6
1944	776.9	1947	1175.4
1930	781.0	1927	1171.8
1910	789.4	1973	1169.6
1961	801.2	1900	1169.2
1964	805.7	1946	1163.5
1955	816.2	1995	1157.4
1953	843.7	1916	1154.1

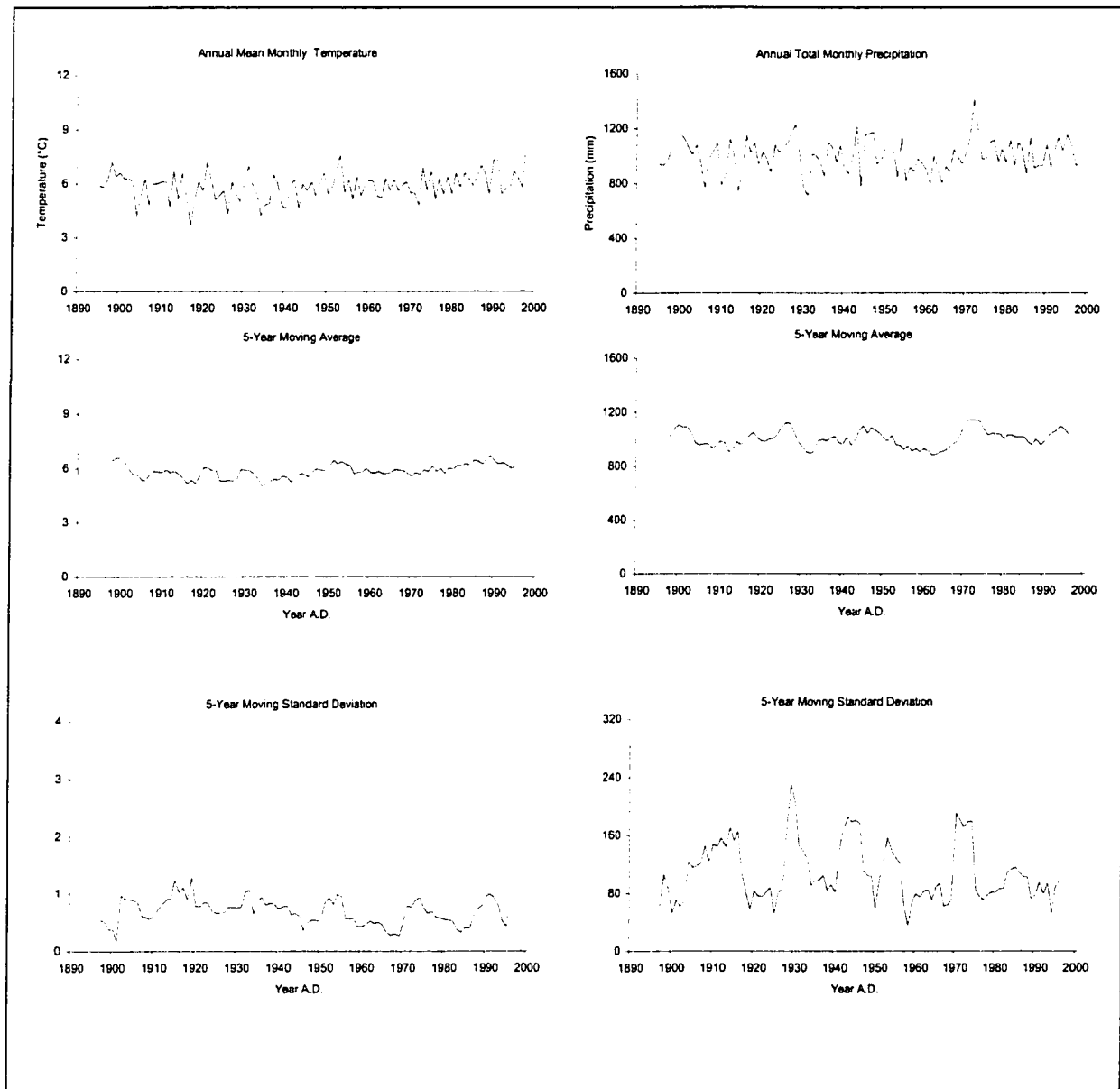


Figure 4-1 Ottawa CDA mean annual temperature (°C) and total precipitation time series with 5-year moving average and standard deviation.

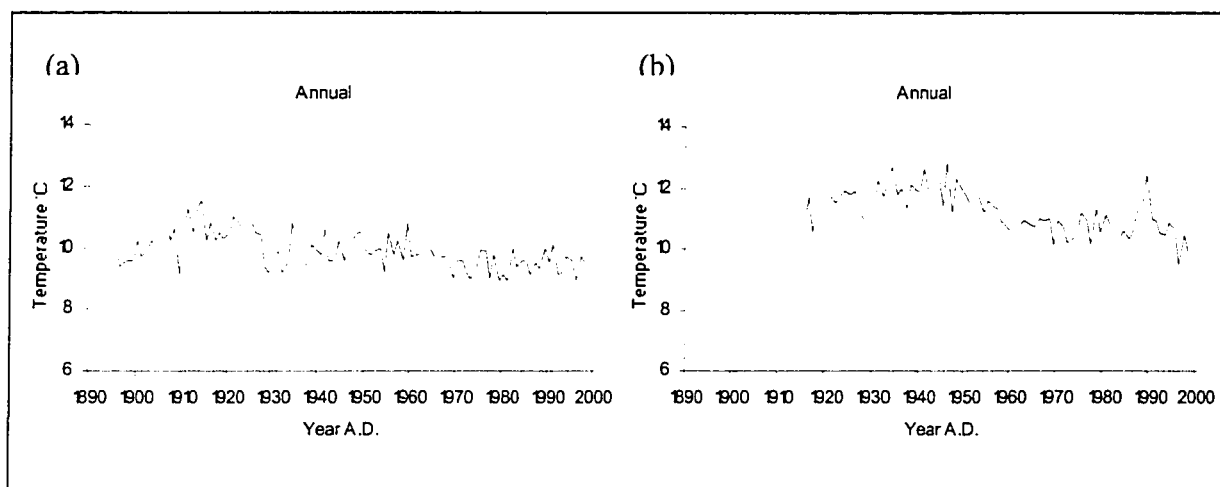


Figure 4-2 Ottawa CDA (a) and Morrisburg (b) range between minimum and maximum monthly temperature (°C)

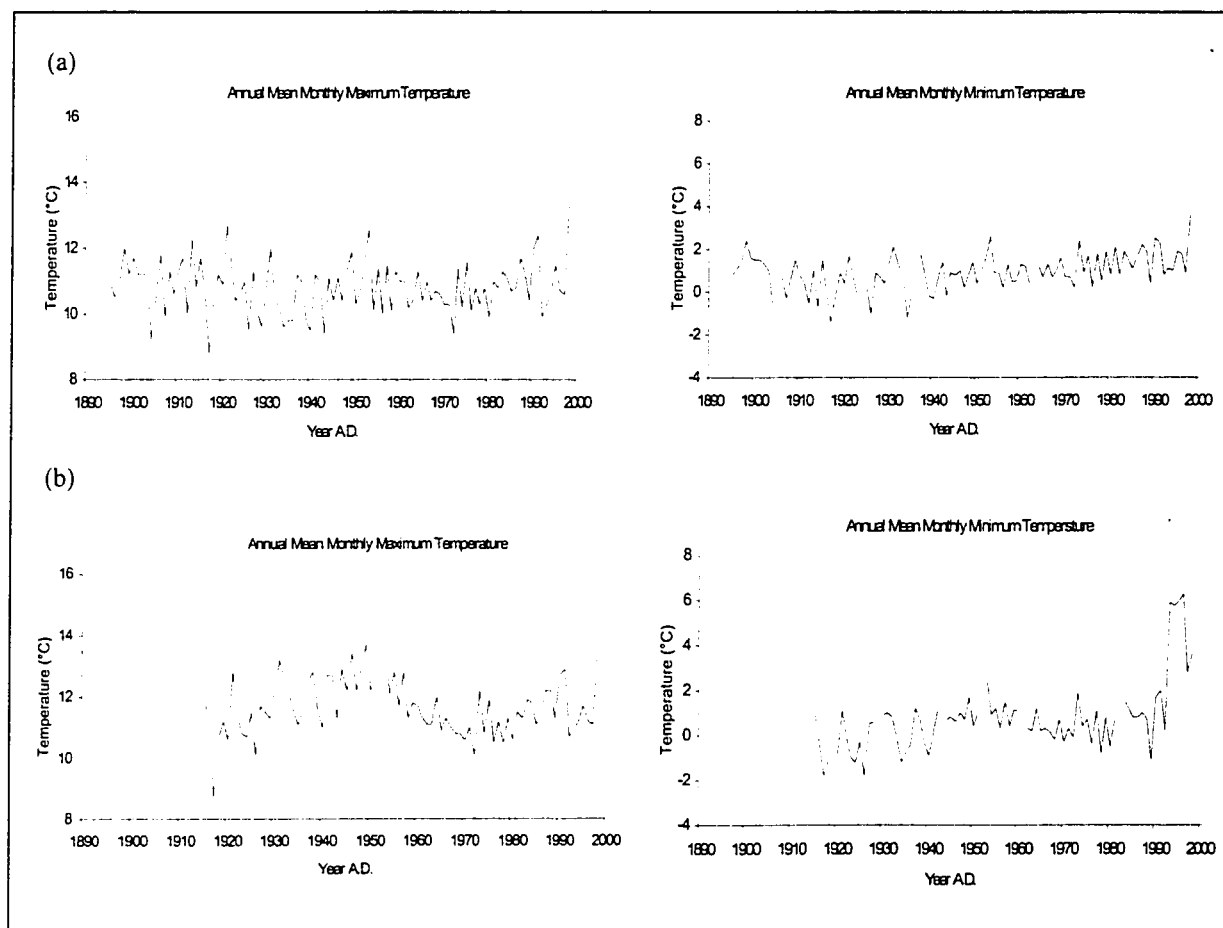


Figure 4-3 Ottawa CDA (a) and Morrisburg (b) mean annual maximum and minimum temperatures.

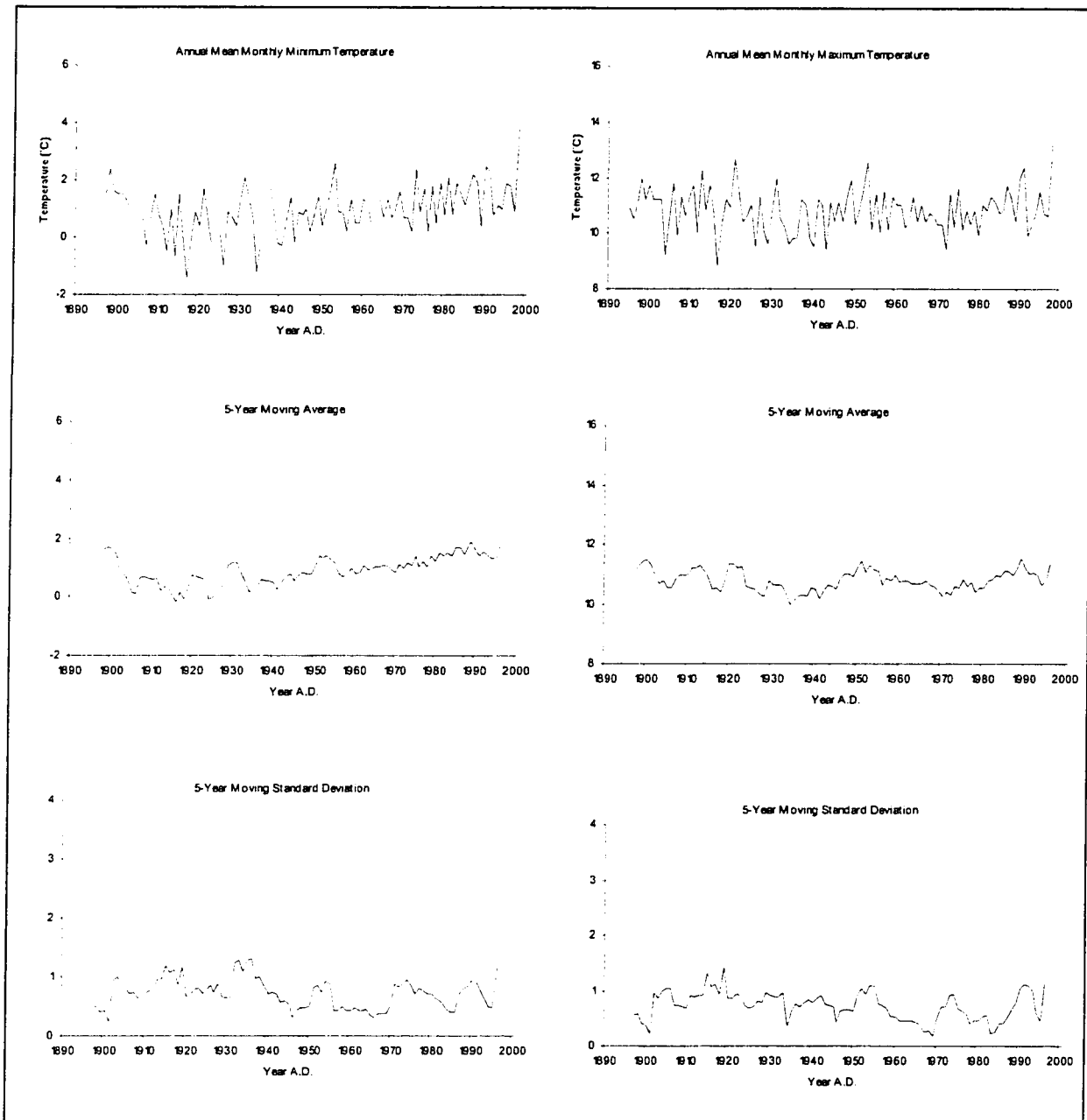


Figure 4-4. Ottawa CDA mean annual minimum and maximum temperature (°C) with 5-year moving average and standard deviation.

5. SEASONAL ANALYSIS: WHICH SEASON IS MAKING THE TEN WARMEST, COLDEST, DRIEST AND WETTEST YEARS WHAT THEY ARE?

In this chapter, we will analyze Ottawa CDA and Morrisburg's temperature and precipitation on a seasonal basis. The warmest, coldest, driest and wettest seasons will be identified for further analysis. The following months are used to represent a given season: December, January and February are winter months; March, April and May are the spring months; June, July and August are the summer months; September, October and November are the autumn months.

5.1. Temperature

The warmest year of the century was 1998 with an annual average air temperature of 8.6°C, and the coldest year of the century was 1917 with an annual average air temperature of 3.7°C (Table 4-2). The seasons which caused these years to be extreme were winter and spring. In both cases, winter and spring were either much warmer (1998) or colder (1917) than the average. Cold springs and winters determine the cooler years. However, in general it was spring temperatures that had a pivotal influence on how extreme a year was, because both coldest and warmest years were strongly influenced by the spring mean monthly temperature. Cold springs and autumns determined the annual monthly maximum temperatures. In other words, a year with a colder than average daytime temperature during spring and autumn typically had annual mean maximum daytime temperatures lower than the average. Years with warm annual minimum temperatures had warm springs and sometimes warm summers. If night-time spring and summer temperatures were above average, then the annual mean monthly minimum temperatures tended also to be above average.

5.1.2. Winter Temperature

The warmest mean winter temperature was in 1953, with an average temperature of -5.4°C

(Table 5-1). The coldest mean winter temperature was in 1934, with an average temperature of -15.3°C . The warmest mean winter maximum winter temperature was in 1998, with an average temperature of -1.6°C (Table 5-2), and coldest was in 1934, with an average temperature of -9.6°C . The warmest mean winter minimum temperature was in 1953, with an average temperature of -9.1°C (Table 5-3). The coldest mean winter minimum temperature was in 1934, with an average temperature of -20.9°C .

5.1.3. Spring Temperature

The warmest mean spring was in 1998, with an average temperature of 8.6°C (Table 5-5). The coldest mean spring temperature was in 1926, with an average temperature of 1.8°C . The warmest mean maximum spring temperature was in 1903, with an average temperature of 14.0°C (Table 5-6); and the coldest was in 1939, with an average temperature of 7.3°C . The warmest mean spring minimum temperature was in 1998, with an average temperature of 3.2°C (Table 5-7); and the coldest was in 1936, with an average temperature of -3.9°C .

5.1.4. Summer Temperature

The warmest mean summer temperature was in 1955, with an average temperature of 21.8°C (Table 5-9). The coldest mean summer temperature was in 1927, with an average temperature of 17.8°C . The warmest mean maximum summer temperature was in 1955, with an average temperature of 28.3°C (Table 5-10), and the coldest was in 1992, with an average temperature of 22.9°C . The warmest mean summer minimum temperature was in 1973, with an average of temperature of 15.7°C (Table 5-11); and the coldest was in 1912, with an average temperature of 11.8°C .

5.1.5. Autumn Temperature

The warmest mean autumn temperature was in 1931, with an average temperature of 10.3°C (Table 5-13). The coldest mean autumn temperature was in 1933, with an average temperature of 5.5°C. The warmest mean maximum autumn temperature was in 1961, with an average temperature of 15.2°C (Table 5-14); and the coldest was 1933, with an average temperature of 10.1°C. The warmest mean autumn minimum temperature was in 1931, with an average temperature of 5.5°C (Table 5-15); and the coldest was 1933, with an average temperature of 0.9°C.

5.1.6. Temperature Time Series

The time series plots of winter mean, minimum and maximum temperatures are similar (Figure 5-1). The 1930s through the 1950s shared some very large fluctuations. In particular in the 1930s the winter changed rapidly from very warm to the coldest, while the 1950s were particularly warm. Since the 1980s, winter temperatures have been increasing. The periods of high inter-annual variability, for example around the 1910s, 1920s, 1930s and 1950s, were followed by periods of lower variability.

Spring temperatures showed less variability than winter (Figure 5-2). There was a steady decrease in temperature between the 1890s and 1940s, then a steady increase between the 1960s and 1990s. There is a great deal of inter-annual variability, with cold and warm years frequently following each other. Note that the inter-annual variability was low in the 1930s, whereas it was quite high during winter.

The patterns of summer mean, minimum and maximum temperatures were not comparable (Figure 5-3). The maximum temperature, that is the daytime temperature, showed a shift in regime approximately every 30 years or so. Between the 1900s and 1920s, the maximum temperatures increased, while being variable from one year to the next, then finally decreased in the 1930s. In the 1950s, the daytime temperature fluctuated markedly from year to year, with the warmest year on record followed by one of the coldest. This period of high variability was followed by a period of low variability but with colder daytime temperatures. Since the 1970s, the summer daytime temperature has fluctuated widely from one year to the next. Sometimes a difference of 4°C between two consecutive years, for example between 1955 and 1956, was seen. The variation in the mean seasonal daytime temperatures is comparable to that found in the maximum seasonal daytime temperature, but the trends in the minimum seasonal temperatures show some differences. Minimum temperatures decreased from the 1890s through the 1920s, but since the 1930s the night-time temperatures have increased. However, as with maximum temperatures, the mean and minimum temperatures were quite variable from one year to the next during the 1920s and 1950s.

Autumn temperatures decreased from the 1890s-1930s, then increased through the 1950s (Figure 5-4). Minimum temperatures show little change since the 1960s, while maximum temperature decreased during the 1960s and 1970s and increased in subsequent years. The 1930s were particularly variable, as was seen in winter.

5.2. Seasonal Precipitation

The wettest year of the century was 1972 with an annual total precipitation of 1418.6 mm, and the driest year of the century was 1931 with an annual total precipitation of 713.8 mm (Table

4-5). The wettest year had a very wet summer and winter and a relatively wet autumn, while spring was dry. The driest year had a very dry summer and winter and a relatively dry spring and autumn.

5.2.2. Precipitation Time Series

Winter precipitation shows few long-term changes, nor changes in inter-annual variability through time (Figure 5-1). In the 1970s winter precipitation was quite high for several consecutive years. Spring precipitation showed a transition in the 1950s, where inter-annual variability decreased and precipitation amounts were relatively high (Figure 5-2). The late 1950s and late 1960s were relatively dry, and the 1930s and 1940s showed large inter-annual fluctuations. Summer precipitation showed large differences between subsequent years (e.g. the 1930s, into the 1940s and during the 1970s) (Figure 5-4). Again there is no obvious long-term trend. Similar to the spring, autumn precipitation showed a regime shift around the 1950s (Figure 5-4). However, since the 1950s autumn precipitation tended to oscillate from high to low from year to year, in contrast to the decreased inter-annual variability seen in the spring.

5.2.3. Number of Precipitation Events

The average number of precipitation events was 48.8 in the winter (Table 5-4) and 40.1 in the spring (Table 5-8). The average number of precipitation events was 38.8 in the summer (Table 5-12) and 44.0 in autumn (Table 5-16).

Winter, spring and autumn show an increase in the number of precipitation events since the 1920s (Figure 5-5). There was an increase in the number of precipitation events during the summer from the 1950s to 1980s; however this was followed by a major decline in the 1980s,

reaching amounts comparable to the beginning of the century. In the middle of the century inter-annual variation was higher than during the most recent two decades (the 1980s and the 1990s).

5.2.4. Gamma Scale and Shape for Winter, Spring, Summer and Autumn

To quantify the frequency distribution of the seasonal precipitation, gamma curves were fit to the precipitation data. All seasons show a decrease in the shape coefficient through time (Figure 5-6). Winter and autumn shape values decreased more through time than summer and spring values. The winter shape coefficient values fluctuated the most through time, showing that the winter inter-annual variability was greater.

The scale coefficient of the fitted gamma curve for winter increased through time. Spring, autumn, and summer show greater variability in the scale coefficient since the 1970s. An increase in the scale coefficient can be translated as an increase in the number of events, particularly small events.

5.3. Summary

- The seasons responsible for producing causing extreme years were winter and spring, as extreme years occurred whenever winter and spring was either much warmer or colder than the average.
- Since the 1980s winter temperatures seem to be increasing.
- Since the beginning of the century there was an overall decreasing trend in spring temperature between the 1890s and the 1940s, then an overall increasing trend between the 1960s and the 1990s.
- Spring maximum temperatures, show a shift in regime approximately every 30 years or

so.

- Since the 1970s the summer daytime temperatures fluctuated widely from one year to the next.
- Since the 1930s the summer night-time temperatures have increased.
- Autumn minimum temperatures show little changes since the 1960s; autumn maximum temperatures decreased during the 1960s and the 1970s, and increased in subsequent years.

APPENDIX D

Table 5-1. Winter mean seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1953	-5.4	43	1934	-15.3	46
1998	-5.5	42	1918	-14.0	38
1933	-5.6	38	1904	-13.2	37
1937	-5.9	48	1905	-12.8	29
1932	-6.2	48	1959	-12.6	58
1983	-6.2	51	1920	-12.4	37
1949	-6.4	42	1935	-12.2	46
1975	-6.6	61	1936	-12.0	43
1995	-6.7	54	1948	-11.9	50
1988	-6.8	64	1994	-11.9	45
Century Median	-9.2	50		-9.2	50

Table 5-2. Winter mean maximum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1998	-1.6	48	1934	-9.6	55
1937	-1.7	41	1918	-9.0	54
1953	-1.7	42	1904	-8.6	45
1933	-1.9	47	1905	-8.1	52
1949	-2.1	55	1936	-8.0	60
1983	-2.1	55	1935	-7.7	59
1991	-2.2	33	1994	-7.6	52
1906	-2.5	28	1907	-7.2	64
1913	-2.6	34	1945	-7.2	58
1975	-2.6	36	1920	-7.1	63
Century Median	-4.9	50		-4.9	50

Table 5-3. Winter mean minimum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1953	-9.1	43	1934	-20.9	46
1933	-9.2	38	1918	-18.8	38
1932	-9.3	48	1959	-18.1	58
1998	-9.4	42	1904	-17.8	37
1937	-10.0	48	1920	-17.7	37
1983	-10.3	51	1905	-17.3	29
1995	-10.5	54	1948	-16.9	50
1975	-10.6	61	1917	-16.6	46
1949	-10.7	42	1911	-16.5	26
1988	-10.8	64	1923	-16.5	44
Century Median	-13.5	50		-13.5	50

Table 5-4. Winter total seasonal precipitation and number of precipitation events

Driest	Precipitation (mm)	# Events	Wettest	Precipitation (mm)	# Events
1956	145.4	38	1971	435.8	60
1944	148.0	47	1916	419.7	52
1989	152.2	58	1898	414.9	55
1906	162.3	29	1908	395.3	38
1933	165.3	38	1997	373.2	77
1961	167.1	48	1960	372.9	58
1964	169.3	50	1972	368.8	58
1948	171.7	50	1924	365.0	40
1986	172.3	62	1934	351.7	46
1897	173.4	47	1903	345.6	36
Century Median	260.9	50		260.9	50

Table 5-5. Spring mean seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1998	8.60	31	1926	1.80	44
1903	8.10	50	1923	2.50	45
1921	8.00	54	1956	2.50	40
1977	7.90	44	1916	2.60	49
1898	7.70	39	1939	2.60	43
1987	7.70	34	1943	2.60	42
1991	7.70	40	1947	2.90	53
1986	7.60	40	1950	3.00	41
1942	7.50	21	1967	3.00	25
1902	7.40	44	1917	3.10	42
Century Median	5.1	40		5.1	40

Table 5-6. Spring mean maximum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1903	14.0	34	1939	7.3	25
1998	14.0	50	1943	7.4	27
1921	13.7	40	1926	7.5	43
1977	13.3	39	1947	7.5	33
1987	13.0	24	1956	7.5	49
1898	12.8	32	1940	7.8	47
1986	12.8	47	1917	8.0	49
1910	12.7	48	1923	8.2	34
1991	12.6	43	1932	8.2	42
1902	12.4	38	1972	8.2	42
Century Median	10.3	40		10.3	40

Table 5-7. Spring mean minimum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1998	3.2	44	1926	-3.9	44
1942	3.0	50	1916	-3.5	42
1991	2.8	44	1923	-3.2	45
1898	2.5	34	1950	-2.5	41
1977	2.5	40	1956	-2.5	40
1987	2.5	39	1939	-2.3	49
1986	2.4	54	1967	-2.3	25
1902	2.3	31	1912	-2.2	33
1973	2.3	49	1934	-2.1	34
1921	2.2	40	1943	-2.1	43
Century Median	0.0	40		0.0	40

Table 5-8. Spring total seasonal precipitation and number of precipitation events

Driest	Precipitation (mm)	# Events	Wettest	Precipitation (mm)	# Events
1903	89.7	21	1947	426.8	53
1915	100.9	31	1909	384.0	42
1959	107.0	33	1974	369.1	58
1905	117.2	25	1916	360.5	42
1914	124.1	24	1901	348.4	45
1965	128.5	28	1945	343.5	49
1906	132.0	29	1919	338.2	45
1941	136.1	30	1943	328.5	43
1935	144.3	32	1993	320.3	48
1957	145.9	31	1936	319.5	55
Century Median	228.6	40		228.6	40

Table 5-9. Summer mean seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1955	21.8	31	1927	17.8	44
1921	21.4	34	1958	17.8	40
1919	21.1	35	1992	17.8	45
1949	21.1	34	1912	18.0	36
1973	21.1	33	1903	18.1	48
1959	20.9	31	1926	18.1	43
1975	20.9	25	1956	18.1	46
1995	20.9	43	1986	18.1	41
1901	20.8	25	1929	18.2	32
1991	20.8	29	1965	18.2	41
Century Median	19.5	40		19.5	40

Table 5-10. Summer mean maximum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1955	28.3	33	1992	22.9	40
1921	28.1	52	1986	23.2	40
1919	27.6	36	1903	23.5	30
1949	27.6	41	1956	23.5	35
1906	27.5	27	1927	23.6	34
1944	27.1	42	1958	23.6	40
1908	27.0	34	1972	23.6	41
1911	26.9	45	1954	23.7	43
1916	26.9	47	1928	23.9	36
1959	26.9	56	1982	24.0	32
Century Median	25.3	40		25.3	40

Table 5-11. Summer mean minimum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1973	15.7	43	1912	11.8	36
1995	15.3	33	1958	11.9	40
1955	15.2	29	1907	12.0	34
1975	15.0	34	1926	12.0	41
1998	15.0	50	1927	12.0	45
1988	14.9	46	1914	12.1	29
1901	14.8	31	1924	12.3	38
1959	14.8	35	1929	12.3	32
1990	14.8	41	1965	12.3	41
1991	14.8	34	1913	12.5	28
Century Median	13.6	40		13.6	40

Table 5-12. Summer total seasonal precipitation and number of precipitation events

Driest	Precipitation (mm)	# Events	Wettest	Precipitation	# Events
1931	122.9	33	1972	496.5	50
1919	148.1	31	1943	456.8	43
1944	158.2	32	1903	422.9	46
1991	159.7	34	1928	416.4	45
1908	159.8	29	1971	370.7	36
1960	160.2	36	1994	366.7	45
1914	164.5	29	1905	363.5	39
1974	167.2	47	1952	357.8	35
1997	169.6	30	1939	355.9	40
1913	171.6	28	1899	355.5	32
Century Median	267.5	40		267.5	40

Table 5-13. Autumn mean seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1931	10.3	34	1933	5.5	41
1961	10.3	37	1917	5.8	37
1900	10.0	39	1904	6.4	32
1998	9.9	24	1936	6.4	48
1948	9.8	44	1925	6.5	50
1908	9.7	35	1939	6.5	40
1971	9.7	53	1976	6.5	60
1994	9.6	38	1980	6.5	54
1953	9.5	40	1972	7.0	43
1963	9.5	34	1974	7.0	47
Century Median	8.1	43		8.1	43

Table 5-14. Autumn mean maximum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1961	15.2	39	1933	10.1	33
1931	15.1	45	1917	10.4	48
1908	14.8	48	1980	10.5	43
1900	14.7	46	1976	10.6	50
1947	14.6	33	1904	10.8	34
1963	14.6	47	1972	10.8	48
1948	14.5	50	1928	10.9	53
1953	14.5	60	1986	11.0	30
1924	14.3	42	1936	11.1	56
1946	14.3	54	1981	11.1	45
Century Median	12.6	43		12.6	43

Table 5-15. Autumn mean minimum seasonal temperature and number of precipitation events

Warmest	Temperature °C	# Events	Coldest	Temperature °C	# Events
1931	5.5	40	1933	0.9	41
1971	5.5	44	1917	1.2	37
1998	5.5	53	1936	1.7	48
1900	5.4	38	1939	1.7	40
1961	5.3	34	1925	1.8	50
1970	5.3	52	1904	2.0	32
1948	5.1	35	1911	2.2	30
1960	4.9	36	1940	2.2	46
1975	4.9	53	1964	2.2	50
1968	4.8	43	1935	2.3	43
Century Median	3.5	43		3.5	43

Table 5-16. Autumn total seasonal precipitation and number of precipitation events

Driest	Precipitation (mm)	# Events	Wettest	Precipitation (mm)	# Events
1897	113.7	33	1995	402.2	58
1895	130.0	25	1918	365.0	52
1956	131.2	39	1967	352.9	49
1961	142.1	34	1928	341.2	47
1915	149.6	42	1989	335.5	51
1930	158.1	28	1925	332.9	50
1952	159.4	37	1945	329.9	56
1984	163.4	40	1981	327.3	48
1908	164.2	24	1912	326.3	40
1938	168.8	31	1983	326.0	50
Century Median	246.3	43		246.3	43

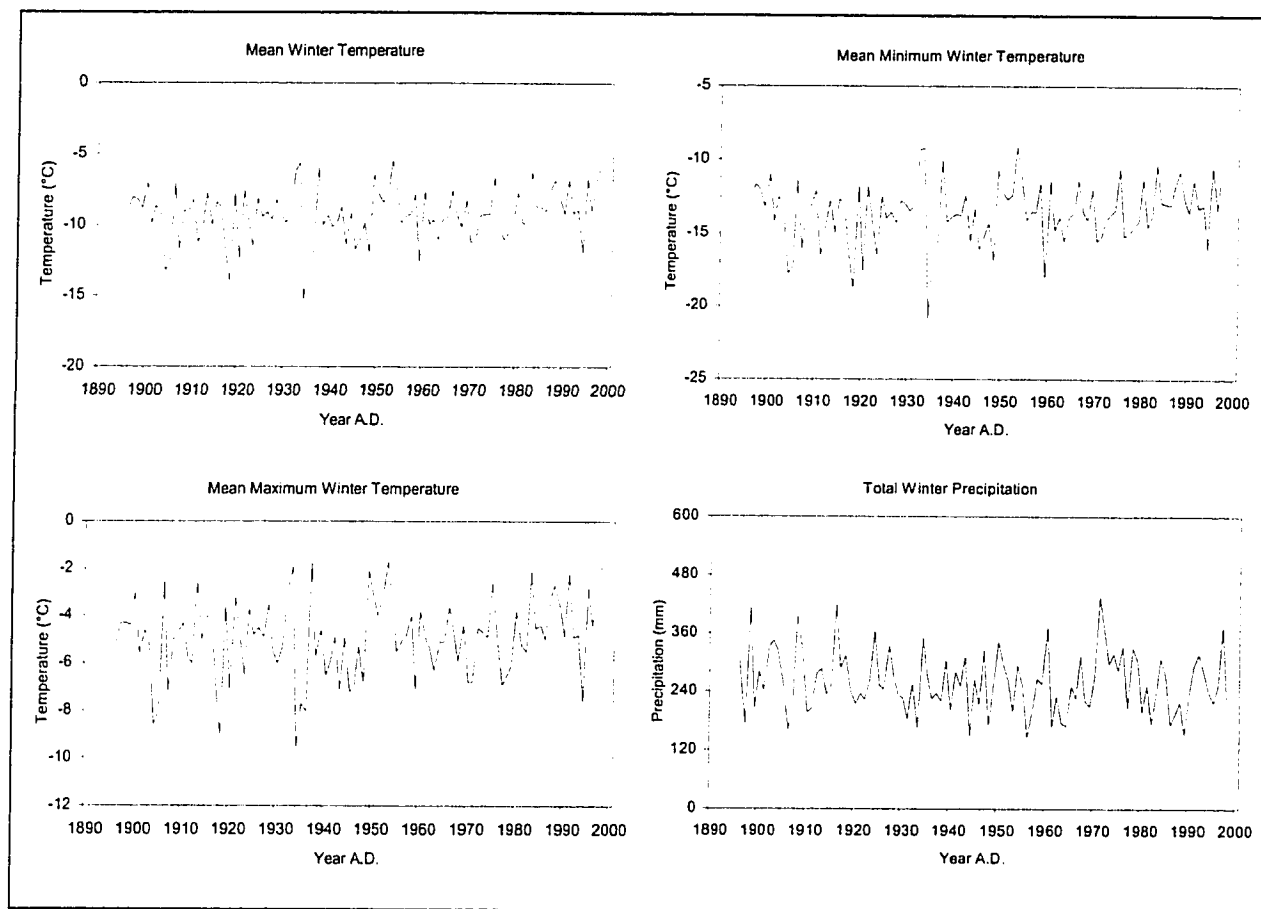


Figure 5-1. Winter mean, minimum and maximum temperature and total precipitation.

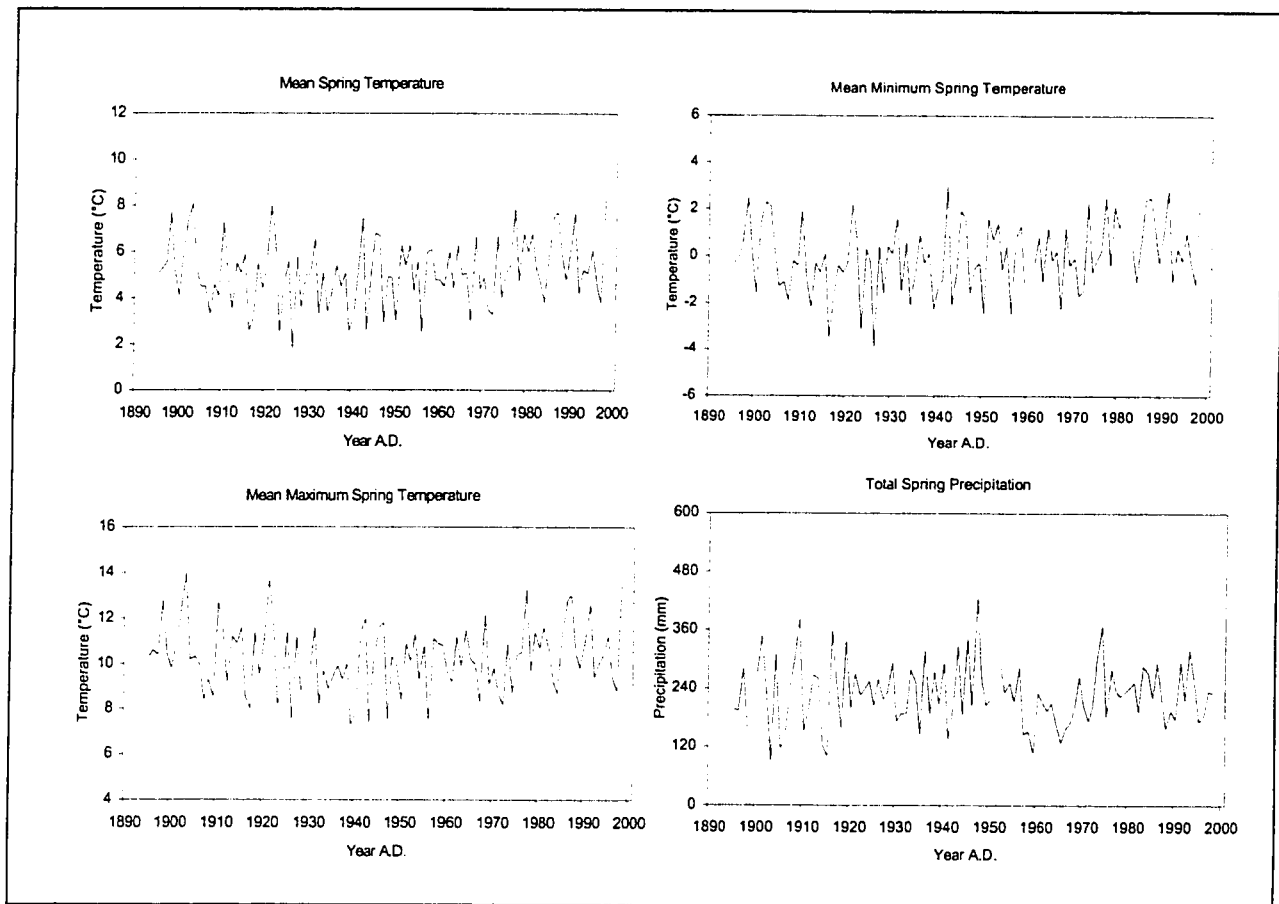


Figure 5-2. Spring mean, minimum and maximum temperature and total precipitation.

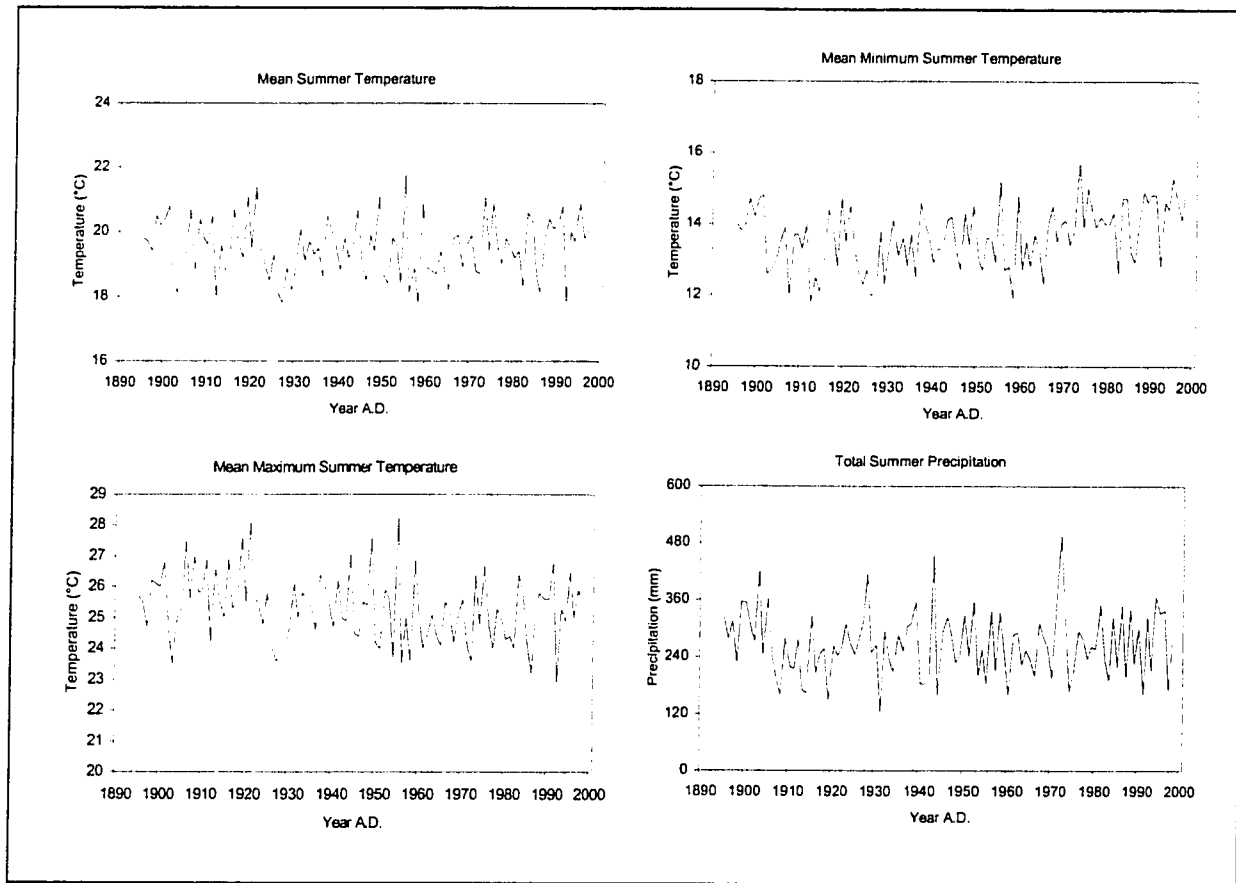


Figure 5-3. Summer mean, minimum and maximum temperature and total precipitation.

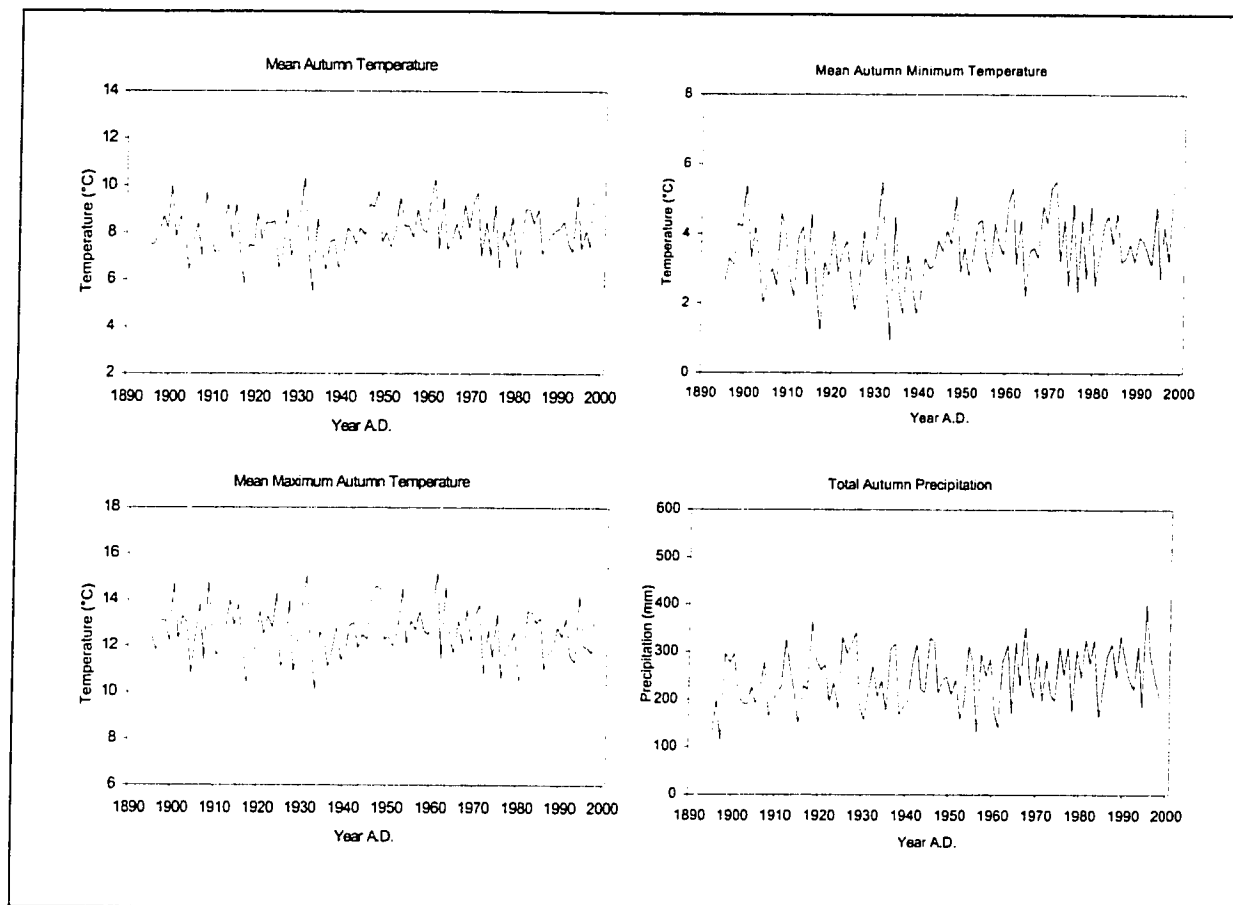


Figure 5-4. Autumn mean, minimum and maximum temperature and total precipitation.

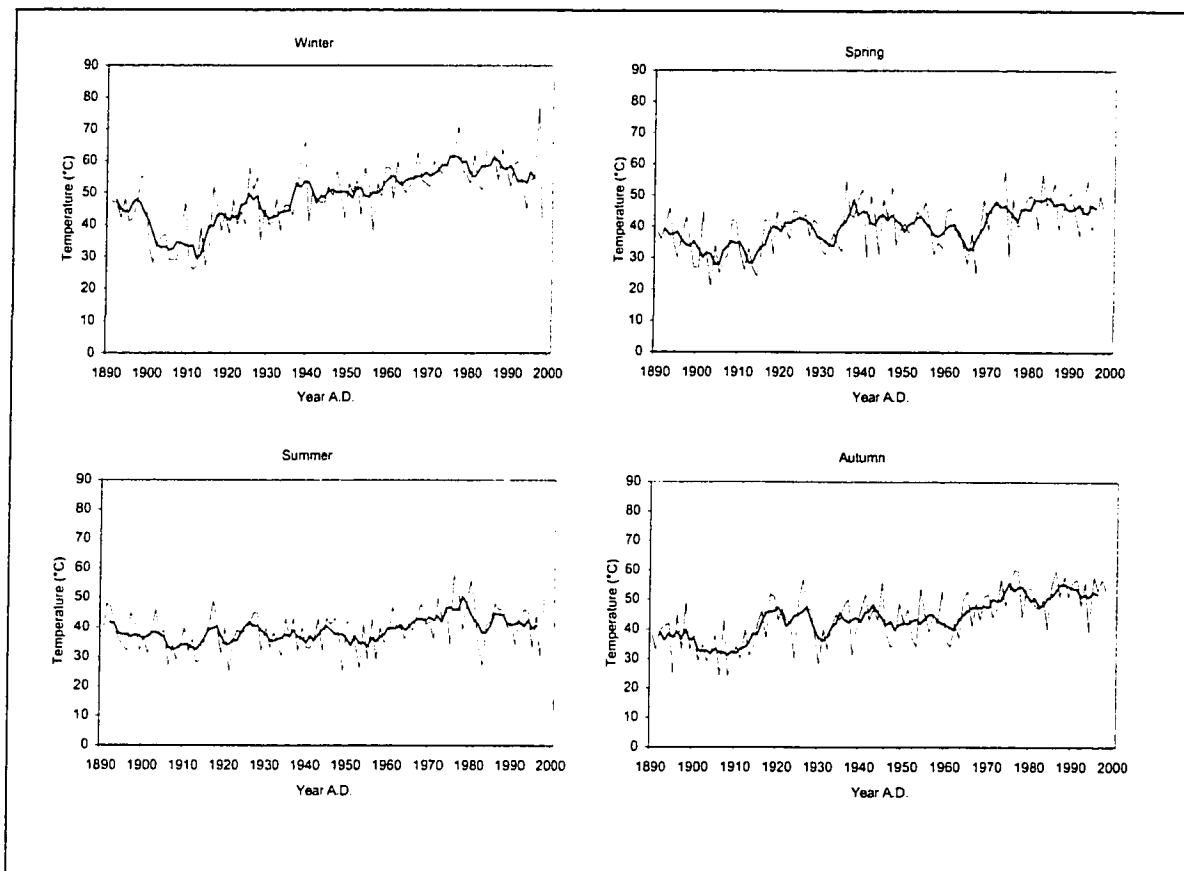


Figure 5-5. Number of precipitation events time series for winter, spring, summer and autumn.

