TRENDS AND VARIABILITY OF TEMPERATURE AND PRECIPITATION IN NORTHWESTERN ONTARIO DURING THE 20^{TH} CENTURY: IMPLICATIONS FOR FOREST MANAGEMENT

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ABSTRACT

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Key words: climate variation, proxy indicators, boreal range, extension of time series, homogeneous time series, standard differences, proxy data, continentality, diurnal temperature range, spectral frequency, disturbance, adaptive strategies.

Time series of temperature and rainfall in Northwestern Ontario are joined and adjusted to provide a database for analysis of regional climate change. Processes used to locate and adjust for non-climatic discontinuities are provided. Temperature trends were computed for 1916-1998. All available stations have increases in mean annual temperature. The greatest warming occurred in the spring at all stations with most stations $\geq$ 1.0° C warmer. Some increase in winter and the growing season temperature has taken place. A slight negative change has taken place in the fall in most stations. The warming has been greater in minimum temperatures than maximums with resulting declines in the diurnal temperature range especially evident in the first half of the period. Average rainfall has increased at all stations in the region. An analysis of daily rain events suggests increases in frequency and amounts of individual events $\geq$40 mm in southern locations and 30.0 - 39.9 mm in the northern stations. Trends and variability in these variables during the 20th century are analysed to define a base and context for predictions of significant climate change in the 21st century. Ecosystem change because of climate change is likely to have major impacts on forest management and wood-based products, an economic sector of major importance in the region.

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DEDICATION

Kerstin Muth

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LIST OF ACRONYMS

AF	Anthropogenic forcing
Climat	Second-order climatological station (Environment Canada)
DTR	Diurnal temperature range
EC	Environment Canada
EMR	Energy, Mines and Resources
ENSO	El Niño Southern Oscillation
GCM	Global circulation model
GHG	Greenhouse gas
GS	Growing season
HBC	Hudson's Bay Company
IPCC	Intergovernmental Panel on Climate Change
NA	North America
NH	Northern Hemisphere
NWO	Northwestern Ontario
PNA	Pacific North America
QBO	Quasi-biennial oscillation
SH	Southern Hemisphere
SST	Sea surface temperature

INTRODUCTION

Temperature and precipitation are primary determinants of the distribution of vegetation. These climatic variables also contribute to (or limit) the health and productivity of agricultural and forest ecosystems and related regional economies (Winnett 1998). Changes in these and related climate variables have affected such ecosystems in the past with consequences for species health and distribution. There is evidence of adaptation to climate change and variation in the past (Pollard 1991). One of the adjustments, in times of prolonged climate change, has been the migration of vegetation zones. The boreal forest, for example, has existed both north and south of the present boundaries during the Holocene time period (approximately the past 10,000 years) in response to natural climatic variations (Ritchie 1983; Ball 1986).

There is considerable evidence that the Earth is currently undergoing a time of significant climate change. Meteorological instrument records and proxy climatic indicators such as tree-rings indicate that the 20th century warming trend is unusual when compared with recent centuries (Mann et al. 1998). Climate is typically highly variable which has complicated the assignment of cause to this current trend. It is now generally acknowledged that part of the observed warming is due to human activities (IPCC 1996; Tett et al. 1999) but quantification of this contribution is not direct as no distinct human pattern has emanated from naturally occurring meteorological processes (Corti et al. 1999). Human-induced climate change is expected to increase in the 21st century, although an atmospheric pattern bearing a specific human signature is unlikely to emerge. A more probable outcome would entail frequency changes of natural circulation patterns and associated warmer temperatures (Corti et al. 1999).

1.1 The Boreal Forest and Climate Change

The location of the circumpolar boreal forest is mainly determined by air temperature and precipitation. Many stages of growth and reproduction of boreal species are directly or indirectly related to weather and climate (Singh and Wheaton 1991). Other variables such as soil type, nutrient status and topographical features also affect distribution. The vegetation of Northwestern Ontario (NWO) is primarily a boreal forest ecosystem with a transition to hardwoods of the Great Lakes Basin in the south with dwarf and tundra species to the north. The present location of the boreal forest in NWO is approximately coincident with an annual mean temperature of -4° C in the north and 2° C in the south (based on 1951-1990 normals). The NWO boreal forest is termed by Sargent (1988) as the 'wet boreal forest', approximately associated with climate features of 1100 - 2200 growing degree days and precipitation of 500 - 1000 mm annually.

The northern limit of the boreal forest is thought to be determined by temperature (Singh and Wheaton 1990; Hogg 1994), specifically summer warmth (Black and Bliss 1980) with soil type providing a further limitation (Smith et al.

1998). In Ontario, the transition from boreal species to the tundra biome is located between 16° C and the 12° C isotherms of mean daily temperature in July (Kemp 1992; Natural Resources Canada 1997) as illustrated in Figure 1.1. The average summer position of the arctic front is approximately coincident with the 14° C isotherm (Bryson 1966).

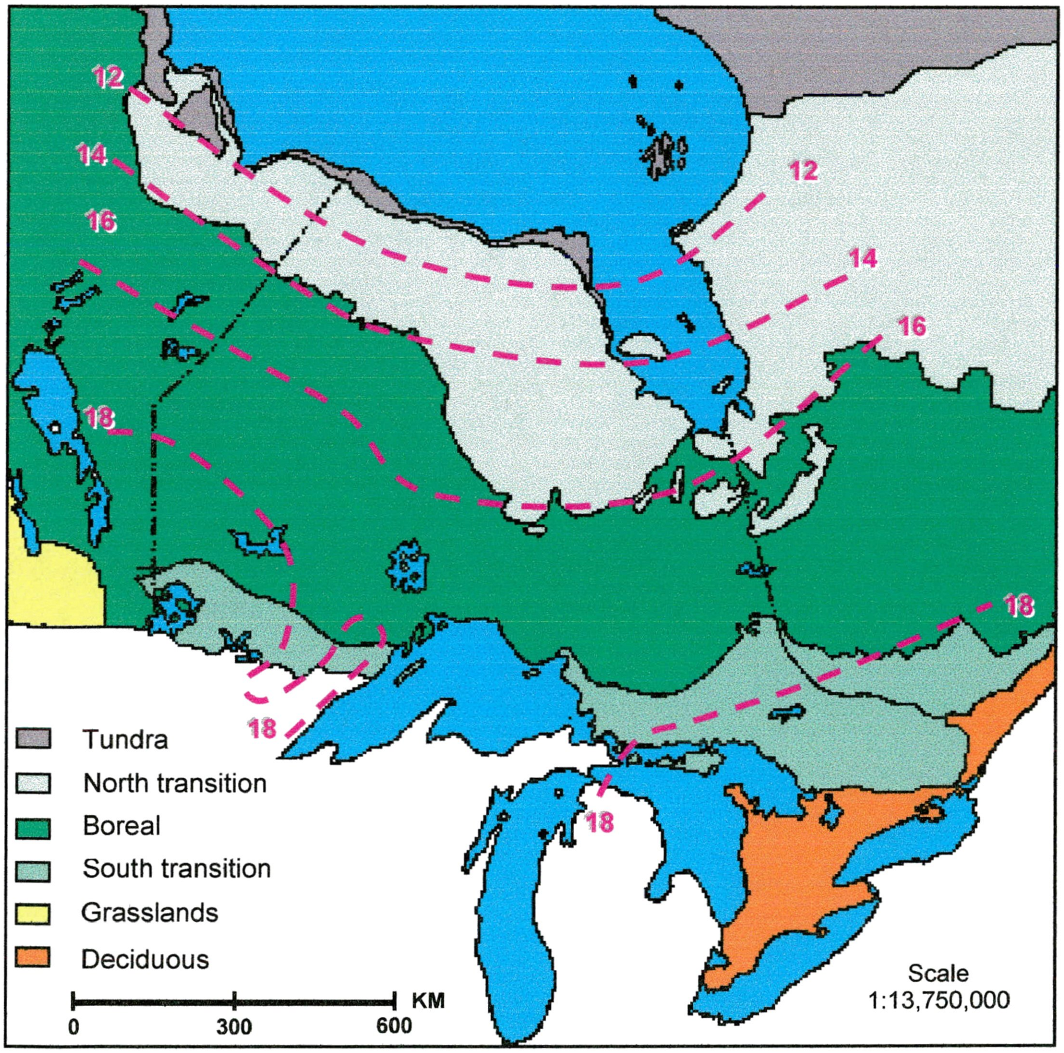

Figure 1.1 The present location of the boreal forest in Ontario. Selected July isotherms (based on 1951-1990 mean temperatures, °C) have been added. Source: after EMR 1974; Kemp 1992; Natural Resources Canada 1997.

The southern transition has additional thresholds and interactions. Hogg (1994) found a close relationship between moisture deficiency and this ecotone in western Canada. Other climatic features can influence the transition by limiting (or encouraging) competition. Arris and Eagleson (1989, cited in Hogg 1994) noted that an absolute minimum temperature of -40° C restricts the northward migration of cold-sensitive broadleaved species.

Change in thresholds and interactions are likely to cause shifts or variations in the area climatically suitable for the boreal ecosystem (Sargent 1988; Mackey and Sims 1993). The physical process of this relocation is likely to be disturbance, a fundamental process within the boreal forest. Fire has, by far, the most impact on distribution and structure of the biome (Weber and Flannigan 1997). Other natural disturbances (insect infestations, disease and blowdowns) also have a role (sometimes by providing additional fuel during a fire event).