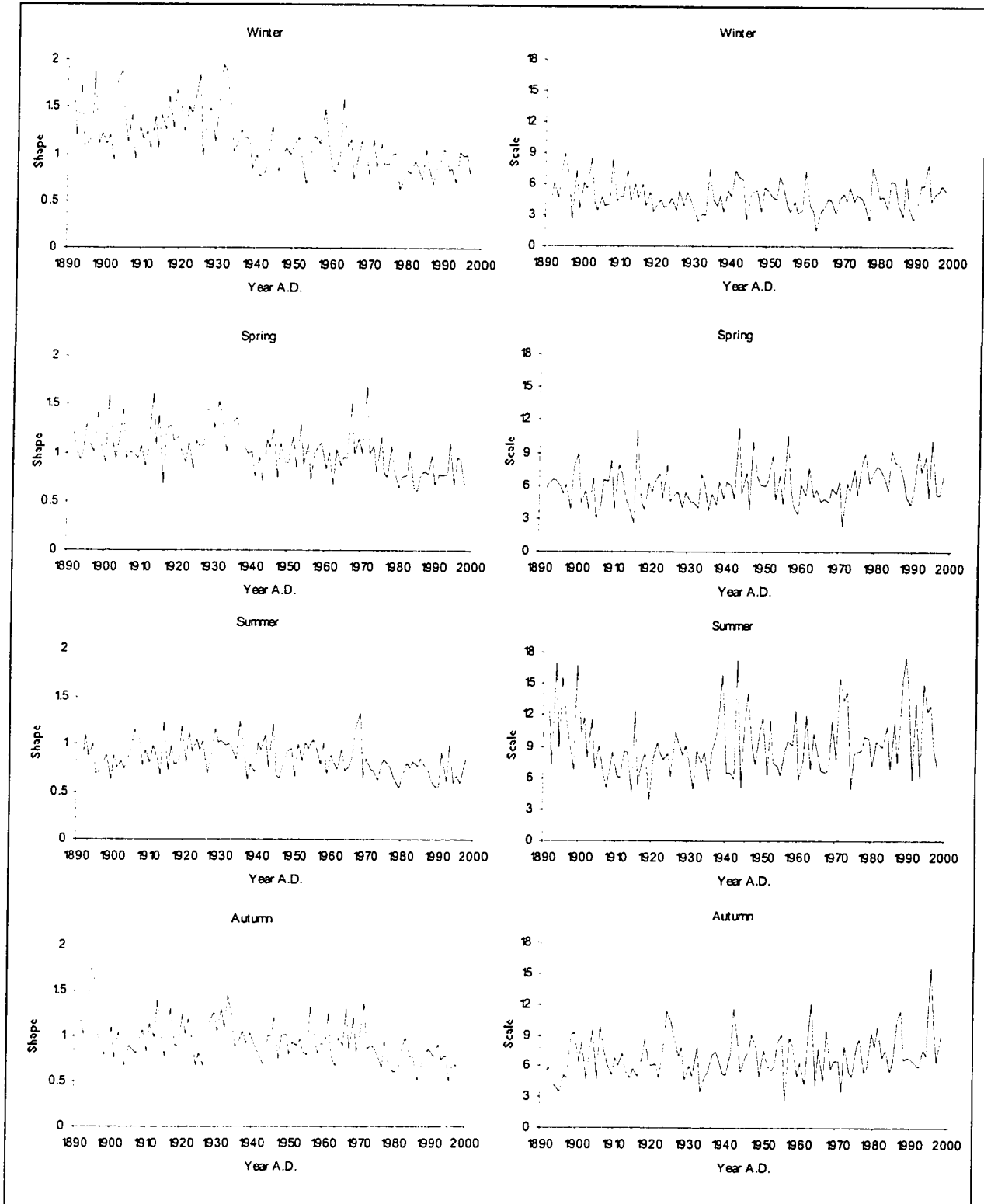


Figure 5-6. Ottawa CDA gamma scale and shape time series for winter, spring, summer and autumn.

6. MONTHLY ANALYSIS: WHICH MONTH(S) MAKES THE SEASONS WARMER, COLDER, DRIER AND WETTER?

In this section, monthly data will be analyzed using the central month of each season to represent the season. Time series plots are used to illustrate the tendencies in the mean monthly temperature and total monthly precipitation. Both the Ottawa CDA and Morrisburg stations were used since we might expect shorter time periods to show more spatial differences, and these two stations had the longest time series. These plots can be used to identify not only long-term trends, but also periods of time (5 yr, 10 yr...) of above or below average conditions.

6.1. Mean Monthly Temperature

Which month(s) made the seasons warmer or colder? In general, most seasons were warmer or colder because every month was either warmer or colder. The transition seasons, spring and autumn, both have at least two months out of the three months contributing to the cooling. In spring of 1984, the months of March and May had below average temperatures, but April temperatures were above average. In autumn of 1933, October and November had below average temperatures but September temperatures were above average.

6.2. Temperature 5-year Moving Averages

January mean monthly temperatures were high some years between 1905 and 1915, but there was a cold year during this period and two cold years around 1920 followed the period (Figure 6-1). The 1930s were relatively warm, however, some individual years were cold during this period. The 1950s were very warm with no cold years; therefore the moving average was quite high. Around the 1990s the moving average was quite high; however, one cold January occurred in 1995. Overall January mean monthly temperatures show little trend over time.

April mean temperatures were high between 1895-1905 (Figure 6-1). The 1940s were relatively cold, and therefore the moving average was quite low. From the 1960s to 1970s the temperature was first warm then cool. The overall warming trend tends to decrease during these years. Several warm years occurred during the late 1980s. The overall trend during the century is one of cooling until the 1940s and warming since.

July mean temperatures were high between 1890-1910 (Figure 6-1). Closer to the 1920s, the temperature fluctuated from warm to cold years. The 1920s were relatively cool. Since then the temperature shows no discernible trend.

October mean temperature was cool between the 1890s and the 1930s, however in the second half of the 1930s a warming trend occurred which continued into the 1940s (Figure 6-1). From the 1940s to the 1970s the temperature was cool, but it has been warming since.

6.3. Maximum, Minimum and Mean Monthly Temperature

Standard deviations were computed on overlapping 5-year periods to produce an index of short-term inter-annual variability. Trends in the inter-annual variability of the mean monthly maximum and mean monthly minimum temperatures are parallel; periods of higher variability occur in both variables simultaneously.

6.3.2. January

The 5-year running standard deviation of the mean monthly temperature for January shows no long-term linear trend (Figure 6-2). The standard deviation was high in the 1910s, 1930s and 1990s. The mean monthly minimum temperatures (Figure 6-3) seem more variable than the

maximum (Figure 6-1) and mean monthly temperatures, especially in the 1930s. Other periods that had high variability were the 1910s and 1970s, whereas the 1920s and 1960s had very low variability. Warm periods tended to have lower variability.

6.3.3. April

The 5-year running standard deviation of the mean monthly temperature can be divided into five main periods (Figure 6-1). The inter-annual temperature variation was high from 1910 through the mid 1930s, in the 1940s, and in the 1970s; it was low in the late 1930s and in the 1960s. Higher variability for both minimum (Figure 6-3) and maximum temperatures (Figure 6-2) was seen in the early 1940s, and in addition in minimum temperatures in the 1910s.

6.3.4. July

The inter-annual temperature variation for July was lower than that of January and April (Figure 6-1). The period around the 1920s had high variability in both minimum and maximum temperatures, as did the 1950s and 1960s. Maximum temperatures (Figure 6-2) were more variable than minimum temperatures (Figure 6-3) in the 1950s, while the reverse was true in the 1960s. The mean temperatures show a clear period of higher variability in the mid 1950s, which was due to the increased variability in daytime temperatures.

6.3.5. October

The temperature variability in October was lower than that for January and April (Figure 6-1). It is characterized by higher frequency change than in July, going quickly from more variable to less variable 5-year periods. Notable times are the high variability in the 1970s and around 1900-1905, and the low variability in the late 1950s. The variability tended to be low during warm periods and higher during colder periods of the century. The inter-annual variability was

higher than summer (July), although this is a typical observation for any region with defined seasonality.

6.4. Range between Minimum and Maximum Mean Monthly Temperatures

The range between daytime and night-time temperatures was largest in summer and smallest in winter (Figure 6-9). The range between the minimum and maximum mean monthly temperatures in all months has decreased from the beginning of the century, although less markedly so in January. The difference between night-time and daytime temperatures is smaller most recently as compared to a century ago for the months of April, July and October. The cause of this has been an overall increasing trend in minimum temperatures.

The range between night-time and daytime temperatures was larger at Morrisburg than at Ottawa (Figure 6-9). At both stations, the long-term trend in the range has been decrease in all four months. However, at Morrisburg the two months with the most noticeable decrease are July and October; the slopes of the linear regression coefficient are between 2-4x times greater than for the other two months. At Morrisburg, the range for October and July was greater and decreased at a steeper slope than Ottawa. However, in both months, there was a major decrease in the range in the 1950s.

6.5. Total Precipitation

Which month(s) make the seasons drier or wetter? In general, every month contributes to the seasons being drier or wetter. However, there were two exceptions. The driest winter of 1956 was dry in December and January and wet in February. The other exception was the wettest autumn (1995), in which September was drier than average while October and November were

wetter than average.

The key season which determined high annual precipitation was summer. In the ten driest years both summer and spring were drier than average. In general, it appears that lower summer and spring precipitation accompanied warmer years, while colder years were accompanied by higher summer precipitation (Figure 6-4). In general Ottawa and Morrisburg show similar trends (Figure 6-4 and Figure 6-8); however there were large differences between the stations in July, when more convective precipitation is received. Inter-annual variability was also different in Morrisburg and Ottawa in the summer, with Morrisburg having less variability and fewer dry years than Ottawa.

6.6. Total Monthly Precipitation 5-year Running Mean

For January precipitation the wettest years were between 1890-1900, 1910-1920, 1945-1950, 1975-1980 and 1990-1995 (Figure 6-4). April precipitation seems to vary between 5 to 10 years of wet and dry cycles. For July precipitation, the wettest years were between 1890-1895, 1925-1930, 1935-1940, 1950-1955 and 1970-1975. For October, the wettest years were between 1915-1920; however, the years between 1945-1955 were a significant dry period.

6.7. Total Monthly Precipitation 5-year Standard Deviation

Monthly total precipitation data from both Ottawa CDA and Morrisburg were analyzed (Figure 6-4 and Figure 6-8). The climate stations do not always demonstrate the same tendencies; whenever different this will be stated.

6.7.2. January

The 5-year running standard deviations of the monthly total precipitation for January show high

variability around 1945 and 1980 (Figure 6-4 and Figure 6-8). Morrisburg had unusually higher variability around 1980. Both stations had periods of low variability around 1985, 1970 and 1935. However, several periods were quite different at the two stations. Around 1915 Ottawa CDA had low variability whereas Morrisburg had high variability. For the 1930s Ottawa CDA had low precipitation variability compared to Morrisburg, which had high precipitation variability.

6.7.3. April

The 5-year running standard deviation of the monthly total precipitation for April oscillates between periods of high and low variability (Figure 6-4 and Figure 6-8). Periods of relatively high variability are 1890 to 1905, 1920 to 1925, 1950 to 1955 and 1965 to 1970. The variability has been increasing at Ottawa since 1980. Morrisburg also had high variability during this period, but the increase in variability after 1980 was more sudden than for Ottawa.

6.7.4. July

Due to their dissimilarities, July monthly total precipitation is discussed separately for Ottawa and Morrisburg (Figure 6-4 and Figure 6-8).

Inter-annual July precipitation is more variable at Morrisburg than Ottawa. In Ottawa, the July variability was relatively low between 1900-1920. Variability slowly increased from 1915 to 1950, and has remained generally stable since then. The early 1960s and the 1970s were relatively less variable. In Morrisburg, total July precipitation was more variable than Ottawa. The standard deviation of the monthly total precipitation is particularly high between 1915-1930, 1940-1950 and 1966-1980, and particularly low between 1955-1965.

6.7.5. October

Except for two periods the tendencies in the Morrisburg and Ottawa 5-year running standard deviation are similar (Figure 6-4 and Figure 6-8). Both stations had high precipitation variability around 1915, between 1955-1958, 1960-1965, 1940-1945 and since 1990. Both stations have low precipitation variability between 1945-1955, 1958-1960 and 1965-1990. The two stations differ for two distinct periods, 1925-1930 and 1930-1940, during which Morrisburg had lower variability than Ottawa. At Ottawa, variability generally increased from 1905 through the 1930s. Between 1935 and 1960 there were alternating 5-year periods with high and low variability.

6.8. Summary

- In general, most seasons were warmer or colder because every month was either warmer or colder.
- January mean monthly temperatures were high for some years around 1905-1915, although there was a cold year during this period and two cold years around 1920 followed the period. The 1930s were relatively warm; however, some individual years were cold during this period. The 1950s were very warm with no cold year, and therefore the moving average was quite high.
- The overall trend for April mean monthly temperatures was one of cooling until the 1940s and of warming since.
- The 1920s July mean monthly temperatures were relatively cool. Since then the temperature show no discernible trend.
- From the 1940s to 1970s October mean monthly temperatures were cool, and it has been warming since.
- The standard deviation was high for January monthly temperatures in the 1910s, 1930s

and 1990s. The mean monthly minimum temperatures seem more variable than the maximum and mean monthly temperatures, especially in the 1930s.

- For January monthly temperatures, warm periods tended to have lower variability.
- For April mean monthly temperatures, the inter-annual temperature variation was high from 1910 through the mid 1930s, in the 1940s, and in the 1970s; it was low in the late 1930s and 1960.
- The inter-annual temperature variation for July was lower than that in January and April.
- The temperature variability in October was lower than January and April.
- October monthly temperatures were different from July; October is characterized by higher frequency change, going quickly from more variable to less variable 5-year periods.
- The variability tended to be low for October monthly temperatures during warm periods and higher during colder periods of the century.
- The range between the minimum and maximum mean monthly temperature in all months has decreased more or less steadily from the beginning of the century, although less markedly so in January. The cause of this has been a steadily increase in minimum temperature.
- The range between night-time and daytime temperatures is larger at Morrisburg than at Ottawa.
- In general, every month contributed to the seasons being drier or wetter.
- The key season which determined high annual precipitation was summer, except for the ten driest years in which both summer and spring were drier than average.
- In general, it appears that warmer years were accompanied with lower summer and spring

precipitation, while colder years were accompanied with higher summer precipitations.

- Inter-annual variability was also different at Morrisburg and Ottawa in the summer; Morrisburg had less variability and fewer dry years than Ottawa.
- April precipitation seems to vary between 5 to 10 years of wet and dry cycles.
- In the 1930s January precipitation at Ottawa CDA had low precipitation variability compared to Morrisburg, which had high precipitation variability.
- Precipitation variability has been increasing at Ottawa since 1980. While Morrisburg also had high variability during this period, the increase in variability after 1980 was more sudden than at Ottawa.
- Inter-annual July precipitation was more variable at Morrisburg than at Ottawa.
- At Ottawa, the variability of July precipitation was relatively low between 1900-1920. Variability slowly increased from 1915 to 1950, and has remained generally stable since then.
- At Morrisburg July monthly precipitation was more variable than at Ottawa.
- During the 1930s the variability in October monthly precipitation was greater at Ottawa than at Morrisburg.

APPENDIX E

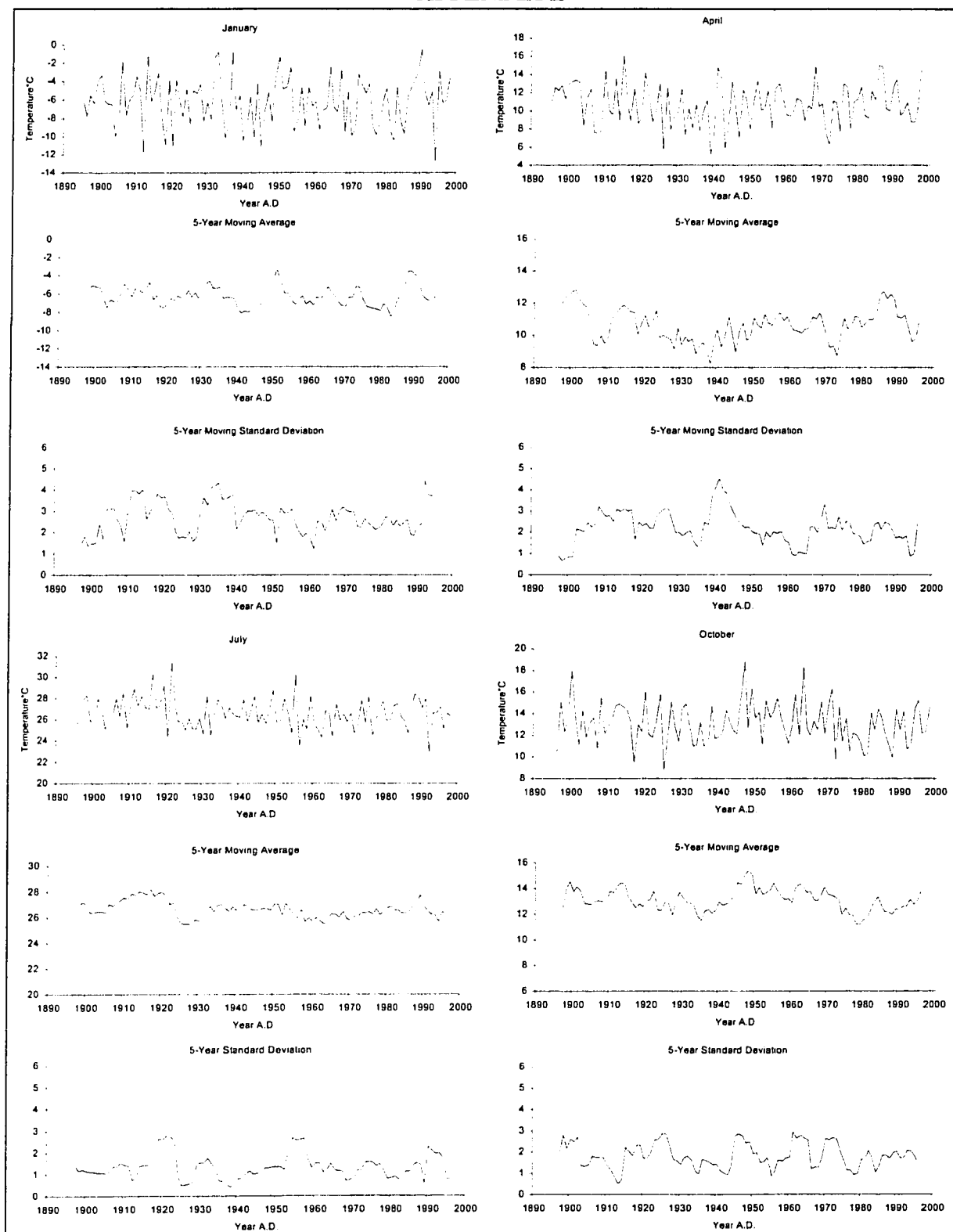


Figure 6-1 Ottawa January, April, July and October mean monthly maximum temperature (°C), 5-year moving average and standard deviation.

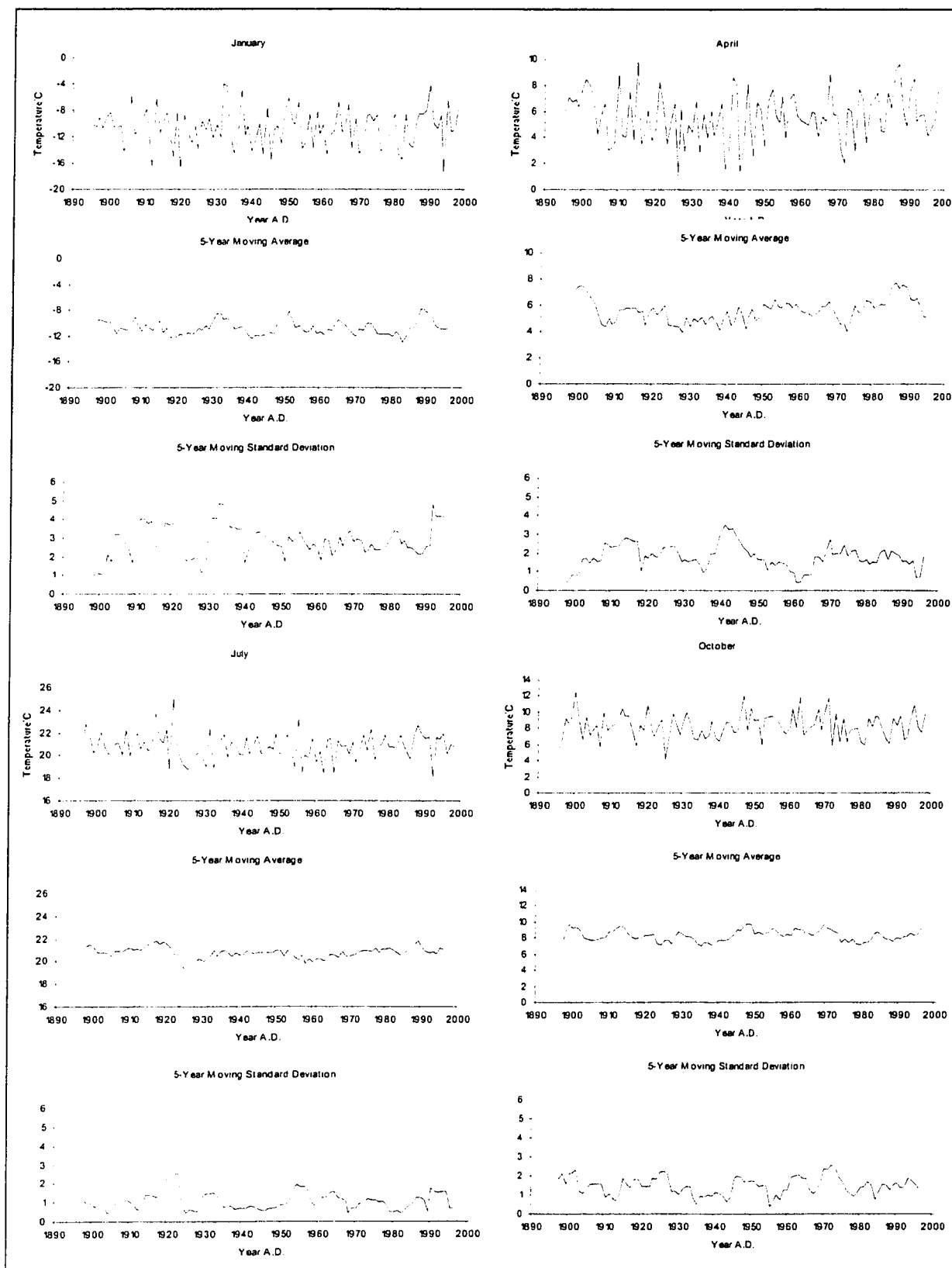


Figure 6-2 Ottawa January, April, July and October mean monthly temperature ($^{\circ}\text{C}$), 5-year moving average and standard deviation.

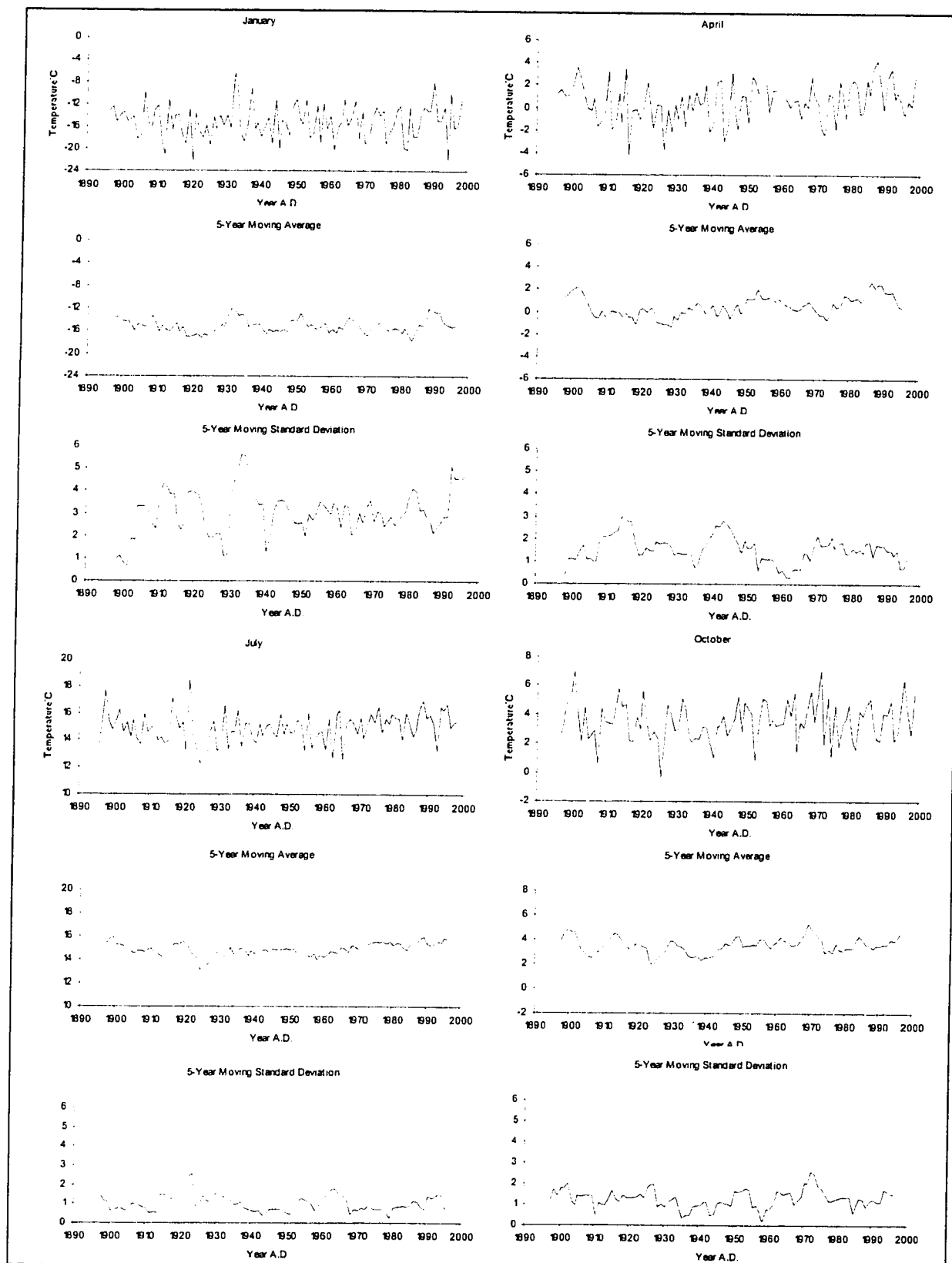


Figure 6-3 Ottawa January, April, July and October mean monthly minimum temperature ($^{\circ}\text{C}$), 5-year moving average and standard deviation.

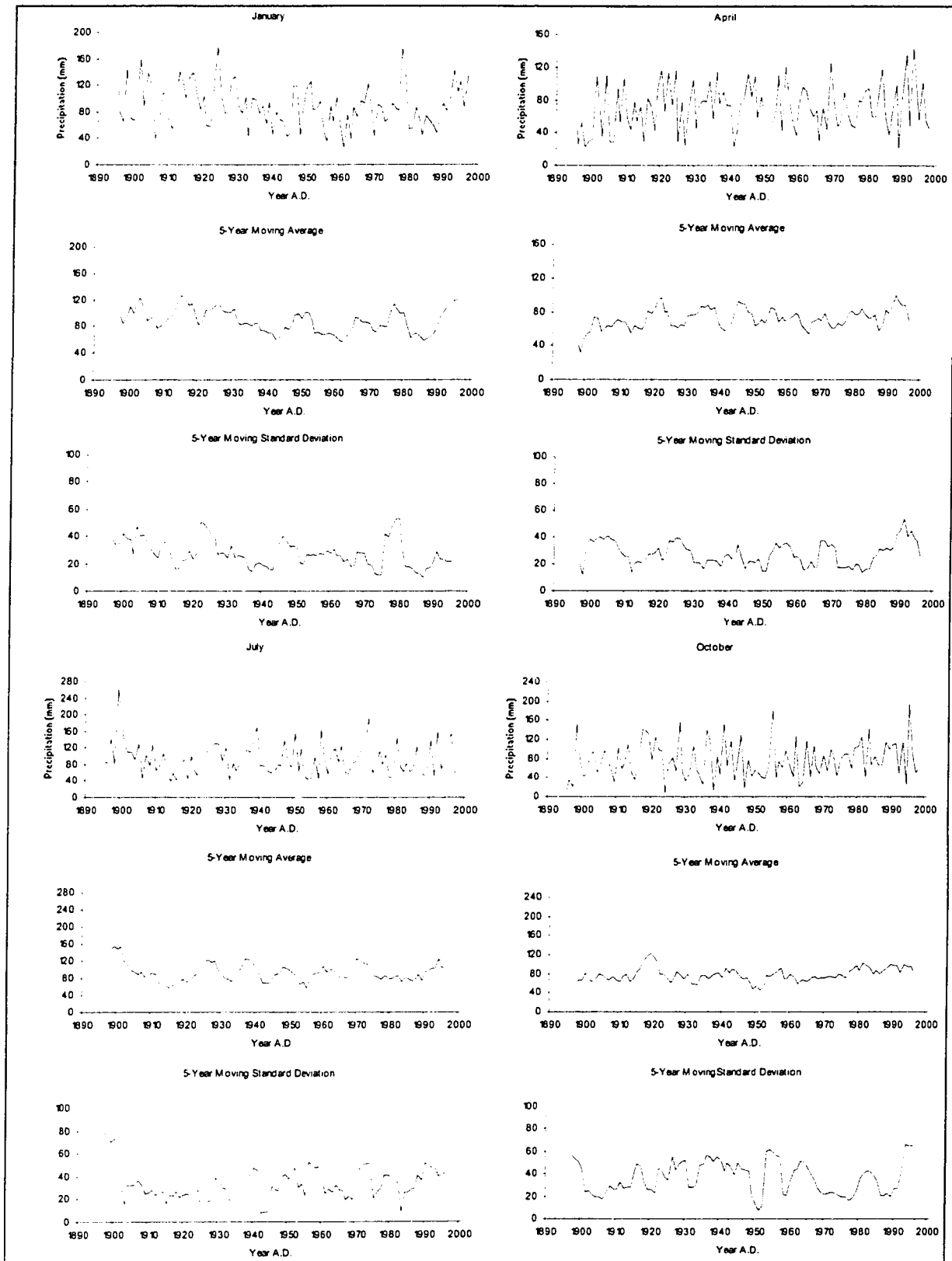


Figure 6-4 Ottawa January, April, July and October total monthly precipitation, 5-year moving average and standard deviation.

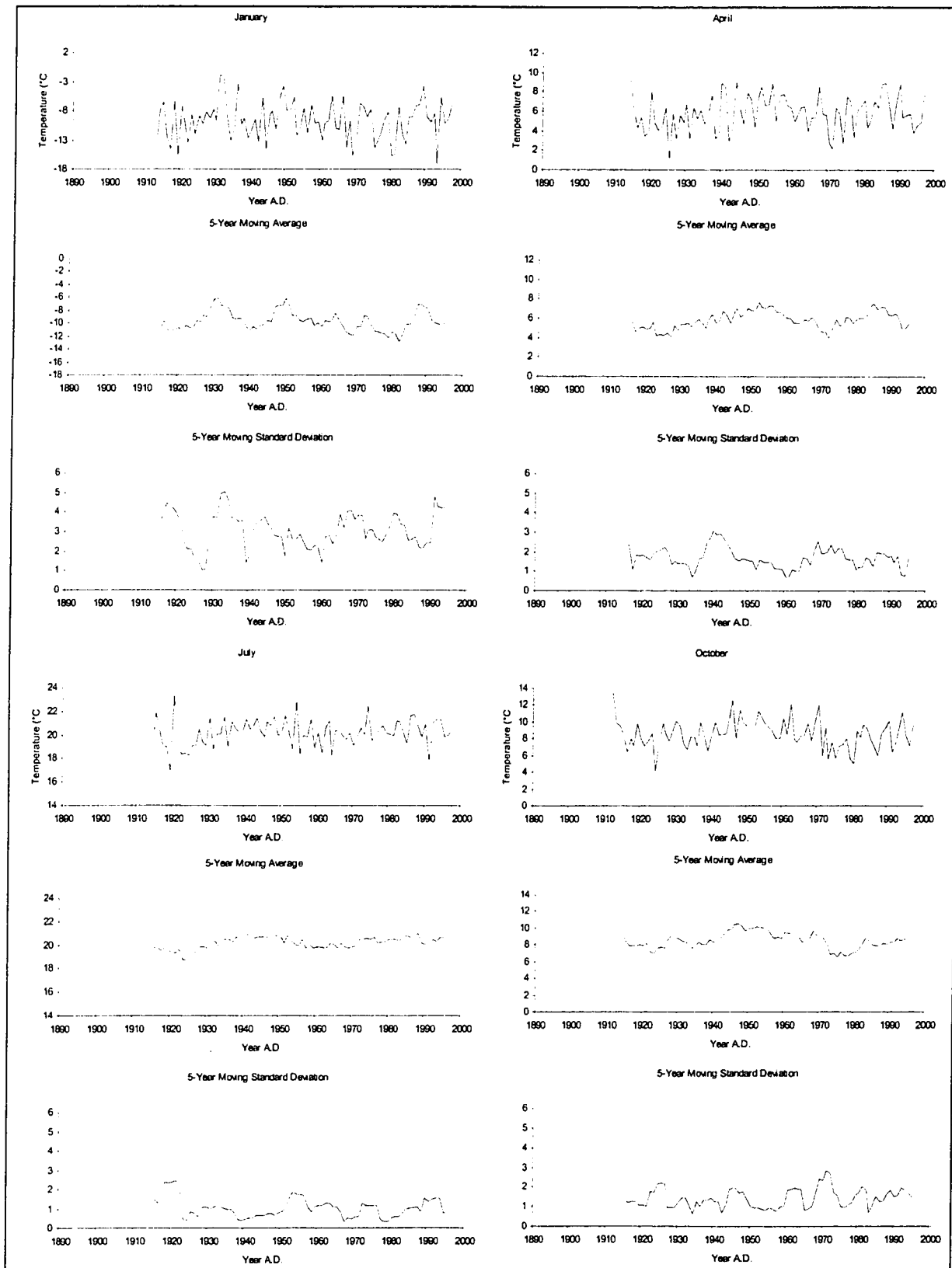


Figure 6-5 Morrisburg January, April, July and October monthly mean temperature (°C), 5-year moving average and standard deviation.

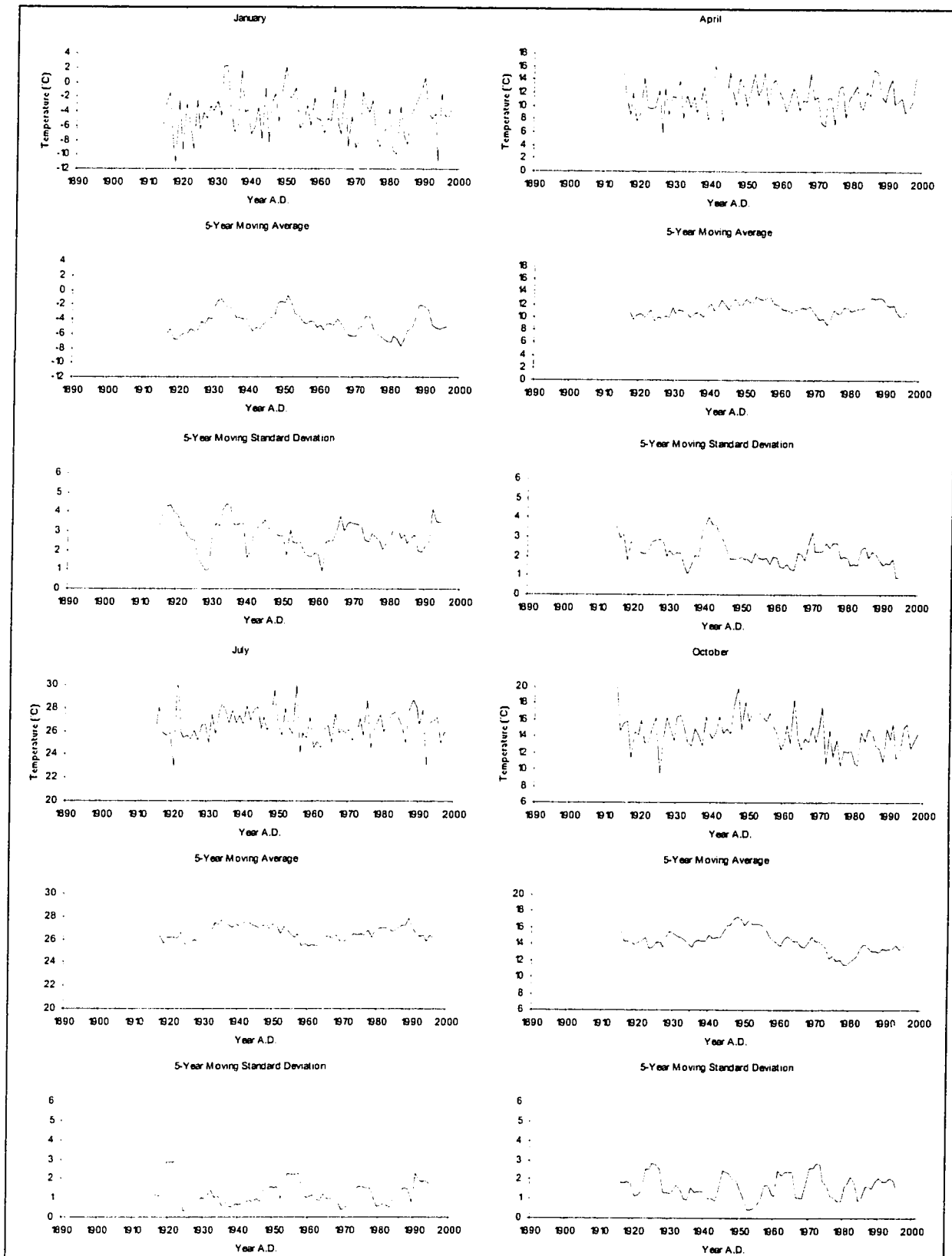


Figure 6-6 Morrisburg January, April, July and October mean monthly maximum temperature (°C), 5-year moving average and standard deviation.

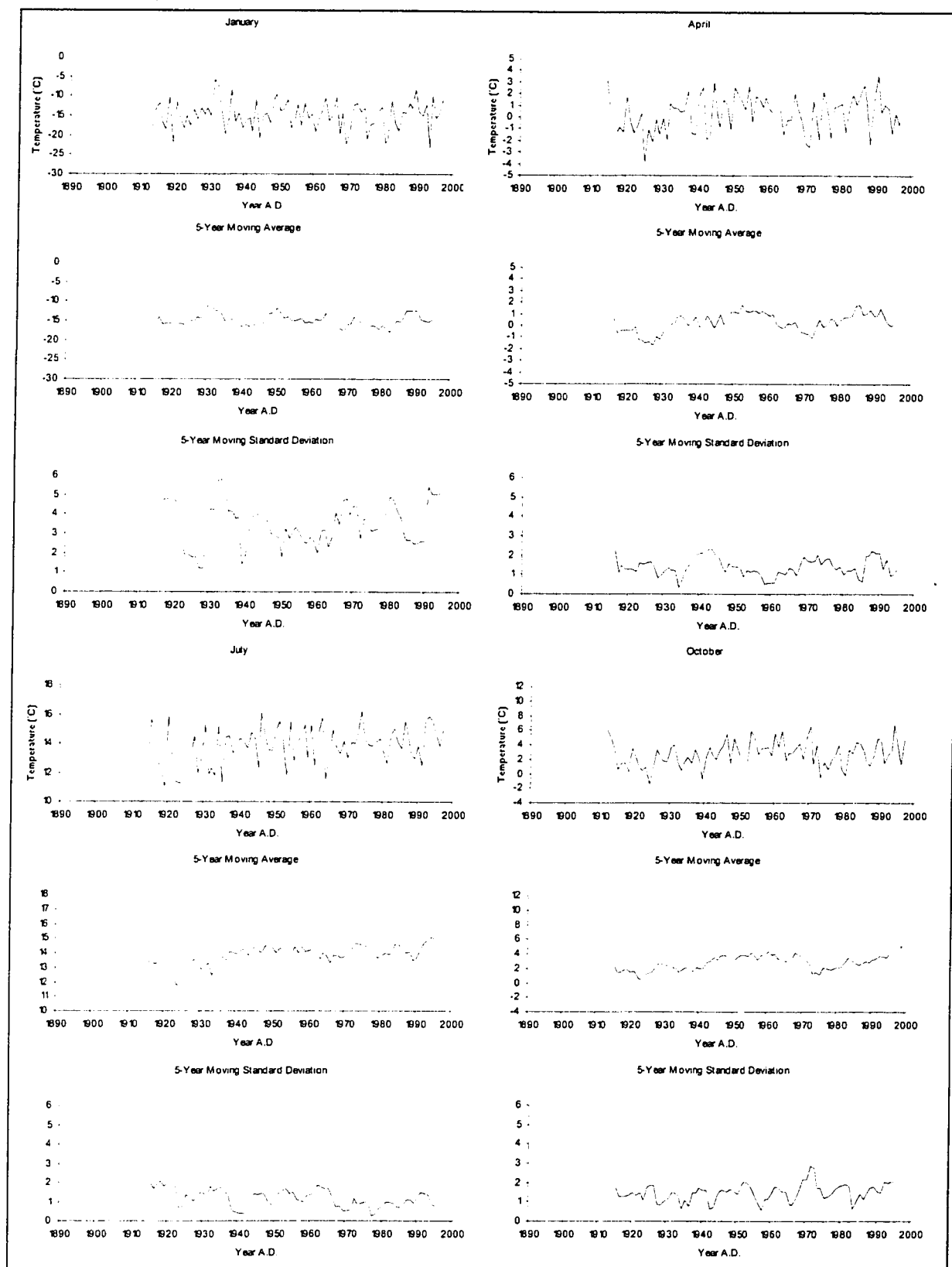


Figure 6-7 Morrisburg January, April, July and October mean monthly minimum temperature (°C), 5-year moving average and standard deviation.

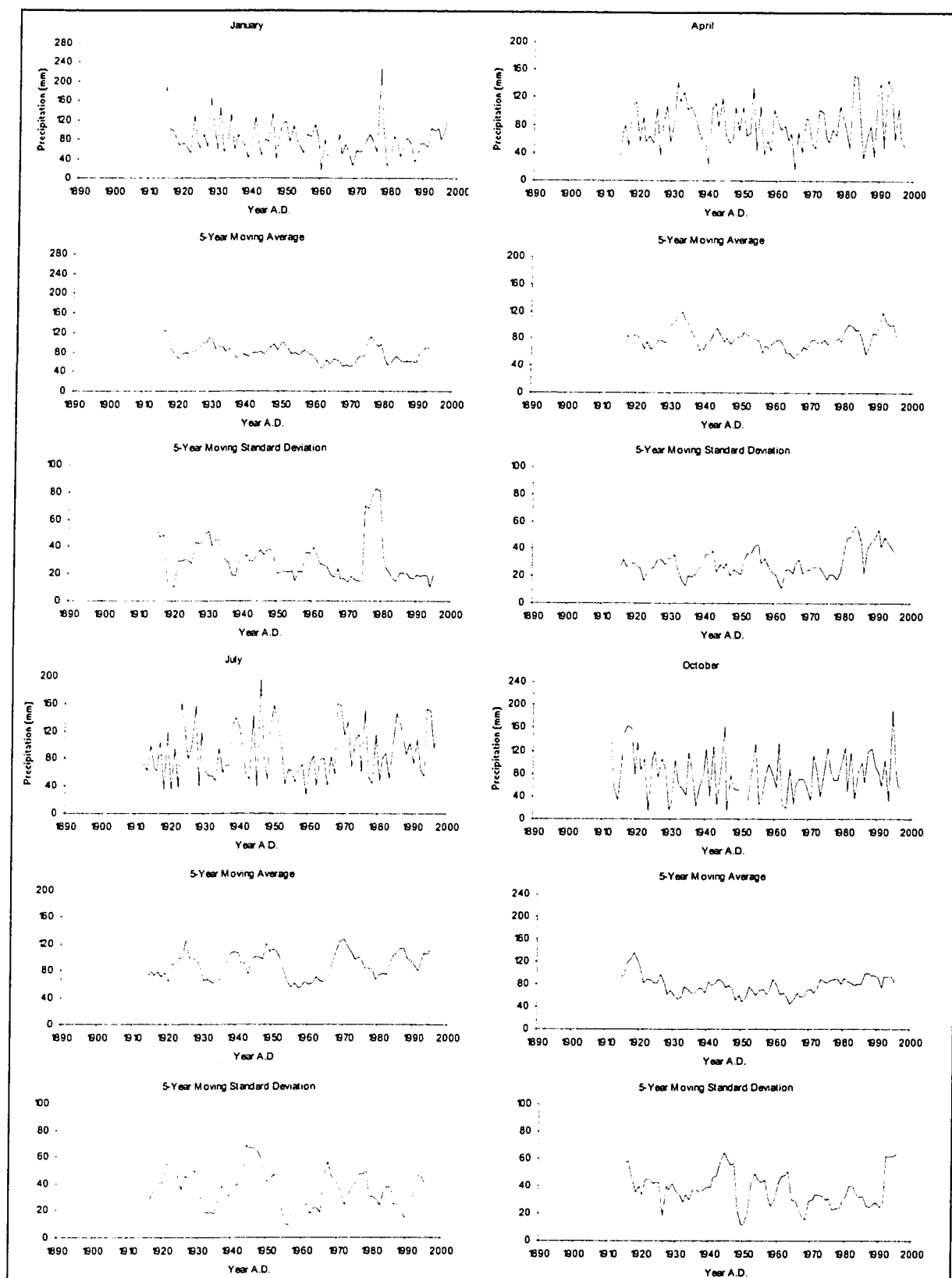


Figure 6-8 Morrisburg January, April, July and October total monthly precipitation (mm), 5-year moving average and standard deviation.

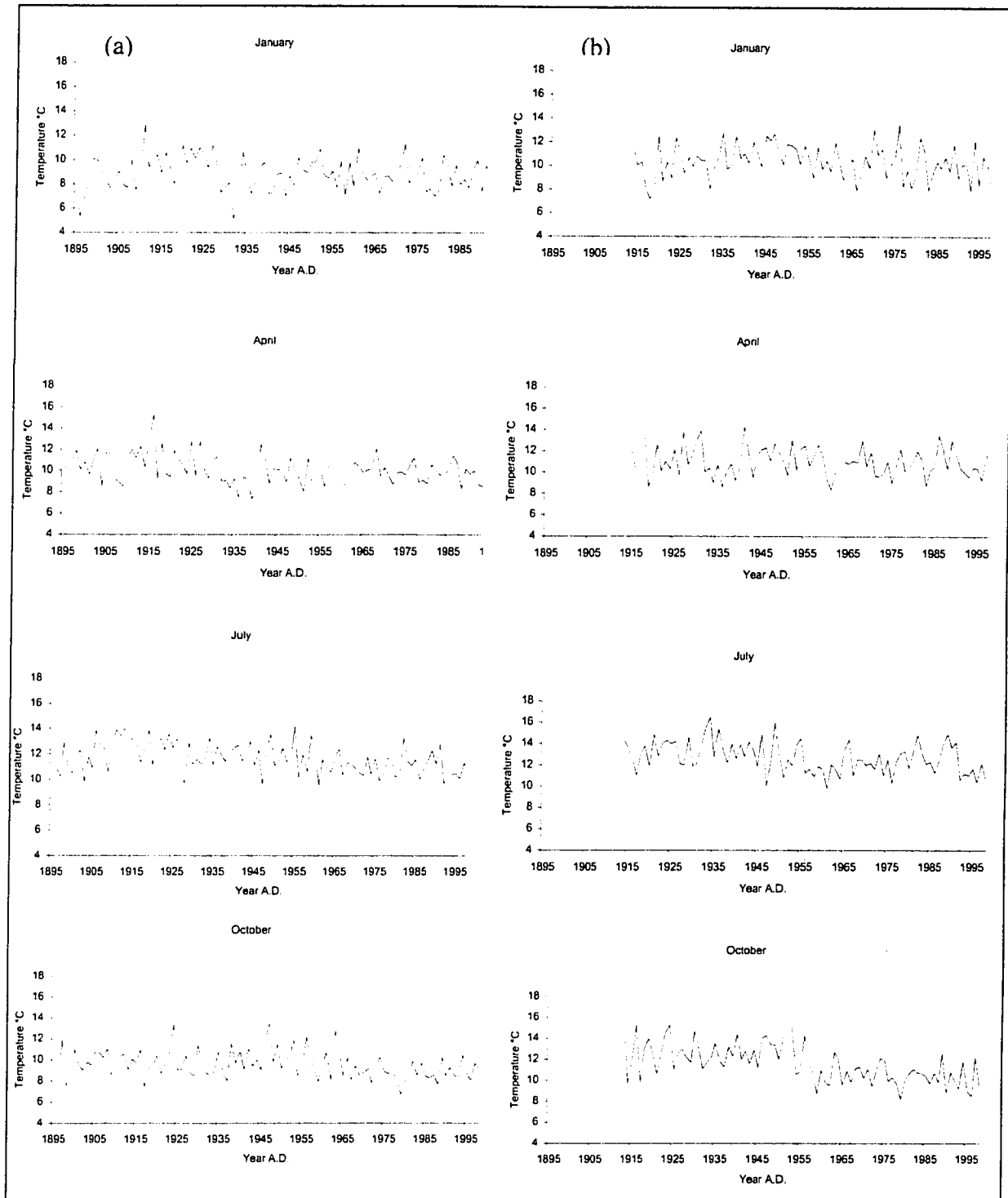


Figure 6-9 Ottawa CDA (a) and Morrisburg (b) diurnal temperature range (°C).

7. DAILY ANALYSIS: HOW MANY DAYS CONTRIBUTE TO WARMER, COLDER, DRIER AND WETTER MONTHS?

The purpose of the analysis of daily air temperature and precipitation is to determine how many days contribute to warmer, colder, drier and wetter months. A second purpose is to determine how the annual cycle manifests itself in warm, cold, dry and wet years. In addition, a further analysis of the growing season will enable us to understand the differences through time in the start and end of both the growing and heating season. This is done through a daily mean temperature histogram analysis of the warmest, coldest, driest and wettest years, followed by an analysis of extreme days (by calculating the number of days with extreme low and high temperatures). The last section again analyzes the ten warmest, coldest, driest and wettest years in terms of the number of days with extreme temperatures but also the duration, starting and ending date of the growing and heating seasons.

7.1.2. Annual Cycle of the Mean Daily Air Temperature

Time series plots of mean daily air temperatures illustrate general trends in the annual cycle at Ottawa (Figure 7-2 and Figure 7-14) and Morrisburg (Figure 7-28 and Figure 7-37). Since the form of the annual cycles at the two stations is similar, only the Ottawa CDA data are discussed in detail in following sections. The general form of the curve for annual temperatures is roughly a sine wave, with minimum temperatures around day 320-360 and maximum temperatures around day 180-240.

Typical temperatures in spring can range between -20°C and 0°C . Spring can be quite variable with rapid alternations from $<-20^{\circ}\text{C}$ to $>0^{\circ}\text{C}$ in a few days. The spring of 1933-34 was particularly cold (Figure 7-6), and that of 1949-50 was warm (Figure 7-8). Extensive cold

periods, for example in 1961 (Figure 7-9) and in 1975 (Figure 7-11) can be typically followed by warm days. Some springs such as 1967, had quite variable daily mean temperatures throughout the whole season (Figure 7-10).

Transition to spring can be abrupt or smooth. For example, the transition is abrupt in 1896 (Figure 7-2), 1905 and 1906 (Figure 7-3), 1916 (Figure 7-4) and 1949 (Figure 7-8). Prolonged springs are rare, although 1910 is an example (Figure 7-4). Typically mean daily air temperatures rise above 0°C between days 80-100.

Typical temperatures in summer are between 10°C and 30°C. The transition to summer was typically smooth, as seen in 1967 (Figure 7-10) and 1956 (Figure 7-9). Summer can have a broad peak at its maximum temperature, as seen in 1914 and 1915 (Figure 7-4), or maximum temperatures can be limited to a few days, for example in 1916 (Figure 7-4). Some summers can have peak temperatures early in the summer season, as seen in 1919 (Figure 7-5). Some summers show the reverse and slowly rise to their maximum around day 200.

The transition from summer to fall can be sudden in some years, for example in 1905 (Figure 7-3), in 1947 (Figure 7-8), and in 1956 (Figure 7-9), whereas in other years temperatures gradually decrease, for example in 1913 (Figure 7-4), 1961 (Figure 7-9), and 1970 (Figure 7-10). Mean daily air temperatures typically fall below 0°C around day 300.

The transition to winter can be smooth, for example in 1919 (Figure 7-5), and 1941 (Figure 7-7), or abrupt, for example in 1917 (Figure 7-5), and 1943 (Figure 7-7). In some years winter lasts longer than average, as seen in 1923 (Figure 7-5).

7.1.3. Growing Season

The length of the growing season can be used as an indicator of climate variations in a region (Robeson, 2002). Several methods can be used to characterize the length of the growing season, such as the fluctuations of lilac first blooms (Cayan *et al.*, 2001); however, the approach used here is based solely on instrumental climate data. The growing season is defined as the period of time each year beginning when the average daily air temperature reaches 5°C for a 5-day period and lasting until daily air temperature is 5°C for a 5-day period. The growing season is a particularly important period of the year because during this period perennial crops such as pastures and forages can grow (Environment Canada, 1999). The heating season is defined here as the period of the year where the mean daily air temperature is below 10°C and when heating is necessary. The duration, starting date and ending date of the growing and heating season will be compared among the ten warmest, coldest, wettest and driest years.

On average the start of the growing season in most years is near the 107th day of the year (around mid-April) and the end of the growing season is around the 295th day of the year (around the last week of October). The length of the growing season varies through time; on average the growing season lasts for 192 days.

Time series analysis of the starting date, ending date and duration of growing season enables us to see trends, that is, if the start, end, or duration of the growing has changed over the 20th century. The start of the growing season fluctuated through time (Figure 7-56). From 1904-1909 and 1923-1948 the growing season started later than the average of the 107th day. Before 1903, between 1949-1960 and from the mid 1960s to 1998, the growing season started earlier

than the average. The end of the growing season also fluctuated thorough time (Figure 7-56). The century average is on the 295th day. Between 1897-1903, 1910-1920, 1946-1960, 1970-1979 and from 1984-1998 the growing season has been ending later than the average date. The growing season ended before the average date in the early 1890s, between 1904-1910, 1922-1946 and some years in the 1990s. Between the 1890s and early 1900s the duration of the growing season was longer than average (Figure 7-56), but less than average between 1904-1912. A few years in the 1910s and early 1920s were above average. From 1922-1945 the duration of the growing season was below average. Since the 1950s the duration of the growing season has been increasing, with the exceptions of some years. Similar results were found in Illinois, where the growing season has increased by roughly a week (Robeson, 2002). The inter-annual variability of the duration of the growing season was low before 1903, and high from 1903-1919. From 1920-1935 and 1941-1960 the variability was low; and from 1936-1940, during the 1970s, and during the 1990s, the variability was high.

7.1.4. Daily Mean Temperature Histograms

To compare the ten warmest, coldest, driest and wettest years, histograms for the frequency of daily temperatures were compared (Figures 7-48 to 7-51). Note that the y-axis scale is different between the ten warmest and coldest years. The ten warmest years had more days with a daily mean air temperature above 20°C and 15°C compared to the ten coldest years (Figure 7-48 and 7-49). In addition, the ten warmest years had fewer days with mean daily air temperatures below -25°C and -30°C compared to the ten coldest years. The mean daily air temperature did not differ between the driest and wettest years (Figures 7-50 and 7-51). Most histograms show a multi-modal distribution of daily mean air temperature, usually having two dominant modes for summer and spring (as seen in Figure 7-49). The following section describes the method used to

fit Gaussian curves to solve the multimodal distribution.

7.1.5. Mixture Model Method

The method used enables the researcher to identify the most significant modes of a distribution (Viau *et al.*, 2002). Furthermore, this method offers an objective way to choose the optimum number of modes. The first step is a k-Means cluster analysis, used to determine the initial values based on the number of curves to be fitted. Secondly, the location of the means and values of the standard deviation of the Gaussian curves is determined by maximizing the log-likelihood ratio. The optimal number of components can be determined by analysis of changes in the log-likelihood ratio as new curves are fit. The procedure was implemented in SAS using procedures FASTCLUS and NLP (D. Atkinson and A. Viau, Department of Geography, University of Ottawa, personal communication).

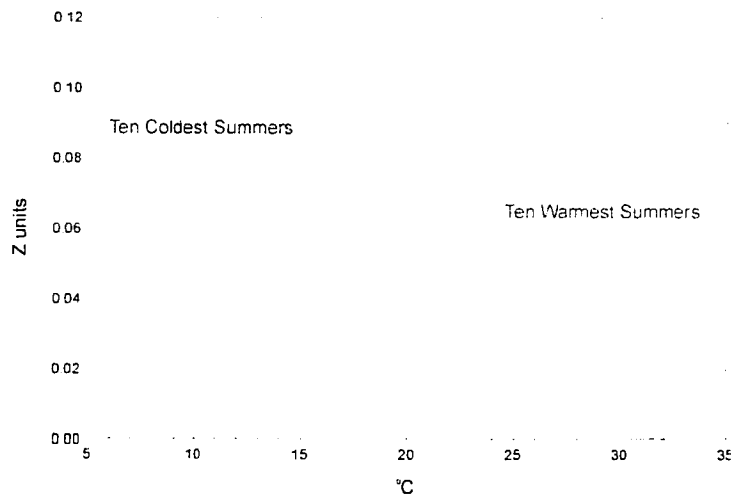


Figure 7-1 Normal distribution of the summer mode fit by the mixture model. Actual mean values of the ten warmest and ten coldest years of the past century are shown.

The mixture model results, for example Figure 7-1, show two dominant peaks corresponding to

summer and winter modes. In addition, smaller modes were found in several years. In both dominant modes the means were greater in the warm years than in the cold years, more than 1.5°C. Standard deviations are comparable (Table 7-1 and Table 7-2). In addition, other modes were sometimes fitted, especially colder modes in the ten colder years.

The mixture model was also used to determine dominant modes in the ten driest and wettest years. Mean values were greater in the driest years for the two dominant modes. There are a greater number of modes in the driest years than in the wettest ones (Tables 7-3 and 7-4). Further, the model found more intermediate modes in the driest and wettest years than in the coldest and warmest years.

7.1.6. Extreme Temperatures

The number of days with minimum temperatures $\leq -30^{\circ}\text{C}$ has decreased through time (Figure 7-62). One notable cold year was 1934 in which the minimum temperature was $\leq -30^{\circ}\text{C}$ for 21 days. Since 1980, almost every year has had few days with a minimum temperature $\leq -30^{\circ}\text{C}$ and indeed several consecutive years did not have any. A similar, but less pronounced, result is seen for days with a minimum temperature $\leq -25^{\circ}\text{C}$. Since the beginning of the century, the number of days with a maximum air temperature $\geq 30^{\circ}\text{C}$ has decreased through time (Figure 7-62). This trend, however, is less pronounced for the number of days with a maximum daily air temperature $\geq 25^{\circ}\text{C}$. The number of days with a daily mean air temperature shows a general increase for both $\geq 20^{\circ}\text{C}$ and $\geq 15^{\circ}\text{C}$. During the first half of the century, years had fewer days with a mean temperature of $\geq 20^{\circ}\text{C}$ and $\geq 15^{\circ}\text{C}$. The tendency is more pronounced for $\geq 20^{\circ}\text{C}$ (Figure 7-62).

7.1.7. The Growing Season in The Ten Warmest, Coldest, Driest and Wettest Years

This section documents the start and end dates of the growing season during the ten coldest, warmest, driest and wettest years (Figure 7-58 to Figure 7-61). The y-axis is the number of consecutive days above 5°C. Whenever there are five 5°C consecutive days, the growing season is defined to start. The growing season started earlier in eight of the ten warmest years compared to the coldest years, and finished later in most of the warmest years as well (Table 7-5). In the warmest years the growing season tended to begin around the 96th day (first week of April, Figure 7-58) as compared to the 114th day (last week of April) for the coldest years (Figure 7-59). The growing season tended to end around the 303rd day (last week of October) in the warmest years, compared to around the 293rd day (first week of October) in the ten coldest years. The length of the growing season varied from an average of 206 days for the warmest years compared to 178 days for the coldest years (Table 7-5).

The ten warmest years (Figure 7-58) are more variable during the transition periods compared to the ten coldest years (Figure 7-59). That is, the shift from spring to summer and summer to autumn was more gradual, with the temperature fluctuating from days with mean daily air temperature $\geq 5^{\circ}\text{C}$ to days with $\leq 5^{\circ}\text{C}$, in the warmest years.

7.2. Daily Precipitation

Two questions are investigated in the analysis of daily precipitation. First, how many days contribute to the drier and wetter months? Second, how is precipitation distributed through time? Several analyses will quantify these changes and describe the range of variability. One key analysis will be to compare how precipitation distribution manifests itself during the ten warmest, coldest, wettest and driest years. Trends through time of the distribution of

precipitation are also presented. The amount of daily precipitation and its distribution among the seasons are of interest. Another interesting aspect is the lack of precipitation in a given season.

We will first compare the precipitation amounts and distributions at the Ottawa and Morrisburg stations using available data (from 1890 onwards for Ottawa and from 1914 for Morrisburg). This is followed by a description of major precipitation events or significant periods with lack of precipitation. Next extreme events are described followed by a discussion of the mean distribution. Finally, an analysis comparing the ten warmest, coldest, wettest, and driest years will be presented.

7.2.2. Eastern Ontario's Precipitation Distribution

Eastern Ontario has a temperate continental climate (see section 1.3 page 7), and as expected precipitation is distributed throughout the year (Figures 7-15 to 7-27 and 7-38 to 7-47). There is no clear annual cycle in precipitation as there is for temperature. Precipitation periodicities are not usually seen, and if any are discovered they may be purely statistical features that have no physical existence (Stringer, 1972). A typical precipitation event had less than 20 mm of precipitation although events with greater than 80mm have been recorded. Most years averaged 142 measurable precipitation events.

7.2.3. Daily Precipitation

Throughout the last century there was considerable variability in daily precipitation. The maximum amount of daily precipitation, 93.2 mm, occurred in 1942 (Figure 7-20). Several years, such as 1916 (Figure 7-17) and 1943, also had a day of extreme precipitation above 70 mm (Figure 7-20). Some years tended to have more uniformly distributed precipitation, with

moderately sized events at regular intervals, for example in 1898 (Figure 7-15), in 1949 (Figure 7-21), and in 1993 (Figure 7-26). In contrast some years tended to have more extremes, as seen in 1892 (Figure 7-15), in 1903 (Figure 7-16), and in 1946 (Figure 7-21). Some days with very little precipitation were followed by heavy precipitation, for example in 1903 (Figure 7-16) or 1899 (Figure 7-16). These years had relatively long droughts, almost 30 days without rain followed by relatively heavy precipitation. In these two years the droughts occurred during the growing season, between May 1st and July 1st. However, during the growing season most years rarely received many consecutive precipitation events. In contrast some years, such as 1892 (Figure 7-15) and 1986 (Figure 7-25), had at least two weeks of consecutive precipitation events during the growing season. Several years, such as 1918 (Figure 7-18) and 1943 (Figure 7-20), had a heavy precipitation event, with at least 40 mm of rain, during the autumn.

7.2.4. Comparisons between Ottawa and Morrisburg

Time series plots of total daily precipitation were also prepared for Morrisburg (Figures 7-38 to 7-47). In recent years, both Morrisburg and Ottawa often recorded major precipitation events on the same day, for example in 1980, 1994, and 1996. However in the early part of the 20th century, Morrisburg, in some years, had heavier precipitation events. The frequency of measurable precipitation events was low in the 1930s, increased in the 1950s, and again increased in the 1980s at both stations.

The total annual amount of precipitation has not significantly changed over the 20th century. This suggests that over the last half of the century Eastern Ontario had more days with precipitation, but the amount of precipitation per event was reduced. In the 1990s there were fewer events with intermediate amounts of precipitation but more days with light or heavy

precipitation.

7.2.5. Daily Precipitation Distribution

Dry years had fewer precipitation events compared to wet years (Figures 7-54 and 7-55). Wet years had almost double the amount of precipitation. The y-scale is smaller in the ten driest years than it is in the ten wettest years (Figure 7-55). This is not due to heavier precipitation in a given day but to more days with measurable precipitation.

7.2.6. Description of the Ten Warmest, Coldest, Driest and Wettest Years

To develop possible scenarios of future climates, the ten warmest, coldest, wettest and driest years were studied. The ten warmest years typically had well-distributed precipitation throughout the year and had close to the average of 142 events. However, since the 1980s the warm years tended to have more measurable precipitation events compared to the long-term trend. Since the 1980s, the nature of precipitation events is somewhat different as well; most events were either very light or heavy, with few intermediate-sized events. Extreme events became more common. The driest and wettest years were not different in terms of growing season starting and ending dates. The ten wettest and driest years do not show any differences in their temperature shifts in the transition periods from spring to summer and from summer to fall (Figure 7-60 and Figure 7-61).

7.3. Summary

- The general form of the curve for annual temperatures is a sine wave, with minimum temperatures around day 320-360 and maximum temperatures occurring around day 180-240.
- Spring can be quite variable with rapid alternations from $<-20^{\circ}\text{C}$ to $>0^{\circ}\text{C}$ over a few

days.

- The transition to spring can be abrupt or smooth and gradual.
- Typically the mean daily air temperature rises above 0°C between days 80 and 100.
- The transition to summer is typically smooth.
- Summer can have a broad peak at its maximum temperature or its maximum temperature peaks can be composed of a few days.
- The transition from summer to fall can be sudden in some years, whereas in other years temperatures gradually decrease.
- Mean daily air temperatures typically fall below 0°C around day 300.
- As in spring, the transition from fall to winter can be smooth and gradual or abrupt.
- On average, in most years the start of the growing season is near the 105th day of the year (around mid-April) and it ends around the 295th day (last week of October).
- The length of the growing season has varied through time, but on average the growing season lasts for 192 days.
- Before 1903, between 1949-1960 and from the mid 1960s to 1998 the growing season started earlier than the long-term average.
- From 1897-1903, 1910-1920, 1946-1960, 1970-1979 and from 1984 to 1998 the growing season has been ending later than the average.
- The inter-annual variability of the length of the growing season was low before 1903, between 1920-1935, and between 1941-1960; it was high during 1903-1919, 1936-1940, the 1970s, and the 1990s.
- Most histograms show a multi-modal distribution of daily mean air temperature, usually with two dominant modes for summer and spring.
- The ten warmest years had more days with a mean daily air temperature above 20°C and

15°C compared to the ten coldest years. In addition, the ten warmest years had fewer days with a mean daily air temperature below -25°C and -30°C compared to the ten coldest years.

- The mean daily air temperature did not differ between the driest and wettest years.
- The number of days with a minimum temperature $\leq 30^{\circ}\text{C}$ has decreased through time.
- Since 1980, almost every year had few days with a minimum temperatures $\leq 30^{\circ}\text{C}$ and indeed several consecutive years do not have any.
- The number of days with a daily mean air temperature $\geq 20^{\circ}\text{C}$ and $\geq 15^{\circ}\text{C}$ showed a general increase.
- Eight out of the ten warmest years had earlier growing season onsets compared to the coldest years. In warm years the growing season generally began around the 96th day (first week of April) compared to the 114th day (last week of April) for the cold years. The growing seasons generally ended later in the warmest years also.
- The ten warmest years were more variable during the transition periods, spring and autumn, compared to the ten coldest years.
- There is no clear annual cycle in precipitation as there is for temperature.
- A typical precipitation event had less than 20 mm of precipitation, although events with greater than 80mm were recorded.
- Most years averaged 142 measurable precipitation events.
- During the growing season, most years rarely had many consecutive precipitation events.
- The total annual amount of precipitation has not significantly changed over the 20th century.
- Eastern Ontario had more days with precipitation in the second half of the century, but the amount of precipitation per event was lower.

- The frequency of measurable precipitation events tended to be low in the 1930s, increased in the 1950s and increased again in the 1980s at both Ottawa and Morrisburg.
- In the early part of the 20th century, Morrisburg, in some years, had heavier precipitation events than Ottawa.
- Since the 1980s the warm years tended to have more measurable precipitation events compared to the long-term average.
- The annual distribution of precipitation has been somewhat different since the 1980s. Most events were very either light or heavy, and there were many fewer intermediate-sized events. Extreme events became more common.
- The driest and wettest years were not different in terms of growing season starting and ending dates
- The ten wettest and driest years do not show any differences in the pattern of temperature shifts from spring to summer and from summer to fall

APPENDIX F

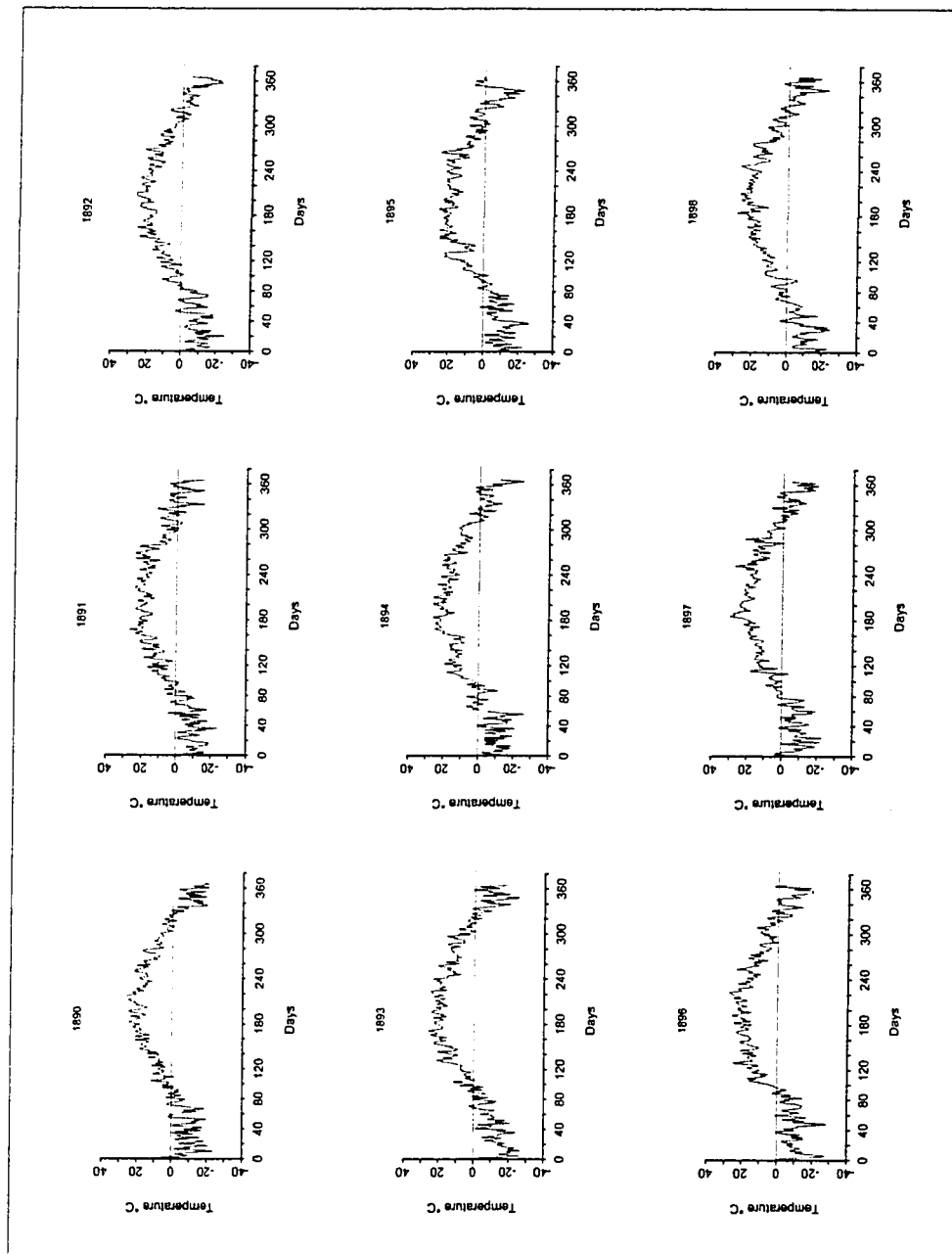


Figure 7-2 Ottawa annual temperature cycle for the years 1890 to 1898.

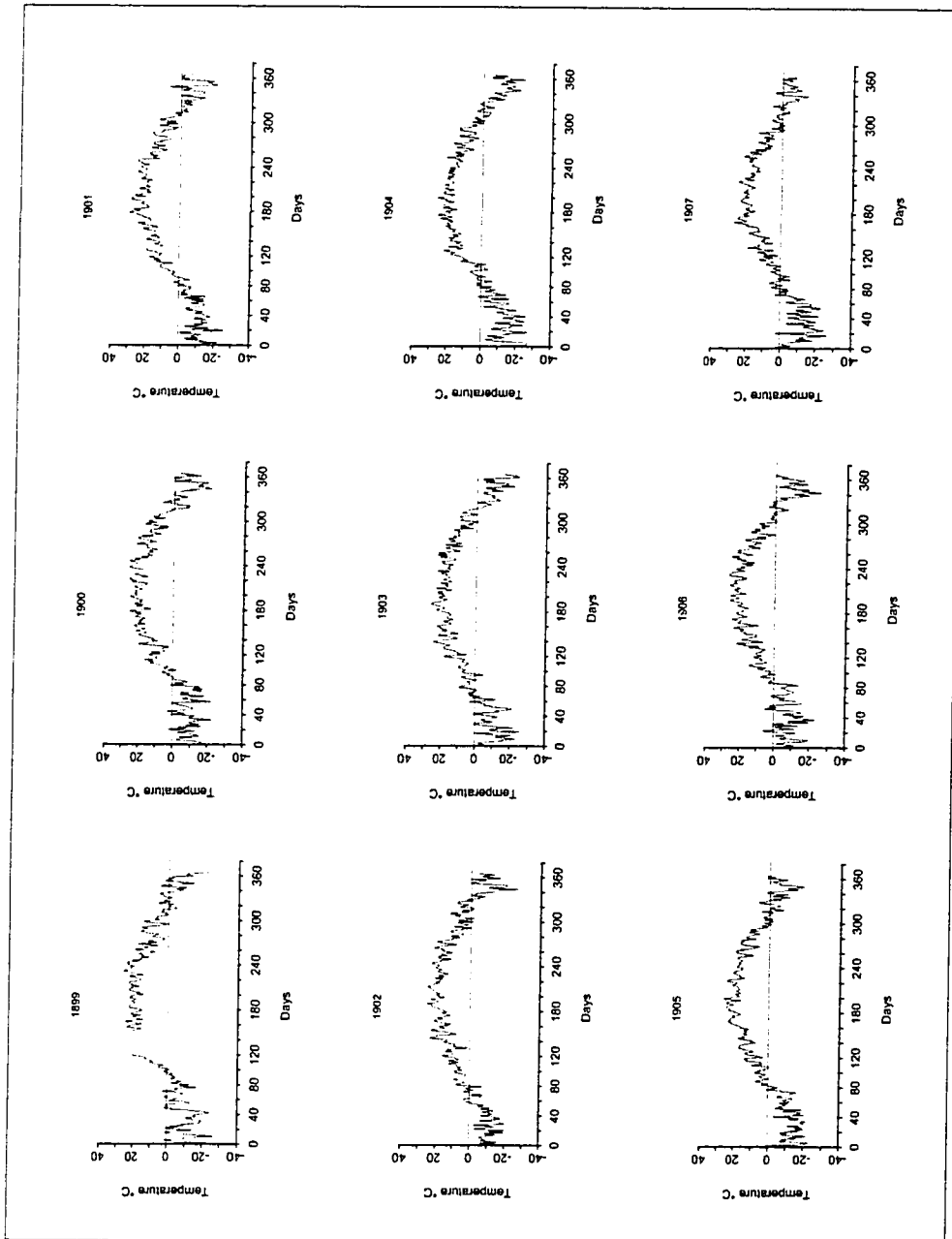


Figure 7-3 Ottawa annual temperature cycle for the years 1899 to 1907.

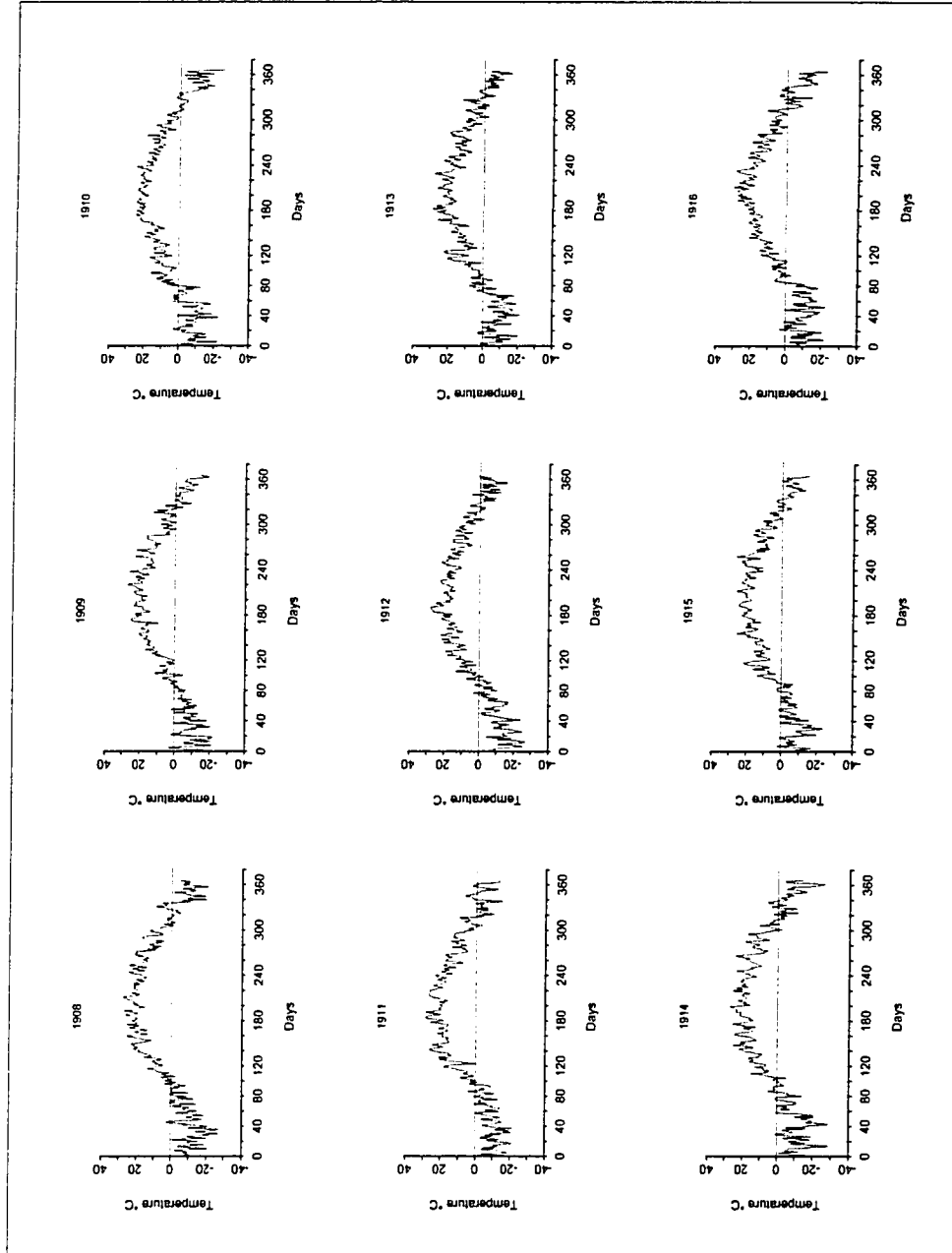


Figure 7-4 Ottawa annual temperature cycle for the years 1908 to 1916.

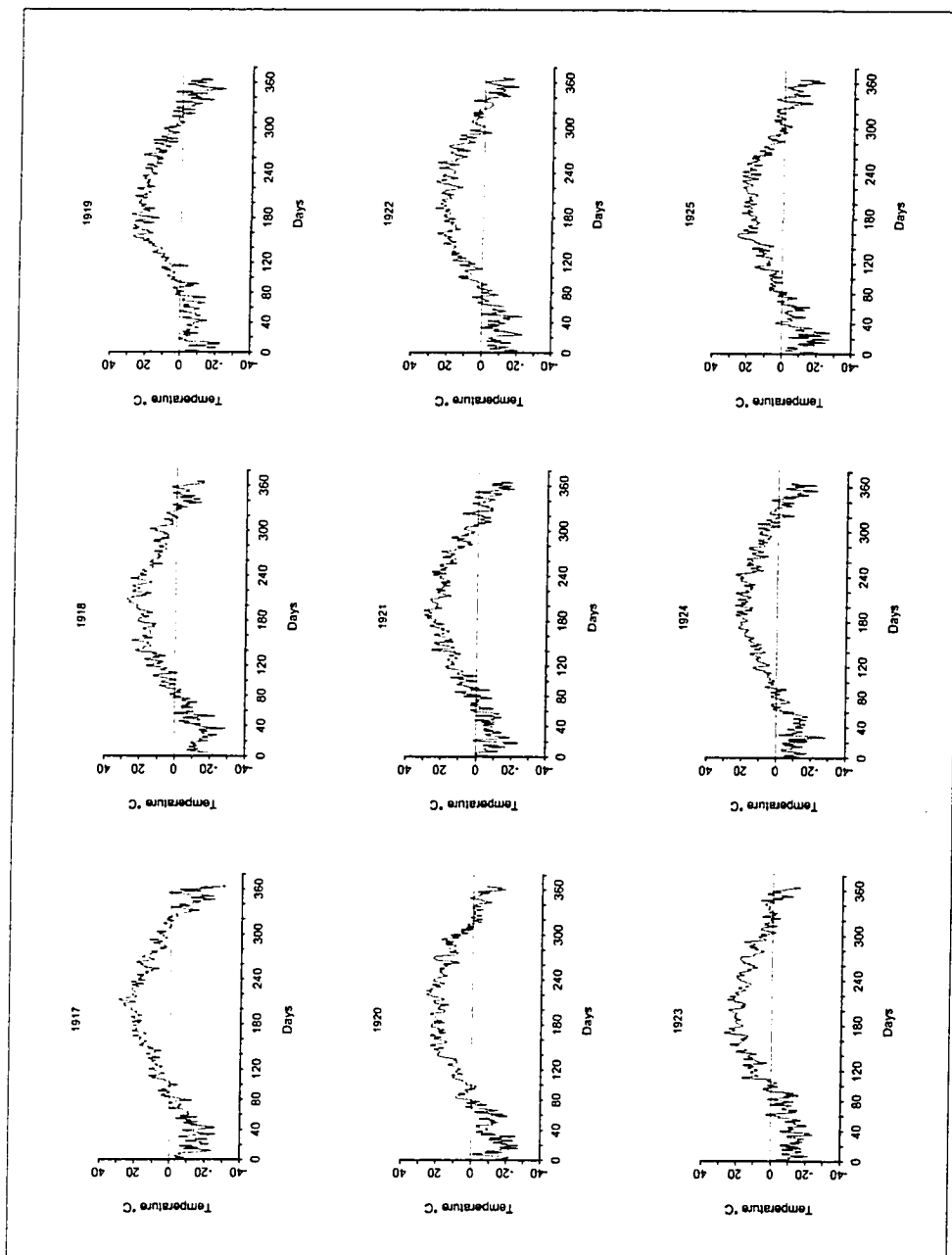


Figure 7-5 Ottawa annual temperature cycle for the years 1917 to 1925.

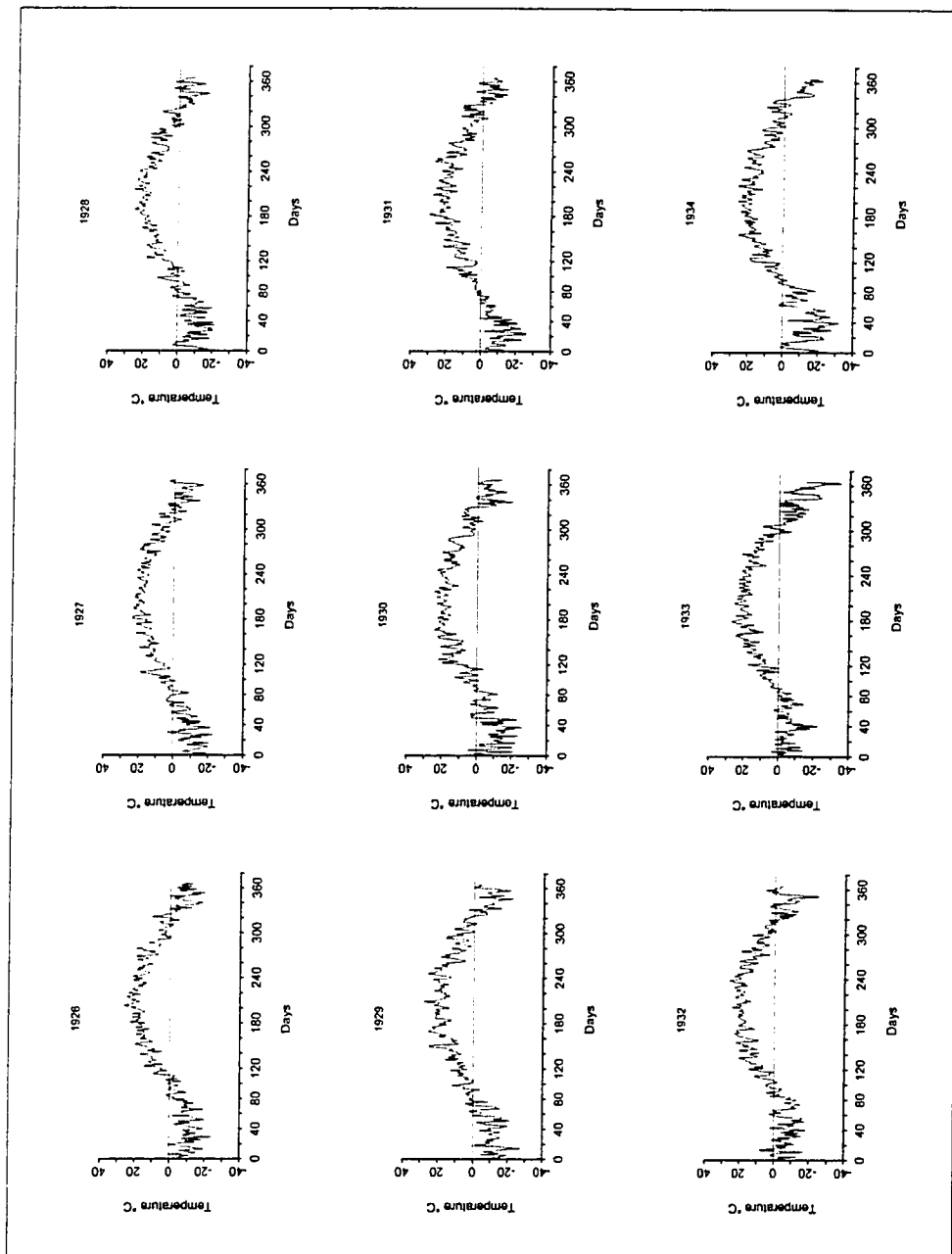


Figure 7-6 Ottawa annual temperature cycle for the years 1926 to 1934.

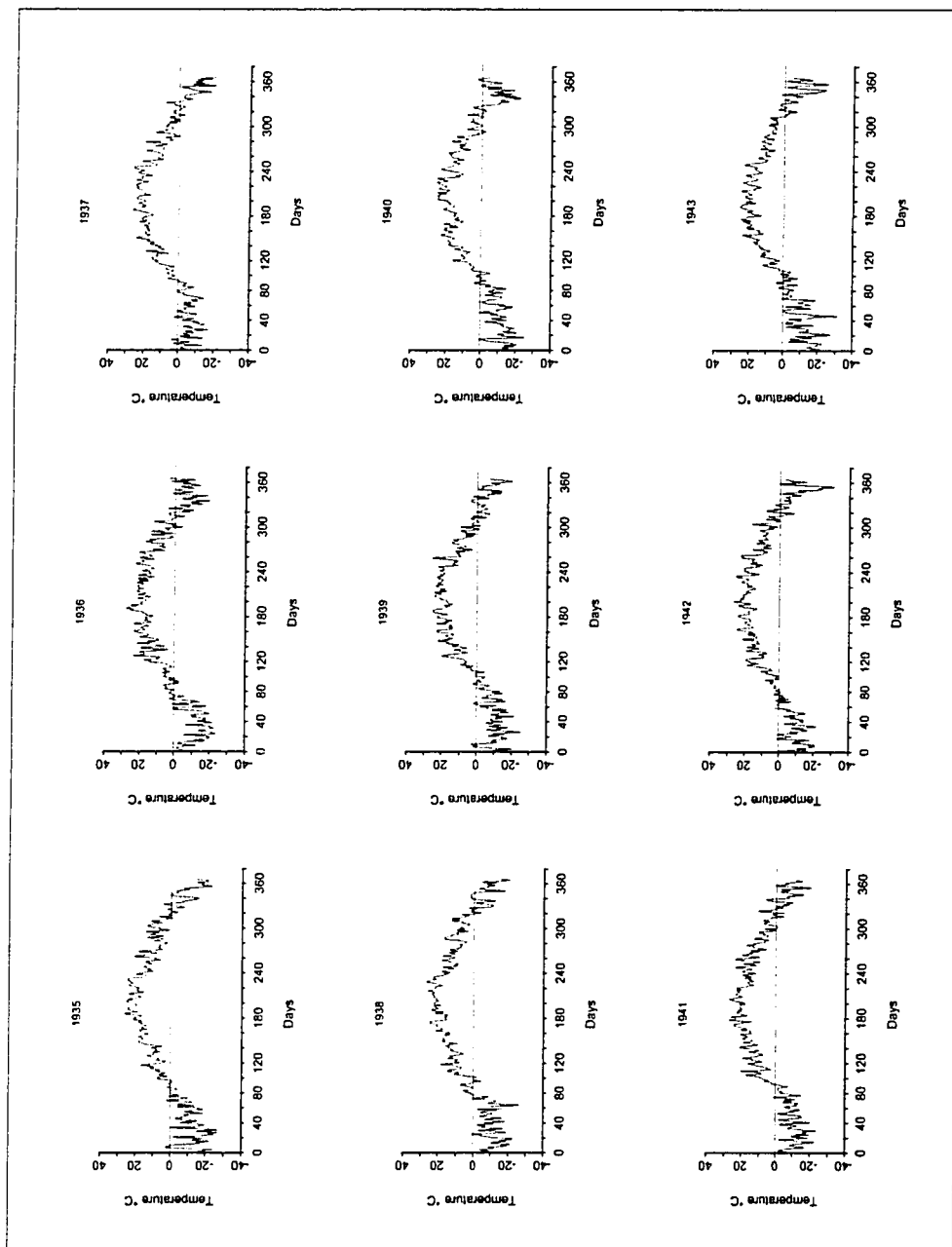


Figure 7-7 Ottawa annual temperature cycle for the years 1935 to 1943.

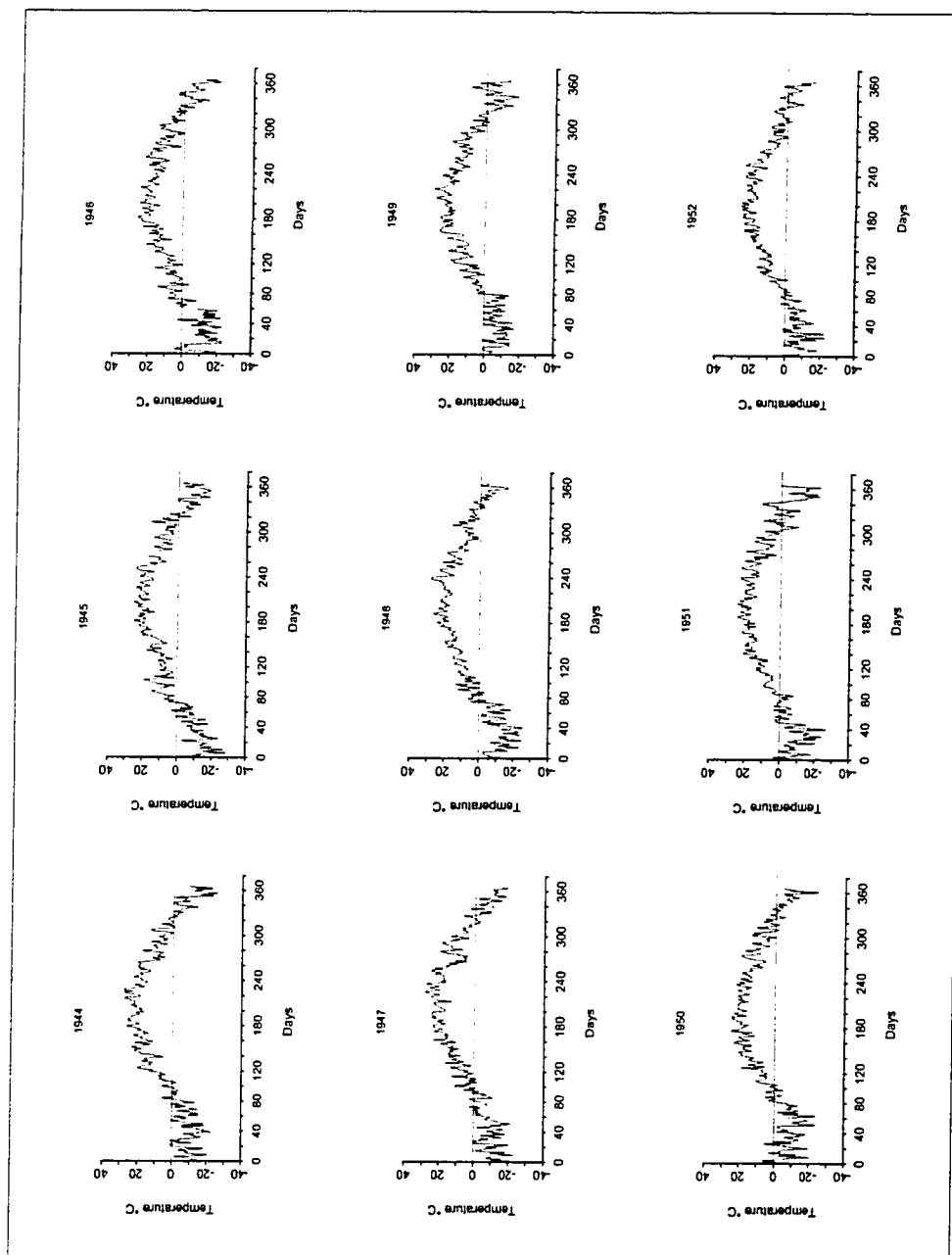


Figure 7-8 Ottawa annual temperature cycle for the years 1944 to 1952.