Major impacts on the vegetation in the NWO region are likely in the 21st century even if the lower projections of warmer temperatures take place. It is likely that the limits of the boreal forest will respond to changes in the environment. Pollard (1991) and Lockwood (1998) stated that extremes in temperature and precipitation are likely to have more impact on vegetation health and growth than gradual changes in long-term averages. Emanuel et al. (1985) suggested that the boreal forest could, with changes in temperature and moisture availability, almost disappear from North America (NA). In Ontario the suitable temperature range of most boreal and broadleaf species is expected to shift to the north by 500 km during the 21st century (Smith et al. 1998) with earlier and longer growing seasons. The area of the boreal forest would decline, limited by Hudson and James Bay in the north and with replacement by broadleaf species in the south (Duinker 1990).

1.2 Purpose of Study

The mainstream of atmospheric science literature suggests that both natural and anthropogenic climate change have taken place in the 20th century. Research has resulted in projections of continuing, likely accelerating, climate change that will affect the natural environment and human activities. Adaptation to the consequences of climate change requires research, planning and action at the global, national and regional levels. In large countries like Canada the effects of climate change are likely to be quite varied. Thus, the adaptive strategies will need to be appropriate for the ecosystems and communities within individual regions.

In NWO the landscape cover is primarily boreal forest and many human activities are associated with this landscape. Forest-based industries have considerable economic significance for the region and unanticipated change in the extent and health of the boreal forest could have disruptive impacts on these industries. Credible projections of future climate would assist in the selection of strategies.

The first stage in building such a climate scenario requires analyses of historical and recent trends and comparison with other regions and larger scales. Often the raw data are flawed because of nonclimatic influences. There are established methods to determine, and adjust for, homogeneity in temperature and precipitation records (Crowe 1992; Jones et al. 1996; Vincent and Gullett 1999). Some of these procedures are used in this study to produce homogeneous series for selected NWO stations. Neighbouring station records are used to adjust series and estimate missing data (Crowe 1992). A refinement of this technique that uses weighted estimates from two or more neighbouring temperature series is presented. A combination of the above methods is used to construct a 20th century temperature and precipitation database.

The purpose of this study is to assess the following climatic features in NWO during the 20th century:

- trends and variability in temperature and precipitation;
- frequency of extreme temperature and precipitation events;
- cycles in temperature; and
- to provide an overview of ongoing climate change in the region.

Features and trends of NWO climate are compared with averages and tendencies of the Northern Hemisphere (NH) and other mid-continent findings.

There is growing conviction that GCMs can provide reasonably accurate temperature projections at global to regional scales, but less confidence for regional prediction of precipitation and other meteorological variables such as wind and sunshine. Examining both observed 20th-century climate change and GCM-projected climate change in the region, a review is presented of some potential changes to vegetation in the boreal forest.

CLIMATE CHANGE

2.1 Global and Northern Hemisphere Climate Change

The Earth's annual-mean temperature has warmed by approximately 0.7° C during the 20th century (Hasselmann 1999). This positive trend results from two warming phases occurring from approximately 1910 to 1940 and from 1970 to the present (Tett et al. 1999). In the NH these times of warming were separated by about three decades of slight temperature decline (Figure 2.1). In the Southern Hemisphere (SH) the warming trend resumed after a shorter decline during the 1940s.

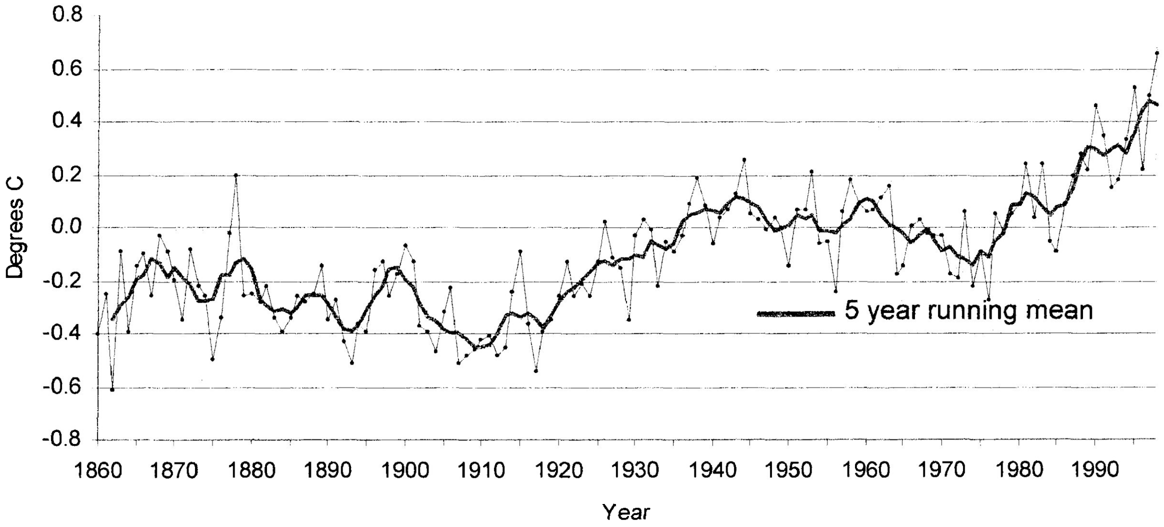

Figure 2.1 Annual Northern Hemispheric temperature 1860-1998: deviation from 1961-90 normals. Source: after Climate Research Unit 1999.

2.1.1 Global energy balance

The incoming and outgoing radiation (energy) of the Earth is in relative equilibrium (Kemp 1994;Trenberth et al. 1996). A radiative forcing agent is a factor capable of disturbing this balance in the earth/atmosphere system (IPCC 1996). In the atmosphere, many gases in minor amounts absorb radiation and increase the energy retained by the earth/atmosphere system (IPCC 1996). This positive radiative effect, commonly termed the “greenhouse effect”, results in higher surface temperatures. Carbon dioxide (CO_2) is the most prevalent, but gases like methane (CH_4), nitrous oxide (NO_2) and about 20 others also contribute. Without the greenhouse gases, the average global temperature would be approximately 32°C cooler than the present average global temperature of 15°C (Kemp 1994). The physical connection between greenhouse gas (GHG) concentration in the atmosphere and air temperature has been understood and discussed for more than a century. Changes in the amounts of GHGs in the atmosphere can affect the global energy balance (Trenberth et al. 1996). Long-term ice-core evidence confirms that past fluctuations in air temperature have been closely related to changes in the atmospheric concentration of CO_2 and CH_4, two of the principal GHGs (IPCC 1990).

2.1.2 Anthropogenic climate change

The concentrations of major and many minor GHGs have been enhanced by a range of human activities. The human contribution is complex because it is comprised of positive and negative radiative effects: increases in atmospheric GHG concentrations (positive), depletion of the ozone layer (generally positive), the release of aerosols into the atmosphere (generally negative) and changes in land use (positive or negative). The overall result has been a positive contribution to the Earth's radiation budget. Quantification of the human contribution is difficult because human and natural components are dynamic; the definition of a base for measurement is elusive. It is also likely that there is interaction between natural cycles and the human components (Corti et al. 1999).

The historical and projected increase in GHGs is considered the prime driving force in calculations of climate change. The chemist Arrhenius, in a paper published in 1896, was the first to detail the theoretical temperature consequences of a doubling of CO_2 (cited in Goody et al. 1998).

Carbon dioxide has the most impact and contributes about 64% of the total radiative forcing (Solomon and Srinivasan 1996). The impact of other GHGs is often converted into an equivalent of CO_2. Modelling of atmospheric circulation change, and resulting modification of surface weather and climate, is usually based on an increase of the CO_2 plus equivalent. Many model projections are based on an effective doubling of CO_2 ($2 \times CO_2$). Estimates vary as to when this could take place. It could be as early as 2020 but, if stabilisation of emissions at 1990 levels agreed to at Kyoto and Buenos Aires is realised (an unlikely scenario), it could be delayed until around 2050 (United States Department of Energy 1998). Even total adherence to the Kyoto protocol will not halt the rise in atmospheric concentrations of CO_2. With the present use of technology, current thinking about economic expansion and projected increases in world population, equilibrium will not be achieved even by the mid 21st century. Levels of CO_2 will continue to increase beyond this date. The 2 x CO_2 is expected to result in a global temperature between 1 and 4.5° C warmer than present (Kattenburg et al. 1996). However, this increase is not expected to be uniformly experienced around the planet. Greater increases are expected in the mid- and higher latitudes. It is also thought that the central areas of continents will tend to have more pronounced temperature increases in comparison to regions with proximity to oceans.

The transition to a world with 2 x CO_2 is, of course, well underway. The base level of atmospheric CO_2 during the initial stage of industrialisation around 1800 was approximately 280 ppmv (Friedli et al. 1986). The current concentration is 365 ppmv, about 1.3 x the base amount. (If other GHGs are included, the level is nearly 1.5 x CO_2.). The observed temperature changes in many regions in Canada (Gullett and Skinner 1992) and other land areas in the NH (Jones 1994; Michaels et al. 1998) imply that the associated warming is taking place. The temperature increase in the 20th century has resulted mainly from an increase in daily minimum temperatures, with less change in daily maxima. In addition to increasing concentrations of GHGs, local and regional increases in cloud cover and changes in land use (examples: urban growth, irrigation) are other possible causes contributing to the observed trend in the minimum temperatures (Easterling et al. 1997; Lockwood 1998).

2.1.3 Climate change and vegetation

Upward trends in surface temperatures are likely to affect rates of interaction between the land surface and the lower atmosphere. An altered hydrological cycle could affect vegetation at several stages. Increased surface evaporation and transpiration could result in moisture deficiencies and surface cooling. This change of state could then contribute 1) negative feedback to the warming process because of cloud formation and reduced solar radiation for vegetation and 2) positive feedback because of increased water vapour, the most potent GHG. The effects could vary with the season and by location. Manabe and Wetherald (1987) have predicted that a reduction of soil moisture in summer is likely in mid-continental areas of NA.