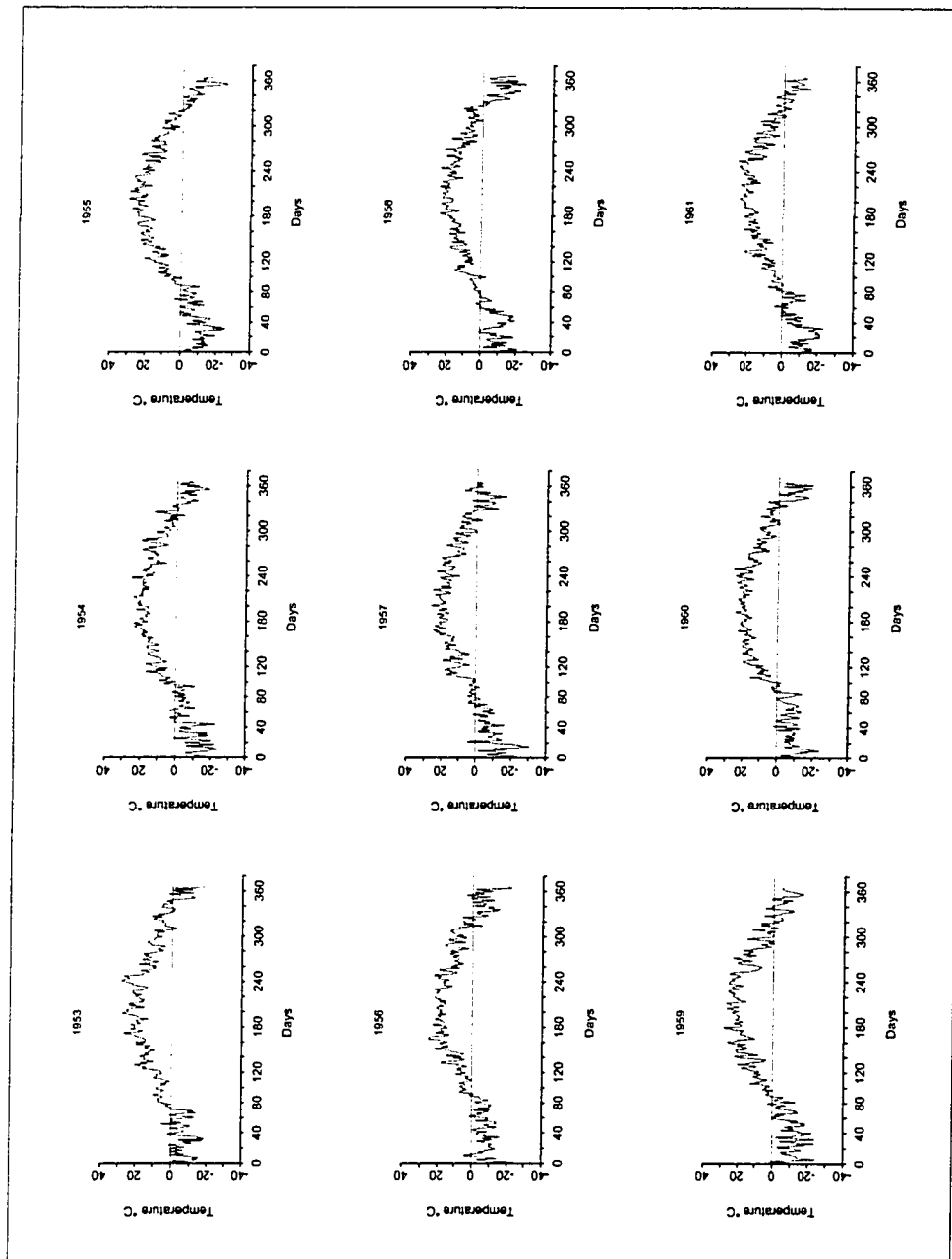


Figure 7-9 Ottawa annual temperature cycle for the years 1953 to 1961.

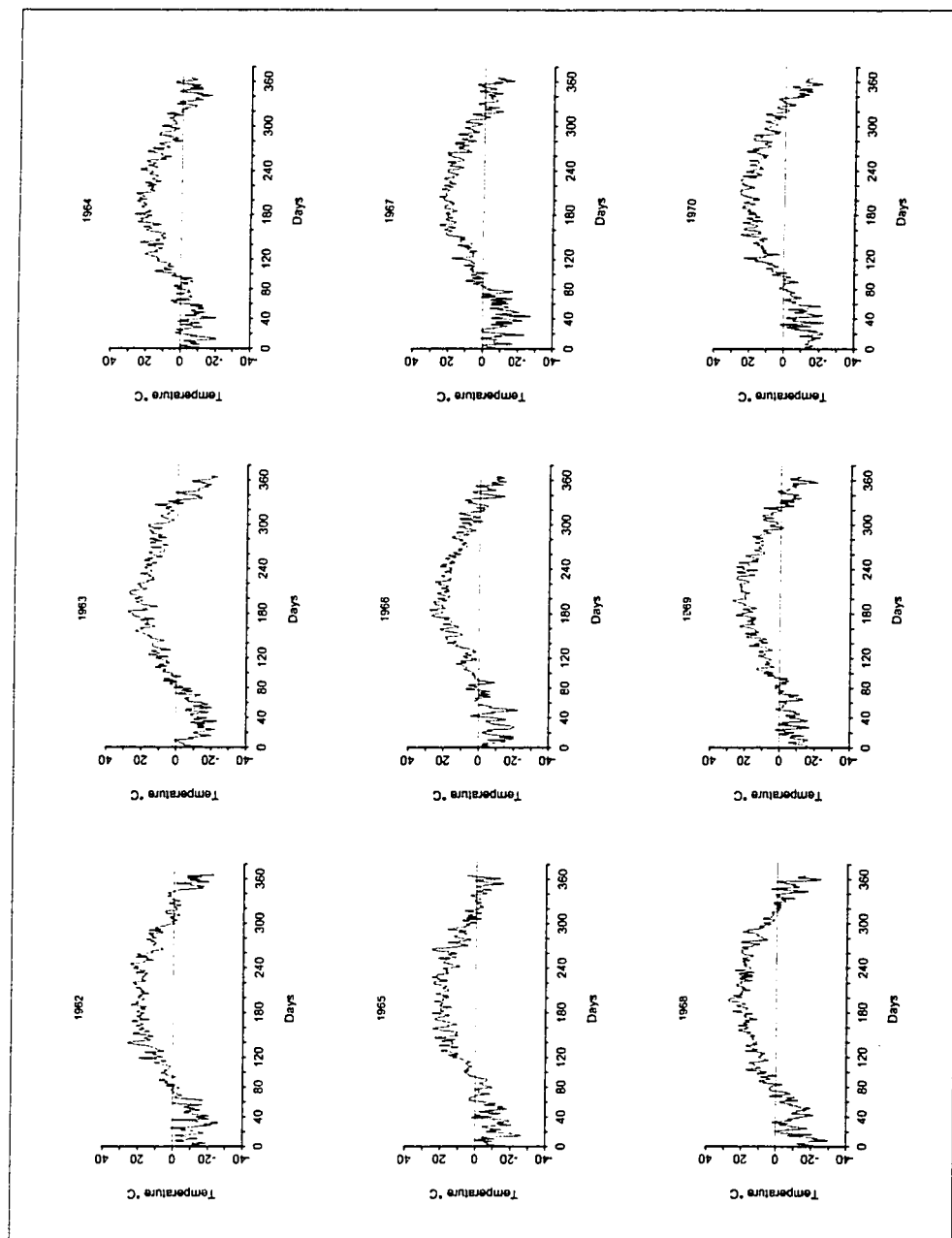


Figure 7-10 Ottawa annual temperature cycle for the years 1962 to 1970.

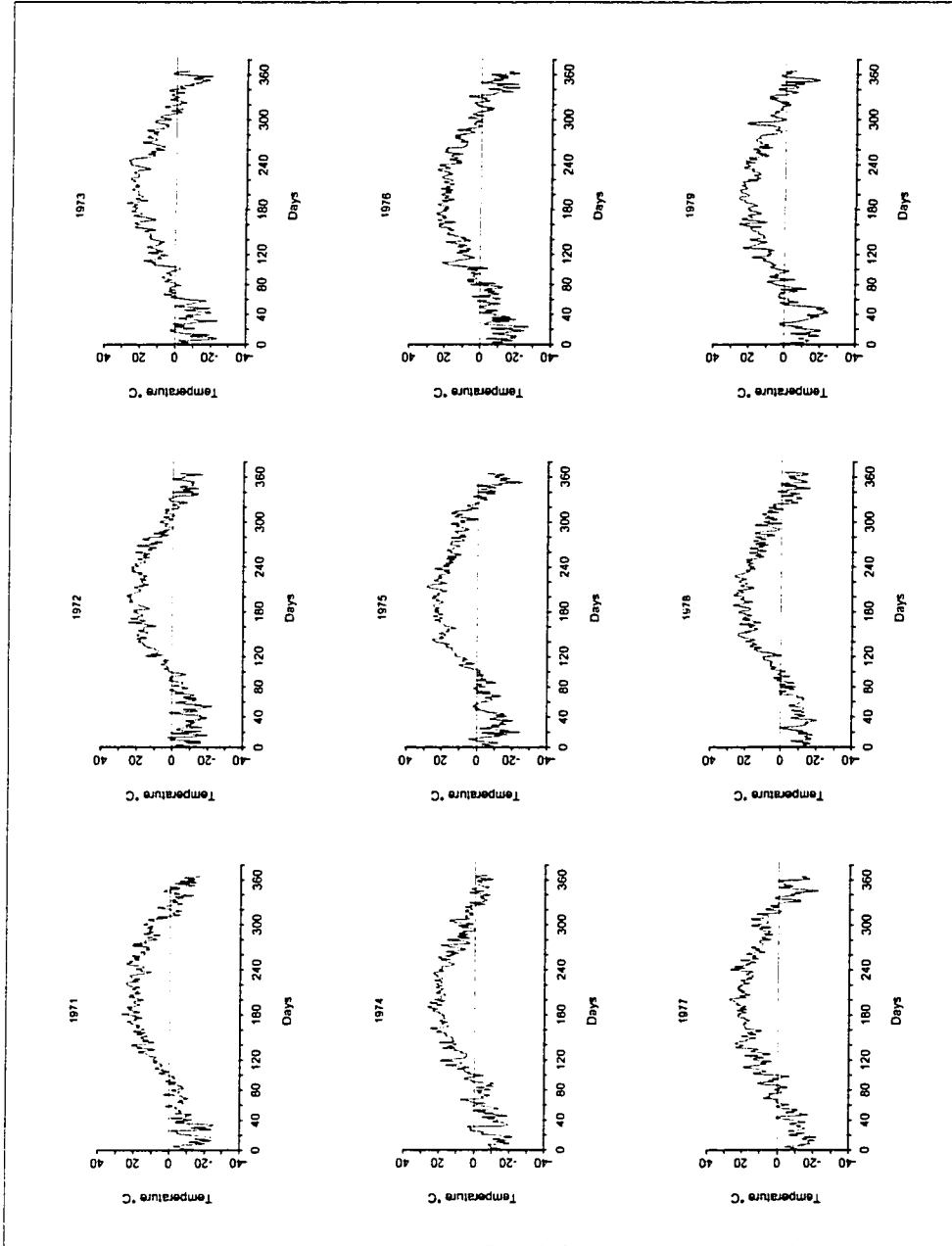


Figure 7-11 Ottawa annual temperature cycle for the years 1971 to 1979.

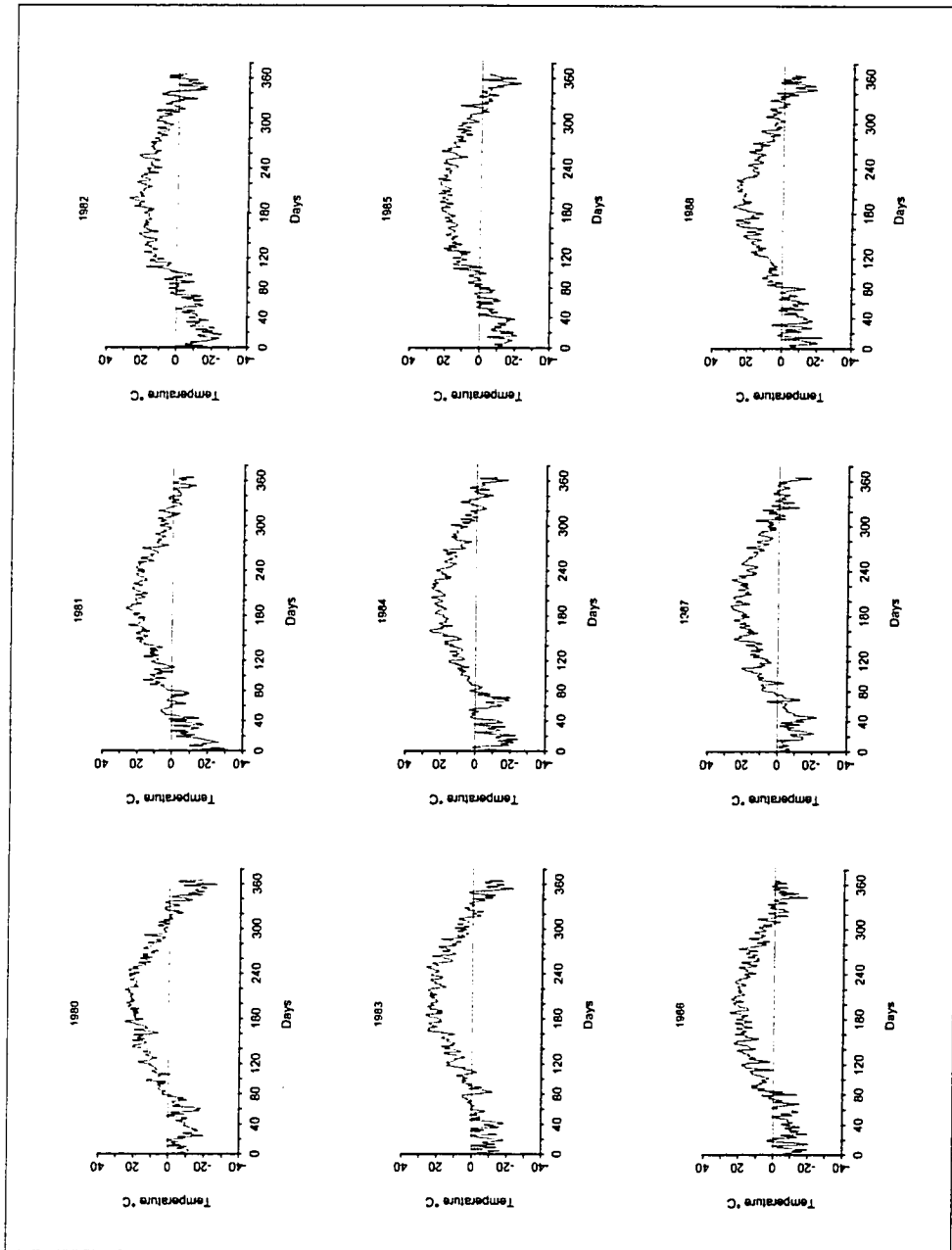


Figure 7-12 Ottawa annual temperature cycle for the years 1980 to 1988.

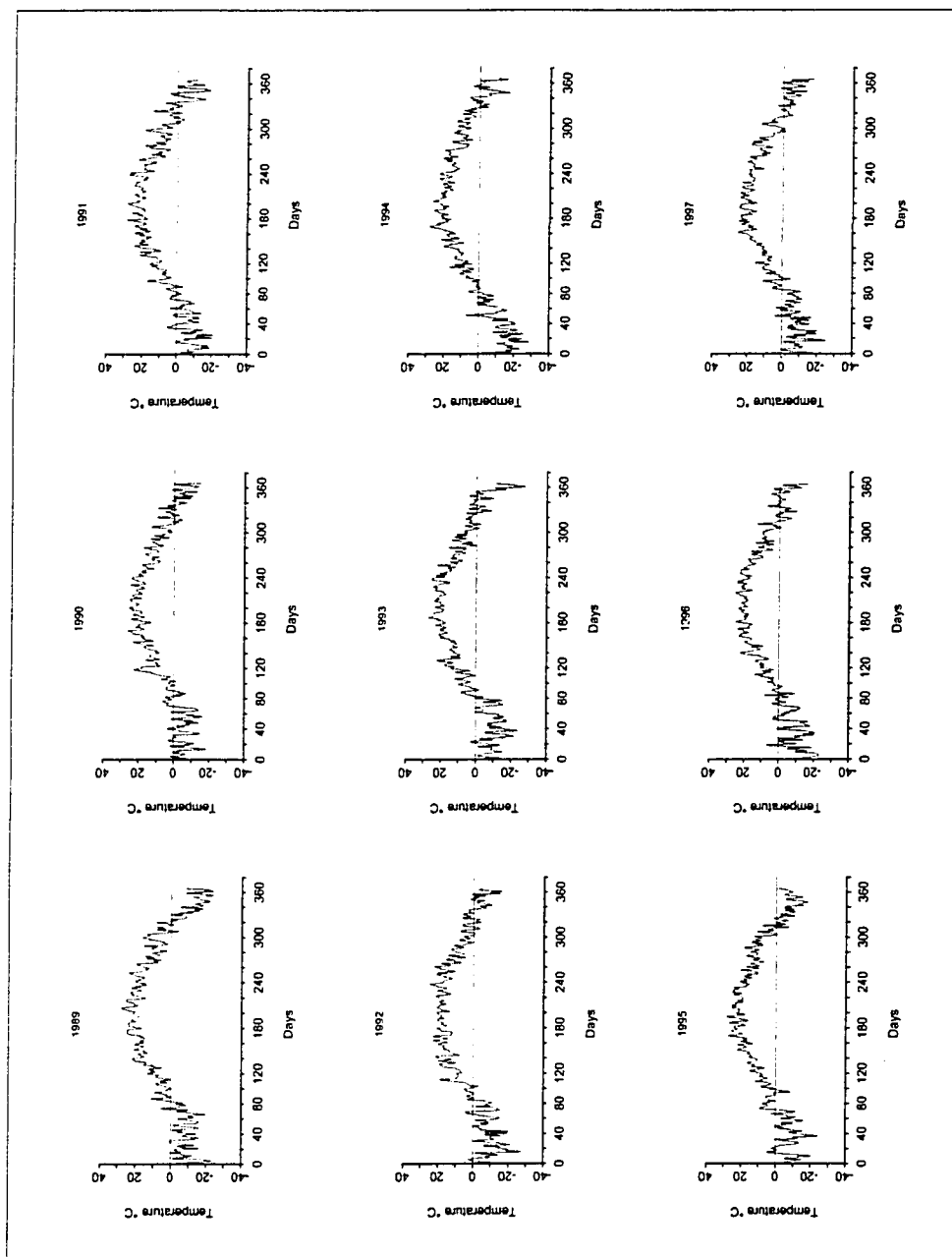


Figure 7-13 Ottawa annual temperature cycle for the years 1989 to 1997.

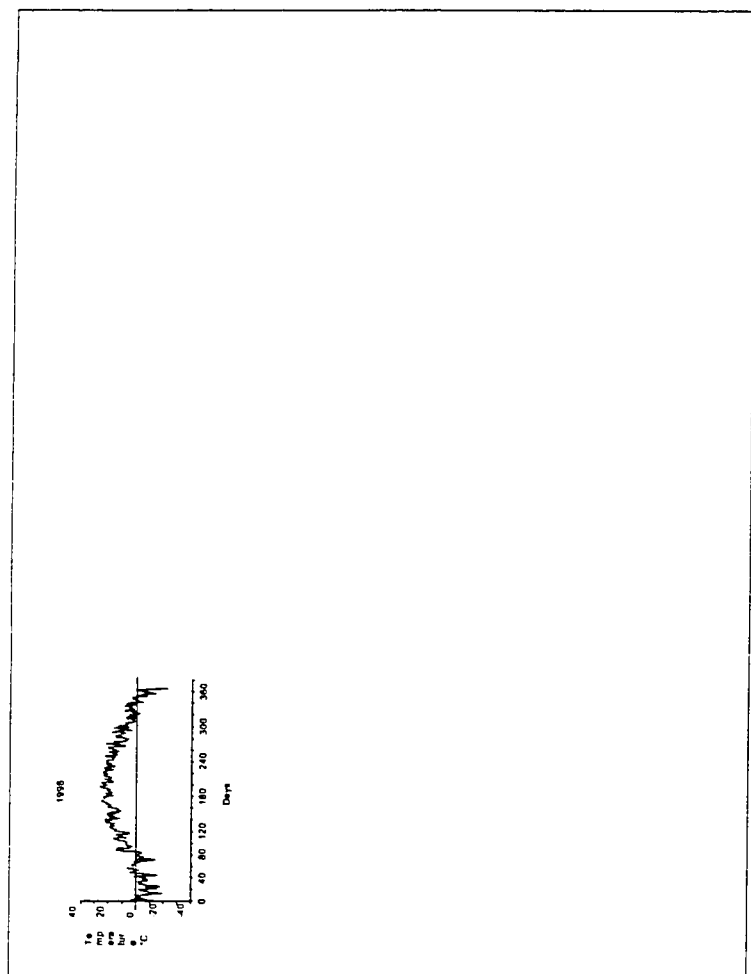


Figure 7-14 Ottawa annual temperature cycle for 1998.

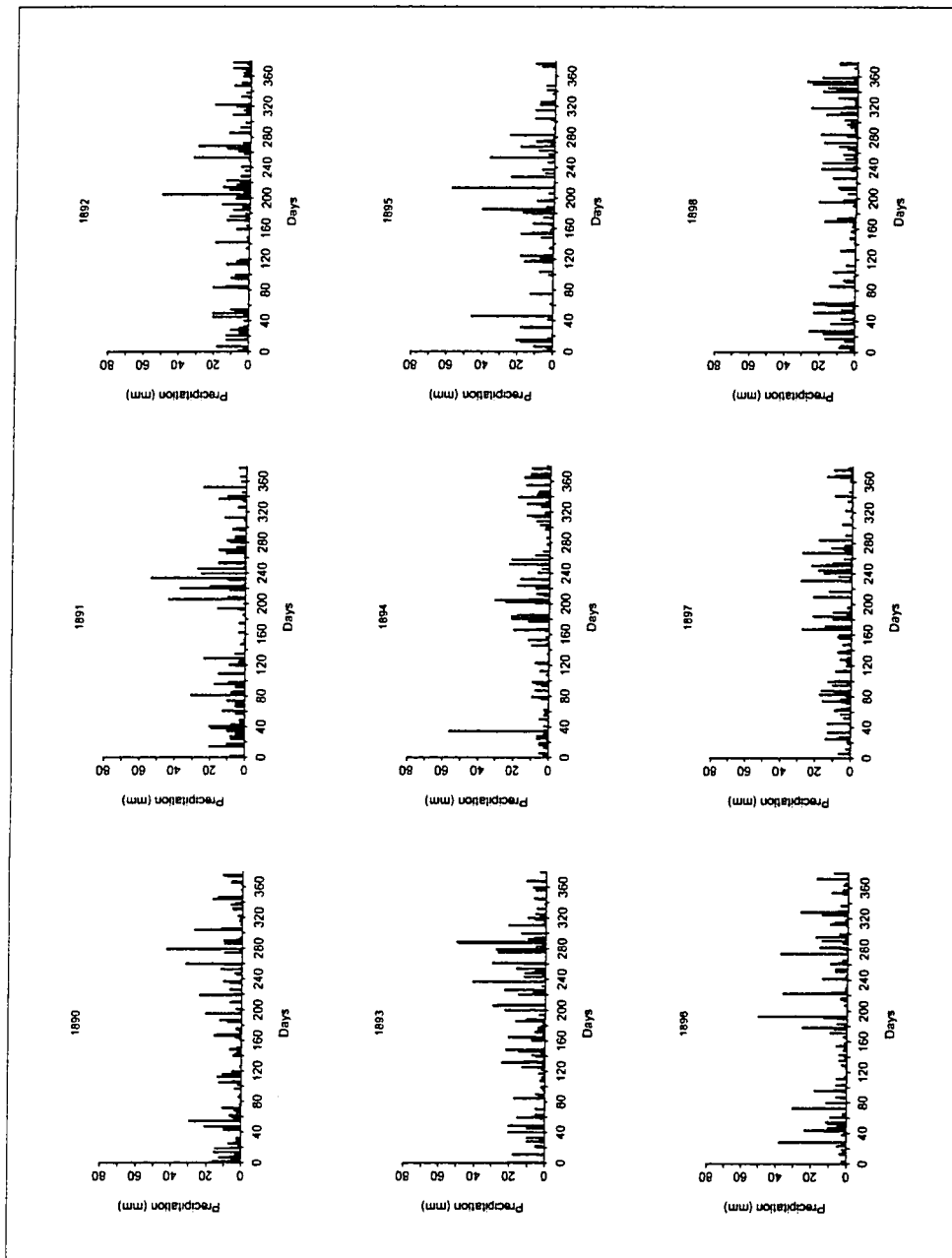


Figure 7-15 Ottawa annual precipitation events for the years 1890 to 1898.

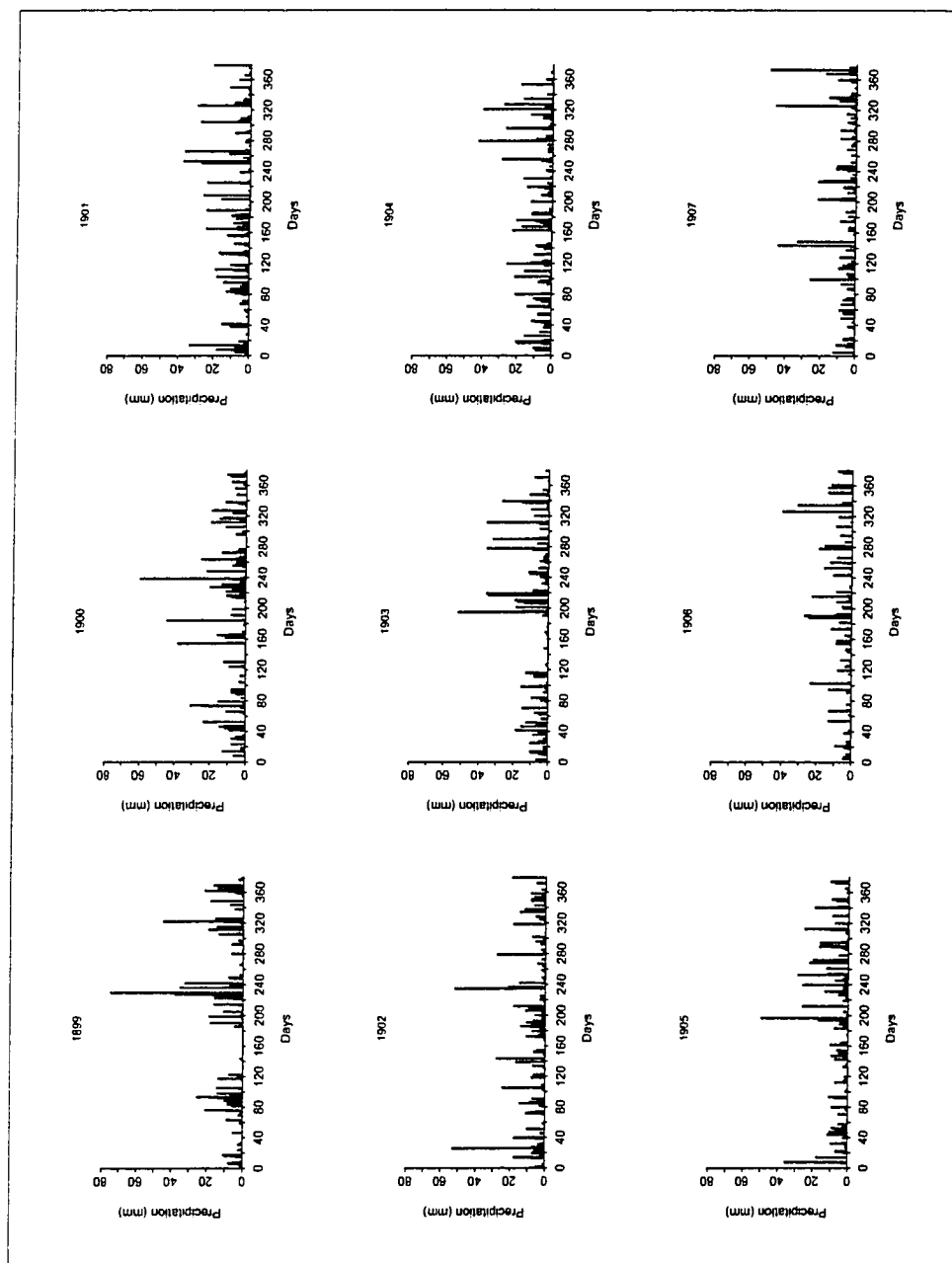


Figure 7-16 Ottawa annual precipitation events for the years 1899 to 1907.

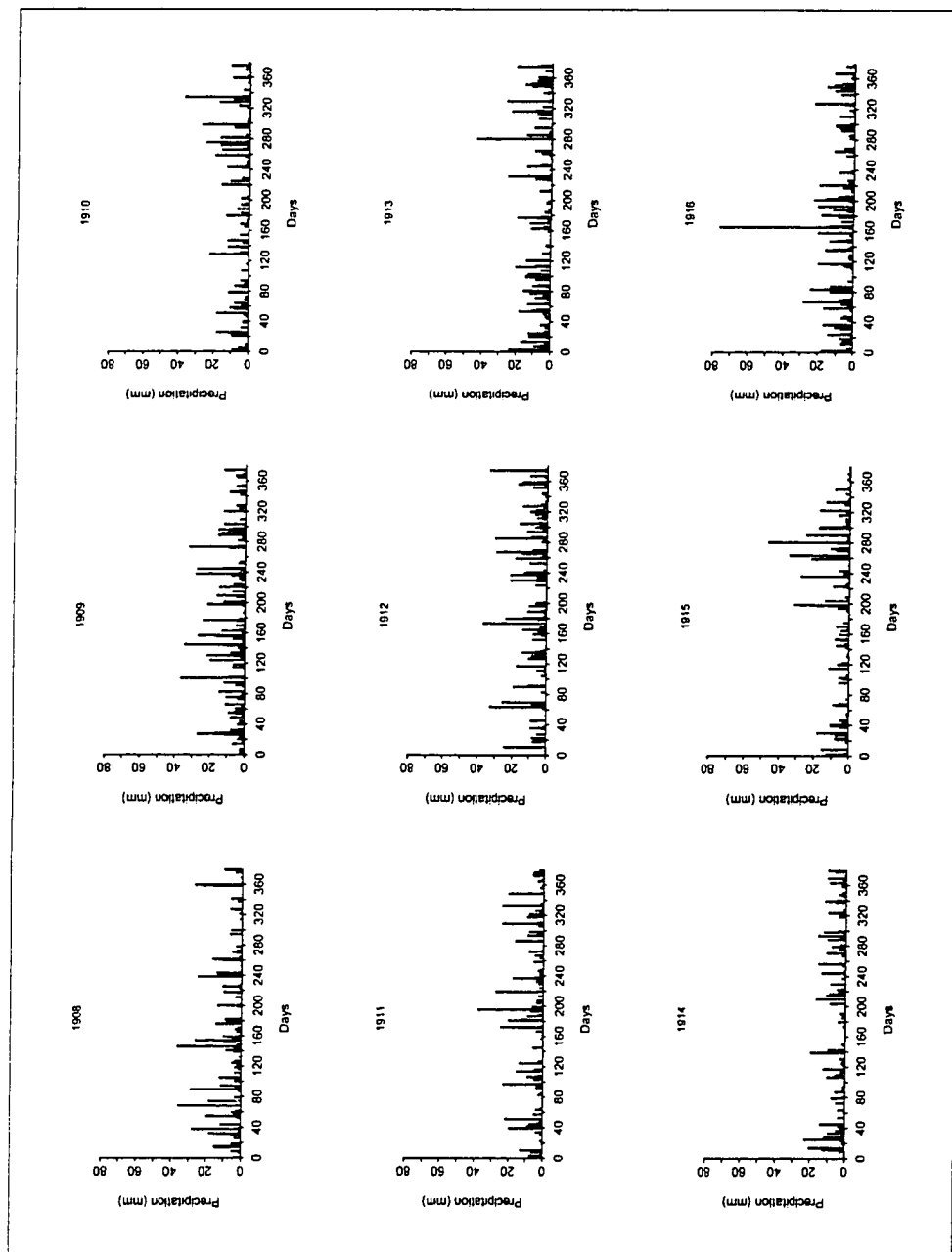


Figure 7-17 Ottawa annual precipitation events for the years 1908 to 1916.

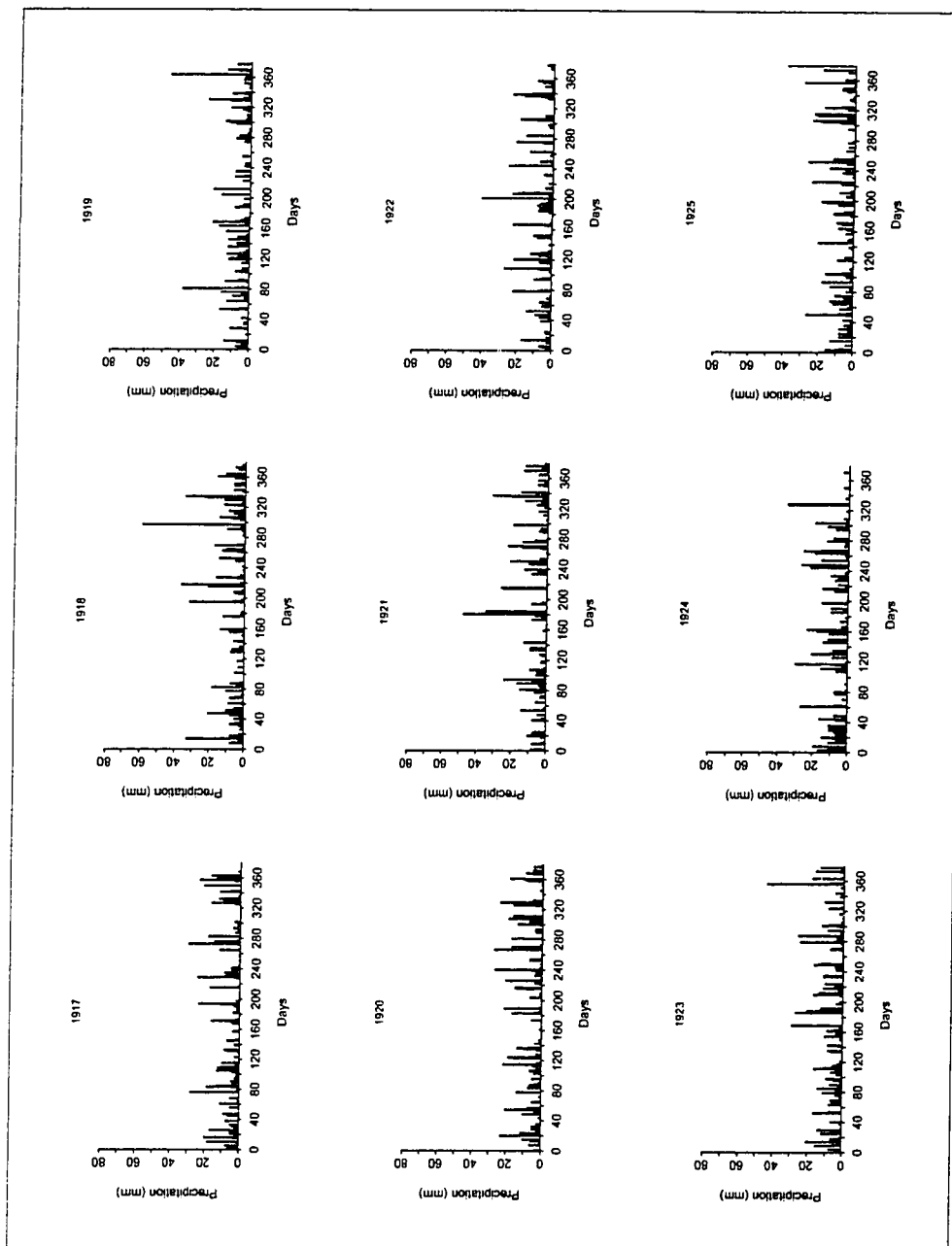


Figure 7-18 Ottawa annual precipitation events for the years 1917 to 1925.

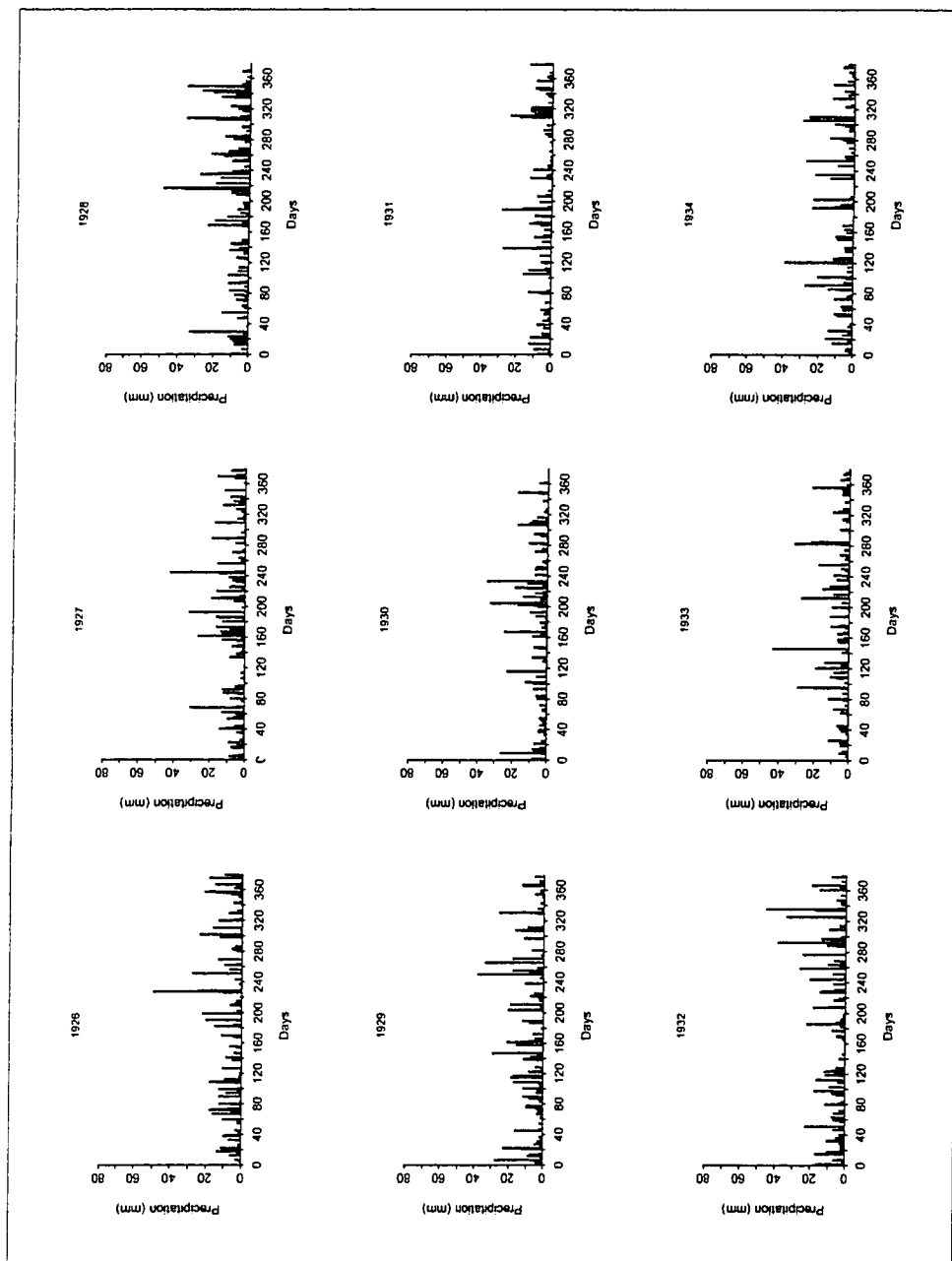


Figure 7-19 Ottawa annual precipitation events for the years 1926 to 1934.

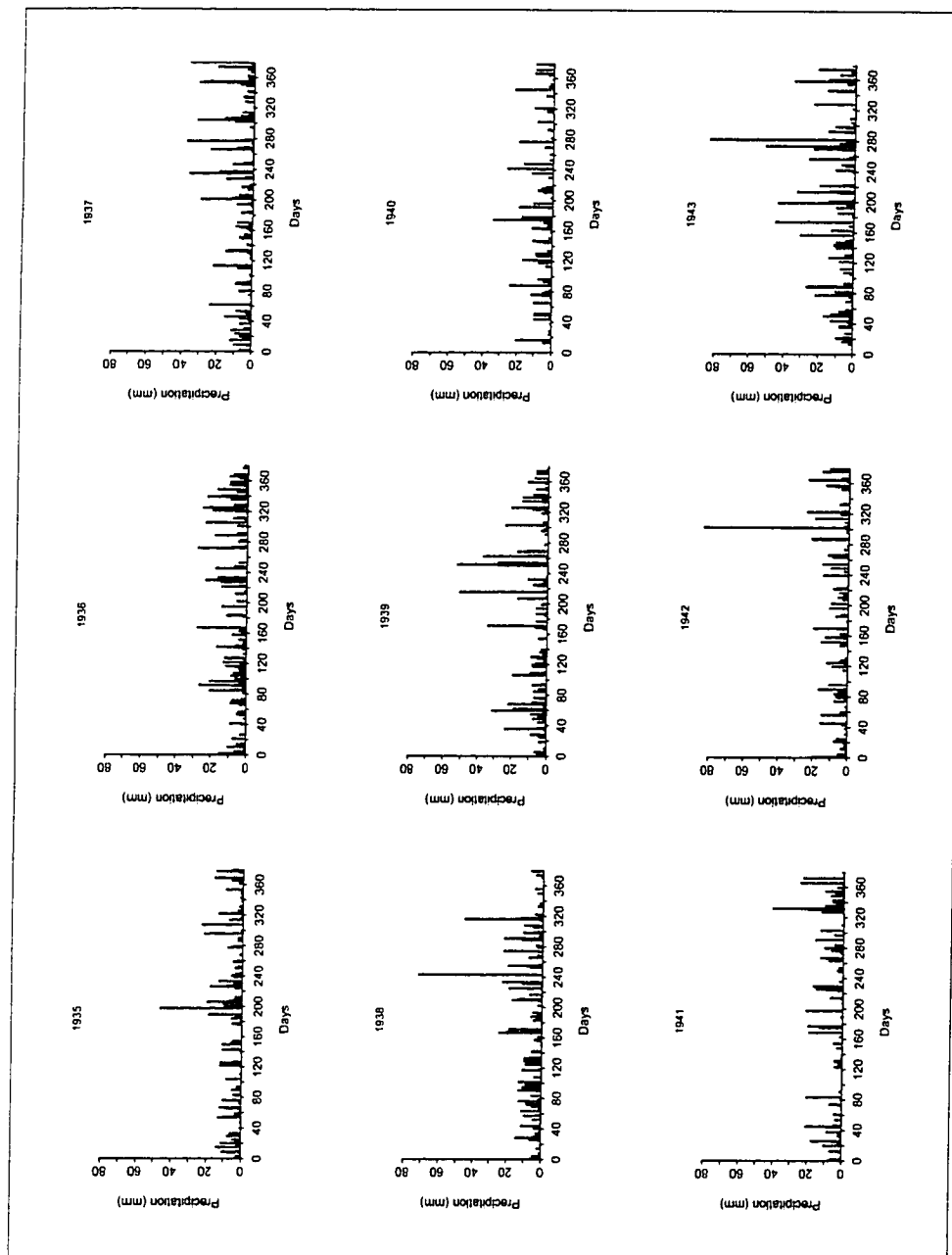


Figure 7-20 Ottawa annual precipitation events for the years 1935 to 1943.

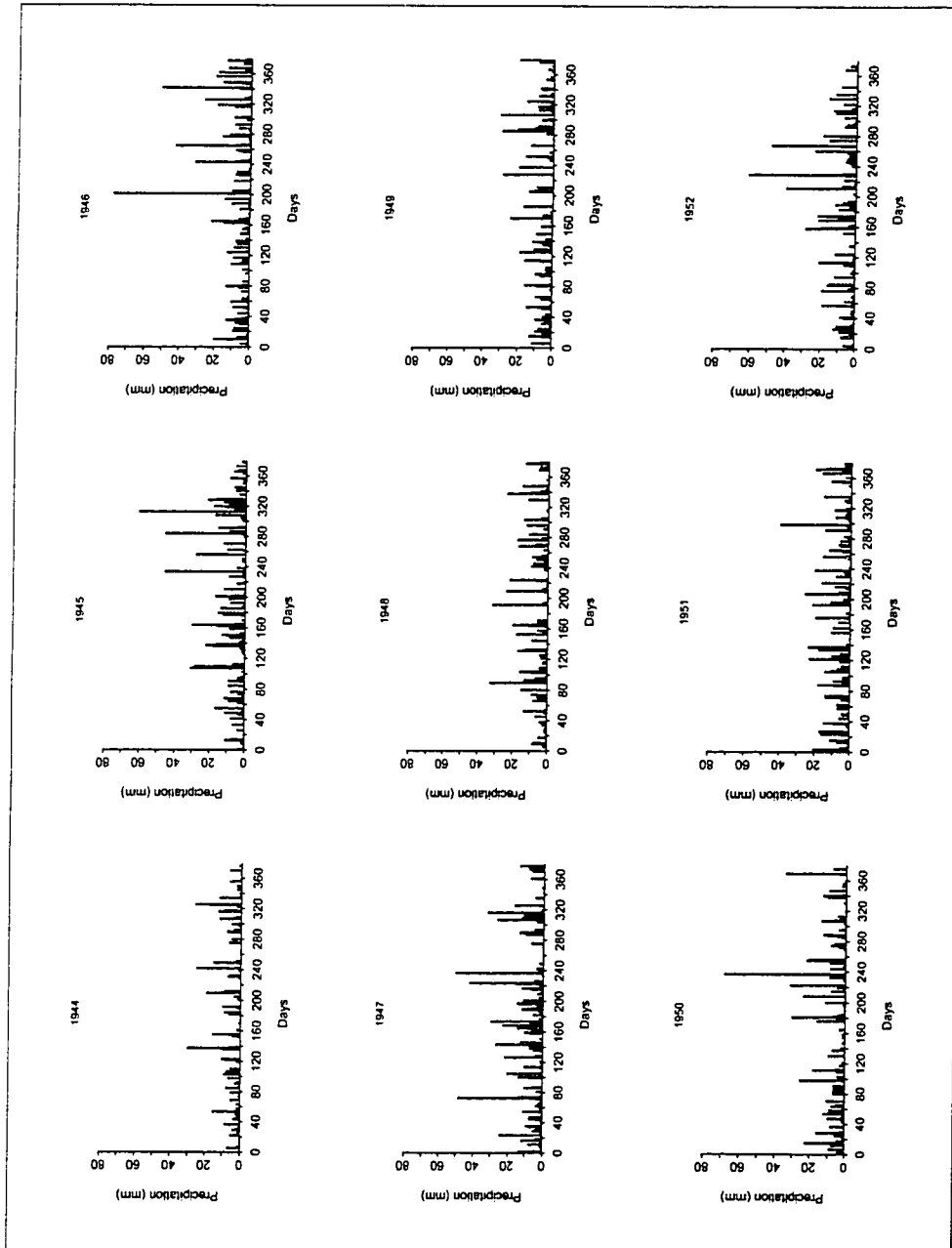


Figure 7-21 Ottawa annual precipitation events for the years 1944 to 1952.