Changes in the variability of temperature and precipitation are also important in assessing the impact of changes on vegetation (and associated socio-economic consequences) of a region. Karl et al. (1995) suggested that increasing levels of CO_2 and associated warming should be coupled with decreasing variability. The authors noted that variability has declined in the NH, especially in the United States and China. The converse of this was noted by Parker et al. (1994). They compared the period 1954-1973 with 1974-1994 and found a slight increase globally, but significant increases in central NA.

2.1.4 A summary of 2 x CO_2 predictions for Northwestern Ontario

All GCMs project increases in global mean temperature and precipitation for a 2 x CO_2 atmosphere (Kattenberg et al. 1996). An average of several GCMs (Manabe et al. 1991; Boer et al. 1992; Russell et al. 1995) suggests that NWO winter and spring temperature means could be 4° C warmer, and summer and autumn 2.7° C warmer. The Canadian Centre for Climate Modelling (Boer et al. 1992) predicts an increase, compared to 1951-80 normals, of approximately 7° C for the winter and spring seasons, 4° C for summer and 2.7° C for autumn (ranges have been averaged). At the end of the 21st century, with the increase in the annual mean temperature, NWO is predicted to be 2 to 5° C warmer than the present (Smith et al. 1998).

Predictions of changes in the amount, variability and character of precipitation by various models do not have the same consistency as for temperature. This is not surprising; prediction of precipitation is difficult at all spatial and temporal levels. Furthermore, these complexities of precipitation are not captured by the coarse resolution of GCMs that offer only broad generalisations at the regional scale. The models suggest that winter, spring and autumn would have increased precipitation. In summer the Canadian model predicts a change of 0 to 15% less precipitation, while the other models predict no change. This has potential implications for the boreal forest, given arguments by Hogg (1994) that the southern boundary may be defined more by moisture deficiency than temperature.

Moisture stress in vegetation could be offset by an increase in rainfall totals during the growing season. Such an increase is tentatively predicted by several GCMs for a 2 x CO_2 atmosphere (Manabe et al. 1991; Boer et al. 1992; Russell et al. 1995), but it is not assured that the increase would compensate for the increased evapotranspiration. Generally, the water-use efficiency increases in response to higher CO_2 levels, though higher temperatures seem to reverse this effect (Gates 1993). Predictions regarding the frequency of drought, intensity of rain and changes in variability of precipitation are presently beyond this kind of modelling.

2.2 Investigation of Climatic Trends at the Regional Scale

Projections of regional climate change (and resulting mitigation policies) should not be taken directly from coarse-resolution GCM model scenarios of future climate. The rapidity of warming in recent decades combined with projections of further warming in the 21st century has stimulated research into potential consequences in various countries, including Canada. The Canada Country Study: Climate Impacts and Adaptation (Environment Canada 1997-1998) is an example of this process at national and provincial levels.

2.2.1 Climatology of the study area: Northwestern Ontario

Northwestern Ontario is located in central North America (Figure 2.2). The study area is confined to the southern portion of the region because virtually no long-term climatological data are available north of 52° latitude. The western boundary is the border between Manitoba and Ontario. The southern limit is defined by the international border with the United States and Lake Superior. The eastern boundary is 85° West longitude. The landscape has considerable water surface and is dominated by features typical of the Canadian Shield.

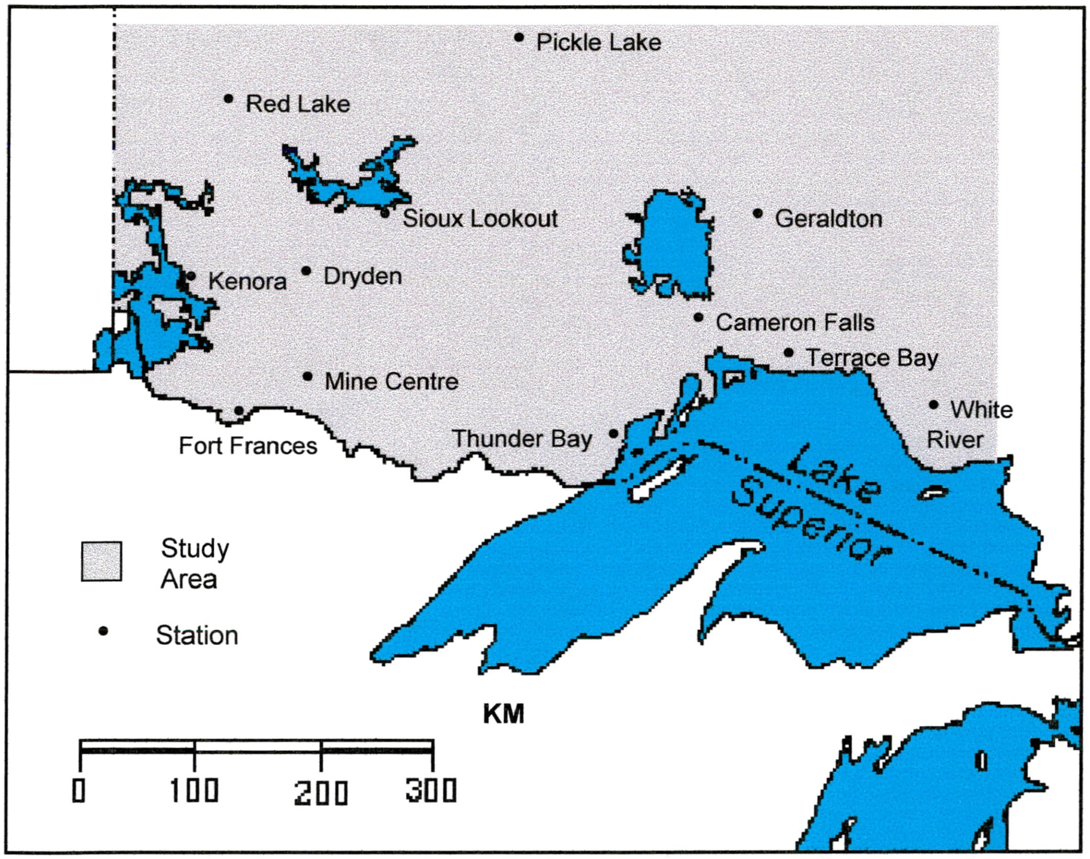

Figure 2.2 Study area and principal stations.

Average surface air temperatures decline in the NH from south to north for two reasons:

- less solar radiation is absorbed as the inclination of the sun decreases; and

- horizontal transfer of tropical heat energy with atmospheric circulation diminishes with distance.

When averaged, annual mean temperatures decline by approximately 1.1° C per degree of latitude in Ontario (Saunders, 1994). The same relationship was calculated for eastern Minnesota (directly south of the study area) using data from Baker et al. (1985).

Air mass movement, combined with the seasons, brings a procession of changes in temperature, moisture and atmospheric stability to the region. Figure 2.3 depicts the source regions of air masses that occur with some regularity in the region. Monthly and annual mean temperatures are determined, to a considerable extent, by the frequency and persistence of these air masses. The air masses of central NA have distant source regions as illustrated in Figure 2.3. Transport takes place because of upper air flow (Rossby waves). Generally there is a westerly component to this movement. Sometimes this flow is zonal, i.e. following lines of latitude, but typically a wave pattern of varying amplitude is present with an interchange of air masses (from different distant source regions) taking place two or more times per week. Locations within a region experience air mass characteristics that are modified by distance and time.

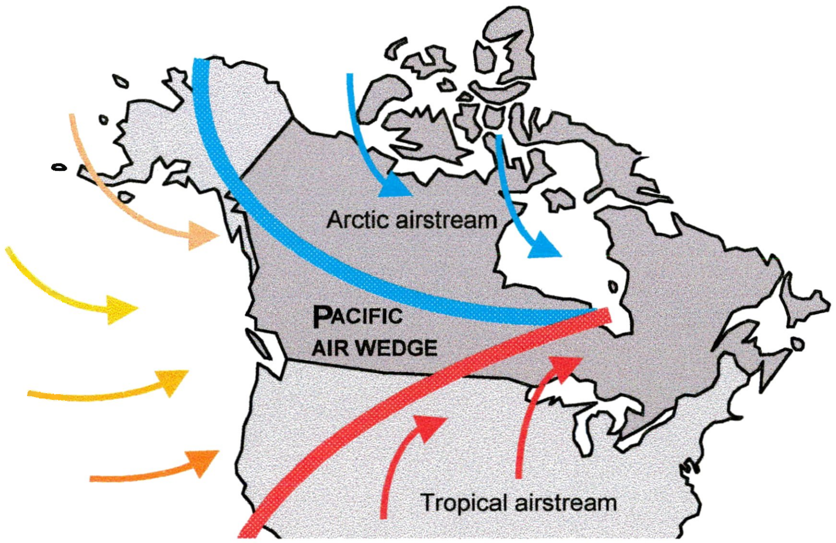

Figure 2.3 Pacific air wedge and air mass source regions.
Source: adapted from Kemp, 1992.

The annual mean temperatures of three locations in NWO, separated by hundreds of kilometres, are highly correlated during the five decades (displayed in Figure 2.4). Although considerable differences may be present at locations on a daily basis, the monthly, seasonal and annual averages are generally consistent.