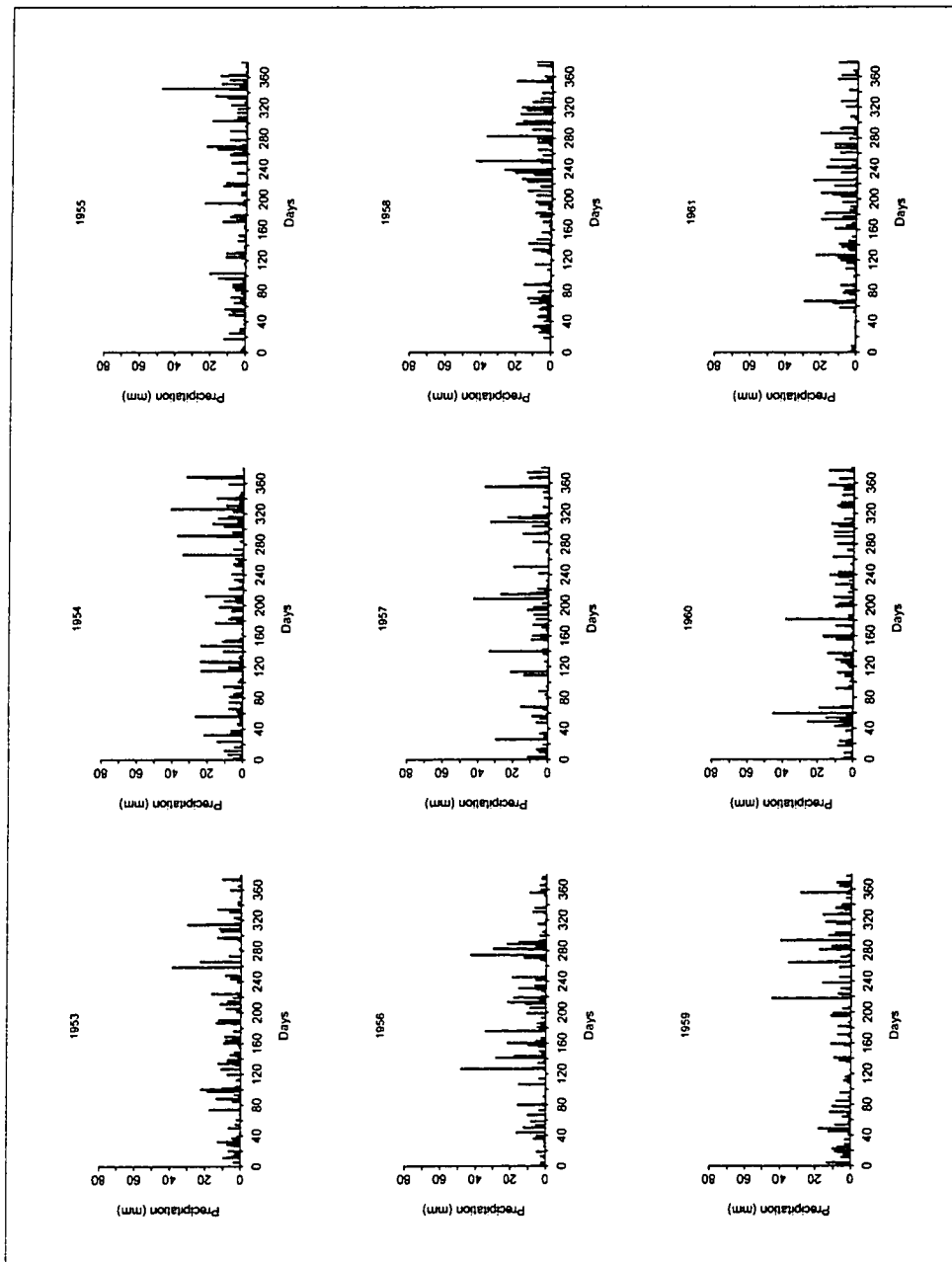


Figure 7-22 Ottawa annual precipitation events for the years 1953 to 1961.

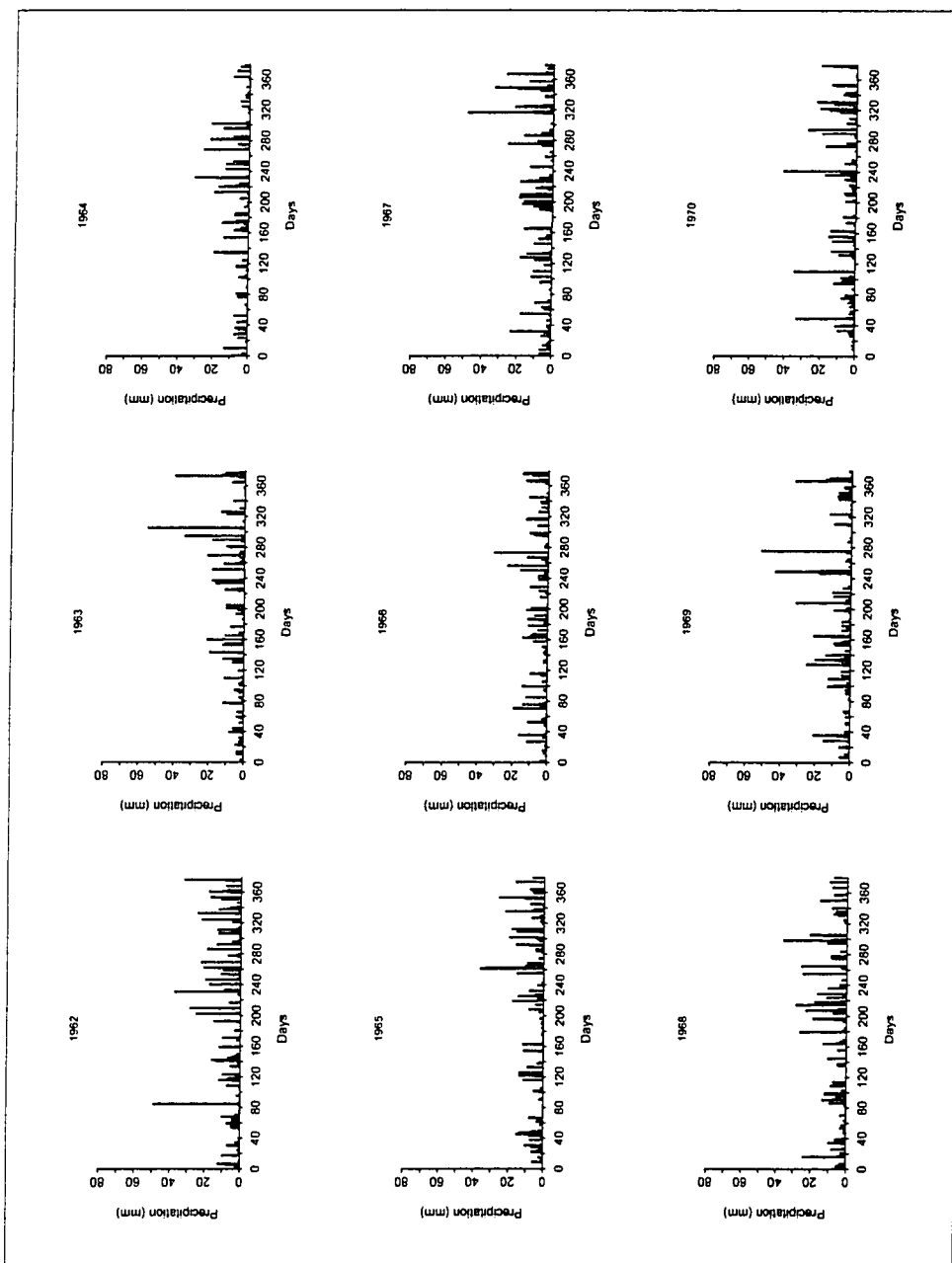


Figure 7-23 Ottawa annual precipitation events for the years 1962 to 1970.

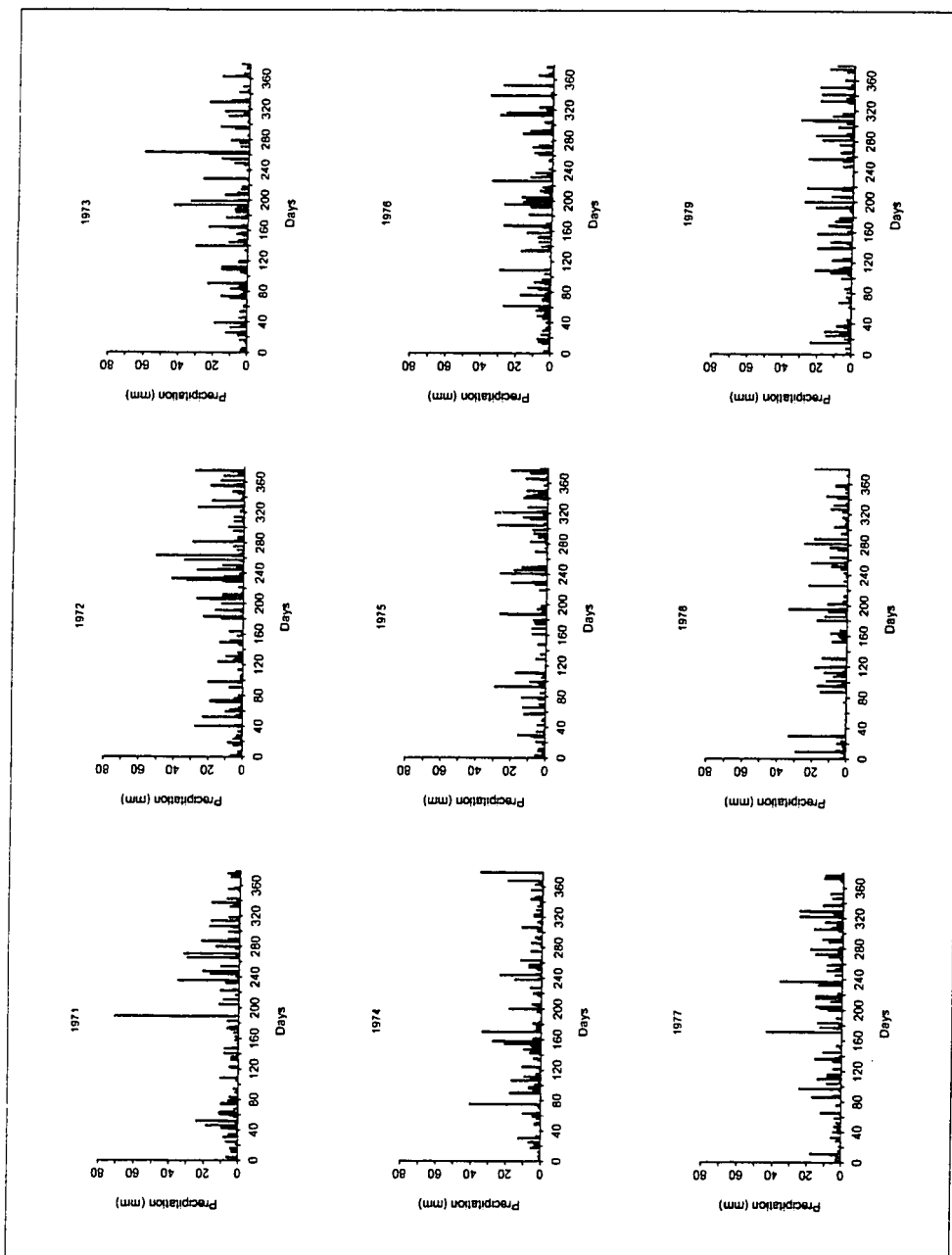


Figure 7-24 Ottawa annual precipitation events for the years 1971 to 1979.

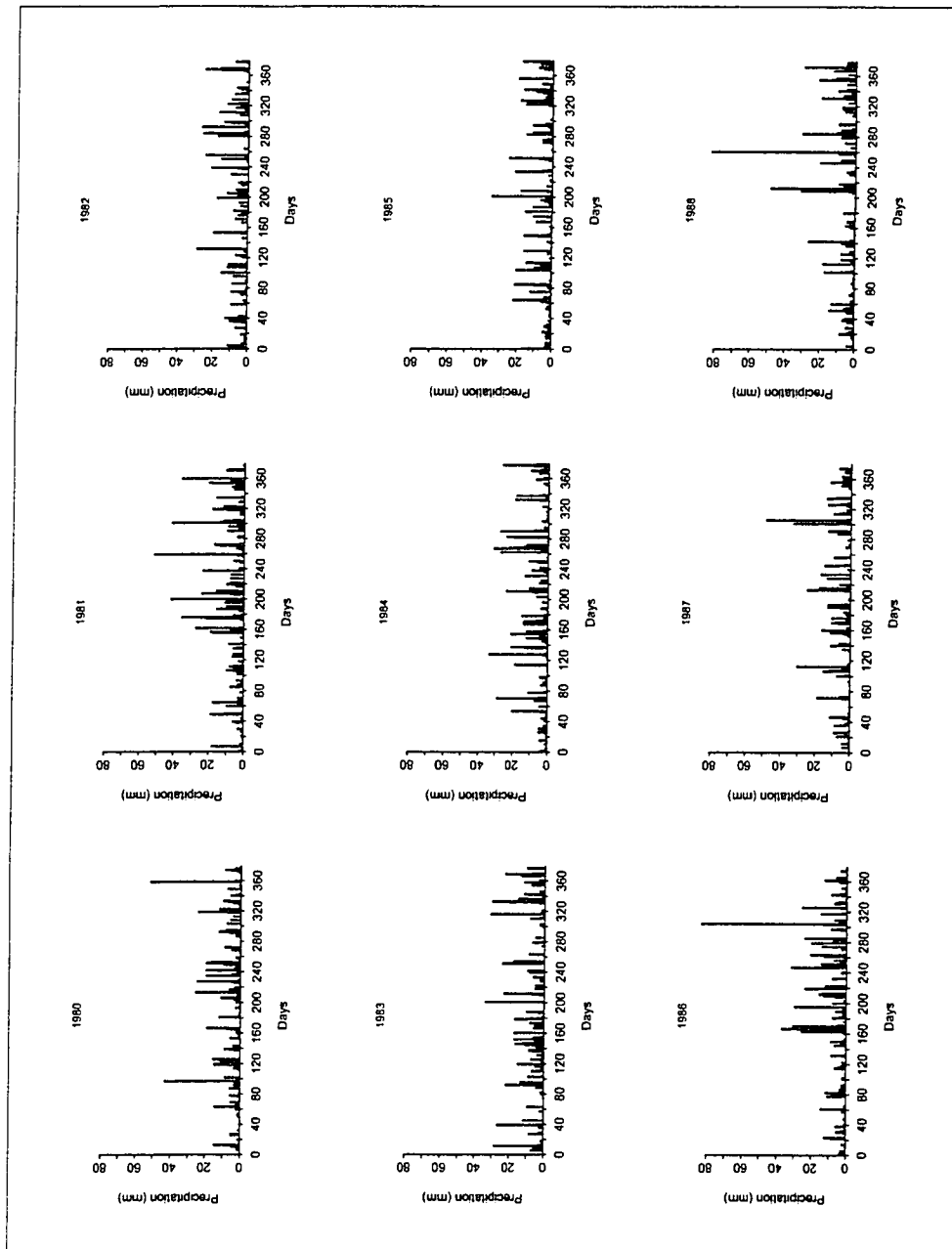


Figure 7-25 Ottawa annual precipitation events for the years 1980 to 1988.

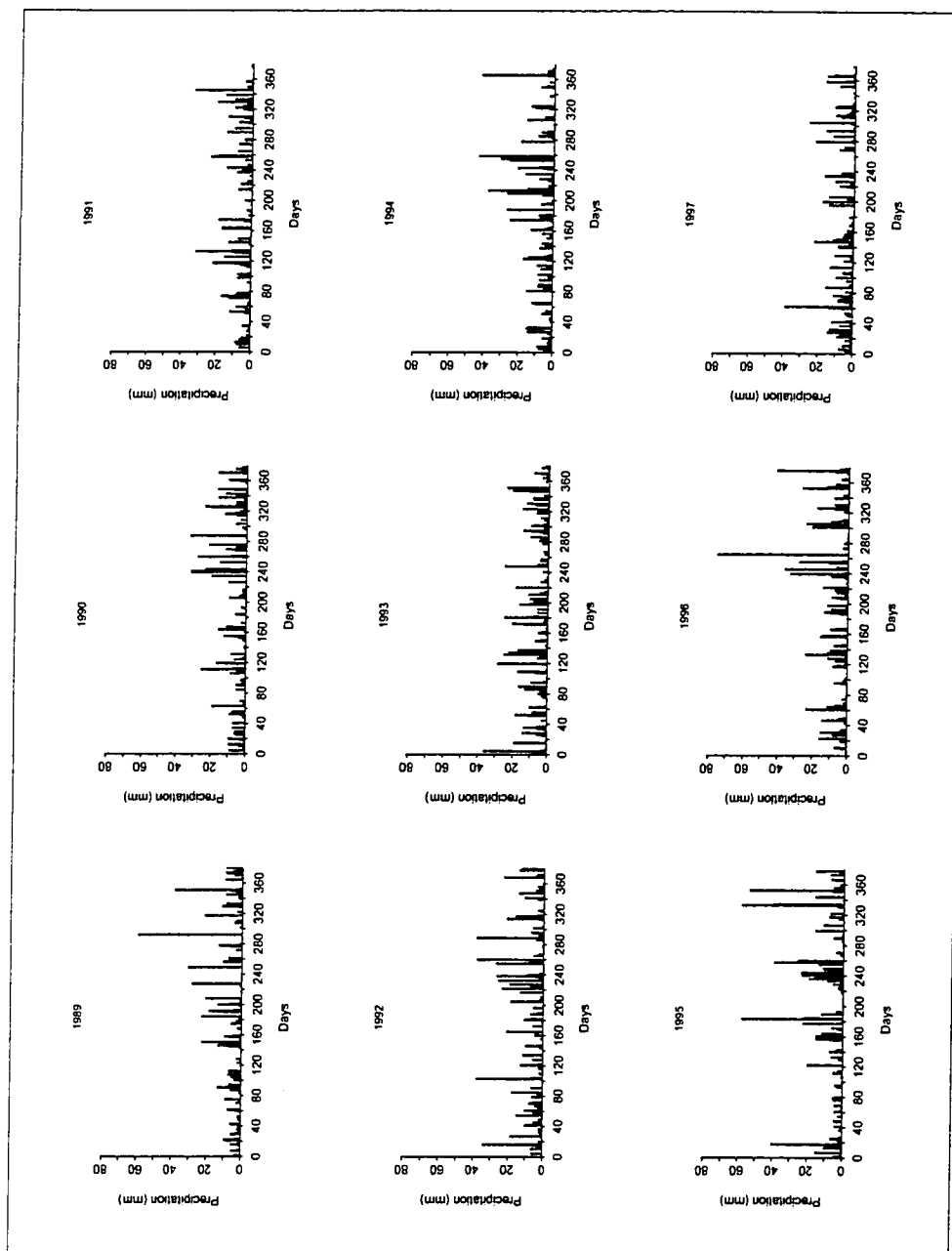


Figure 7-26 Ottawa annual precipitation events for the years 1989 to 1997.

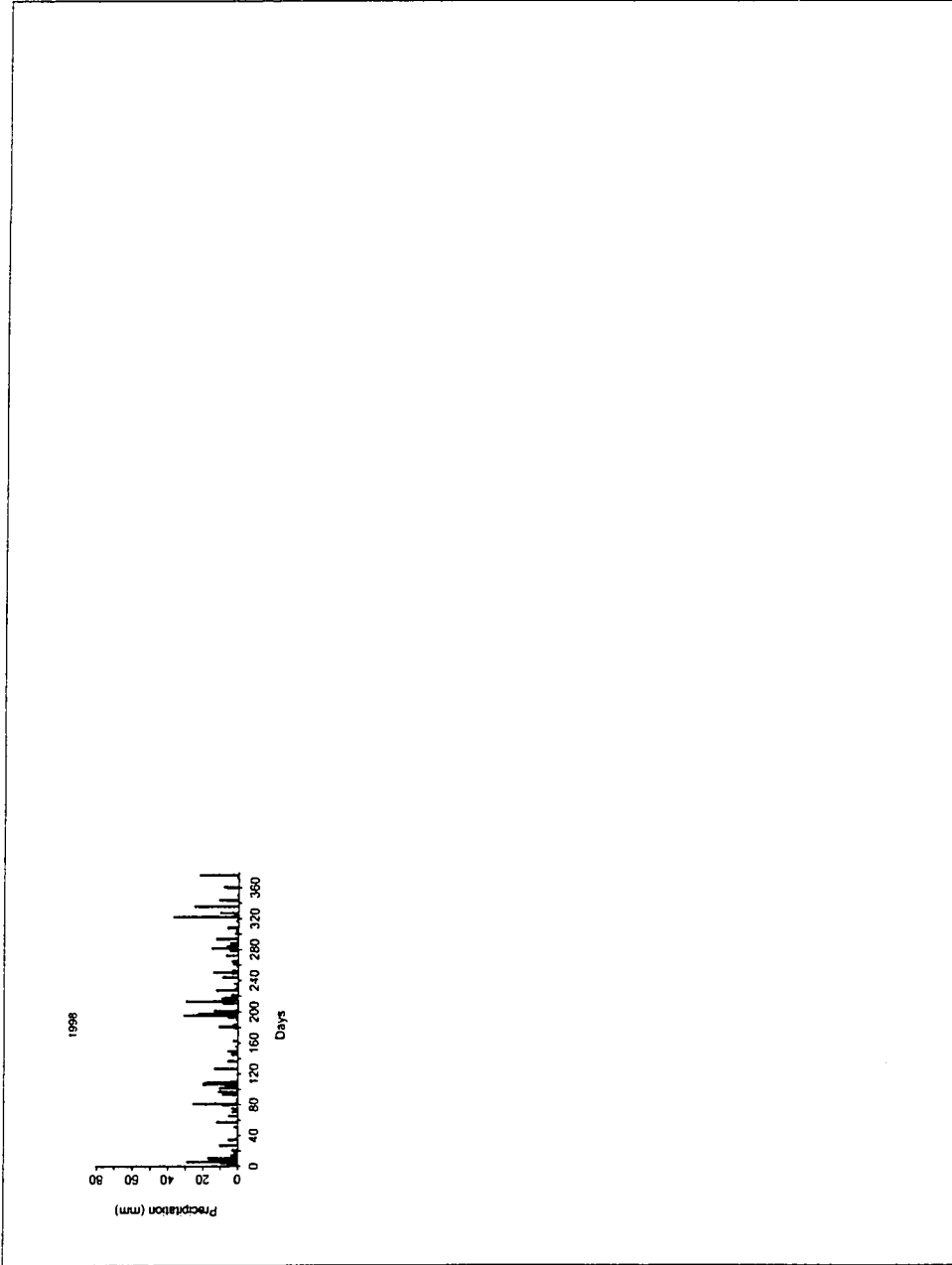


Figure 7-27 Ottawa annual precipitation Events for 1998.

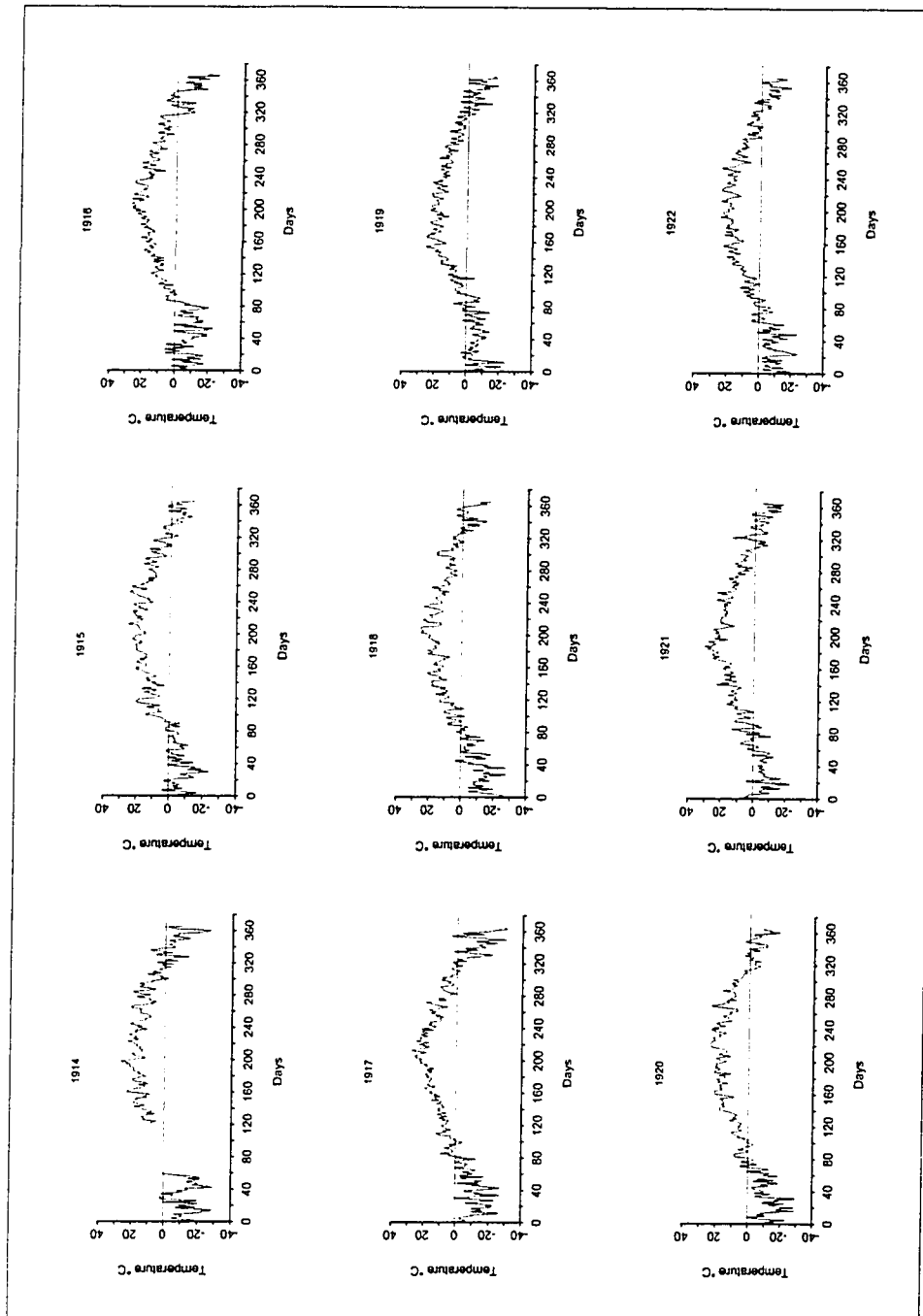


Figure 7-28 Morrisburg annual temperature cycle for the years 1914 to 1922.

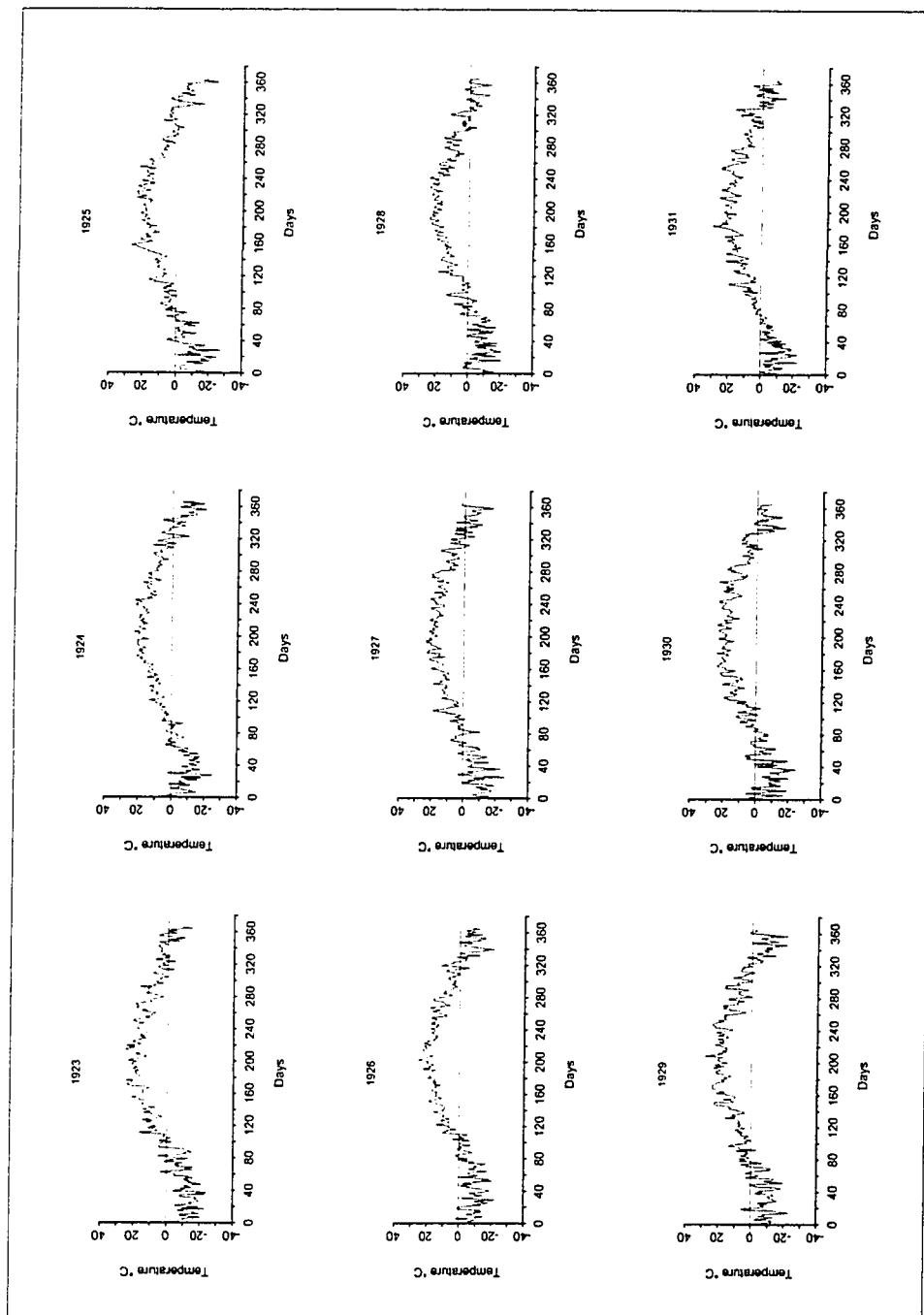


Figure 7-29 Morrisburg annual temperature cycle for the years 1923 to 1931.

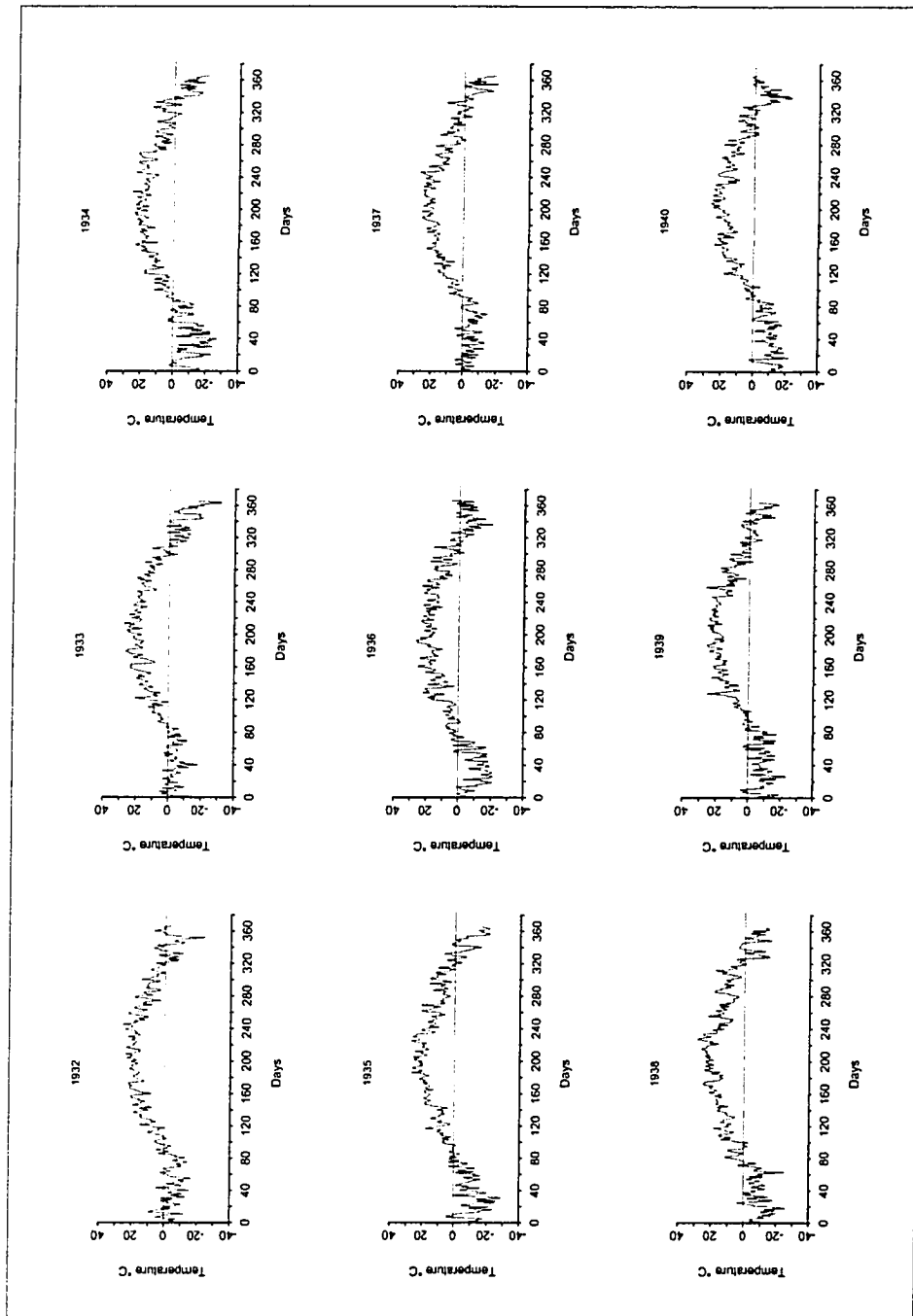


Figure 7-30 Morrisburg annual temperature cycle for the years 1932 to 1940.

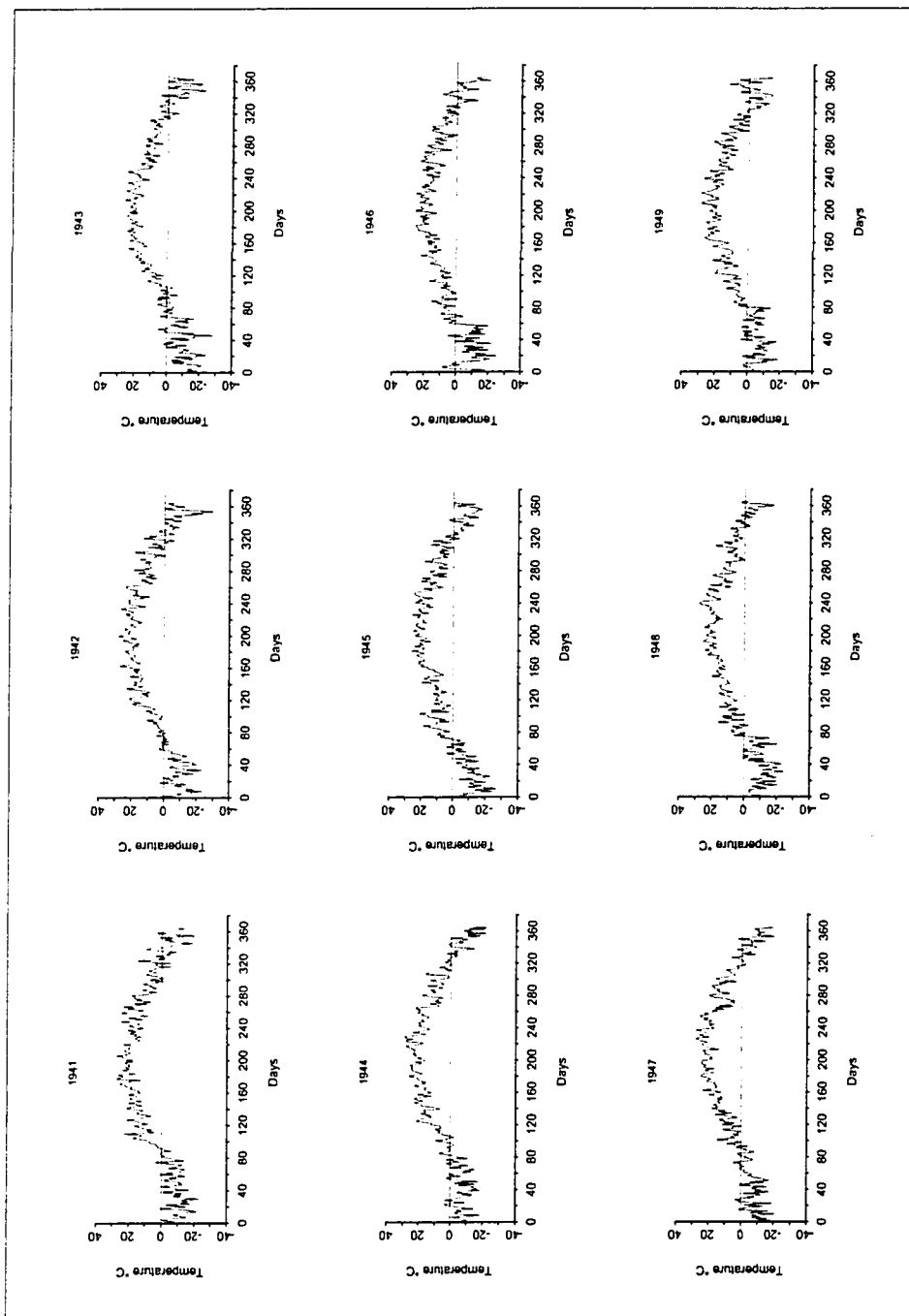


Figure 7-31 Morrisburg annual temperature cycle for the years 1941 to 1949.

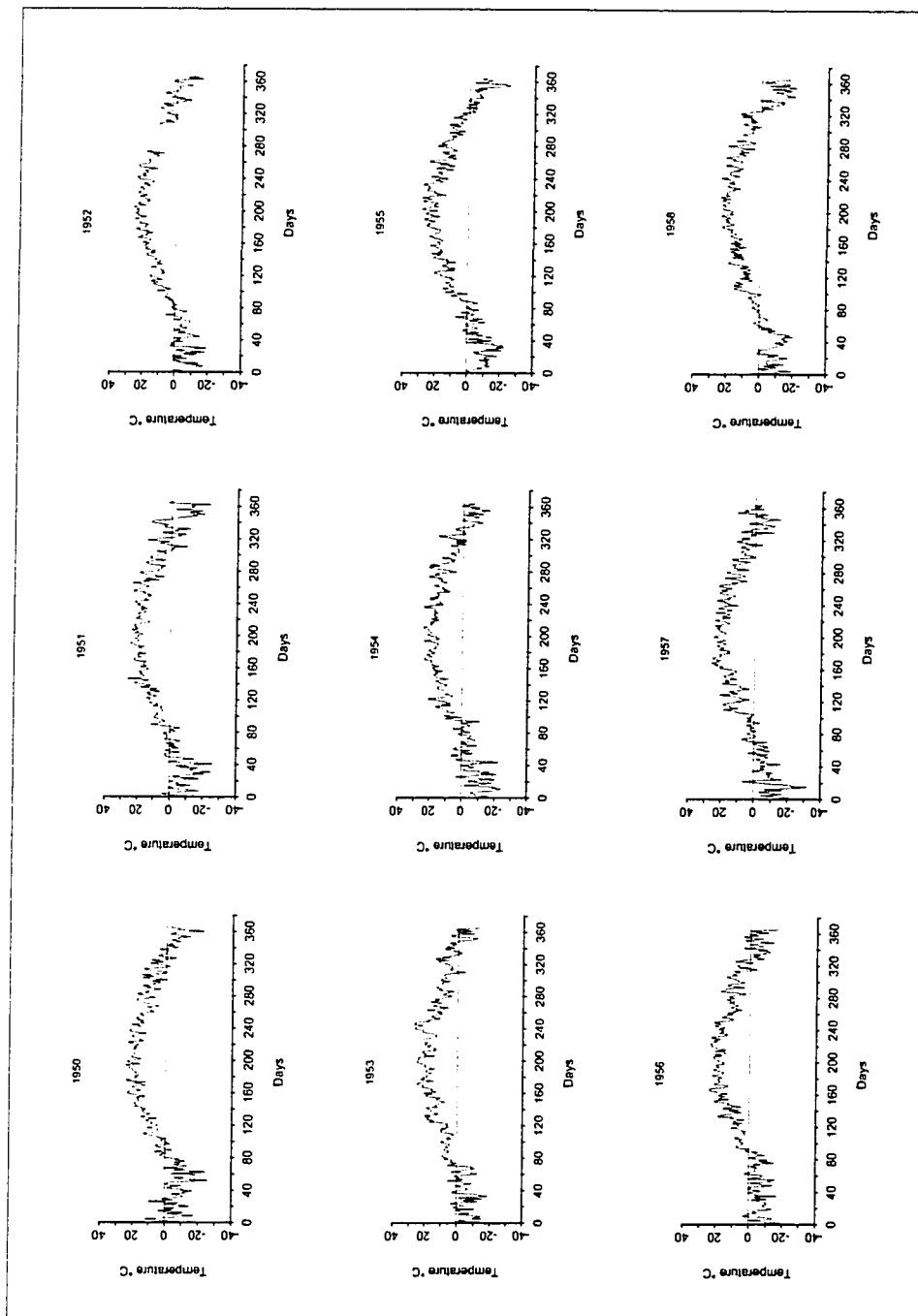


Figure 7-32 Morrisburg annual temperature cycle for the years 1950 to 1958.

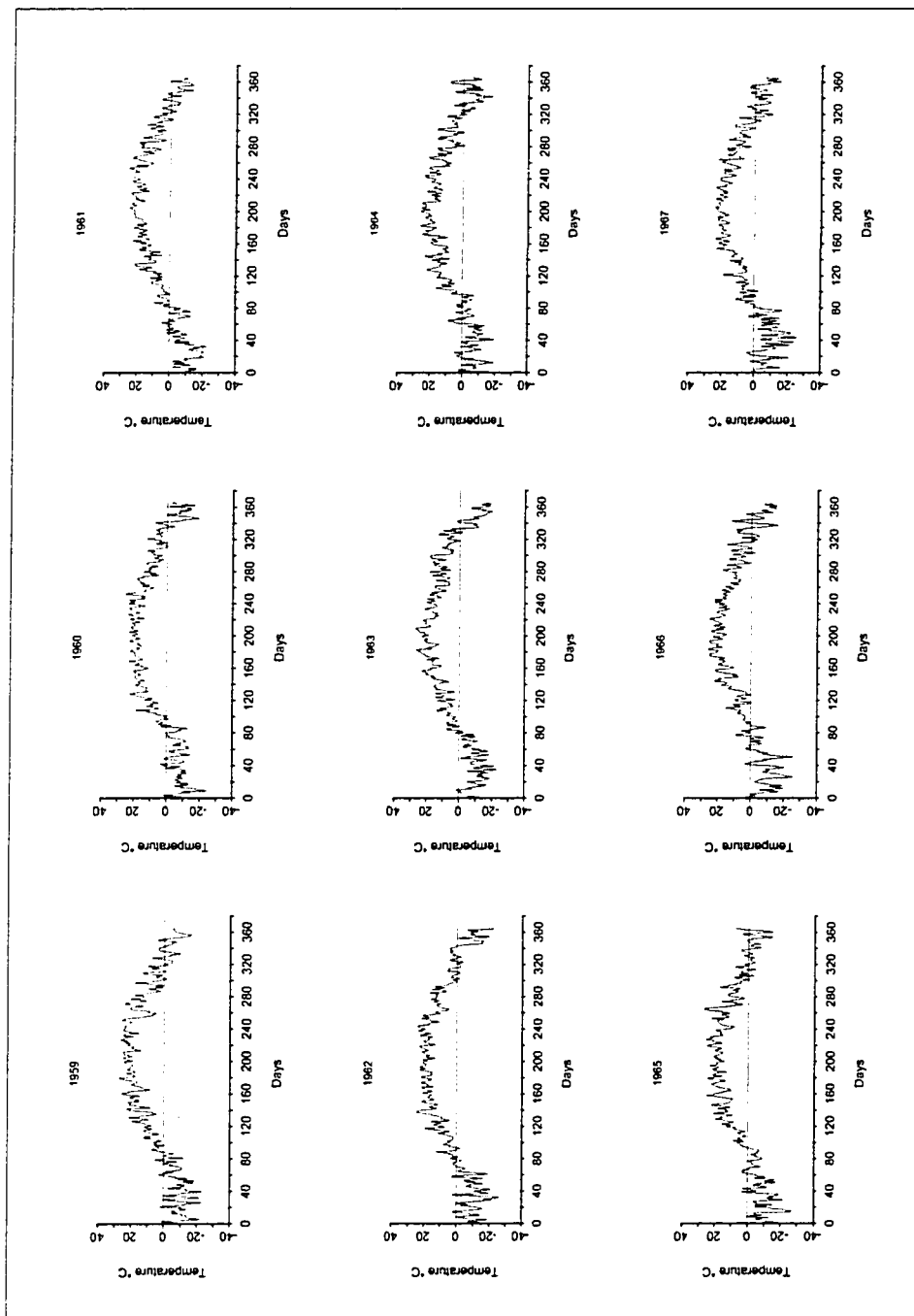


Figure 7-33 Morrisburg annual temperature cycle for the years 1959 to 1967.

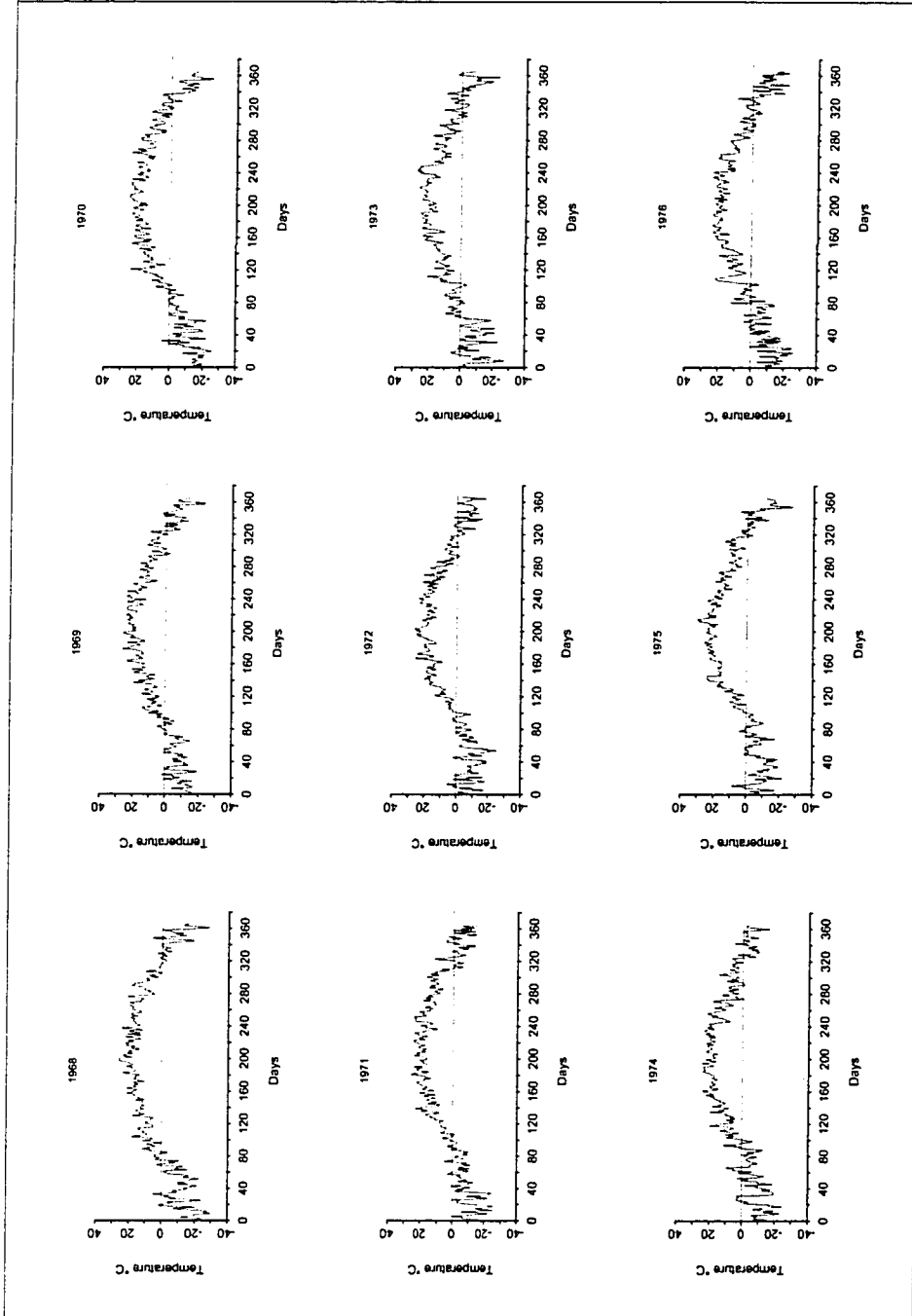


Figure 7-34 Morrisburg annual temperature cycle for the years 1968 to 1976.

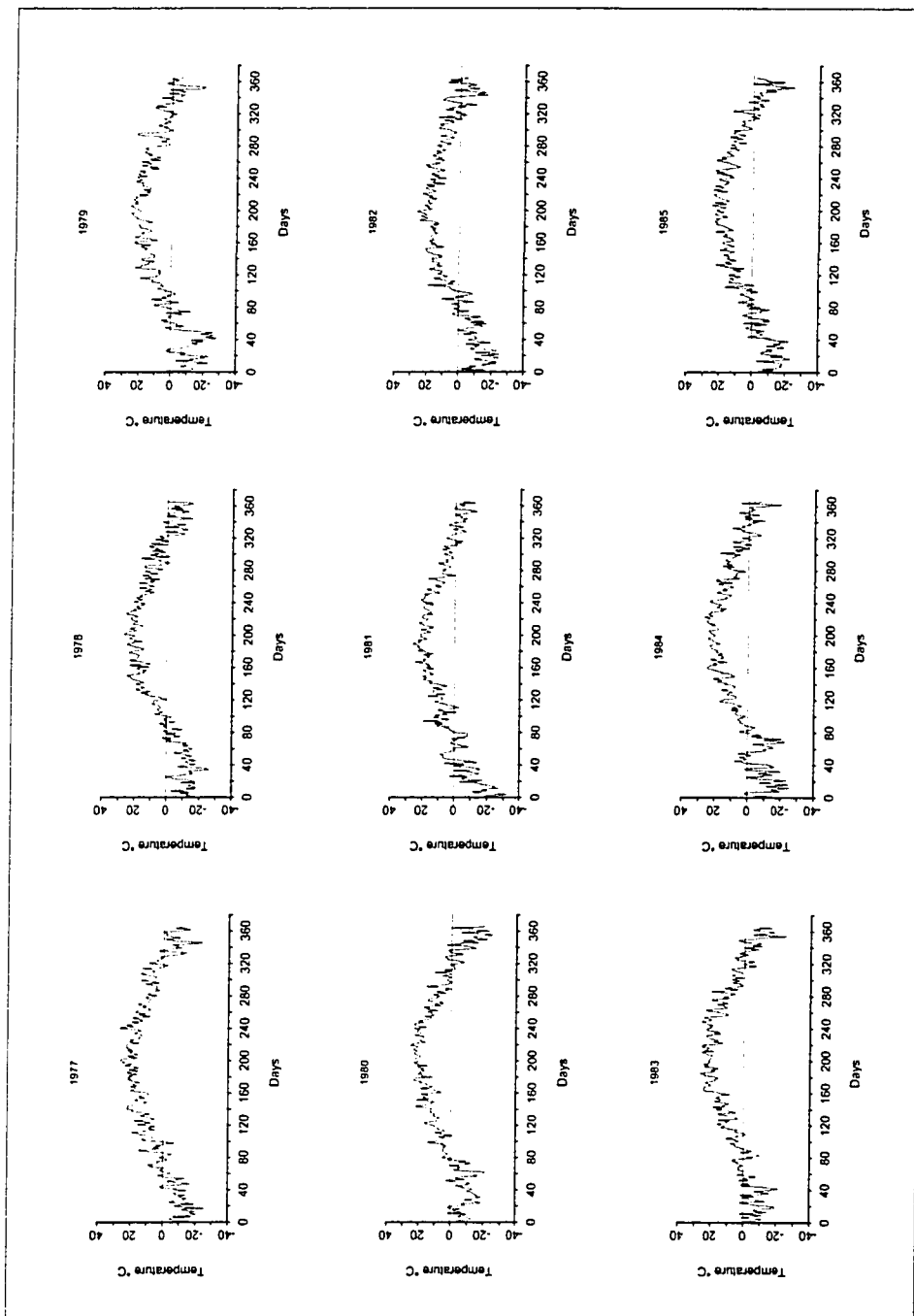


Figure 7-35 Morrisburg annual temperature cycle for the years 1977 to 1985.

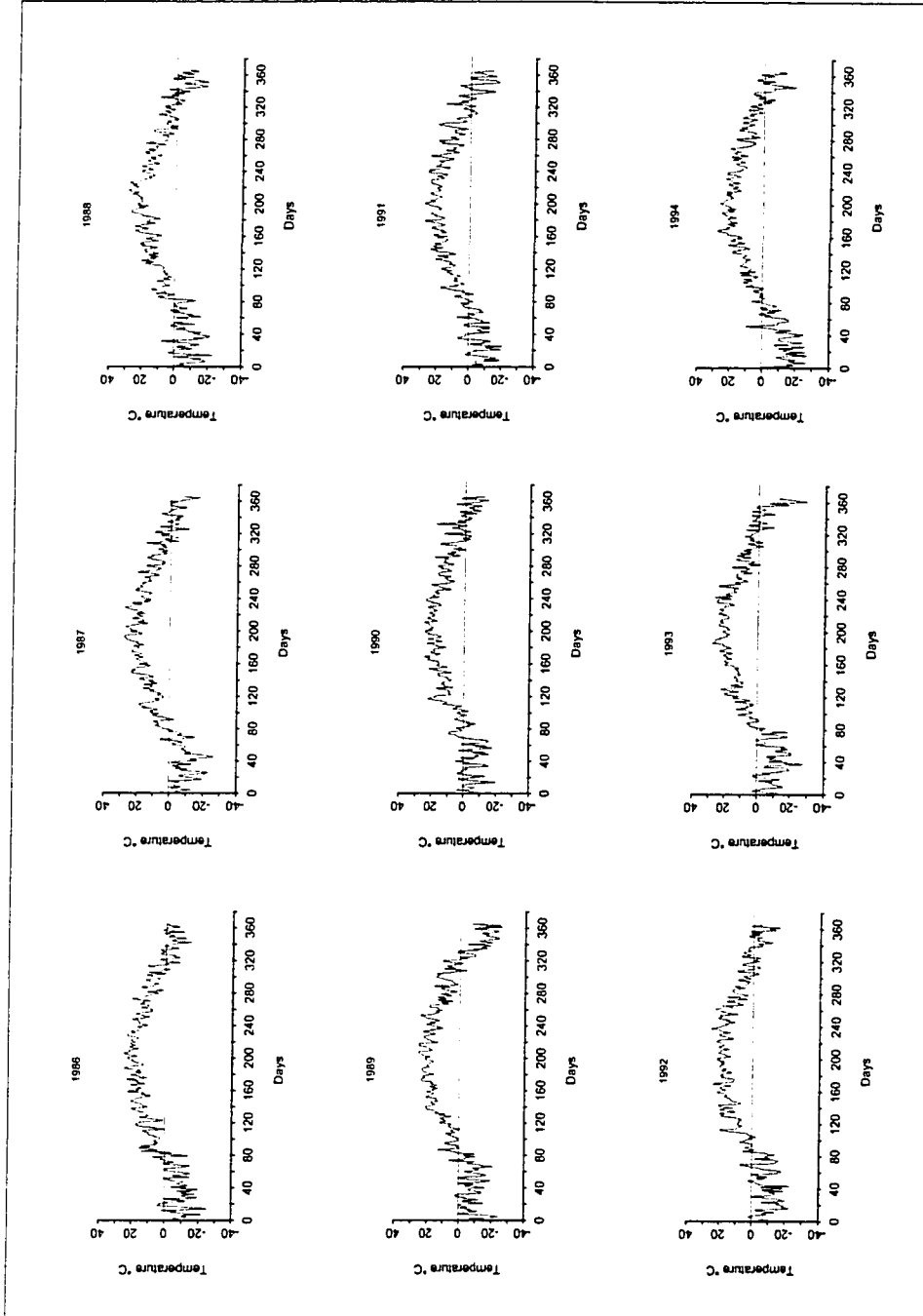


Figure 7-36 Morrisburg annual temperature cycle for the years 1986 to 1994.

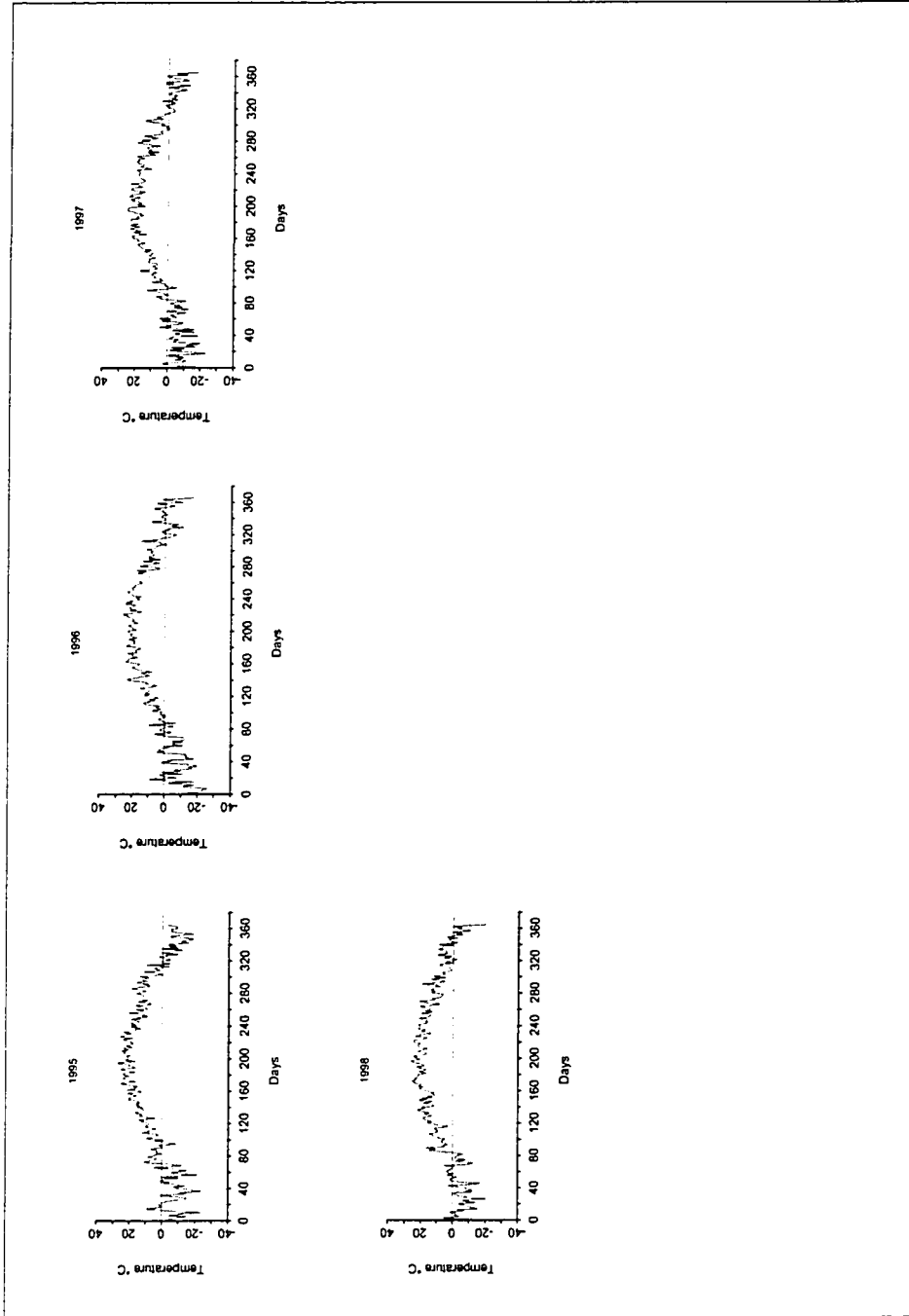


Figure 7-37 Morrisburg annual temperature cycle for the years 1995 to 1998.

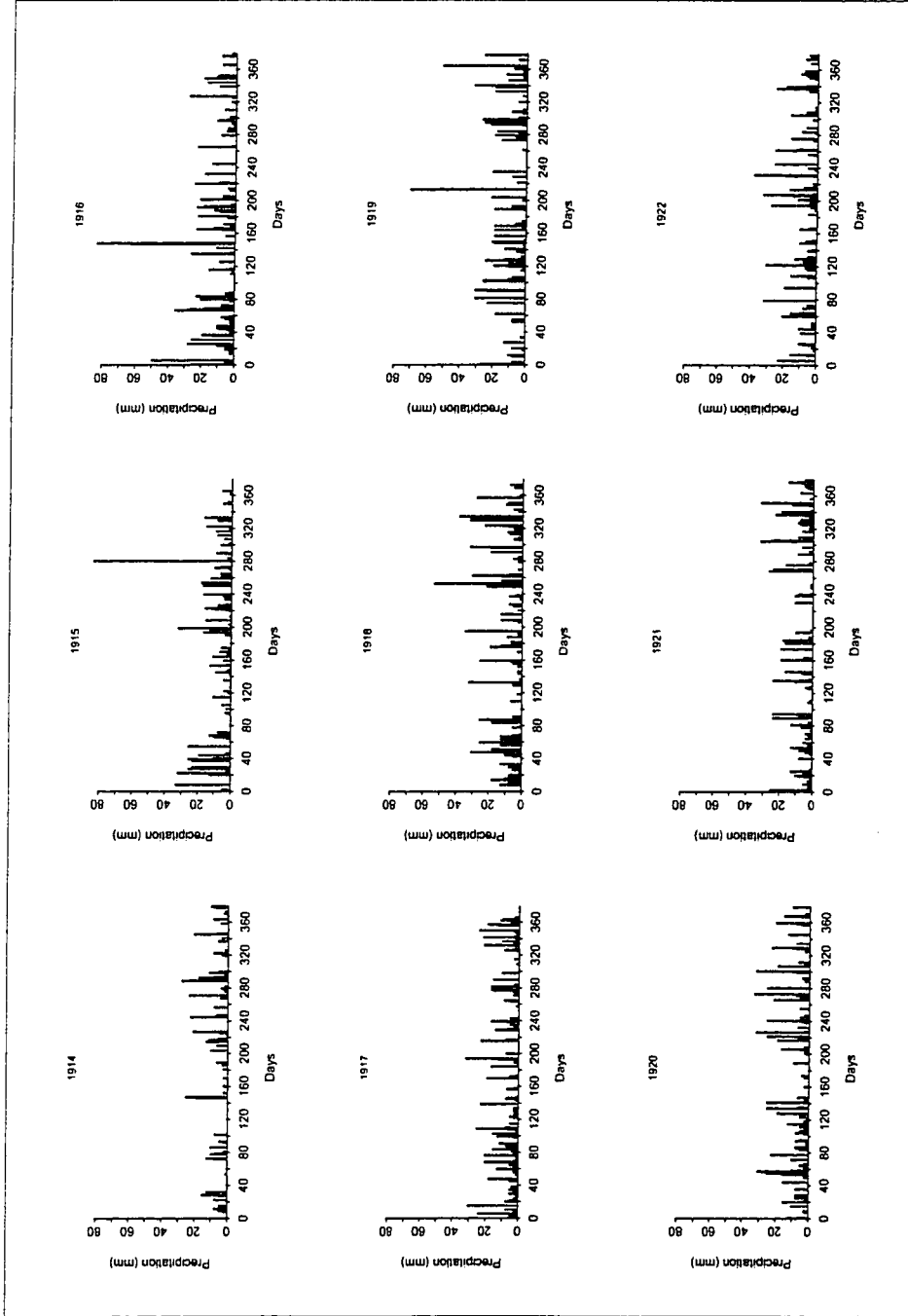


Figure 7-38 Morrisburg annual precipitation events for the years 1914 to 1922.

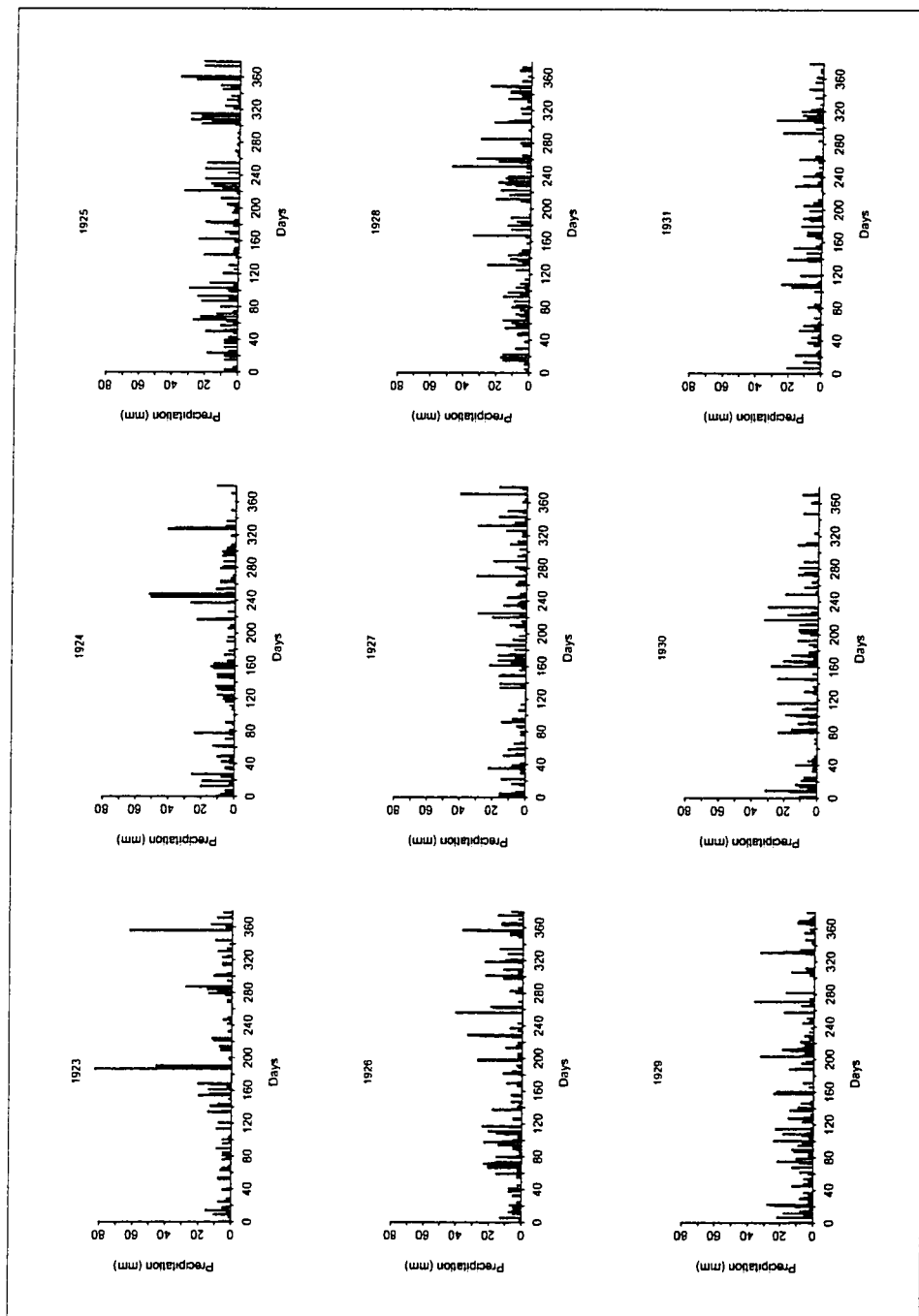


Figure 7-39 Morrisburg annual precipitation events for the years 1923 to 1931.

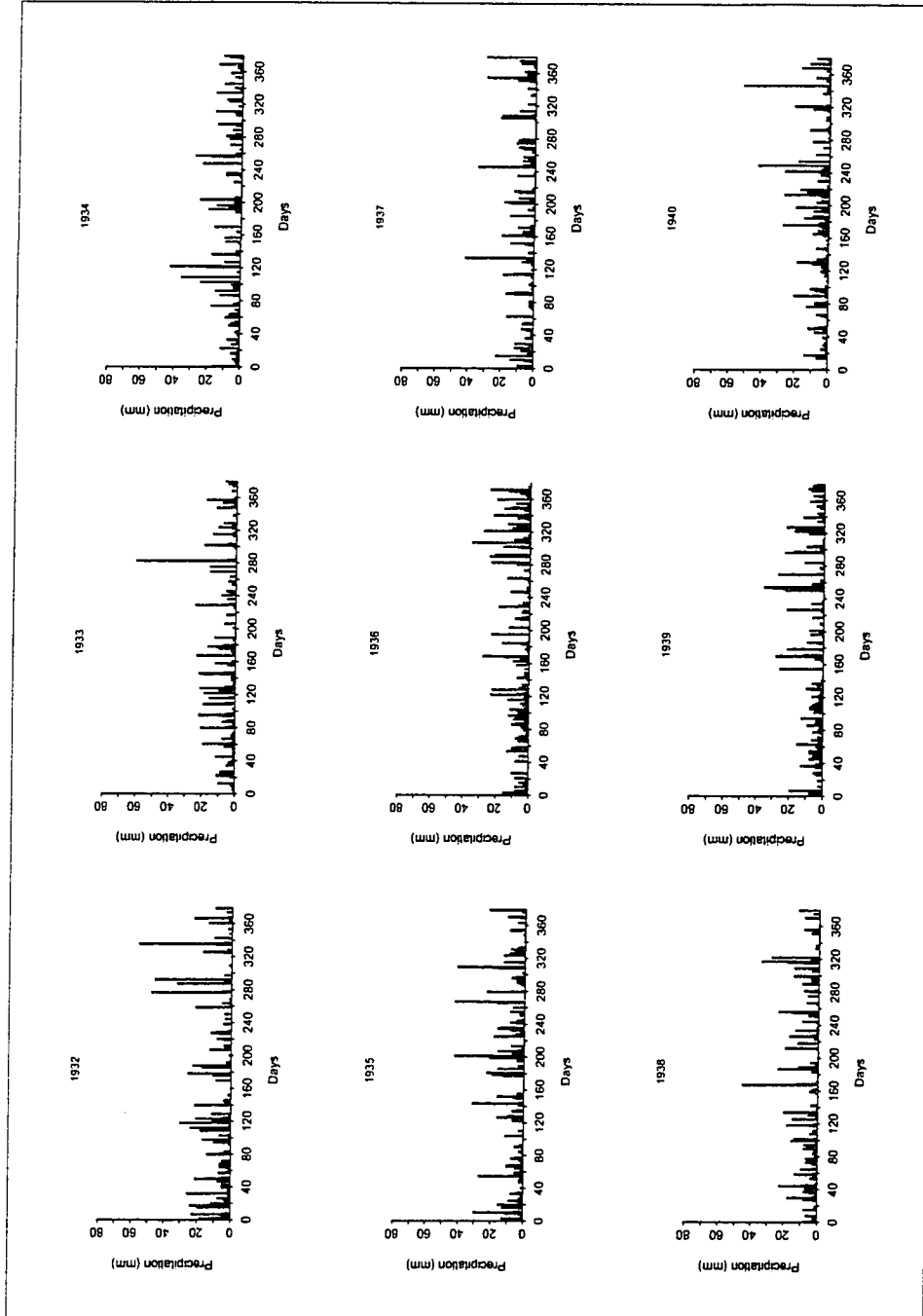


Figure 7-40 Morrisburg annual precipitation events for the years 1932 to 1940.

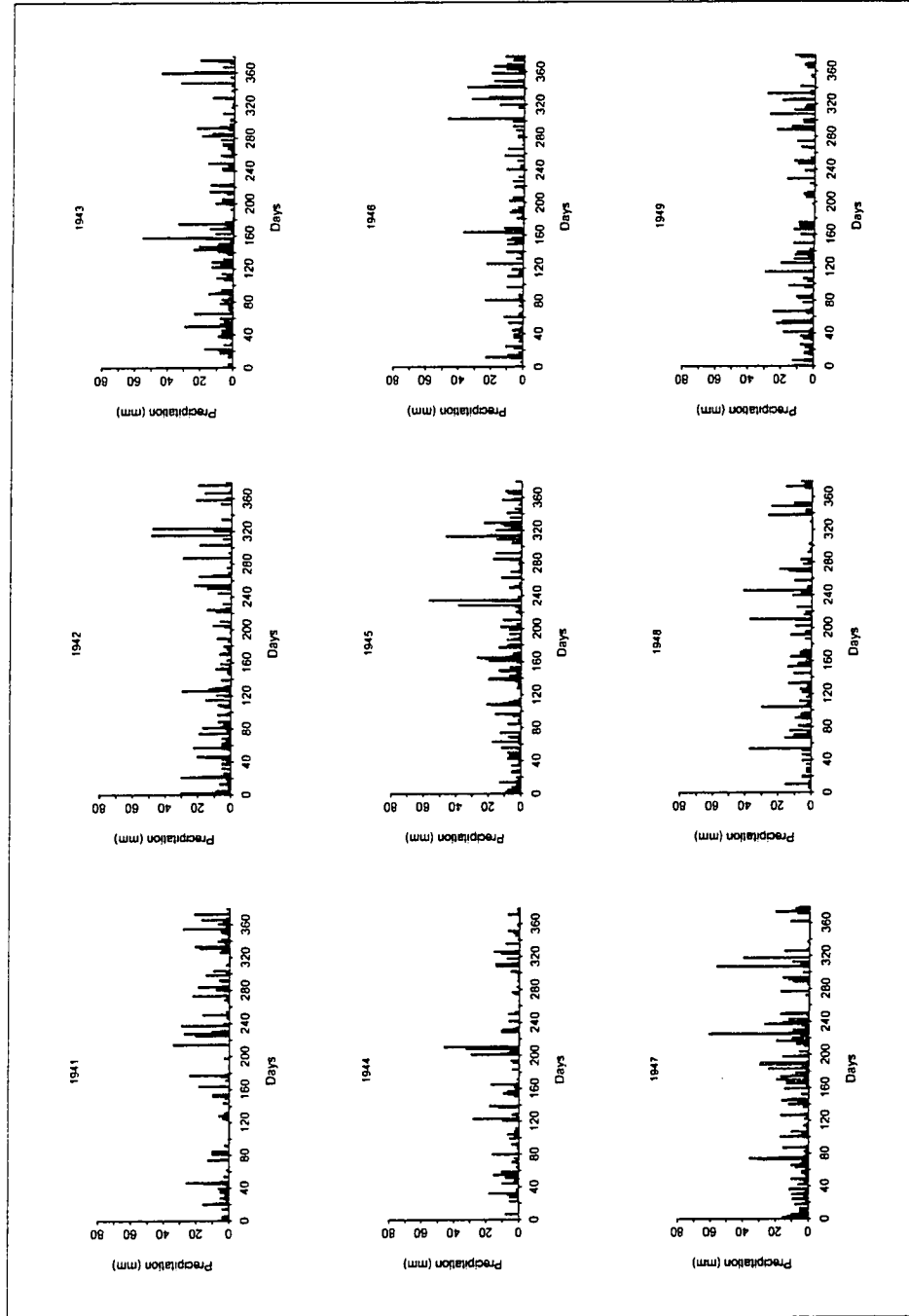


Figure 7-41 Morrisburg annual precipitation events for the years 1941 to 1949.

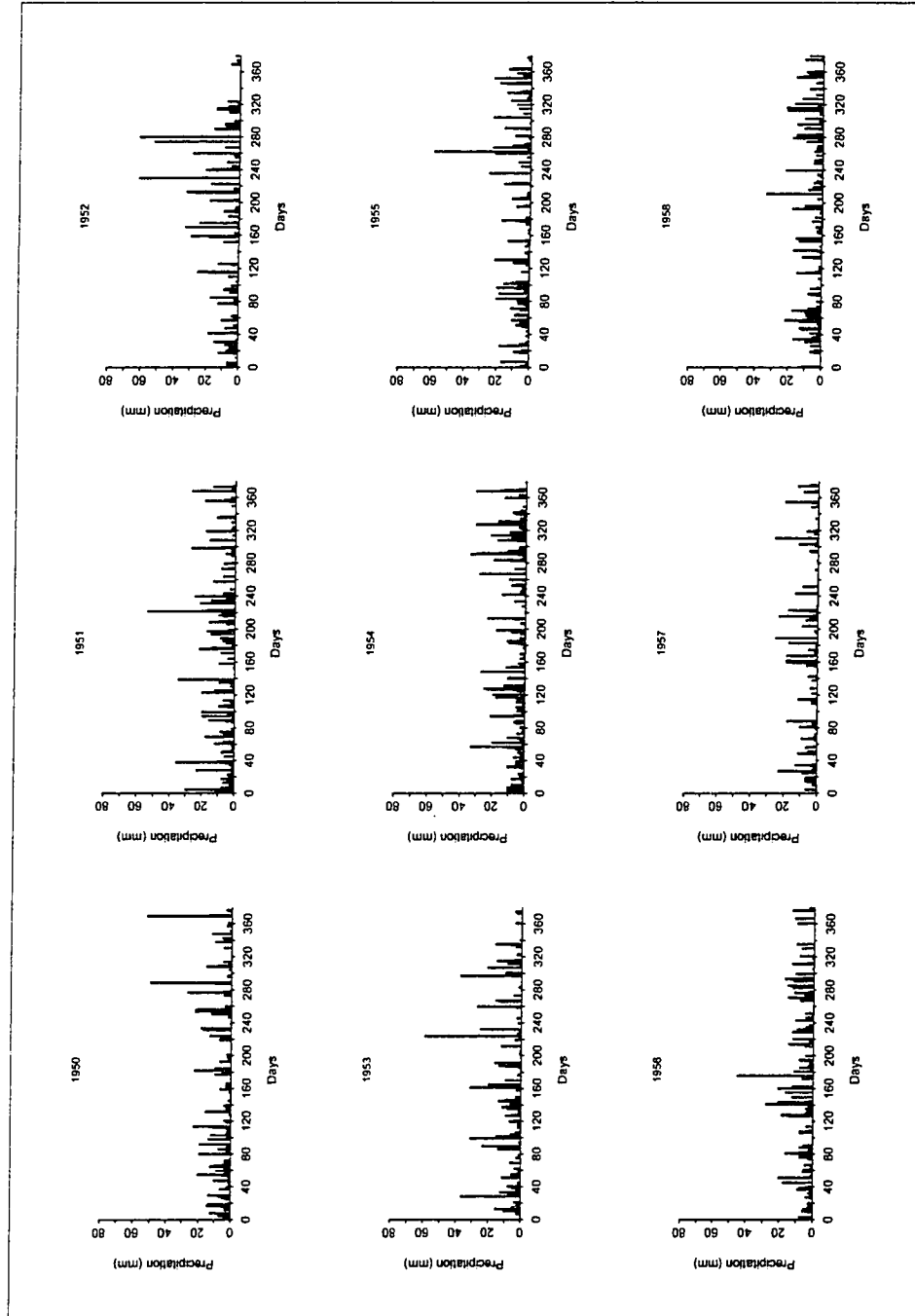


Figure 7-42 Morrisburg annual precipitation events for the years 1950 to 1958.

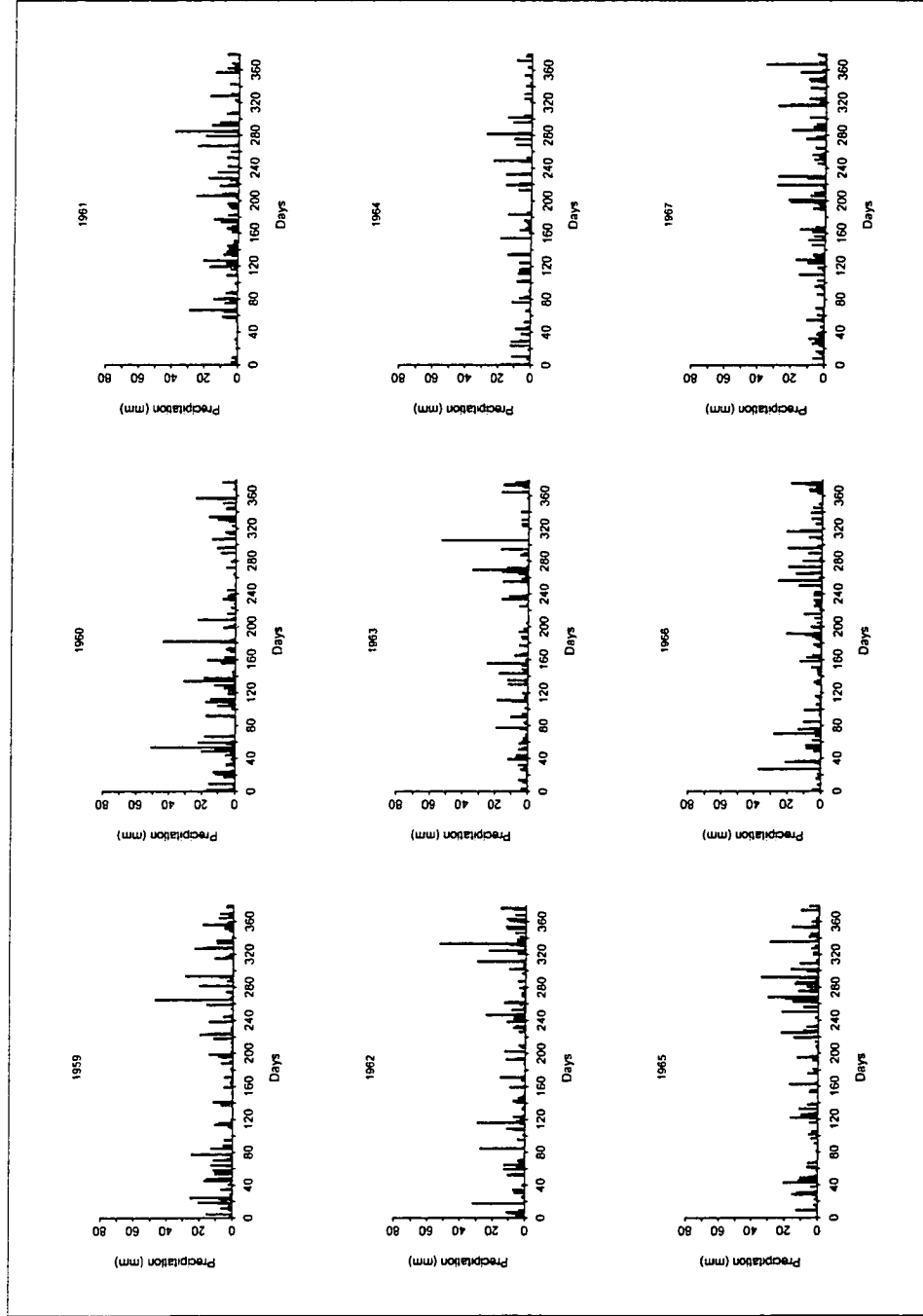


Figure 7-43 Morrisburg annual precipitation events for the years 1959 to 1967.

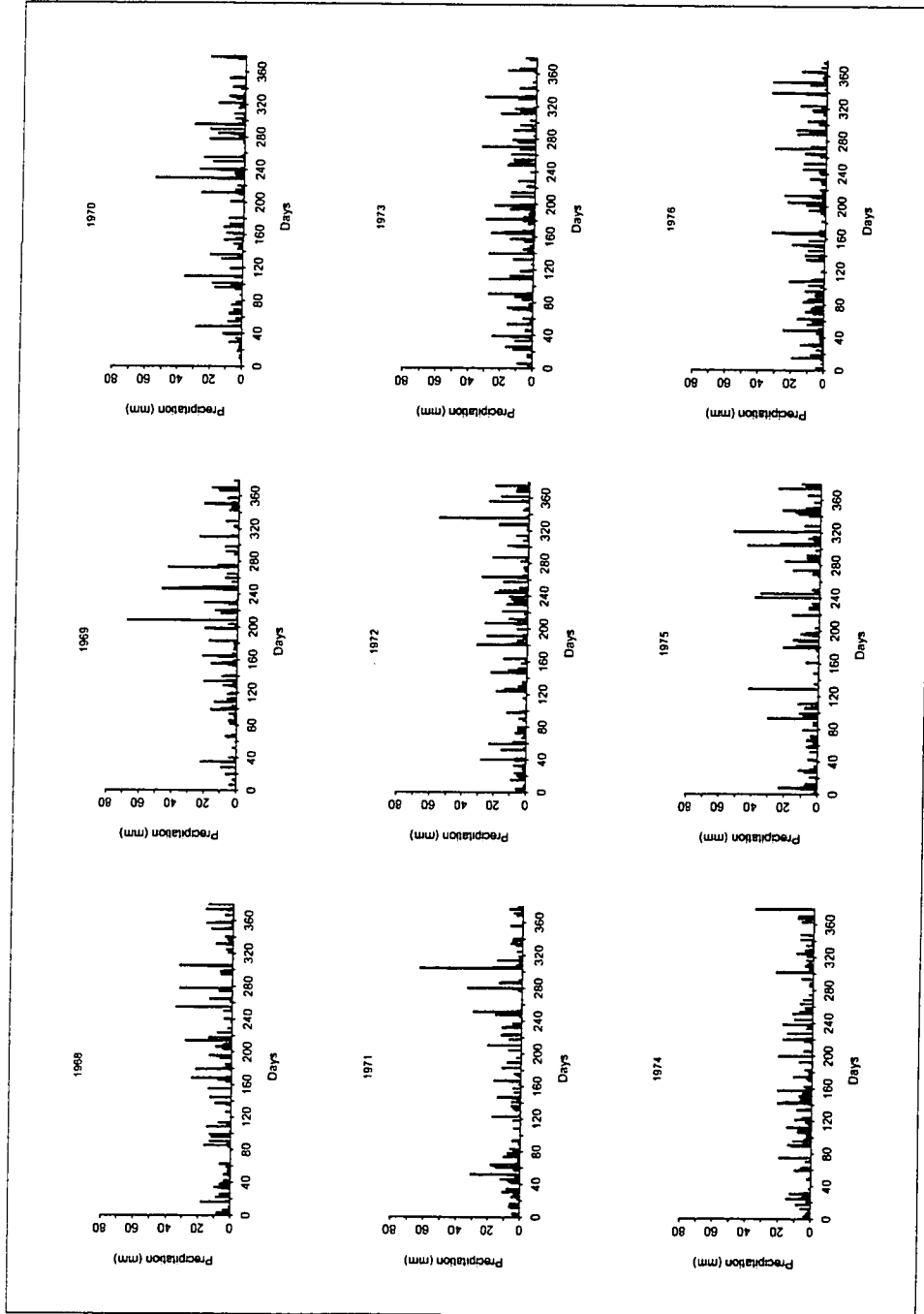


Figure 7-44 Morrisburg annual precipitation events for the years 1968 to 1976.

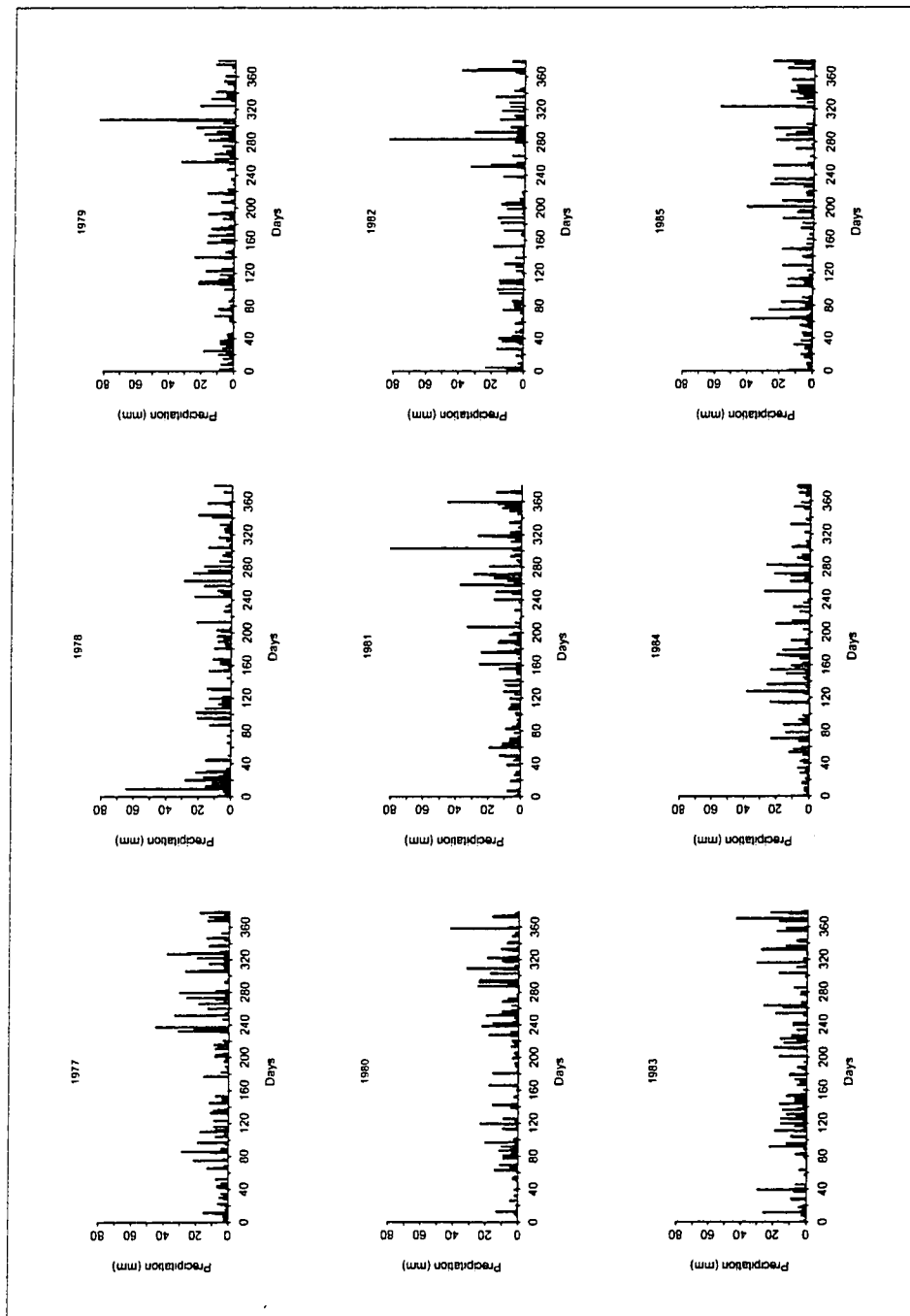


Figure 7-45 Morrisburg annual precipitation events for the years 1977 to 1985.

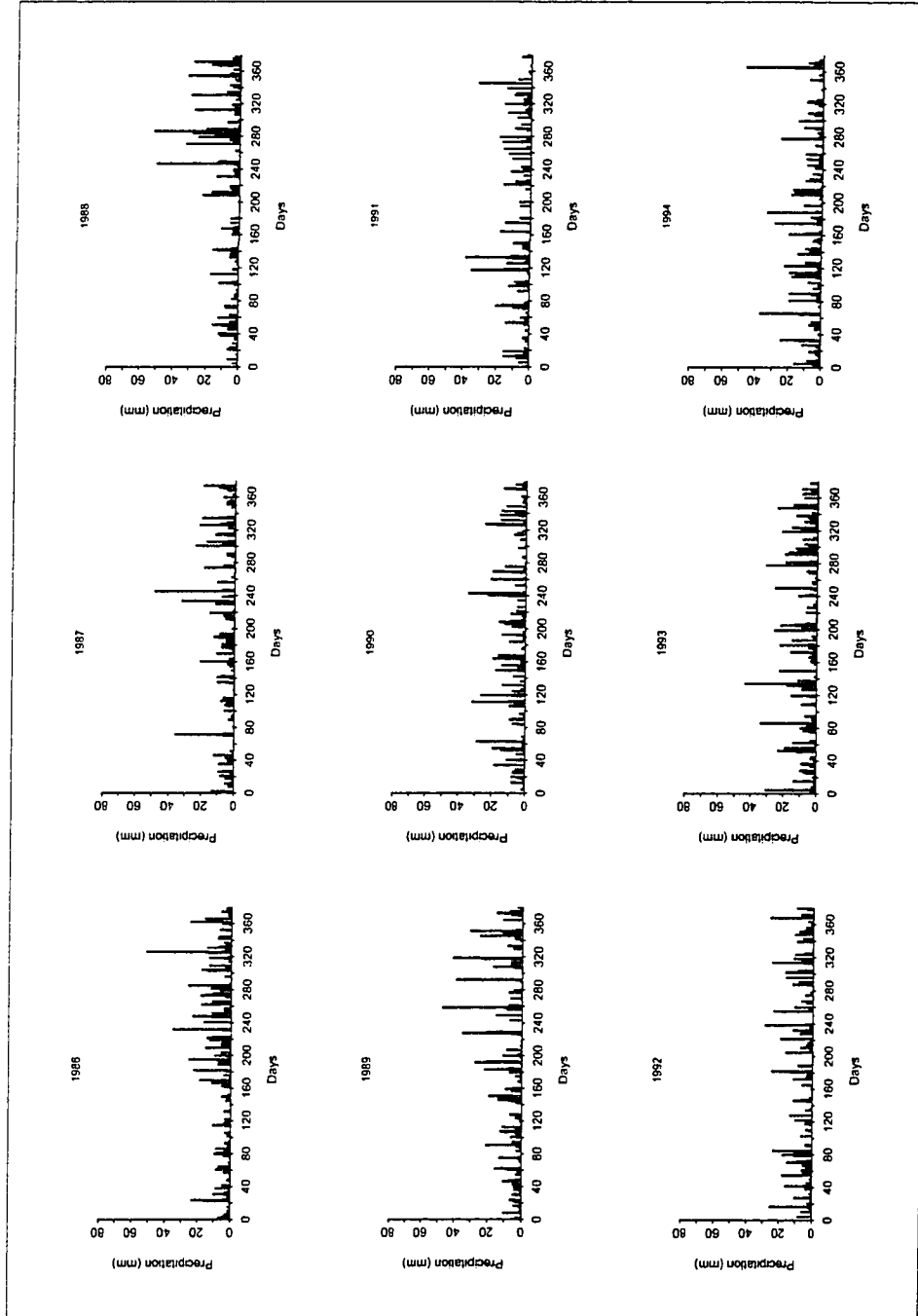


Figure 7-46 Morrisburg annual precipitation events for the years 1986 to 1994.