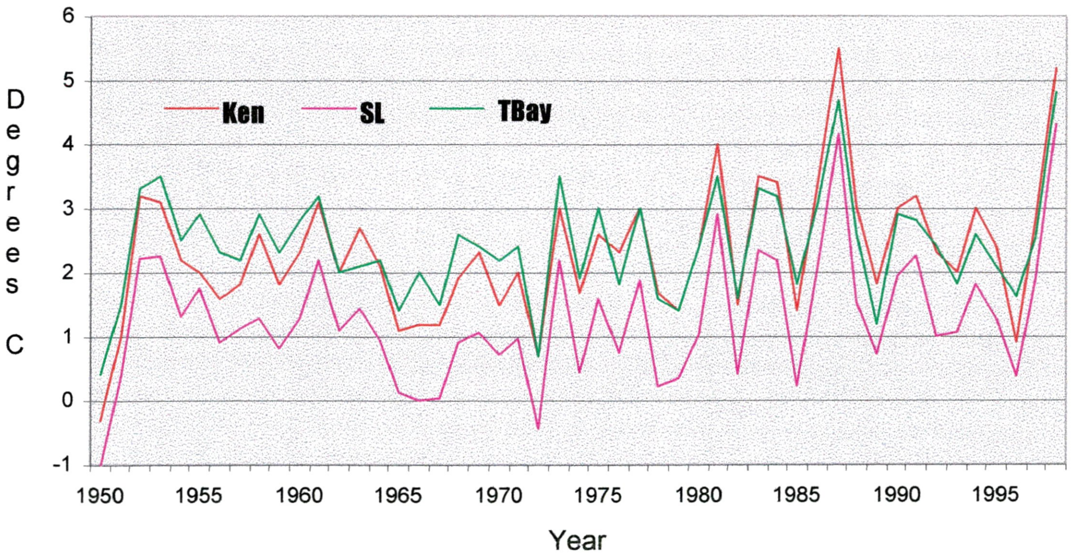

Figure 2.4 Annual mean temperatures of 1950 – 1998: Kenora (Ken), Sioux Lookout (SL) and Thunder Bay (TBay).

Other factors within the region contribute to spatial temperature variation. Adiabatic cooling (warming) takes place with increasing (decreasing) altitude coupled with declining air pressure at a theoretical rate of 1° C per 100 m (Baker et al. 1985). The difference between the highest elevations in NWO and Lake Superior is less than 500 m. Changes in elevation are not pronounced but can have significant effects on local climates, especially amounts and character of precipitation, in the region (Atmospheric Environment Service, 1972).

Most rain events during the growing season (GS) are associated with convection, showers associated with frontal passage, daytime heating, or a combination (Environment Canada 1982, 1992; Kemp 1992). The warmest months typically receive the most rainfall, although stations near Lake Superior generally have a secondary peak in September. This average rainfall distribution is approximately coincident with seasonal warmth. Moisture deficiencies are minimal when growth and these features are in phase and varying amounts of stress result when they are not.

Lake Superior, the world's largest freshwater lake (82,000 km^2 surface area) frequently affects local air temperatures and precipitation distribution, and also can alter atmospheric circulation patterns and generate weather downstream (Murphy 1998). The climate of the region is termed continental because maritime moderation is thousands of kilometres distant in any direction, but the lake reduces the continentality of locations for some distance inland. The impact of this inland sea is evident in maps of monthly seasonal isotherms (Chapman and Thomas

1968; Saulesleja 1986; Kemp 1992). The temperature difference of water and land retards warming (cooling) in the spring (autumn) season.

2.2.2 History of meteorological observation in the region

Instrument and observation records were kept by Hudson's Bay Company (HBC) employees at many locations in central and western Canada. Occasional records were also kept at Northwest Company posts. The journal entries tend to be fragmented; most of the trading posts were operated on a seasonal basis. These records can be useful, especially when combined with various climatic proxy evidence such as tree-ring analysis (Ball 1992). Such information can contribute knowledge of past major climate events and trends. Generally, this information is qualitative and only approximate comparisons of different climatic periods can be made.

The westward expansion of settlements in the later 1800s resulted in the establishment of some weather stations. The construction of the Canadian Pacific Railway (and the telegraph lines that followed soon after) across Canada was closely connected with weather stations along the route. The observations could be used to warn of severe weather conditions further along the route in both directions. These early records also tend to be fragmented, but missing values in the records can be estimated in some situations.

The oldest continuous record of meteorological observations began in 1877 in Port Arthur (now part of the city of Thunder Bay). Many stations in the region were established in the early 1880s soon after the construction of the Canadian Pacific Railway. Most of these stations have a considerable amount of missing data in their first years and only Port Arthur and White River have relatively continuous records into the 20th century.

During the first three decades of the 20th century, stations were reopened at Kenora, Ignace and Schreiber. New stations were established in a number of agricultural communities near Kenora, Fort Frances, Dryden and Thunder Bay.

The growth of aviation in the 1930s affected the siting of meteorological observing stations in NWO (and across Canada). Sites were often relocated to supply precise and timely weather information for air traffic at airports. Any site change has the potential to compromise the homogeneity of a climate record and these relocations often involved sites with quite different topographical features. Generally, parallel observations at the town sites and the airport were not taken at all or, in the case of Kenora, for less than one year.

In the middle decades of the 20th century, the number of meteorological stations continued to grow and the network expanded further into the north. First-order stations, with paid staff and hourly observations, were typically located at airports. Second-order stations (often termed *climat* stations), operated by volunteers or staff of other government departments, were located at residences (often on farms) and government agricultural and forestry buildings.

In the 1980s and1990s the number of operating stations in NWO, and in Canada, decreased dramatically. Some automatic stations were established in more northerly locations.

2.3 Detection and Adjustment of Inhomogeneities in Regional Climate Records

The development of climate change scenarios requires accurate assessment of historical climate trends and variability. Observations at a climatological station result in a record that is site-specific. If the siting is relatively representative of an area, the record can contribute to an understanding of the local and regional climate. Archived time series often have missing data and are of insufficient duration to permit analysis of trends and other features. Techniques have been developed to construct or combine time series with relatively close temporal and spatial proximity (Baker et al. 1985; Ball 1992; Crowe 1992). Of course, combining two or more site-specific records almost certainly results in discontinuities.

Observations at a meteorological station with a consistent observing system during an extended time period constitute a homogeneous record, i.e. containing only variations in weather and climate. However, non-climatic influences can easily affect readings and introduce shifts that exaggerate or diminish actual trends and frequencies. Instrument placement and the immediate site conditions have been regulated in Canada for more than a century, but changes in siting and observation procedures have taken place at all stations. Station histories (metadata) may help to identify potential inhomogeneities, but may be incomplete, or not document all changes (Gullett et al. 1991). Many potential sources of inhomogeneity were considered in this investigation. The following occur as *changepoints* (Vincent 1998), i.e. abrupt changes, with the potential to introduce a step(s) in a series:

- station location;
- type of instrument, measurement procedure or observation time; and
- instrument location or exposure.

If such changes result in discontinuities, these steps may be obscured by climatic variation. If the shift in monthly or annual temperature means and precipitation totals is relatively large, it may be revealed by visual inspection, followed by statistical comparison, with neighbouring records (Jones et al. 1996).

Trends from gradual, natural or human-induced modification may add inhomogeneities. In the immediate vicinity, growth or alteration of vegetation and construction of buildings and other structures can create non-climatic trends and are unlikely to be noted in metafiles. Urban growth, even if not adjacent to an observation site, may influence temperature readings.

Many sites in NWO were relocated from a town centre to an airport site. A simple combination of such records is likely to introduce a combination of discontinuities. The town or city sites likely were being influenced by urban development. The airport locations probably avoided or had a reduced urban heat-island influence because it was the practice to build airports beyond the current settlement. The topographical features of the sites would generally be different because flat, uniform landscape is sought for airport locations.

2.3.1 Air temperatures

Temperature is a continuous variable and, when summarised in months and years, is usually normally distributed (Jones and Hulme 1995). The high degree of correlation among locations helps to make it the easiest meteorological variable to analyse at various spatial scales. However, there are often barriers to meaningful analysis. In 1961, a change in observation time was made at principal (most airports) stations across Canada. The climatological day, 00Z - 2359Z prior to this change, was redefined as 06Z - 0559Z to conform, approximately, to the calendar day in North America. The new hours of observation increased the likelihood that the same or similar minimum temperatures could be recorded on two successive days (Bootsma 1976, cited in Vincent and Gullett 1999; Karl et al. 1986).

The introduced bias is estimated to be a step decrease of 0.6 - 0.8° C in eastern Canada (Manitoba - Ontario boundary to the Atlantic coast) and less in western Canada (Vincent and Gullett 1999). Daily mean temperatures, mean = (max + min)/2, would also be affected by such a bias in the minimum. This introduced discontinuity was of sufficient magnitude to require exploration to determine if it were spatially and/or temporally consistent across NWO. Such a step would distort individual station records and make comparison more complicated between first-order and *climat* stations.

2.3.2 Precipitation

Inhomogeneity in precipitation can have the same causes as detailed above for temperature. The complexities of precipitation and its measurement make regional assessment more difficult than for temperature. There are many difficulties in obtaining representative and accurate measurements of precipitation (von Storch 1995).

The inherent spatial and temporal variability of precipitation does not permit the same licence used in estimating missing temperatures. Precipitation is not a continuous variable like temperature; events at neighbouring stations do not confirm an occurrence at a site with missed data. One or two missing temperatures in a monthly record are not likely to change the monthly average significantly, but it would be possible for most or even all the monthly precipitation to have occurred on the missing day(s).

Variation in topography can have considerable influence on amounts and character of precipitation (Raupach and Finnigan 1997). Even with relatively uniform terrain, precipitation amounts can have considerable variation over short distances. This is especially true during the growing season (GS) when most precipitation falls in the form of showers. Rain showers are most common, although snow showers are not uncommon early and late in the season. The amount delivered by individual convective cells can vary greatly and comparison of daily station measurements often confirms this, but monthly and seasonal totals smooth this variation.

The intensity of events can create measurement problems. Higher-intensity rain and snow showers can overwhelm measuring devices and underestimate the amount, especially when high winds are present.

Precipitation in NWO occurs in a liquid, frozen and, occasionally, freezing state. Change in the ratios of the states can yield information about the duration of the growing and dormant seasons but, because these states often complicate the measurement of precipitation, trends may be unreliable.

The Nipher snow gauge, an instrument that converts solid snow into water, began to be used in the late 1950s in Canada. Before this, and currently at most *climat* stations, a snow/water ratio of 10:1 was/is assigned. A snowfall of 10 cm would contribute 10 mm to the daily and subsequent precipitation totals. However, the snow/water ratio is highly variable. I have measured relatively dry snow at 35:1 and, at the other extreme, slush with a ratio of 3.5:1. The use of the Nipher snow gauge is an obvious improvement in measurement. However, difficulties are encountered with comparison of Nipher readings and data employing the simple 10:1 ratio.

There is evidence from this study that rainfall amounts have increased during the GS. It appears that the additional amounts tend to occur in June and July and could balance the additional evaporation that higher spring and summer temperatures cause. Some caution is needed in assessing these higher totals for several reasons: 1) monthly variability has also increased and the increases of a few millimetres are not significant; 2) the increases are not consistent throughout the region; and 3) when averaged, the additional amount is due to major rain events.

Moisture in the form of light-to-medium rain occurrences is more likely to be utilised by vegetation. For example, a monthly total of 100 mm in 10 events of 10 mm would be much more supportive of growth than two events of 50 mm. Heavy rains tend to become runoff rather than being retained, and available, in the soil (Flannigan 1999).

METHODS

The objectives of this study required monthly and annual summaries of a sufficient number of meteorological stations to represent the climate of the region. Ideally, this summary would begin in the 19th century with a calculation of a regional climatology based on an average of grid values with similar methods to that of Karl and Williams (1987) and Jones and Hulme (1995), and others. The station density excludes such an approach. The limitations on regional climate analysis are further compounded by problems also experienced in other regions: station closures, site relocation and environmental site change.

The detection of climatic trends and change in frequency of events requires extended, continuous and homogeneous time series. This was accomplished by 1) combining close-proximity station records, 2) estimating missing values with the use of simultaneous records from neighbouring stations, and 3) adjusting recorded values to reduce site change and/or relocation inhomogeneities.

3.1 Selection and Assessment of Station Records

Station records of all available Environment Canada (EC) stations in NWO were examined. Most of these archived data were in digital format (Environment

Canada 1997-1998), some were available electronically, and some were on file in printed form. Monthly averages of maximum, minimum and mean temperatures and monthly totals of rain, snow and combined precipitation were assessed.

The longest available records in the region are located in the south and centred approximately on the 49th parallel. This southern tier consists of Kenora (beginning in 1900), Fort Frances (1917), Mine Centre (1915), Dryden (1915), Atikokan (1914), Thunder Bay (1877), Cameron Falls (1924), Schreiber (1909) and White River (1889). Some of these stations have spotty data prior to the year noted.

Several observation programs commenced in the 1930s at higher latitude sites (50° or higher) but only fragmented records are available for analyses. Sioux Lookout (1914) supplied the only data available from these early years for a northern tier of stations. Other stations of shorter duration or with considerable missing data were noted and grouped according to proximity to the selected sites and commencement year.

Only two stations, Port Arthur (site location in Thunder Bay) and White River, have unbroken records that begin in the 19th century and extend into the 20th. Unfortunately, these sites were closed many decades ago. It was necessary to combine records to assess trends of the 20th century. Most stations have neighbouring sites that could be used to estimate missing temperature data and make adjustments for inhomogeneities created by events such as site relocation. The principal stations used in this study are shown in Figure 2.2 and listed in Table 3.1.

Table 3.1 Station locations and years of operation.

Station		E.C. #	Lat. (°)	Long. (°)	Alt. (msl)	Years	Remarks*
Kenora							
	Airport	6034075	49 47	94 22	410	1938-98	Occl misg
	Town	6034070	49 48	94 32	336	1900-39	Occl misg
Fort Frances							
	Airport	6022476	48 39	93 26	343	1977-98	Occl misg
	Town	6022475	48 37	93 25	343	1917-95	Occl misg
Mine Centre							
		6025203	48 46	92 37	343	1915-98	Occl misg
Dryden							
	Airport	6032119	49 50	92 45	413	1970-98	Occl misg
	Town	6032117	49 47	92 50	372	1914-97	Occl misg
Sioux Lookout							
	Airport	6037775	50 07	91 54	390	1938-98	Complete (after 1938)
	Town	6037768	50 08	91 52	365	1914-32	Occl misg
	Town	6037770	50 08	91 52	374	1931-38	Occl misg
Thunder Bay							
	Airport	6048261	48 22	89 19	199	1941-98	Almost complete
	Port Arthur	6046588	48 26	89 13	195	1877-1941	Almost complete
Cameron Falls		6041109	49 09	88 21	229	1924-97	Occl misg
Terrace Bay							
	Airport	6048230	48 48	87 06	289	1972-98	Occl misg
	Schreiber	6047627	48 49	87 16	302	1909-75	Occl misg
White River		6059475	48 36	85 17	379	1889-1975	Almost complete
Red Lake							
	Airport	6016975	51 04	93 48	386	1965-98	Cons misg
	Town					1939-50	Cons misg
Geraldton							
	Airport	6042716	49 47	86 56	249	1981-97	Occl misg
	Town	6042715	49 42	86 57	331	1968-81	Complete
	Long Lac	6044525	49 54	86 30	317	1921-57	Occl misg

*Occl misg = occasional missing Cons misg = considerable missing

3.2 Station Records

It was possible to create homogeneous series for 1916-1998 for Kenora, Fort Frances, Mine Centre, Dryden, Sioux Lookout, Thunder Bay and Schreiber. Cameron Falls was added as of 1924. Summaries for Geraldton (from 1924) and Red Lake (from 1939) were constructed with the use of temperature series of neighbouring stations (Table 3.1).

3.2.1 Adjustment of inhomogeneous records: Kenora example

The original Kenora site was located in the town and within 100 m of Lake of the Woods. The station opened in 1883 but relatively continuous observations were not taken until 1900. Many months and occasional entire seasons are missing prior to 1916. There is intermittent missing daily data until closure in 1939. Observations began at the Airport site in 1938 with 7 months of simultaneous observations.

The two sites are approximately 12 km apart. The Airport is 410 m above mean sea level (msl), about 74 m higher than the Town site. The records overlap from September, 1938 to March, 1939. The Town location was slightly warmer in all the months in common. The difference in the shared months suggest a likely discontinuity if these two series were to be combined. The monthly rain, snow and total precipitation varied by minor amounts with no pattern apparent. The total precipitation for the seven months was 5% higher at the Town site.

The nearest neighbouring stations are located in Manitoba. The closest are Indian Bay (1915-91), on the west shore of Lake of the Woods, about 55 km

SW and Pinawa (1915-50), about 130 km to the NW. Winnipeg, 200 km to the west, was rejected as a comparison station because of simultaneous site relocation in 1938.

The time series of the Kenora sites, Indian Bay and Pinawa were compared in graph form for the years 1928 to 1950. The time period was partially dictated by the closure of the Pinawa station, but approximately one decade on either side of the site change was judged sufficient to assess the difference in the sites without potentially having interference from other trends. The annual and mid-season (January, April, July and October) temperatures means were graphed and r values (Table 3.2a, b) and period temperatures averaged for the two sites were calculated for all months. Standard differences (Crowe 1992) between the Kenora sites and the comparison stations were calculated by month according to the following formulae:

<u>Annual Standard Difference (ASD)</u>

$$\text{ASD} = \frac{\Sigma_i(\text{Ann Avg Temp Ken Town}_{\text{year } i} - \text{Ann Avg Temp Pinawa}_{\text{year } i})}{\text{Number of years in range}} \tag{3.1}$$

<u>Monthly Standard Difference (MSD)</u>

$$\text{MSD}_j = \frac{\Sigma_i(\text{Mon Avg Temp Ken Town}_{\text{year } i, \text{month } j} - \text{Mon Avg Temp Pinawa}_{\text{year } i, \text{month } j})}{\text{Number of years in range}} \tag{3.2}$$

where *i* ranges from 1928 to 1950 and *j* ranges from January to December.

These calculations result in two estimates of the difference between the Kenora sites. The final adjustment was calculated by combining weighted estimates derived from r^8 values of Indian Bay/Kenora and Pinawa/Kenora. The transformation to r^8 to determine the weighting factor increases contributions of highly correlated monthly standard means in determining the final estimate and, conversely, decreases to the contribution of lesser correlations. It was found that this transformation (r^8) provided the closest estimate of mean temperatures when using series of neighbouring stations (Saunders, 1998). Higher powers of r did not improve estimates. An example of the calculation for the final adjustment to Kenora (Town) mean temperature for the month of July is shown in Tables 3.2a and 3.2b.

The July mean temperatures (1927-1938):	Kenora 20.2° C
	Indian Bay 19.3° C
	Pinawa 19.0° C

Table 3.2a Conversion from July mean standard difference (MSD) to adjusted July mean temperature (1927-1938). Ken^T-Kenora Town, Ind - Indian Bay, Pin - Pinawa).