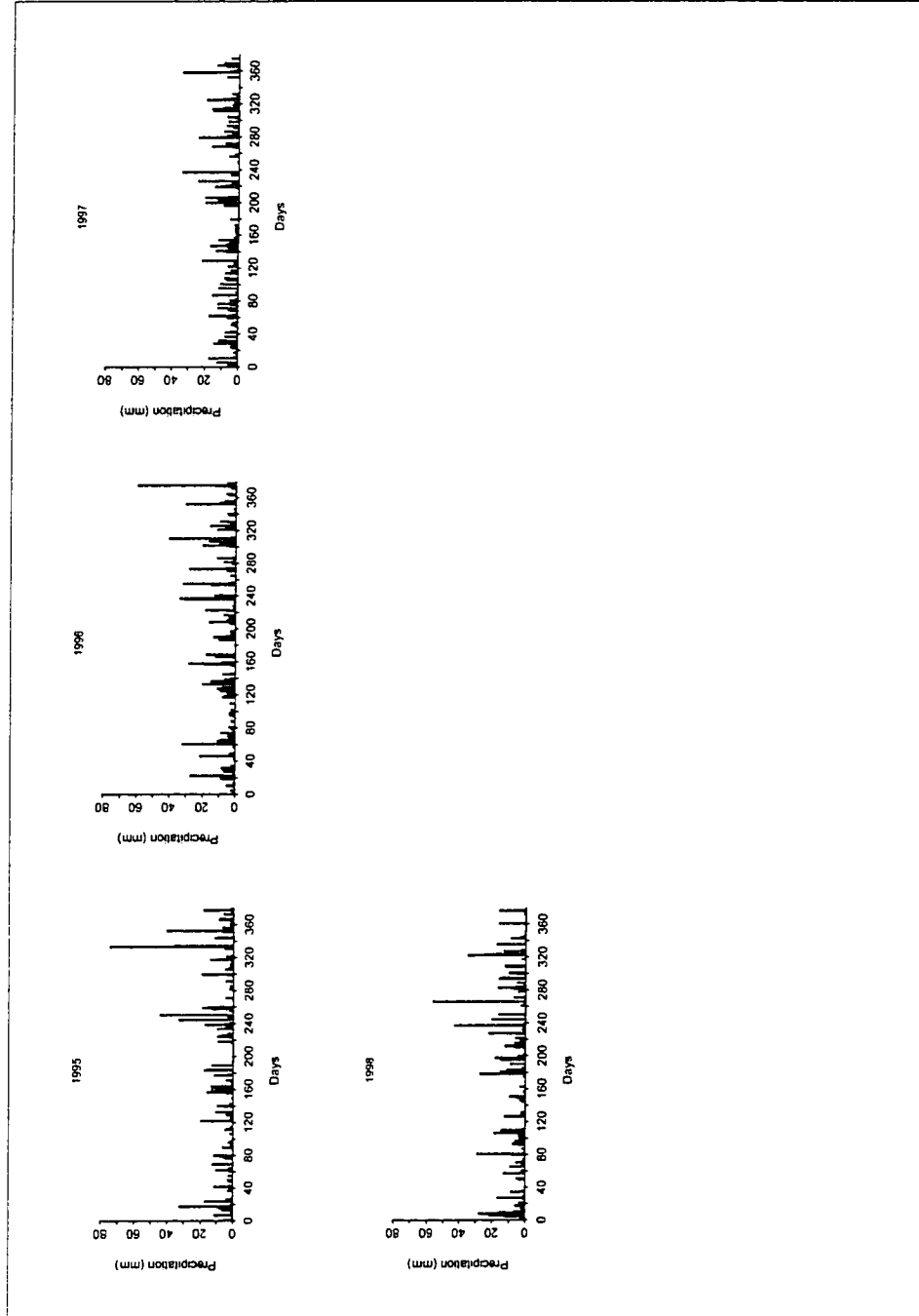


Figure 7-47 Morrisburg annual precipitation events for the years 1995 to 1998.

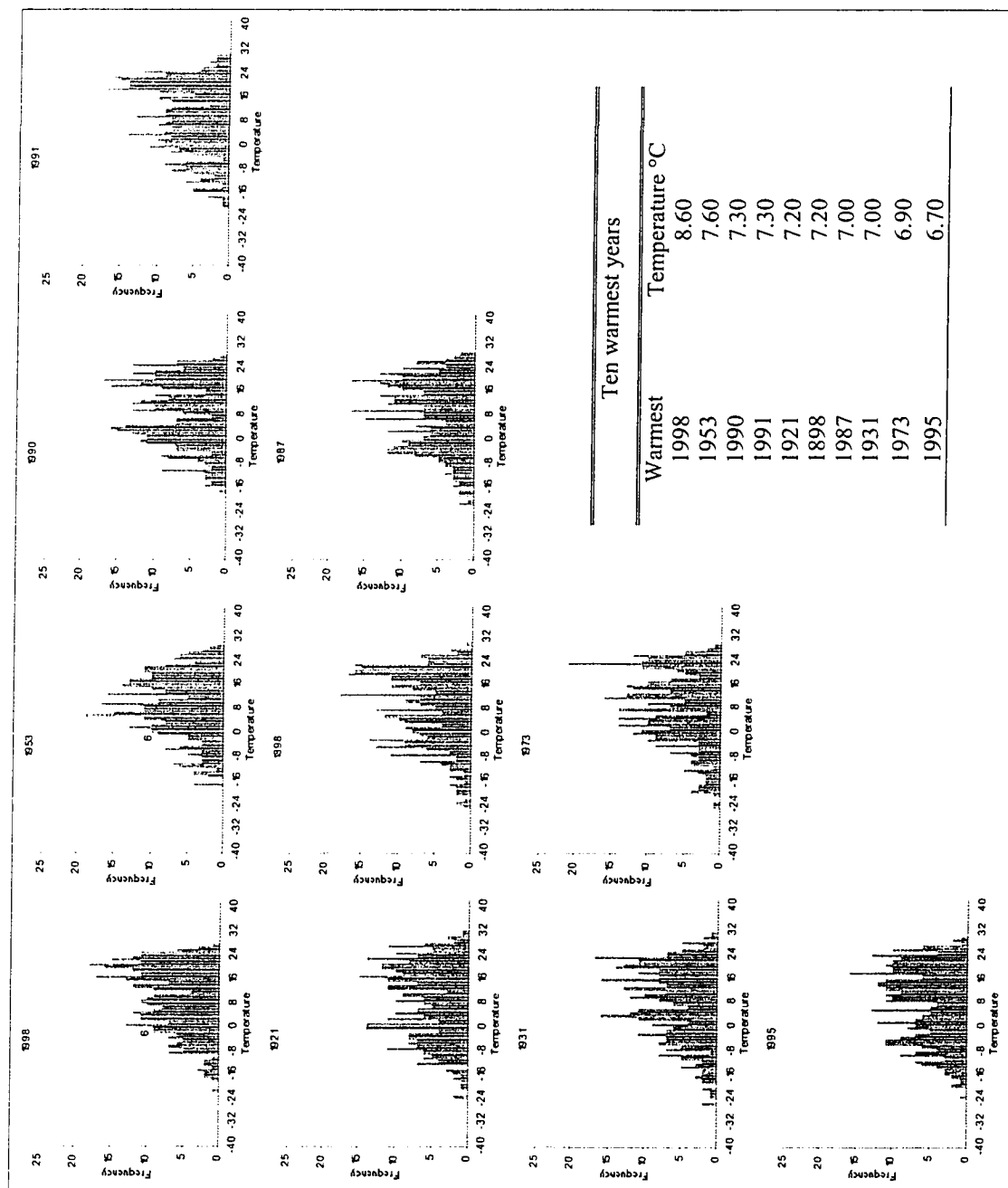


Figure 7-48 Ottawa mean daily temperature distribution for the ten warmest years of the century.

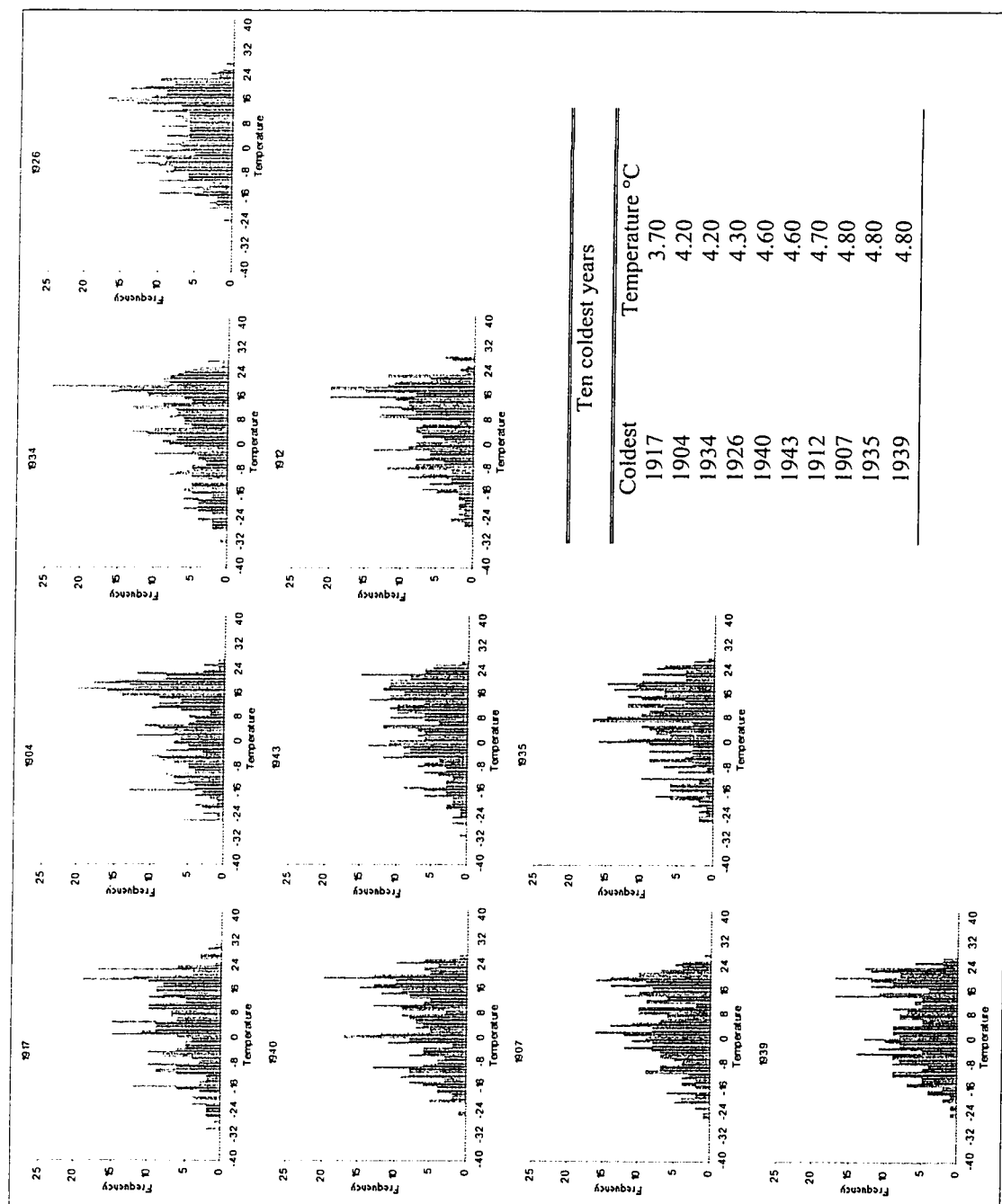


Figure 7-49 Ottawa mean daily temperature distribution for the ten coldest years of the century.

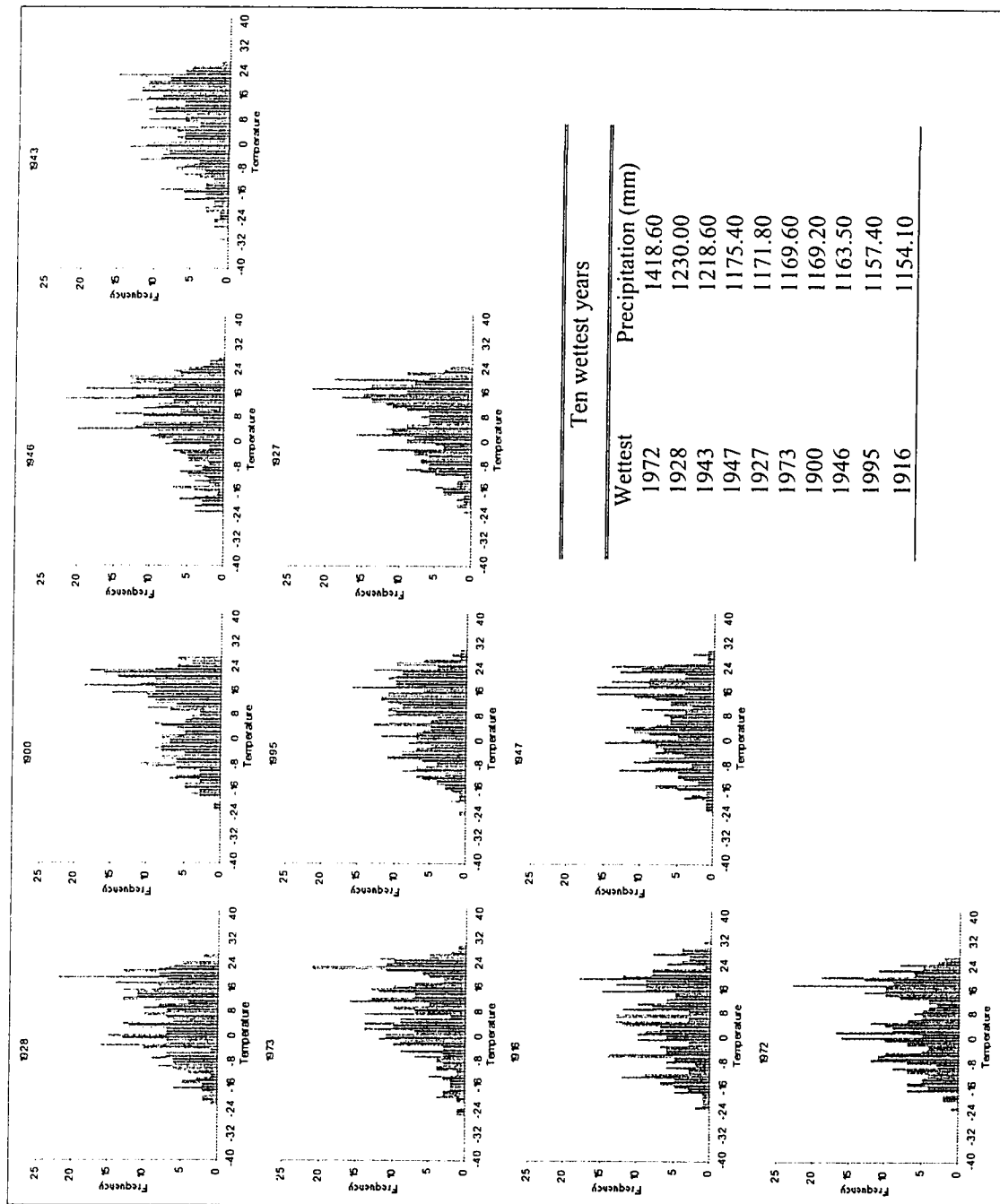


Figure 7-50 Ottawa mean daily temperature distribution for the ten wettest years of the century.

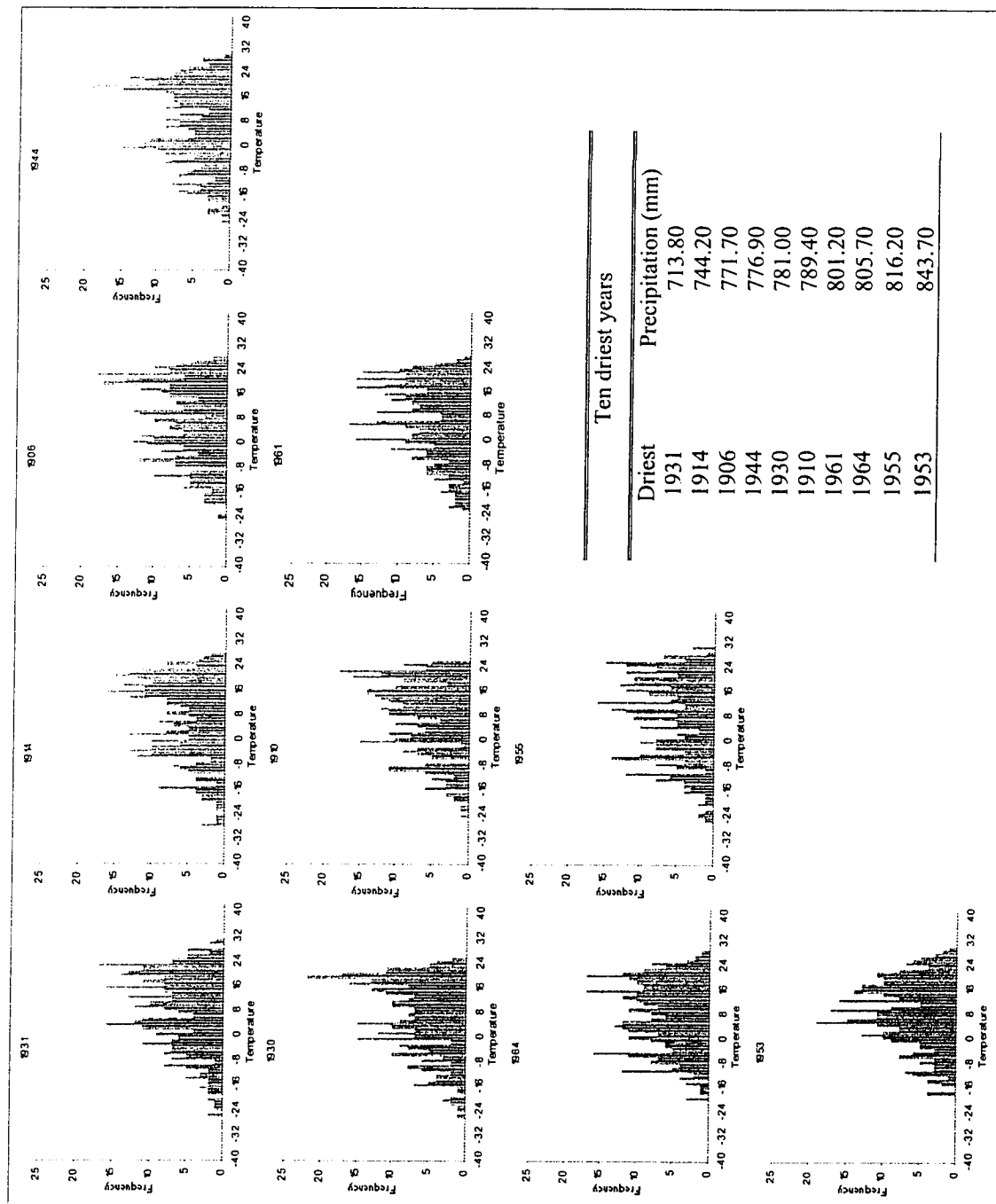


Figure 7-51 Ottawa mean daily temperature distribution for the ten driest years of the century.

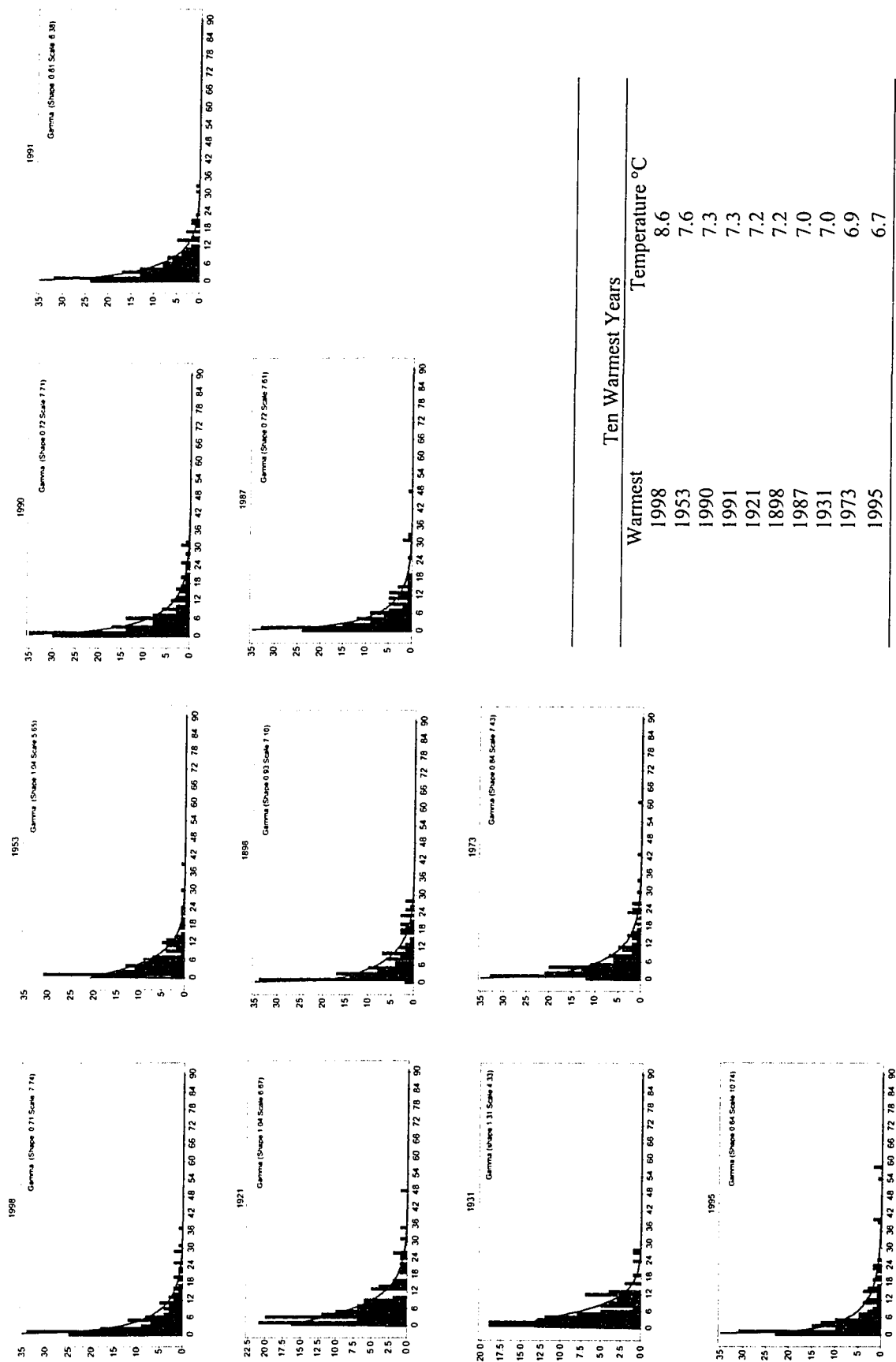


Figure 7-52 Ottawa daily precipitation gamma distribution for the ten warmest years of the century.

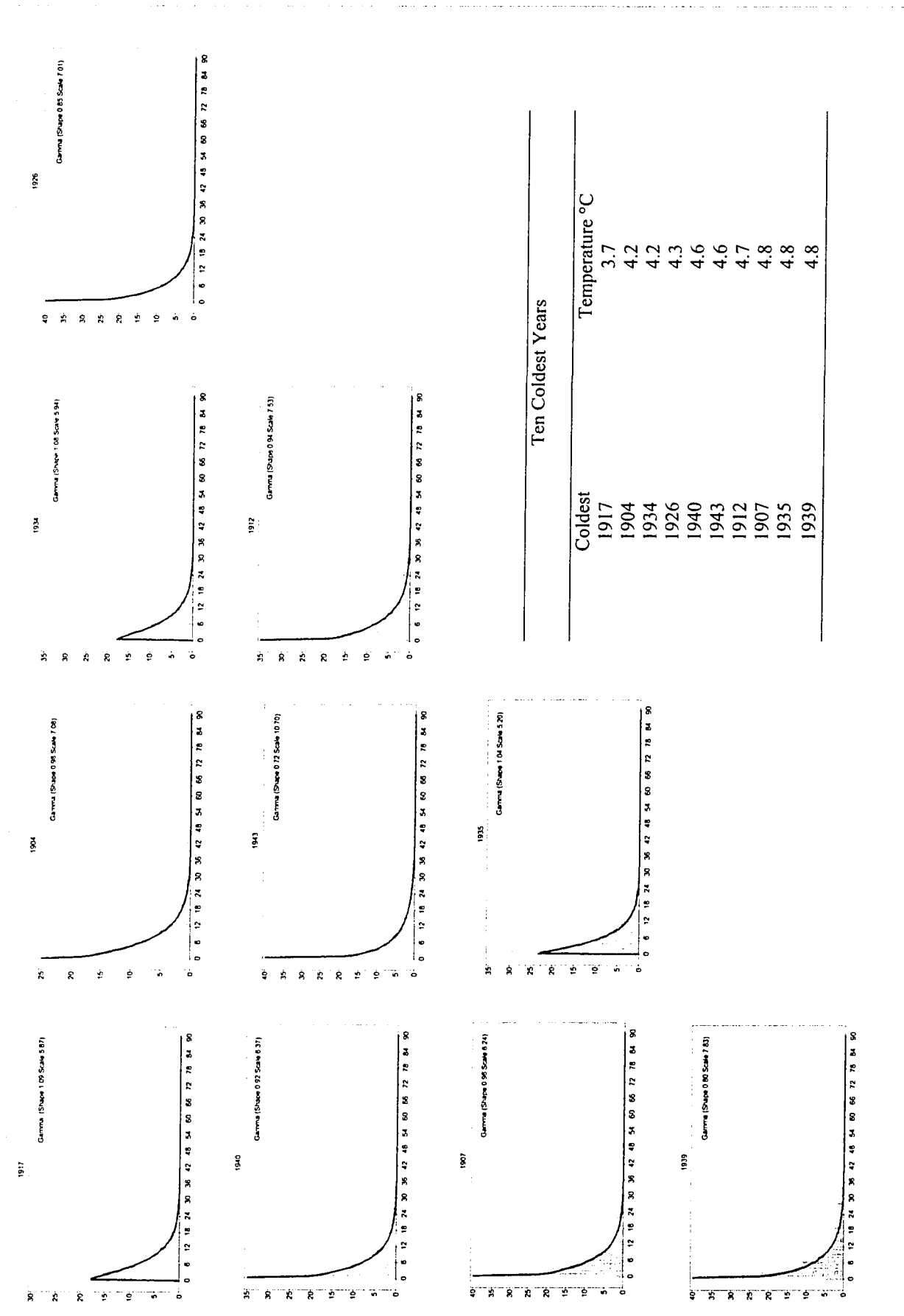


Figure 7-53 Ottawa daily precipitation gamma distribution for the ten coldest years of the century.

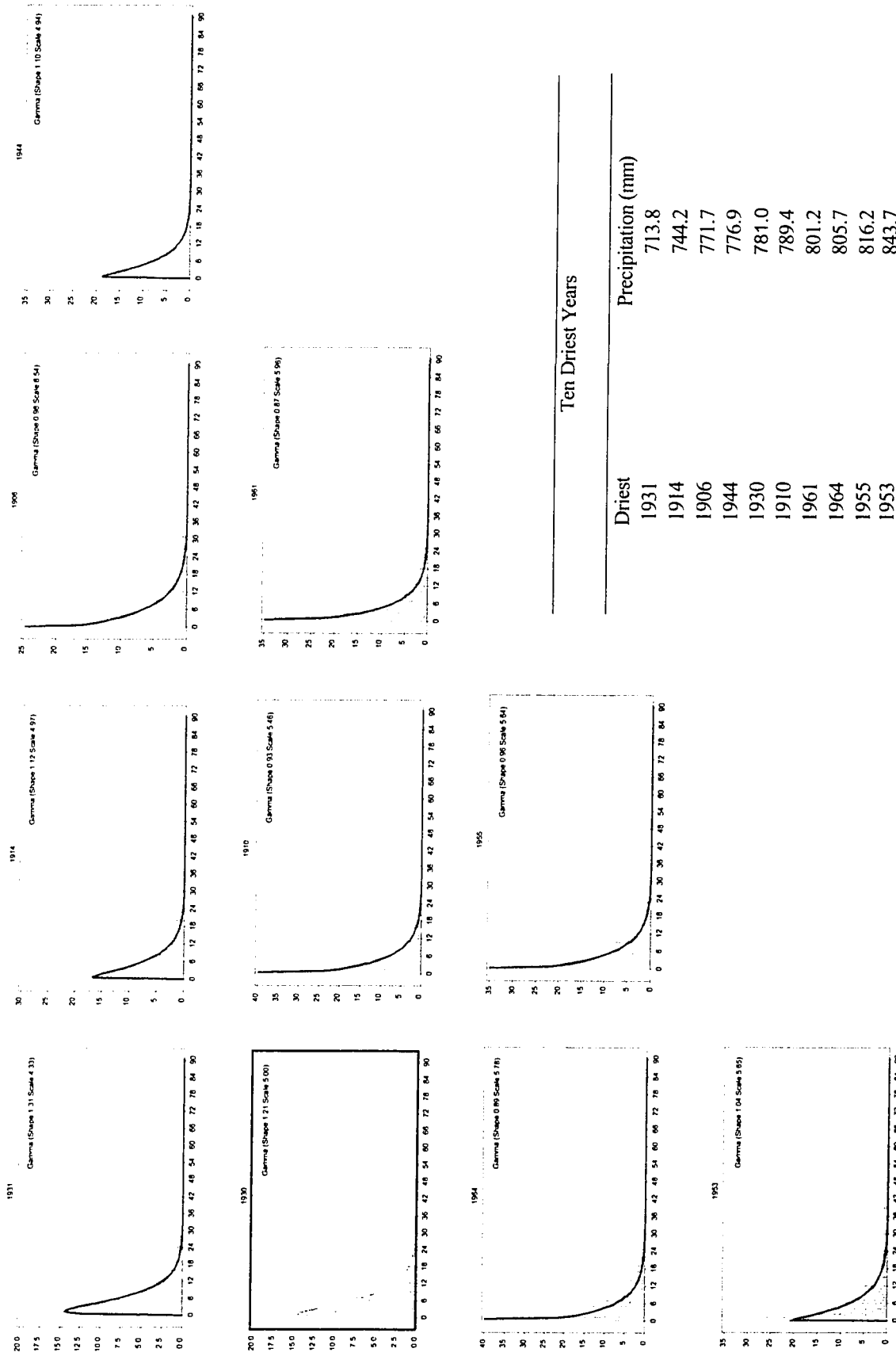
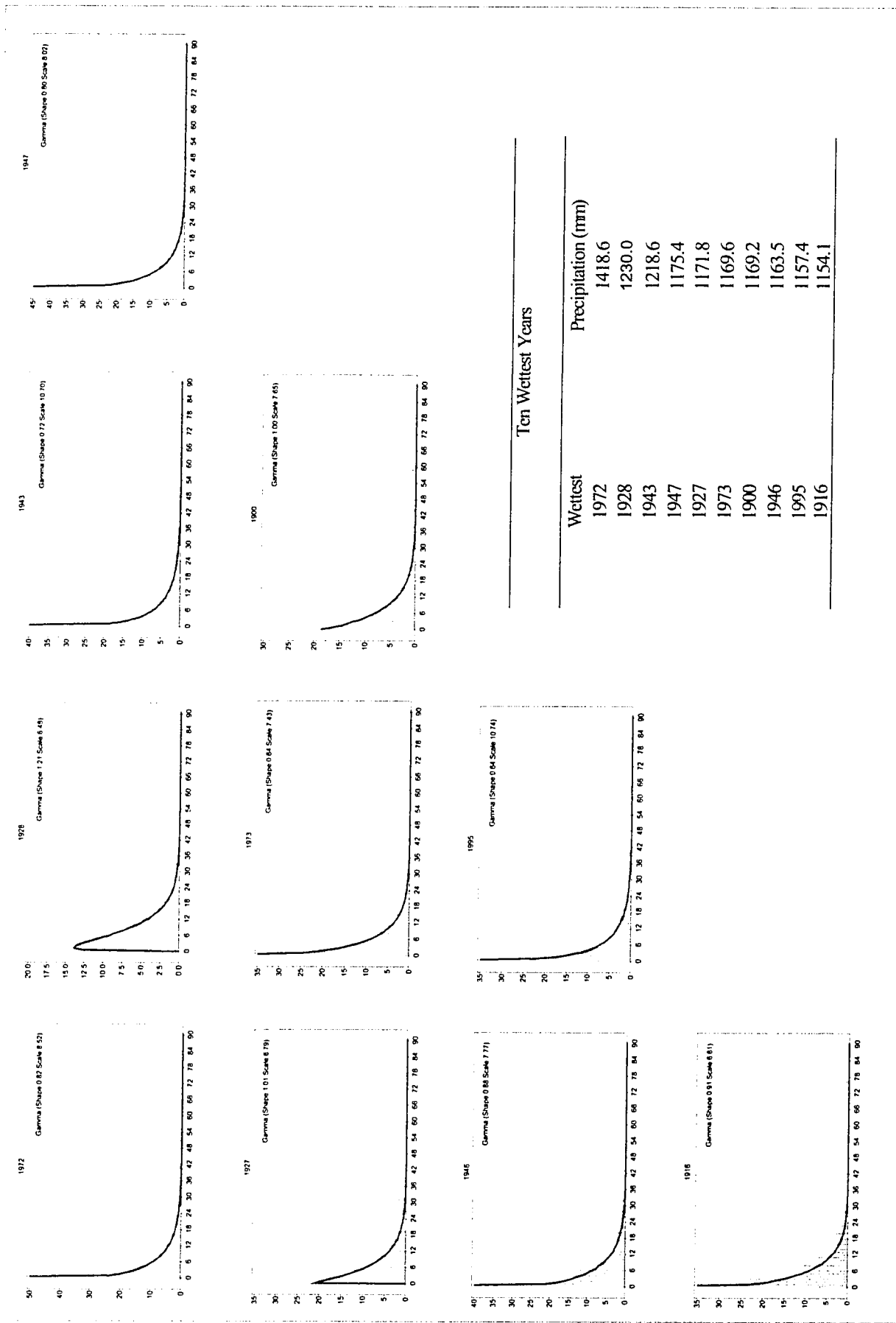


Figure 7-54 Ottawa daily precipitation gamma distribution for the ten wettest years of the century.



Ten Wettest Years	
Wettest	Precipitation (mm)
1972	1418.6
1928	1230.0
1943	1218.6
1947	1175.4
1927	1171.8
1973	1169.6
1900	1169.2
1946	1163.5
1995	1157.4
1916	1154.1

Figure 7-55 Ottawa daily precipitation gamma distribution for the ten driest years of the century.

Table 7-1 Mixture Model Results of the Ten Warmest Years of the 20th Century

Year	# of modes	Mode 1 $\pm$ STD	Mode 2 $\pm$ STD	Mode 3 $\pm$ STD	Mode 4 $\pm$ STD	Mode 5 $\pm$ STD
1998	2			2.81 $\pm$ 8.93		19.16 $\pm$ 3.39
1953	3	-10.71 $\pm$ 4.16		4.79 $\pm$ 5.76		18.26 $\pm$ 4.68
1990	4	-8.29 $\pm$ 4.72		1.41 $\pm$ 2.94	10.43 $\pm$ 1.97	19.28 $\pm$ 3.31
1991	2			2.00 $\pm$ 10.10		20.07 $\pm$ 3.23
1921	2			-1.60 $\pm$ 8.80		18.81 $\pm$ 5.26
1931	2			1.49 $\pm$ 10.79		18.96 $\pm$ 4.22
1898	2			1.68 $\pm$ 10.75		19.54 $\pm$ 3.21
1987	2			0.64 $\pm$ 9.37		17.60 $\pm$ 4.92
1973	2			4.00 $\pm$ 10.97		22.49 $\pm$ 1.86
1995	2			-3.44 $\pm$ 8.12		16.37 $\pm$ 5.78
Mean		-9.50 $\pm$ 4.44		1.38 $\pm$ 8.65	10.43 $\pm$ 1.97	19.05 $\pm$ 3.99

Table 7-2 Mixture Model Results of the Ten Coldest Years of the 20th Century

Year	# of modes	Mode 1 $\pm$ STD	Mode 2 $\pm$ STD	Mode 3 $\pm$ STD	Mode 4 $\pm$ STD	Mode 5 $\pm$ STD
1917	2			0.07 $\pm$ 12.54		18.53 $\pm$ 3.13
1904	2			-4.22 $\pm$ 10.97		17.06 $\pm$ 3.29
1934	3	-16.74 $\pm$ 6.54		3.68 $\pm$ 7.43		18.46 $\pm$ 3.56
1926				-3.93 $\pm$ 8.46		16.03 $\pm$ 4.19
1940	3	-13.77 $\pm$ 4.46		2.10 $\pm$ 7.30		17.60 $\pm$ 3.92
1943	2			-2.14 $\pm$ 11.14		17.20 $\pm$ 4.34
1912	2			-4.08 $\pm$ 9.97		15.57 $\pm$ 4.84
1907	4	-19.11 $\pm$ 3.46	-10.69 $\pm$ 1.24	1.74 $\pm$ 7.41		18.14 $\pm$ 3.41
1935	3	-16.42 $\pm$ 4.99		4.55 $\pm$ 7.82		18.90 $\pm$ 3.76
1939	2			-2.13 $\pm$ 9.45		18.34 $\pm$ 3.78
Mean		-16.51 $\pm$ 4.86	-10.69 $\pm$ 1.24	-0.43 $\pm$ 9.25		17.58 $\pm$ 3.82

Table 7-3 Mixture Model Results of the Ten Wettest Years of the 20 th Century						
Year	# of modes	Mode 1 ± STD	Mode 2 ± STD	Mode 3 ± STD	Mode 4 ± STD	Mode 5 ± STD
1900	2			-3.73 ± 8.84		17.58 ± 4.35
1916	4		-13.90 ± 3.98	-6.19 ± 0.28	2.98 ± 6.13	18.49 ± 5.07
1927	2			-0.93 ± 9.21		16.16 ± 3.67
1928	2			-0.60 ± 9.43		17.30 ± 3.65
1943	2			-2.14 ± 11.14		17.20 ± 4.34
1946	3		-15.85 ± 4.55		4.52 ± 7.08	17.69 ± 3.92
1947	2			-2.24 ± 9.31		18.58 ± 4.47
1972	2			-2.49 ± 8.71		17.90 ± 3.35
1973	2				4.00 ± 10.97	22.49 ± 1.86
1995	2			-3.44 ± 8.12		16.37 ± 5.78
Mean			-14.88 ± 4.26	-2.72 ± 8.13		17.98 ± 4.05

Table 7-4 Mixture Model Results of the Ten Driest Years of the 20 th Century						
Year	# of modes	Mode 1 ± STD	Mode 2 ± STD	Mode 3 ± STD	Mode 4 ± STD	Mode 5 ± STD
1906	2			0.24 ± 10.40		20.06 ± 3.18
1910	3			-2.88 ± 8.98	13.03 ± 3.91	21.29 ± 1.70
1914	2			-2.81 ± 10.60		17.38 ± 4.29
1930	2			0.46 ± 10.44		18.17 ± 2.84
1931	2			1.49 ± 10.79		18.96 ± 4.22
1944	5		-10.27 ± 6.72	-0.88 ± 1.73	7.96 ± 6.06	19.64 ± 3.30
1953	3		-10.71 ± 4.16	4.79 ± 5.76		18.26 ± 4.68
1955	4	-25.05 ± 0.65	-7.06 ± 6.64		11.21 ± 5.51	22.16 ± 3.31
1961	3		-15.91 ± 4.53	2.79 ± 8.40		18.97 ± 3.50
1964	2			0.10 ± 8.67		17.56 ± 4.22
Mean		-25.05 ± 0.65	-10.99 ± 5.51	0.37 ± 8.42		19.25 ± 3.52

Table 7-5 Ten warmest and coldest years of the century with starting date, ending date, and duration of the growing season

Warmest	Temperature °C	Start	End	Duration	Coldest	Temperature °C	Start	End	Duration
1998	8.6	85	307	222	1917	3.7	107	280	173
1953	7.6	89	305	216	1904	4.2	113	298	185
1990	7.3	109	292	183	1934	4.2	120	300	180
1991	7.3	94	302	208	1926	4.3	111	291	180
1898	7.2	98	311	213	1940	4.6	114	290	176
1921	7.2	93	306	213	1943	4.6	112	297	185
1931	7.0	106	305	199	1912	4.7	120	302	182
1987	7.0	81	295	214	1907	4.8	126	282	156
1973	6.9	105	307	202	1935	4.8	108	307	199
1995	6.7	108	302	194	1939	4.8	115	287	172
Average		107	295	193	Average		107	295	193

Table 7-6 Ten wettest and driest years of the century with starting date, ending date, and duration of the growing season

Driest	Precipitation (mm)	Start	End	Duration	Wettest	Precipitation (mm)	Start	End	Duration
1931	714	106	305	199	1972	1419	124	283	159
1914	744	106	298	192	1928	1230	121	299	178
1906	772	107	297	190	1943	1219	112	297	185
1944	777	110	289	179	1947	1175	130	312	182
1930	781	119	291	172	1927	1172	105	296	191
1910	789	104	294	190	1973	1170	105	307	202
1961	801	109	312	203	1900	1169	106	312	206
1964	806	112	295	183	1946	1164	111	306	195
1955	816	100	308	208	1995	1157	108	302	194
1953	844	89	305	216	1916	1154	115	291	176
Average		107	295	193	Average		107	295	193

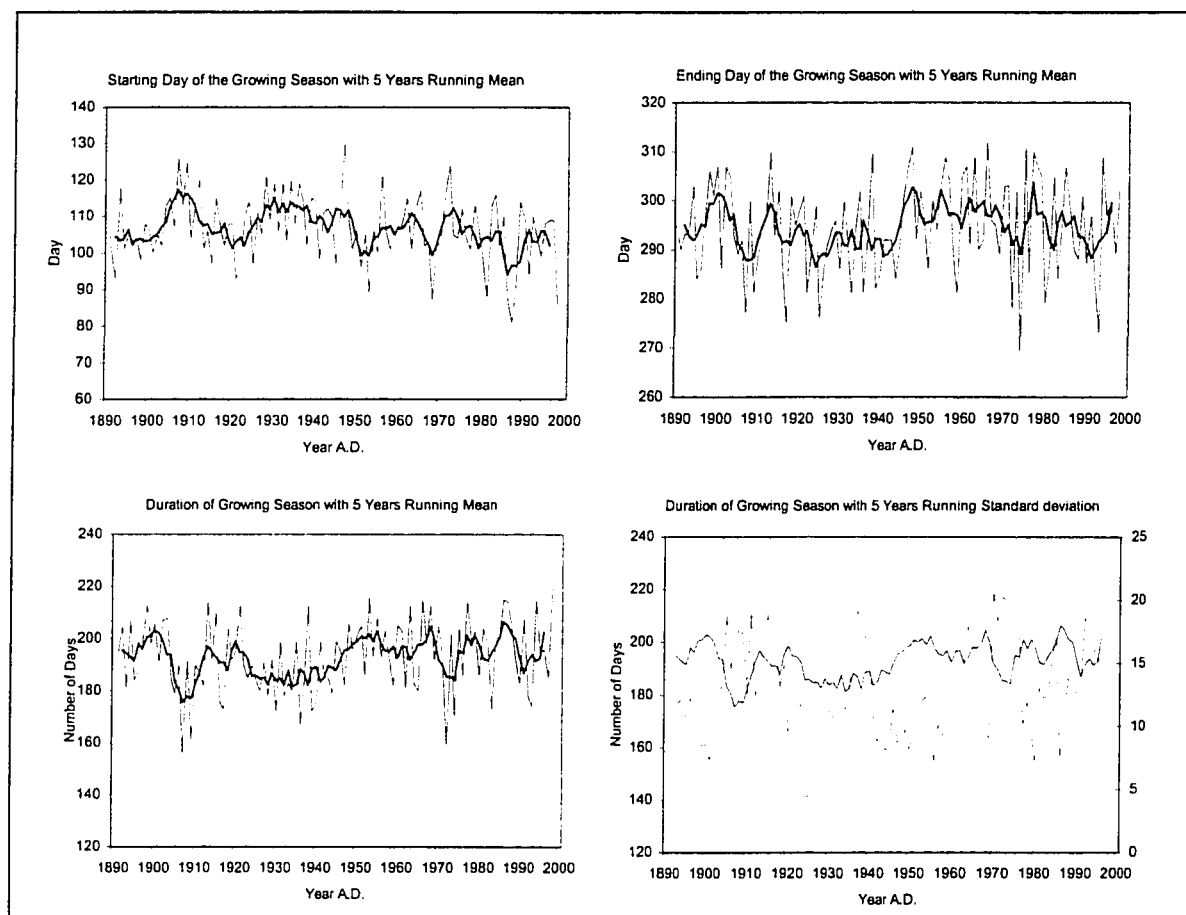


Figure 7-56 Time series of the starting date, ending date, and duration of growing season with 5-years running mean and running standard deviation.