Stations	Recorded MSD (°C)	r	r^8	(%)	Adjusted MSD(°C)
Ken^T/Ind	0.9	0.97	0.78	48	0.43
Ken^T/Pin	1.3	0.98	0.85	52	0.68

Thus the weighted average difference between Kenora Town and Indian Bay/Pinawa is 1.11° C.

The July mean temperatures (1938-1950):	Kenora Airport 19.3° C
	Indian Bay 19.3° C
	Pinawa 19.2° C

Table 3.2b Conversion from July mean standard difference (MSD) to adjusted July mean temperature (1938-1950). Ken^A-Kenora Airport.

Stations	Recorded MSD(°C)	r	r^8	Weighted average (%)	Adjusted MSD(°C)
Ken^A/Ind	0.0	0.96	0.72	56	0.0
Ken^A/Pin	0.1	0.93	0.56	44	0.044

Thus the weighted average difference between Kenora Airport and Indian Bay/Pinawa is 0.044° C. The final adjustment to the Kenora Town mean July temperature value (1916-1938) is 1.11 - 0.044 = 1.07° C.

The derived monthly adjustments were applied to actual monthly means in the Kenora Town time series for all months. The adjusted record is cooler than recorded averages and, in effect, is an estimate of temperatures as if the station had always been at the Airport location.

The precipitation records of the sites were combined without adjustment. Missing months were not estimated. Each station record presented obstacles to standardisation. The procedures used for stations are summarised in Table.3.3.

3.3 Estimates of Missing Data

3.3.1 Temperature

All of the station records used in this study had missing temperature data. In the initial examination of the EC archives, monthly means were calculated from daily data. Any missing values resulted in a missing monthly mean. The daily data were then re-examined. Monthly means were calculated with up to 5 days of missing observations with notes of occurrence. Months with 6 to 9 missing days were flagged as estimates and compared with other station summaries. Environment Canada allows up to 9 missing days. Months with more than 9 missing values were entered as missing, the same procedure as used by Environment Canada (Takata 1999).

Table 3.3 A summary of adjustments and other procedures used to standardise data. N/A - not applicable, EC - Environment Canada. (Additional details available in Appendix A)

Station	Number of Sites	Temperature				Precipitation	
		Adjustments		Missing Data Estimated		Records Combined	Missing Data Estimated
		Years	Stations	Amount	Stations		
Kenora	2	1916-1939	Pinawa Indian Bay	2.8%	Pinawa Indian Bay	Yes	No
Fort Frances	2	1916-1976	Fort Frances (airport)	2.0%	Mine Centre Emo	Yes	No
Mine Centre	1	none		3.4%	Fort Frances Atikokan Dryden	N/A	No
Dryden	2	none		2.5%	Kenora Sioux Lookout	Yes	N/A
Sioux Lookout	3	none		1.2%	Dryden	Yes	N/A
Thunder Bay	2	1916-1935	Duluth Savanne Grand Marais Quorn	0.3%	EC	Yes	N/A
		1916-1940	Grand Marais Savanne Kakabeka				
Cameron Falls	1	none		3%	Thunder Bay MacDiarmid Abitibi Sites	N/A	No
Terrace Bay	2	none		3%	Aguasabon	Not sufficient data	
Red Lake	2	none		N/A	EC Red Lake Kenora Dryden Sioux Lookout	No	No
Geraldton	3	none		Not applicable	Longlac Manitouwadage Nakina Geraldton - Forestry	N/A	No

Missing months in isolation were estimated using standard differences with neighbouring stations. The procedures described above for primary stations typically supplied estimates of monthly means for extended gaps in the records. Clusters of missing months were estimated using the system of weighted estimates described for Kenora.

3.3.2 Precipitation

The above procedure was not used for precipitation totals because a missing day could dramatically reduce a monthly total. Months with missing values were entered as a minimum estimate. This was only an occasional problem in the southern stations (2 or 3 years would be potentially compromised). In the northern stations there are more problems with missing data. Occasionally, entire years were excluded from trend and average calculations if too many data were missing.

3.4 Station Summaries

For each station the average monthly maximum, minimum and mean temperatures and resulting annuals were calculated and put into summary form. Average monthly rain, snow and precipitation totals were summarised in the same format.

The annual mean temperatures of the southern stations were graphed for the time 1916-1998. An example (Kenora) of the typical regional trend is displayed in Figure 3.1. Other long-term temperature trends are shown in Appendix B.

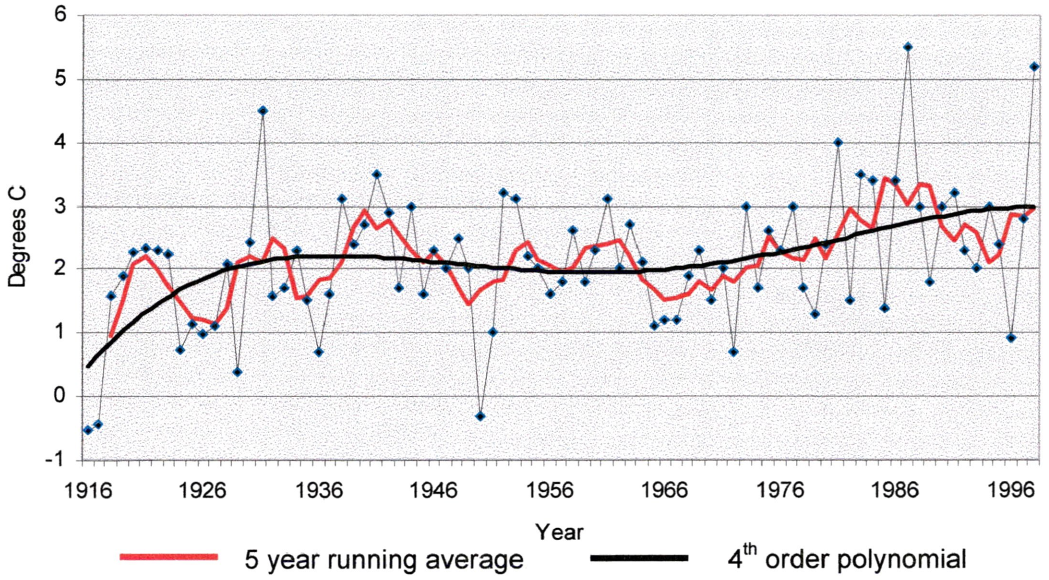

Figure 3.1 Kenora annual temperatures: 1916-1998.

The 5-year running means and the polynomial suggest that longer-term trends were taking place in the 20th century in NWO that were similar to those apparent in the NH (Figure 1.1): a period of warming (~30 years), a time of temperature decline (~30 years) and another period of warming (~30 years). Trend lines and r correlations with the NH data for the running means were calculated for Kenora, Dryden, Thunder Bay and Schreiber/Terrace Bay in an attempt to define these three time periods observed by visual inspection of the plots. The trends of the above stations corresponded closely to Figure 1.1 and a period definition suggested by Tett et al. (1999). They defined two warming periods of 1910-1940 and 1970 to the present. This trend analysis was explored further by plotting the NWO regional seasonal time series. These were not identical, but similar to the annual pattern.

3.5 Temperature: Trends and Other Features

Annual and seasonal mean temperatures for available stations were graphed for the period 1916-1998. Visual inspection suggested that longer frequency change was present. The limits of the periods, 1943/1944 and 1970/1971, were set specifically to capture a change in temperature tendency at those times (example Kenora, Figure 3.2). All station temperature series were analysed for the periods 1916-1943, 1944-1970 and 1971-1998. Three of the seasons were defined in the conventional manner as follows:

Winter - December to February
Spring - March to May
Autumn - September to November

A growing season defined as May to September was considered more appropriate for this investigation than the standard summer definition (June to August).

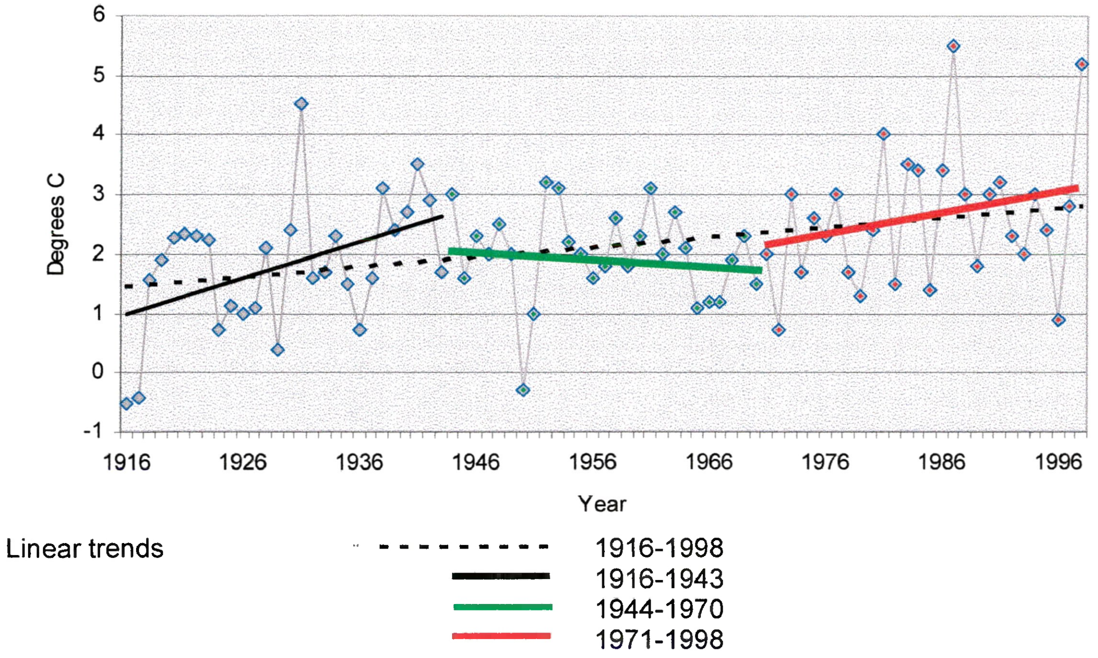

Figure 3.2 Kenora annual temperatures: 1916-1998.

3.5.1 Annual and seasonal temperature trends

Linear regression analysis (least-squares method) was used to determine the best-fit line through the mean temperatures for all time periods (eg. Kenora, Figure 3.2). The resulting equation is

$$y = T_T x + I_T \qquad (3.3)$$

where y is mean temperature in °C, T_T is the slope or temperature trend, x is the year and I_T is the y-intercept representing the initial temperature at the beginning of the period. The total change in temperature over a time period was determined by multiplying the trend (T_T) by the total number of years in the period. Trends and differences in means were assessed for statistical significance at $\alpha = 0.05$ unless otherwise noted.

3.5.2 Comparison of variability

Standard deviations (STD), measures of dispersion of values from the mean, were calculated for temperature and precipitation series of all primary stations for the periods using the following formula:

$$\mathrm{STD} = \sqrt{}\ [(n\sum x^2 - (\sum x)^2]/n^2 \qquad (3.4)$$

3.5.3 Difference of means

The average temperature and precipitation was calculated for the periods: 1916-1943, 1944-1970 and 1971-1998. They were determined by averaging the annual or seasonal means for the years in the time period. Statistical significance between these periods was determined by the following t-test for unequal-sized groups:

$$T = (\mu_1 - \mu_2)/\sqrt{}(s_1^2/n_1 + s_2^2/n_2) \qquad (3.5)$$

Where T is the test statistic, μ_1 and μ_2 are the average temperatures (precipitation) of the periods, s_1 and s_2 are the variances in the periods, and n_1 and n_2 are the number of years in the periods.

3.5.4 Maximum and minimum temperature trends

Change in maximum and minimum temperature means could influence the timing of the growing season and other aspects of vegetative growth within the season. Adjustments were made to the maximum and minimum series with the same procedures as detailed in 3.2.1. Trends for these variables were calculated in the same way as annual temperatures.

3.5.5 Diurnal temperature range

The difference between the maximum (T_{max}) and minimum (T_{min}) temperature means, the diurnal temperature range (DTR), can be used to indicate change in daily variability; higher (lower) values flag a trend to a more (less) extreme daily range. The equation is

$$T_{max} - T_{min} = DTR \qquad (3.6)$$

Trends for DTRs were calculated in the same way as other temperature variables (detailed above).

3.5.6 Growing season: extreme temperature frequency

Analysis of change in the frequency of extreme temperatures was confined to the growing season. A positive (negative) trend in the frequency of extreme maximum during the growing season has potential to increase (decrease) moisture stress in vegetation (Lockwood 1998) and to increase (decrease) fires (Flannigan and Van Wagner 1991).

The limit of ≥30° C was chosen because, in NWO, such events are relatively infrequent but do occur throughout the study area. The lower limit of <0° C during the growing season occurs with approximately the same frequency as ≥30° C but, in addition, flags a physical change. The same classes are used in EC station summaries.

3.5.7 Spectral Analysis

Spectral frequency analyses were conducted in an attempt to isolate recurring climatic cycles and, potentially, to observe changes during different periods during the 20th century. The analyses were performed on the stations for which data exist for the entire period (Kenora, Fort Frances, Mine Centre, Dryden, Sioux Lookout, Thunder Bay and Terrace Bay/Schreiber). The cycles present within the following periods were determined in:

1) the entire period: 1916-1998 (83 yr)
2) two periods: 1916-1949 (34 yr) and 1950-1998 (49 yr)

These periods were chosen because they are (potentially) of sufficient length to contain interdecadal cycles and to allow comparison with other research (e.g., Zhang et al. 1998).

3) three periods (January and July monthly means only): 1916-1943 (28 yr), 1944-1970 (27 yr), 1971-1998 (28 yr).

These three periods correspond with the three periods observed with changes in temperature.

The length of cycles was determined using a fast Fourier transformation (von Storch 1995). The most prominent cycles were selected and summarised.

3.6 Annual and Seasonal Precipitation Trends

3.6.1 Linear trends for the defined periods

As with temperature, linear regression analysis (least-squares method) was used to determine the best-fit line through the mean precipitation for all time periods. The resulting equation is

$$y = T_P x + I_P \tag{3.7}$$

where y is the mean precipitation in mm, T_P is the slope or precipitation trend, x is the year, and I_P is the y-intercept representing the initial precipitation at the beginning of the period. The total change in precipitation over the period was determined by multiplying the trend (T_P) by the total number of years in the period.

Only Kenora, Fort Frances, Mine Centre, Dryden and Thunder Bay had sufficient data to span analyses and comparison of trends for the three defined periods. Other stations were added as relatively continuous observations became available.

3.6.2 Comparison of variability

Averages and variability for the defined periods were calculated with a similar procedure described above for temperature.

3.6.3 Number and intensity of rainfall events

The number of days with rain during the growing season was tabulated for principal stations. Amounts of a trace to 0.5 mm were ignored; a rain day was defined as ≥0.6 mm during the climatological day, the same procedure used to calculate the Fine Fuel Moisture Code (Van Wagner 1987). Daily rainfall was further categorised according to amount. At selected stations (Kenora and Thunder Bay), amounts were grouped in increments of 10 mm (0.6-9.9, 10-19.9, 20-29.9, 30-39.9, 40.0 to 49.9 mm, >50 mm). Other station records were grouped into three classes: 0.6-29.9, 30-39.9 and >40mm.

3.6.4 Annual snowfall

The density of fresh snow can be highly variable as noted earlier. Snowfall analysis of water content (Nipher snow gauge) is much more reliable than measurement by ruler. It allows more-dependable spatial and temporal comparison, but such series are only available from the early 1960s in NWO. Only five records are available in the study area: Kenora, Sioux Lookout, Thunder Bay, Red Lake and Pickle Lake. These raw archival data were analysed for trends.

Records of snow with measurement by ruler are available prior to the 1960s and are still taken at the above stations. This system of measurement was analysed separately to assess longer-term precipitation trends in spring and autumn, transition seasons with both rain and snow. No attempt was made to adjust these data. A summary of adjustment techniques for snow measurement by ruler is given by Mekis and Hogg (1999).

RESULTS

Available station records of the NWO region were reviewed. The most promising (i.e. records with longevity and minimal missing data) stations were selected to explore and assess various climatic variables of the region. Station-specific histories of instrument and location changes were assessed. The data from individual sites were then processed by comparison with neighbouring records. Adjustments were made to remove (or reduce) non-climatic influences (as detailed previously). The resulting database underwent further revisions as missing data were estimated. The findings were summarised in graphs and tables and a selection is displayed in the following pages. Some variables could not be included for all stations because of missing data.

4.1 Linear Temperature Trends

Positive temperature change has taken place in much of NWO during the period 1916 to 1998 (Figure 4.1, Table 4.1). This warming trend is statistically significant at all but one (Terrace Bay/Schreiber) of the longest regional time series. Significance and net change are especially pronounced in western and central stations. This overall trend is comprised of two periods of extended warming: 1) prior to 1944 and 2) after 1970. Little change, though the sign is negative at most sites, took place during the period 1944 to 1970 (Figure 4.2).

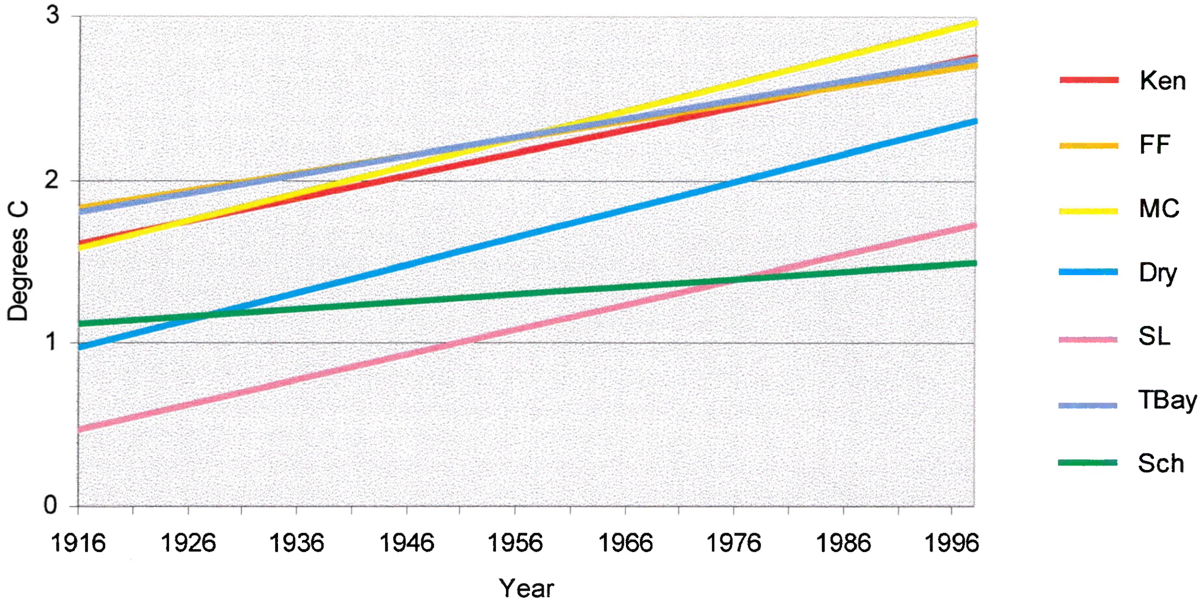

Figure 4.1 Annual mean temperature trends of some Northwestern Ontario locations, 1916-1998.