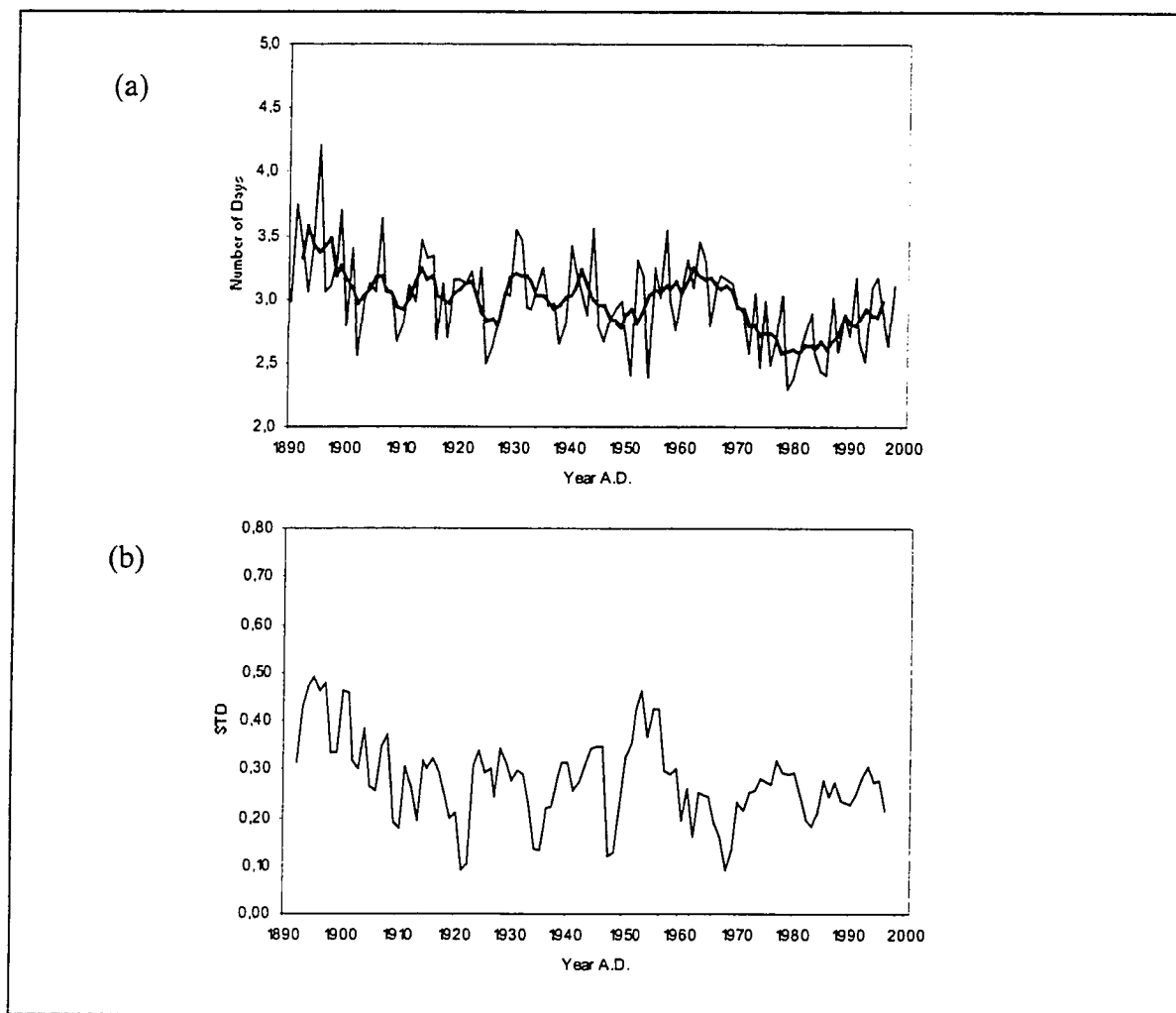


Figure 7-57 (a) Mean number of days between precipitation events and 5-year moving average, and (b) 5-year moving standard deviation.

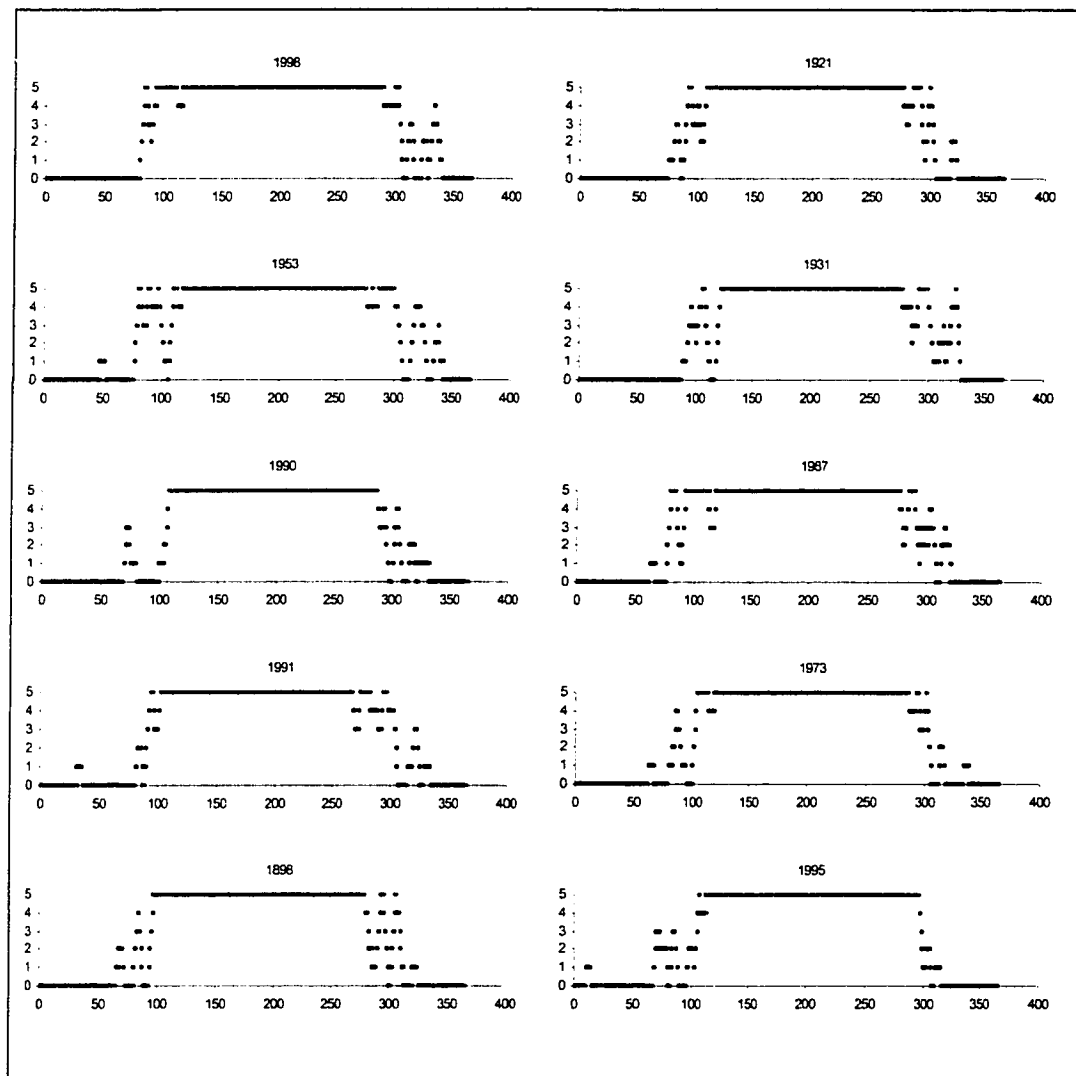


Figure 7-58 Transition into and out of the growing season for the ten warmest years of the century at Ottawa.

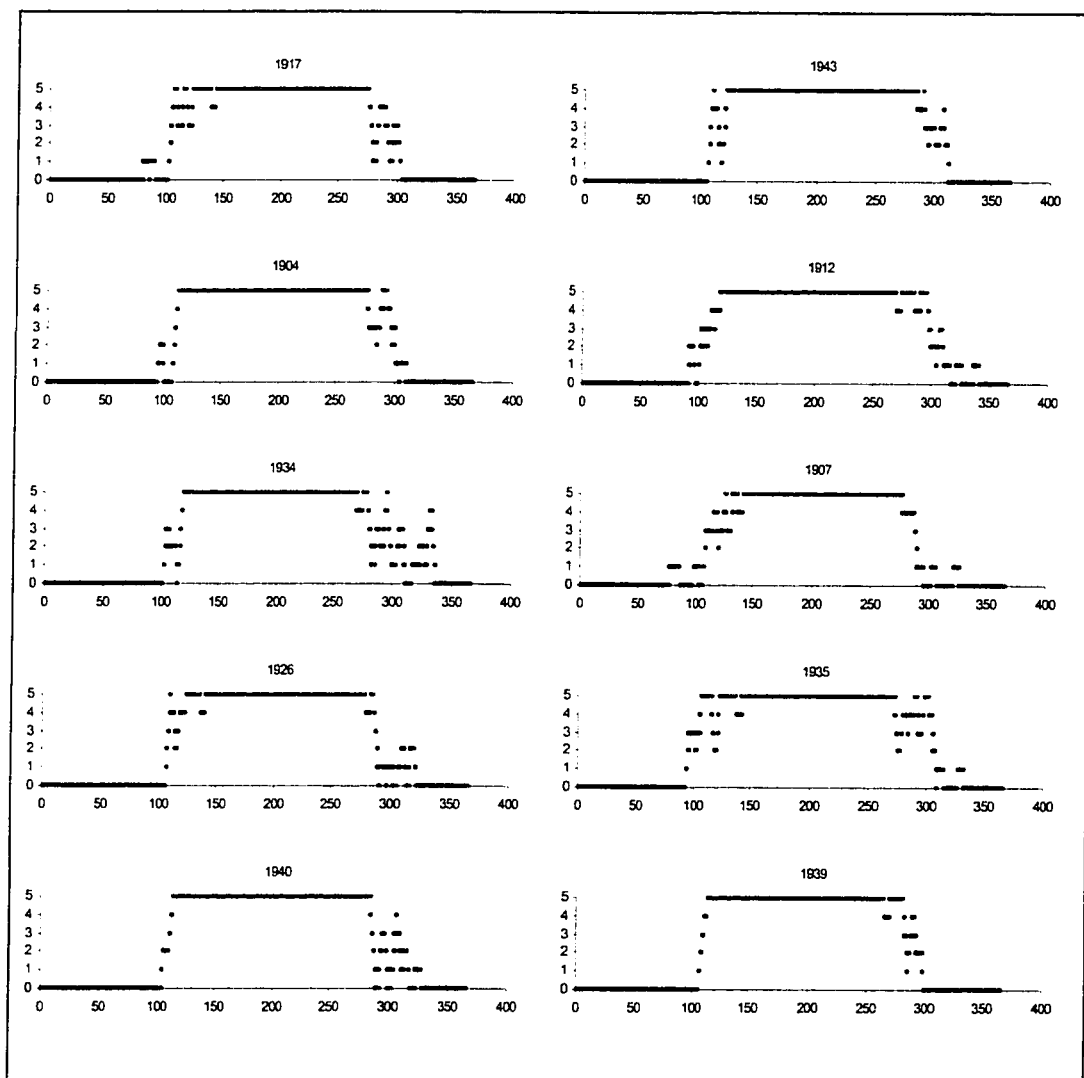


Figure 7-59 Transition into and out of the growing season for the ten coldest years of the century at Ottawa.

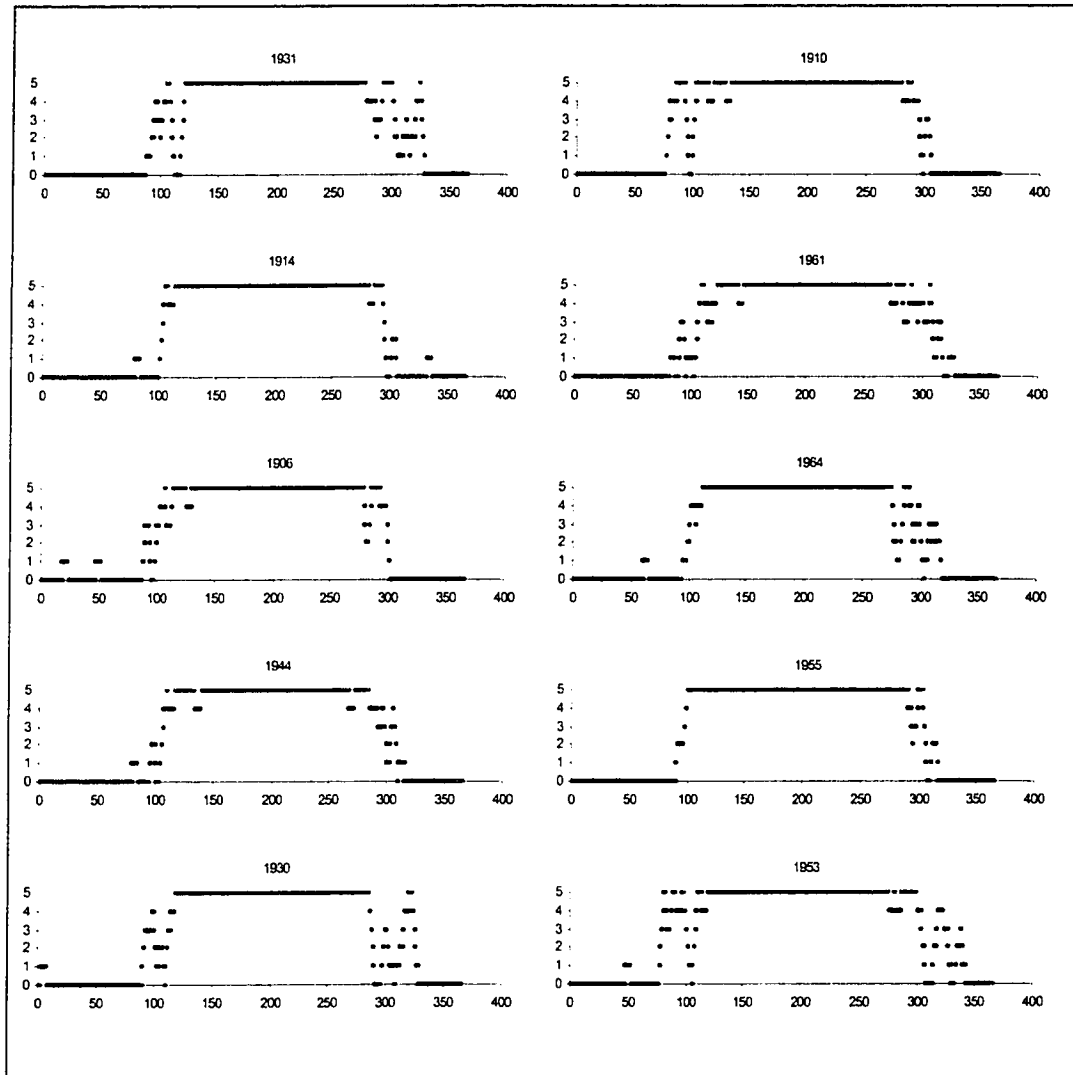


Figure 7-60 Transition into and out of the growing season for the ten driest years of the century at Ottawa.

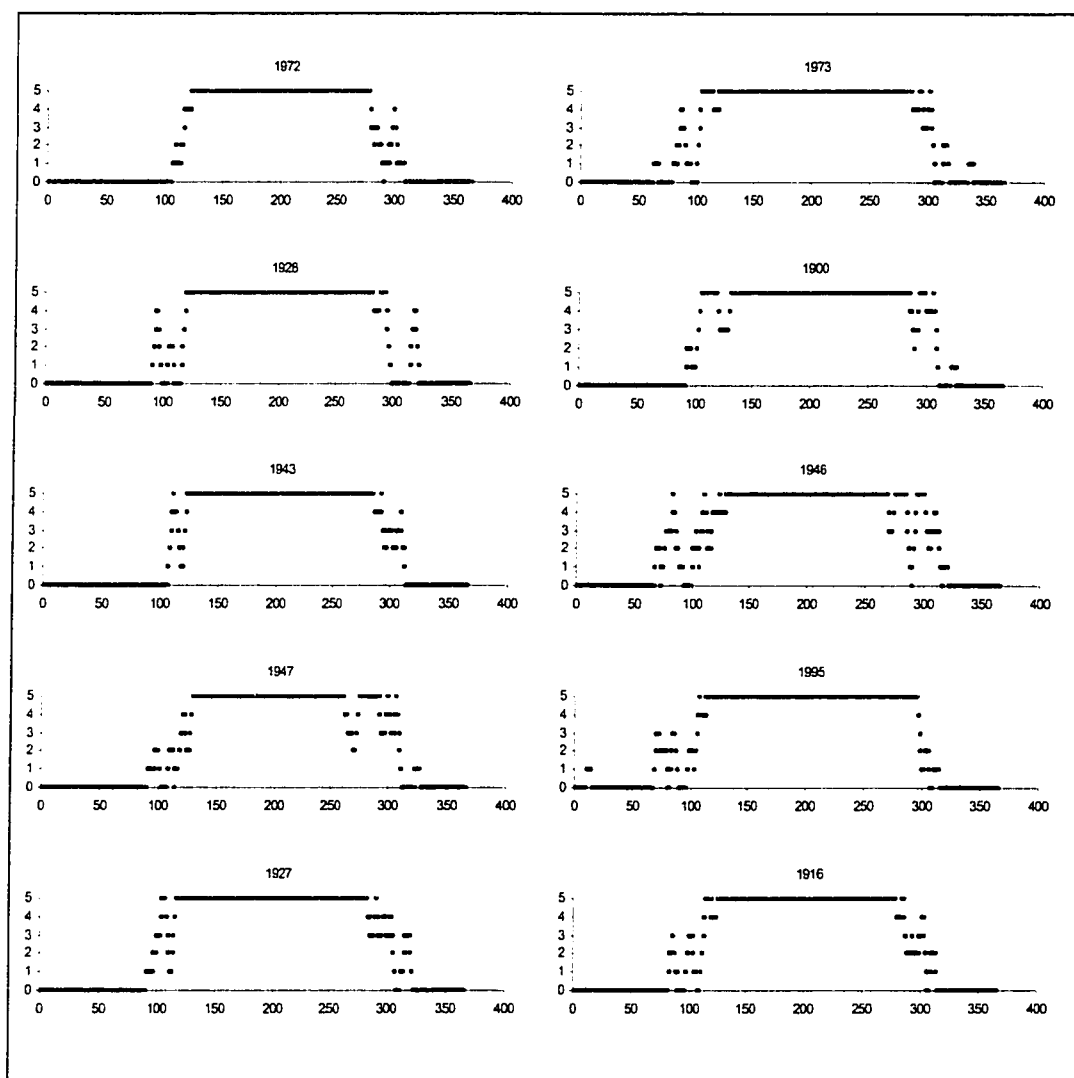


Figure 7-61 Transition into and out of the growing season for the ten wettest years of the century at Ottawa.

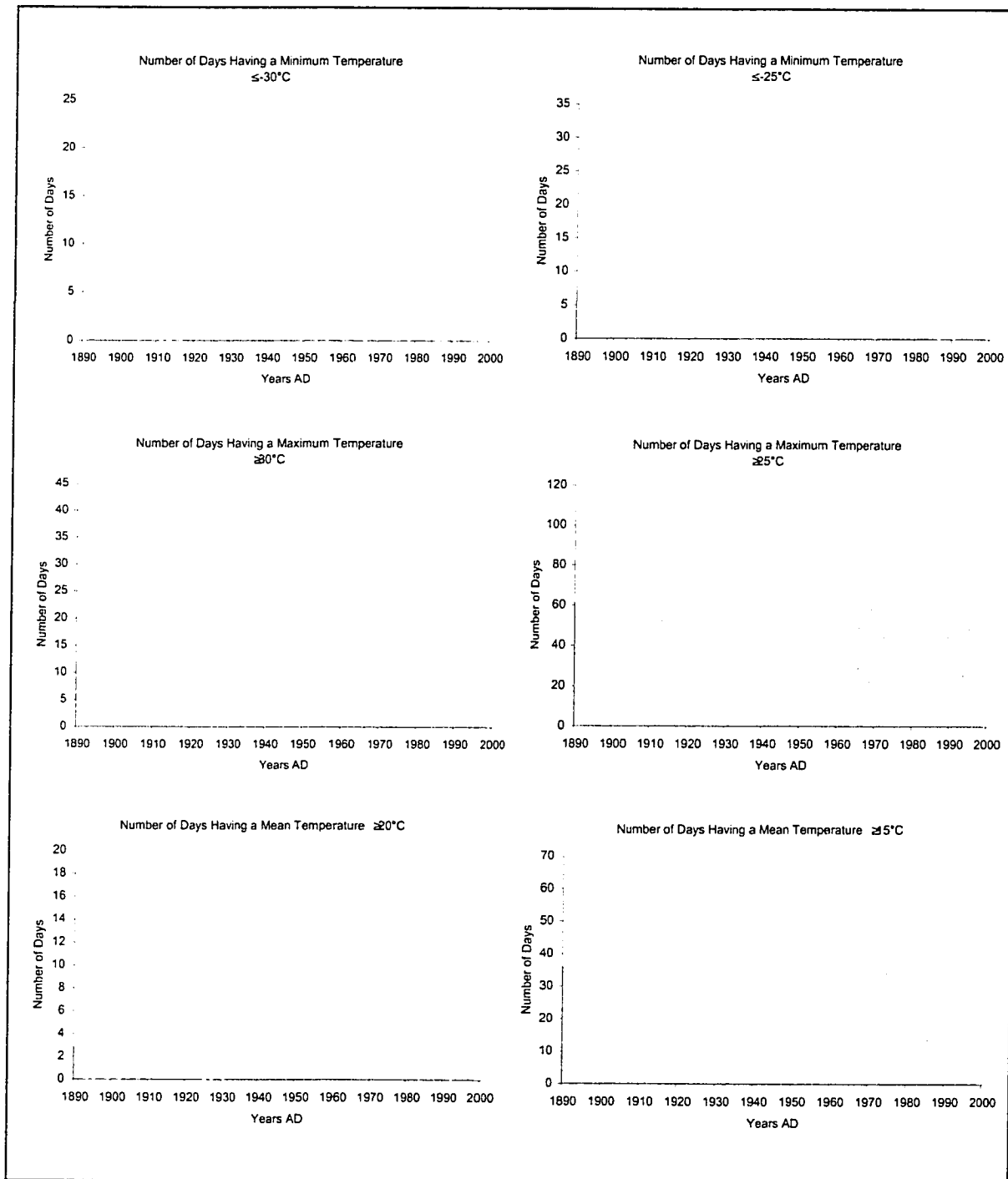


Figure 7-62 The number of days with a maximum temperature $\geq 25^{\circ}\text{C}$ and $\geq 30^{\circ}\text{C}$, a minimum temperature $\leq -25^{\circ}\text{C}$ and $\leq -30^{\circ}\text{C}$ and a mean temperature $\geq 15^{\circ}\text{C}$ and $\geq 20^{\circ}\text{C}$.

8. CLIMATE SCENARIOS FOR INPUT IN IMPACT STUDY

This project was part of an interdisciplinary project involving hydrologists, biologists and social scientists interested in the impacts of climate change. One aspect of this study was to guide the modelling efforts of others involved in the study. Several climate scenarios were selected for input to hydrological and biological studies where models needed climate scenarios. Other research projects use climate scenarios based on existing, observed climate data (Mortsch and Quinn, 1996). These scenarios are not intended to be an exhaustive compilation of all possible future climates. Rather, they serve the specific purpose of trying to deduce the impacts of climate change on environmental parameters. Due to the large number and complexity of these models, there was a limit to the number that could be investigated. This chapter summarizes the methods used to choose the climate scenario years or seasons.

As stated in the introduction, the underlying premise of this project is the use of the analogue method to choose climate scenarios. As discussed by the IPCC (2001), the main reason for using analogues based on the instrumental records is to explore vulnerabilities and adaptive capacities of a given region, in this case Eastern Ontario. The biggest advantage of using the analogue instrumental method is that all scenarios will be realistic since all scenarios occurred in the past (IPCC, 2001). The other advantage is that the scenarios can contain a rich mixture of well-resolved, internally consistent variables (IPCC, 2001). In addition, the data are readily available and the statistical properties well understood (IPCC, 2001). As with any method there are disadvantages as well. The instrumental analogue method might not be able to simulate the magnitude of change that might result from greenhouse gas forcing (IPCC, 2001). The instrumental analogue method uses the past to understand the future; however the future might

not look anything like the past. A second disadvantage is that the scenarios provided by the analogue method usually cover quite small magnitudes of climate change (IPCC, 2001). Finally, no appropriate analogue may be available (IPCC, 2001).

8.1. Methodology used to Select Climate Scenarios

First, scenarios were determined during consultation with other members of the research group. Scenarios were selected, from the instrumental record by choosing, a year or seasons where the values of temperature and precipitation exceeded the 1-in-5 (20%) probability value for the climate record of the 20th century. Although we would have preferred to use the 1-in-10 (10%) probability as the criterion, we soon realised that the 10% probability for both temperature and precipitation has never happened simultaneously in Eastern Ontario. Therefore we used a probability of 1-in-5.

The first step involved in choosing climate scenarios is defining the baseline for average, warm and cold temperatures. Average temperatures were computed over the past 100 years. Warm temperatures were defined as those that exceeded 80% of the temperatures of the past 100 years. Cool temperatures were defined as those that were less than 20% of the temperatures of the past 100 years. Total precipitation was similarly computed over the past 100 years. Wet periods were defined as those in which the precipitation exceeded 80% of the average precipitation periods of the past 100 years. Dry periods were defined as times during which the precipitation was less than 20% of the average precipitation periods of the past 100 years.

After defining warm, cold, dry and wet scenarios, we looked for years or seasons that had both extreme cases, that is a 1-in-5 temperature value and 1-in-5 precipitation value (Figure 8-1). In

some cases, more than one year met these criteria; therefore, we chose the year closest to the 1990s and that was the most extreme. The reason for that was to represent recent climate changes.

Most scenarios chosen are for spring and/or summer. Spring precipitation is important for agriculture productivity and water budget allocation (Bamford, 1988; Mock, 2000). Summer precipitation is important to offset the high potential evapotranspiration, thus reducing drought hazard and supporting agricultural systems (Borchert, 1950; Rosenberg, 1986b; Mock, 2000).

The first two scenarios are simply the average years (1941 and 1909) used as baseline cases (Table 8-1). The second scenario needed was one of a warm winter, wet spring, and dry summer. This scenario examines the impact of a drought following spring floods – a fairly common scenario. The question here is whether the spring aquifer recharge is sufficient to sustain a dry summer. Two years were found fulfilling these criteria (1991 and 1983). The third scenario was that of a warm winter, dry spring, and dry summer. This scenario explores the possibility that the spring recharge is minimal. Combined with little precipitation in summer, this situation could lead to water stress on plants or low stream flow. One year was found, 1966. The fourth scenario was one of a warm spring, wet winter and spring. This scenario explores the possibility of excess water in the spring, following normal moisture demands in the summer. Under this scenario, there is some chance for spring flooding or excessive groundwater recharge. Two years were found for the fourth scenario (1973 and 1991). For the fifth scenario we tried to find the growing season that had the longest time period without any rain, followed by a heavy rain event; one year was found, 1975. Analysis of this scenario will examine the impact of an extreme precipitation event during an otherwise dry summer. Under these conditions, surface

waters are vulnerable because of the possibility of flash flooding and erosion. Aquifers are also vulnerable under this situation, because of the possibility of short-circuiting surface waters to groundwater. The only year found with these conditions was 1975. The sixth scenario was that of a spring and summer both warm and wet. Warm and wet conditions, especially prolonged ones, will stimulate biological activity, promoting excessive algal growth in surface water bodies. In addition, many terrestrial ecosystems will remain waterlogged, promoting anaerobic conditions and stimulating some insect populations. The excess moisture will also affect crop yields. A warm and wet spring can also increase the likelihood of spring flooding with ensuing erosion problems. An increased probability of flooding can also increase the likelihood for groundwater contamination by surface waters in vulnerable areas. On the other hand, an anticipated hydro-geological benefit of warm and wet conditions is a recharge of deep aquifer systems. From an engineering perspective, warm and wet conditions in the spring and summer increases the capacity to dilute effluents, but may cause stress in terms of the capacity of the waterways to handle the higher flow volumes. One year was found for the sixth scenario, 1973. The last scenario was that of a spring and summer both cool and wet. This scenario will examine the impacts of increased moisture on the environment without the compounding effect of warmth. One year was found for the last scenario, 1956. All of these scenarios are summarized in Table 8-1 and Figure 8-2.

APPENDIX G

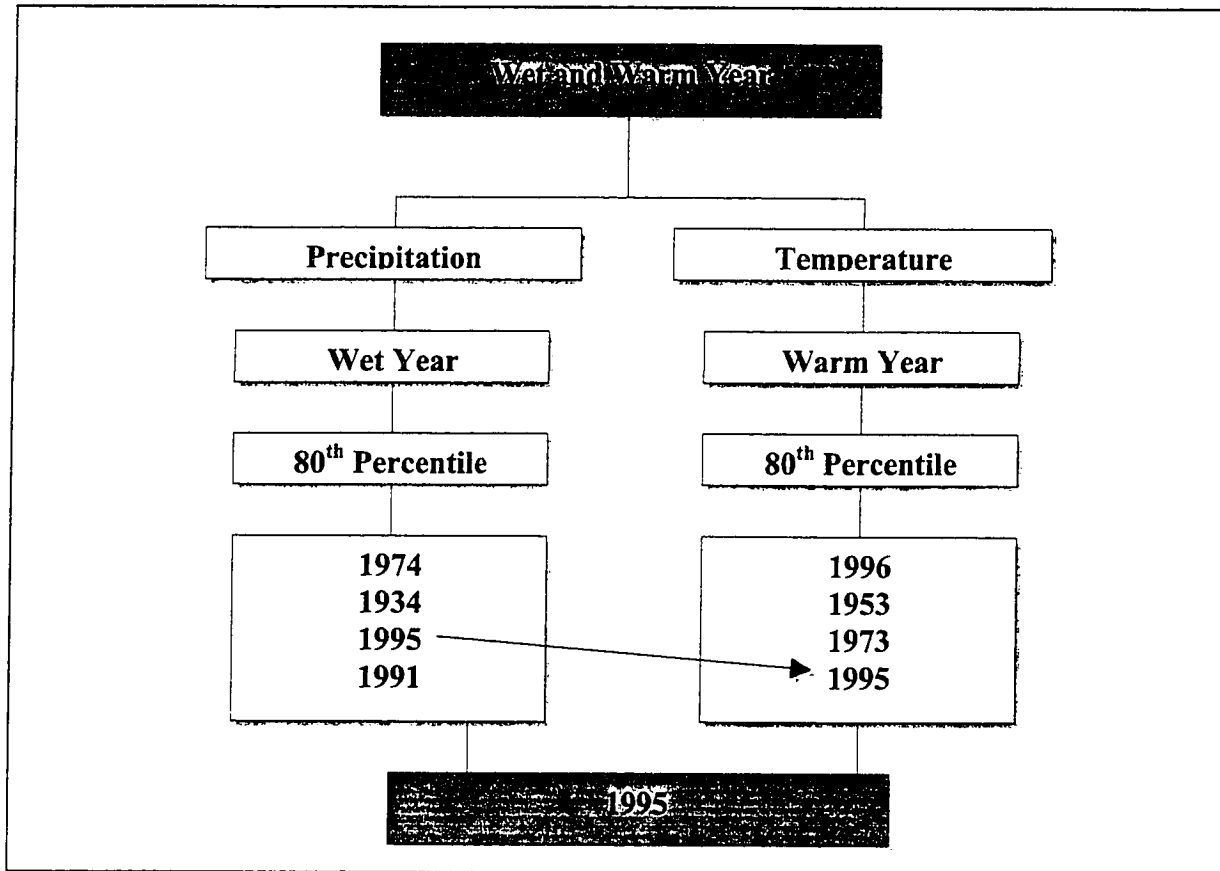


Figure 8-1 Method used to determine possible climate scenarios.

Table 8-1 Scenario year and seasons

Scenario	Temperature	Precipitation	Results
1	Average year	Average year	1941 or 1909
2	Warm winter	Wet spring, dry summer	1991 or 1983
3	Warm winter	Dry spring and summer	1966
4	Warm spring	Wet winter and spring (spring floods)	1973 or 1991
5	Warm summer	Dry periods followed by heavy rain	1975
6	Warm spring & summer	Wet spring & summer	1973
7	Cool spring & summer	Wet spring & summer	1956

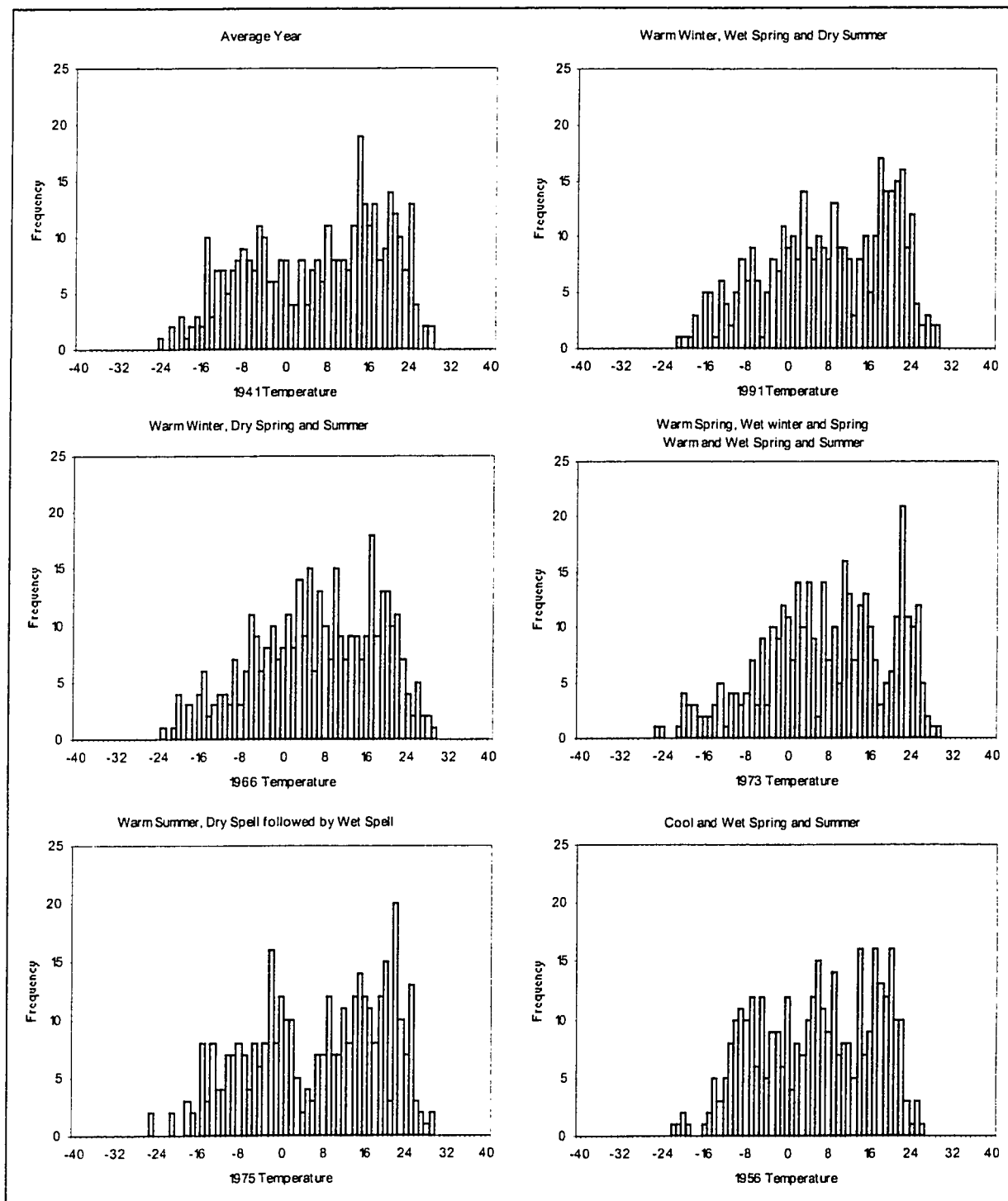


Figure 8-2. Frequency distribution of mean daily temperature for the different scenarios.

9. DISCUSSION AND CONCLUSION

The first question this research project addressed was the number of stations needed to represent Eastern Ontario at a local scale. To answer this question we calculated correlations between the mean monthly temperature and total monthly precipitation of several stations within and just outside the study area. Mean monthly temperatures were more highly correlated than total monthly precipitation. Both winter temperatures and precipitation were more highly correlated than in summer. However, for every climatic variable and for every month, correlations were high. Not surprisingly, stations that are closer together are more highly correlated. The presence of high correlations means that one or two stations with long climate records can be used to evaluate the climate of the 20th century in this region. That is, Eastern Ontario acts as one climatic region.

The second task was to stratify the data and to identify those decades that were warmer, colder, drier and wetter than the instrumental record average. The decade with the warmest mean air temperature was the 1990s followed by the 1980s, and 1890s. Thus, with the exception of the 1890s, the warmest temperatures have occurred in the recent past. Although we have no reason to believe so, it is possible that the early data are less reliable, as station locations and exposure or instrumental accuracy may not have been well accounted for. We will consider all data to be equally accurate in this study. The coldest mean temperatures occurred in the 1930s followed by the 1910s. The warmest maximum air temperatures were found in the 1890s followed by the 1990s, and the coldest decades were the 1930s followed by the 1970s. The warmest minimum air temperatures occurred in the 1990s followed by the 1980s, and the coldest in the 1910s followed by the 1920s. Thus, the 1990s were warmest at night but not during the day.

The ten warmest years of the 20th century were found at the beginning and at the end of the century. The ten coldest years occurred in the early part of the century, between 1904-1939. In the last decade, (1990-1998) we have experienced the four of the ten warmest years of the century, including the warmest year on record (1998), which was a full degree warmer than the second warmest, 1953. There has been an overall increasing trend in the mean annual air temperature since the 1970s, which corresponds with the global trend of increasing temperatures in the recent past (IPCC, 2001). Warmer decades had more than half of the years above average, whereas cold decades were below average for various reasons. In some cases one or two years were far below average causing the mean for the decade to be low. In other cases, five or more years of the decade were below average.

The next analysis was designed to determine why the decades identified above were warmer, colder, wetter or drier. For example, are warm decades above the mean because they had more days above a certain threshold or was it due to incremental increase in the temperature of many days? This was of interest to this study since extreme temperatures can have significant impacts on human activities. The decades having the greatest number of days with maximum temperatures above 30°C were the 1910s followed by the 1940s and the least number of days were the 1990s. The decades having the greatest number of days with maximum temperatures above 25°C were the 1890s followed by the 1940s. The second half of the century had more days with mean temperatures above 20°C and 15°C. The decades having the greatest number of days with minimum temperatures below -30°C were the 1930s followed by the 1940s, whereas the least were the 1990s followed by the 1980s. In the first half of the century, between 1890-1950, there were more days with minimum temperatures below these thresholds. The 1990s,

although warm in the mean, had fewer extreme heat waves and fewer cold snaps as well.

There has been an overall decreasing trend in the DTR since the 1920s. The cause of this was an increase in minimum temperatures. Therefore, the increase in daily temperature range seems due to less energy loss at night rather than to increased solar radiation absorption during the day, consistent with CO₂ forcing of this trend. Another possibility is an increase in cloud amount at night, which would also act to increase night-time temperatures (Folland *et al.*, 1992). The DTR is larger at Morrisburg than at Ottawa. Rural stations usually display the greatest observed DTR (Gallo, 1996). Between 1920 to 1930 and 1950 to 1960, night-time temperatures were more variable than daytime temperatures. The inter-annual temperature variation was high in the 1910s, 1950s, 1970s and 1990s and low during 1920s, 1930s, 1940s and 1960s.

The available data end in 1998. However, if the overall trends identified here persist, the 1990s as well as the 1980s and 1970s tended to be wetter than average. There is no apparent relationship between temperature and precipitation at the decadal scale. Some decades have high temperature variability and high precipitation variability as well; however in other decades, they are inversely related. This means that it will be difficult to project moisture amounts into the future based on the projected temperature trends. It suggests that future climates may be wet or dry and this uncertainty should be built into planning.

Analysis of the different seasons shows the complexity of the climate of Eastern Ontario. The seasons typically causing years to be extreme are winter and spring. When winter and/or spring are either much warmer or colder than the average, this has significant impacts on the yearly

average. Since the 1980s, winter temperatures seem to be increasing. There was an overall decreasing trend in mean spring temperature between the 1890s and 1940s, then a steady increase between the 1960s and 1990s. Spring maximum temperatures show a shift in regime approximately every 30 years. Since the 1930s the summer night-time temperatures have increased. During the last 30 years, summer daytime temperatures fluctuated widely from one year to the next. Autumn minimum temperatures have increased since the 1960s, while maximum temperatures decreased during the 1960s and 1970s and subsequently increased in the 1980s and 1990s. In general, most seasons are warmer or colder because every month in the season is either warmer or colder.

The seasonal distribution of precipitation is as important as total amount and variation as it influences the type of ecosystems that can survive under a particular climate regime. In Eastern Ontario, every month contributes to a season being drier or wetter. The key season determining high annual precipitation is summer. However, both summer and spring were drier than average in the ten driest years. In general, it appears that warmer years were accompanied by lower summer and spring precipitation and colder years with greater summer precipitation.

High inter-annual variability makes planning more difficult, and may have different impacts on ecosystems than less variable conditions. The inter-annual variability was high in January in the 1910s, 1930s and 1990s. Mean monthly minimum temperatures seem more variable than maximum temperatures, especially in the 1930s. Warmer Januaries tended to have lower variability. Inter-annual temperature variability in April was high from 1910 through the mid 1930s and in the 1940s and 1970s, and low in the late 1930s and 1960. The inter-annual

temperature variability of July and October is lower than that of January and April. However, October monthly temperatures are characterized by higher frequency changes, going quickly from more variable to less variable periods of 5 years. The variability tends to be low for October monthly temperatures during warm periods and higher during colder periods of the century.

Although this study has concentrated on climate data from Ottawa as representative of the region, precipitation is spatially variable. Inter-annual variability differs between Morrisburg and Ottawa, especially in the summer, with Morrisburg having lower variability and fewer drier years than Ottawa. April precipitation seems to vary between wet and dry cycles with periods of 5 to 10 years in Morrisburg. In the 1930s the variability of January precipitation was lower in Ottawa compared to Morrisburg. The inter-annual variability of January precipitation has been increasing in Ottawa since 1980. While Morrisburg also had high variability during this period, the onset of this regime was more sudden than occurred at Ottawa. July precipitation was more variable at Morrisburg than at Ottawa. In Ottawa, the variability of July precipitation was relatively low between 1900-1920. Variability slowly increased from 1915 to 1950, and has remained generally stable since then.

Daily temperatures were studied in some detail, since the onset of seasons and extremes within the seasons are critical factors for impact studies. In temperate regions, the form of the annual temperature curve is roughly a sine wave. In Ottawa, minimum temperatures occur around day 320-360 and maximum temperatures between days 180-240 of the year. Spring can be quite variable with rapid alternations between $< -20^{\circ}\text{C}$ to $> 0^{\circ}\text{C}$ within a couple of days. The

transition between winter and spring can be abrupt or smooth. Typically, the temperature rises above 0°C between day 80-100. The transition to summer is typically smooth; summer can have a broad peak at its maximum temperature or the peak can be composed of only a few days. The transition from summer to fall can sometimes be sudden, whereas in other years temperatures gradually decrease. Mean daily air temperatures typically fall below 0°C around day 300. As in spring, the transition to winter can be smooth or abrupt.

The growing season typically begins near the 105th day of the year, which is around mid-April, and ends on the 295th day of the year, which is around the last week of October. The length of the growing season has varied through time; on average it lasts for 192 days. Before 1903, between 1949-1960 and since the mid 1960s, the growing season started earlier. From 1897-1903, 1910-1920, 1946-1960, 1970-1979 and from 1984 to 1998 the growing season has been ending later than average. The inter-annual variability of the duration of the growing season was low before 1903, between 1920-1935 and 1941-1960 and high from 1903-1919, 1936-1940, the 1970s and 1990s.

The frequency histograms of daily temperature provide further information about the seasonal cycle. All years showed multi-modal distributions of daily mean air temperatures, usually having two dominant modes corresponding to summer and spring. The ten warmest years have more days with a daily mean air temperature above 20°C and 15°C compared to the ten coldest years. In addition, the ten warmest years have fewer days with mean air temperatures below -25°C and -30°C compared to the ten coldest years. The number of days having minimum temperatures $\leq -30^\circ\text{C}$ has decreased through time. Since 1980, almost every year had few days

with a minimum temperature $\leq -30^{\circ}\text{C}$ and indeed, several consecutive years had none. The mean daily air temperature does not seem to differ between the driest and wettest years.

Eight of the ten warmest years had growing seasons, which began earlier compared to the ten coldest years, and in most warm years the growing season lasted longer. In warm years the growing season tends to begin around the 96th day (first week of April) compared to the 114th day (last week of April) in the cold years. The ten warmest years are more variable during the transition periods spring and autumn, compared to the ten coldest years. There is no apparent relationship between precipitation amounts and growing season length.

As opposed to temperature, there is no clear annual cycle in precipitation. Furthermore, the total amount of precipitation in a year has not significantly changed over the 20th century. The overall average was 142 days with measurable precipitation in the year. In the latter part of the century, Eastern Ontario experienced more days with measurable precipitation, but the amount of precipitation per day was reduced. Most days received either light or heavy amounts, with fewer days receiving intermediate-sized amounts of precipitation. Extreme events seem to be the rule. On a typical day, less than 20 mm of precipitation fell although events with greater than 80mm in a day have been recorded. During the growing season, it is rare to have many consecutive precipitation days. The frequency of measurable precipitation events tended to be low in the 1930s, increased in the 1950s and increased again in the 1980s at both Ottawa CDA and Morrisburg. There is no apparent difference in the nature of the temperature transition from spring to summer and summer to fall between the ten wettest and driest years.

Although total precipitation amounts ultimately determine factors such as soil moisture, the distribution through the year can have critical impacts, for example, on stream flow and plant growth and survival. Since the 1970s every decade has had an above average number of days with measurable precipitation. The wettest decade was the 1970s followed by the 1990s, and the driest was the 1960s followed by the 1950s. The scale parameter of the gamma distribution is larger in the warmer decades (1890s and 1990s). The smallest scale parameter was found in the 1930s followed by the 1910s. The largest shape parameter was found in the 1920s followed by the 1930s, and the smallest in the 1980s followed by the 1990s.

The key season determining high annual precipitation is summer. In general, it appears that in warmer years summer and spring precipitation was lower, but unusually large values in several years could determine if the decadal means were high or low. The inter-annual variability of January precipitation has been increasing since 1980, whereas the variability of July precipitation increased from 1915 to 1950, and has remained generally unchanged since then. In general, there has been an increase in the number of precipitation days, however individual events can deposit either large or small amounts of precipitation.

Since the mid 1960s the growing season has started earlier and since 1984 has been ending later than the average of the 20th century. The inter-annual variability of the duration of the growing season was high in the 1990s.

What is in store for the future? If we base our predictions on the recent past, we would expect the future to be warm. The increase in mean temperature would be mainly due to an increase in

minimum temperatures in every season, causing an overall decreasing trend in the diurnal temperature range. The increase in daytime temperature should be relatively small in the summer and autumn, but larger in both spring and winter. In the last decade, we have experienced the four warmest years of the century; we might expect to have many subsequent warmer years in the future. In the last century, warm decades could be either relatively wet or dry; however, the 1980s and the 1990s have been both warm and wet. Evidence from general circulation models predicts an acceleration of the hydrological cycle in the future, suggesting that the most recent decades may provide the best analog for the future. However, warm decades tend to have higher inter-annual variability and this should be accounted for in planning.

We have presented a detailed analysis of the climate variability of Eastern Ontario. Of course, the future remains unknown, but the results presented here provide reasonable estimates of future climates. The basic assumption of this project is that the future may consist of an increase in the frequency of the events observed in the warm periods of the past century. However, the large increase of greenhouse gases, which will remain in the atmosphere even if emissions are drastically reduced, might lead to completely different climate patterns or abrupt changes, which we cannot easily foresee. The key is to plan for variability.

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