Table 4.1 Linear trends in annual mean temperatures (°C): 1916-1998 (83 years). Significance levels of $\alpha>0.05$ are not listed.

Station	Years	Avg. Ann. Change (°C/yr)	Significance Level	Total Change in 83 yr
Kenora	1916-1998	0.0141	0.001	1.2
Fort Frances	1916-1998	0.0108	0.05	0.9
Mine Centre	1916-1998	0.0168	0.001	1.4
Dryden	1916-1998	0.0170	0.001	1.4
Sioux Lookout	1916-1998	0.0154	0.001	1.3
Thunder Bay	1916-1998	0.0115	0.01	0.9
Terr/Schreiber	1916-1998	0.0058		0.5
Red Lake	1949-1998	0.0006		0.0
Cameron Falls	1924-1997	0.0199	0.01	1.5
Geraldton	1942-1997	0.0063		0.1

4.1.1 1916-1943

An extended time of warming took place in the NH in the first decades of the 20th century, as displayed in Figure 2.1. This study commences in 1916, based on the availability of simultaneous records across the region. The earlier records of Port Arthur, White River and Kenora exhibit a positive trend that commenced two decades earlier. These temperature series prior to 1916 imply that the NWO region was similar to the NH trend.

A review of Figure 4.2 and Table 4.2 reveals that much of the 20th century warming takes place in the period 1916-1943. All long-term stations except Terrace Bay/Schreiber display this positive change.

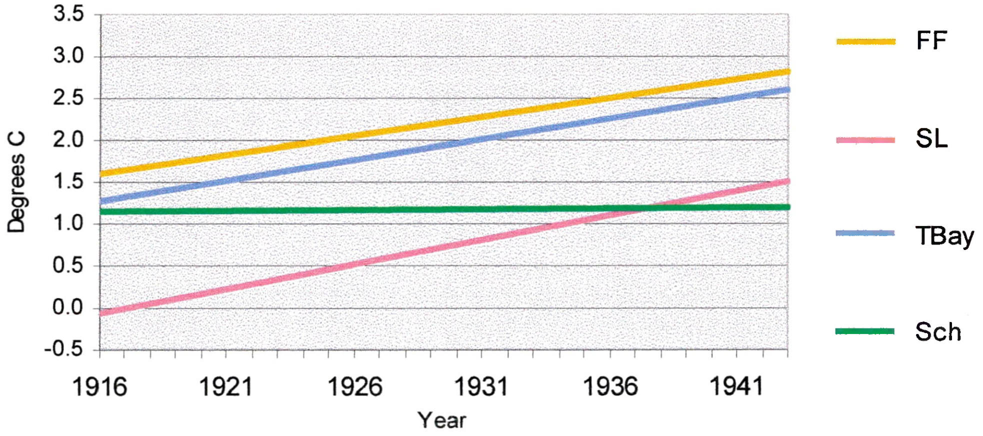

Figure 4.2 Annual mean temperature trends Fort Frances (FF), Sioux Lookout (SL), Thunder Bay (TBay), and Terrace Bay/Schreiber (Sch), 1916-1943.

4.1.2 1944-1970

Little net change occurred at most southern locations. The declines are more pronounced for higher latitude sites, but are not statistically significant (Figure 4.3 and Table 4.2).

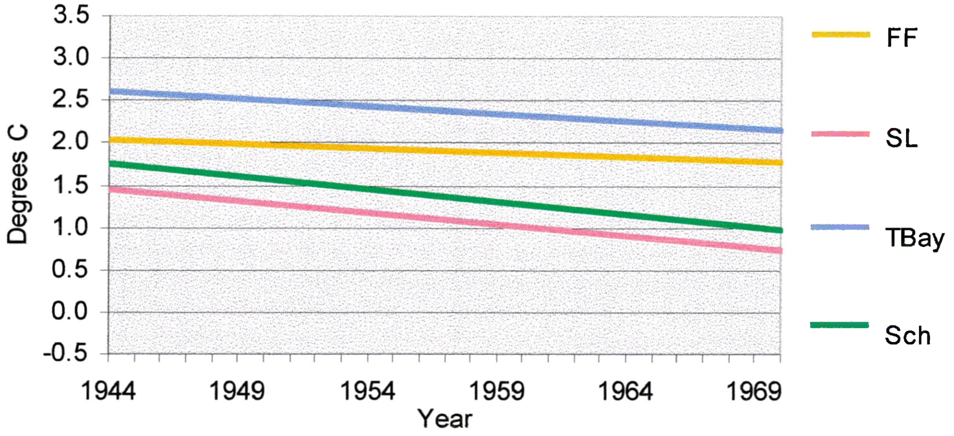

Figure 4.3 Annual mean temperature trends for Fort Frances (FF), Sioux Lookout (SL), Thunder Bay (TBay), and Terrace Bay/Schreiber (Sch), 1944-1970.

4.1.3 1971-1998

All sites reveal positive temperature change. Most southern locations have similar increases of approximately 1° C. More-modest change is apparent at Thunder Bay and the northern stations (see Figure 4.4 and Table 4.2).

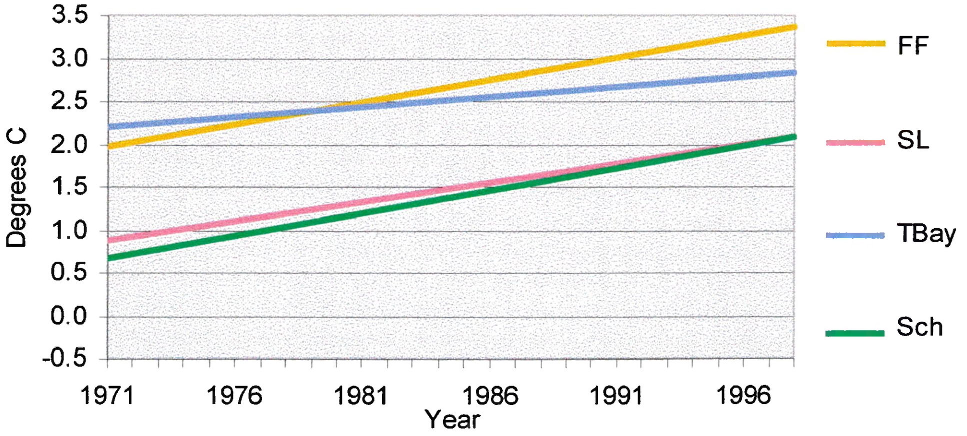

Figure 4.4 Annual mean temperature trends for Fort Frances (FF), Sioux Lookout (SL), Thunder Bay (TBay), and Terrace Bay/Schreiber (Sch), 1971-1998.

Table 4.2 Linear trends in annual mean temperatures (°C): 1916-1943, 1944-1970 and 1971-1998 ($\alpha \leq 0.05$ is indicated by *).

Station	Average Annual Change (°C/yr) 1916-1943	1944-1970	1971-1998
Kenora	0.052*	-0.012	0.019
Fort Frances	0.045	-0.010	0.035
Mine Centre	0.032	0.008	0.026
Dryden	0.040	0.001	0.039
Sioux Lookout	0.059*	-0.027	0.025
Thunder Bay	0.050*	-0.018	0.006
Terr/Schreiber	0.003	-0.030	0.045
Red Lake	misg	-0.024	0.014
Cameron Falls	0.03 (1924-43)	0.016	0.027
Geraldton	misg	misg	0.037
White River	0.027	-0.038	misg

4.2 Comparison of Seasonal Temperature Averages for the Defined Periods

Seasons are well defined in the NWO region compared with tropical and maritime locations. A shift in the timing of seasons, especially through the impact on the growing season, could have major, perhaps profound, impacts on certain flora and fauna.

An examination of seasonal climate trends reveals that more warming has occurred in spring (March to May) than other seasons. A spring warming trend (1916-98) is consistent and varies from 0.7° C to above 2° C at several sites. The spatial pattern is the same as annual mean temperature trends in Table 4.1 and for seasonal averages detailed in Table 4.3. Almost all stations have higher temperature means in winter (December to February) and the growing season (May to September) when the latest time period is compared with earlier times. The changes are smaller than the spring increases (Table 4.3).

Table 4.3 Average temperature by season and period. The symbol * denotes a significant difference ($\alpha<0.05$) between the means of the periods 1916-1943 (1), 1944-1970 (2) and 1971-1998 (3).

Station	Average Temperature (°C)					
	1916-1943	(1*2)	1944-1970	(2*3)	1971-1998	(1*3)
Winter (Dec. - Feb.)						
Kenora	-15.5		-15.6		-14.9	
Fort Frances	-14.7		-15.1		-14.1	
Mine Centre	-15.7		-14.9		-13.9	
Dryden	-16.6		-16.3		-15.3	
Sioux Lookout	-17.1		-16.5		-16.1	
Thunder Bay	-12.7		-12.9		-12.7	
Terrace Bay/Schreiber	-13.3	*	-12.7		-12.6	*
Red Lake	misg		-17.1		-17.1	
Cameron Falls	-14.8(1924-43)		-14.1		-14.1	
Geraldton	misg		-17.6		-17.3	
Spring (Mar. – May)						
Kenora	1.7		1.6	*	3.2	*
Fort Frances	2.0		1.7	*	3.1	
Mine Centre	1.7		1.9	*	3.2	*
Dryden	1.1		1.2		2.5	*
Sioux Lookout	0.2		0.4		1.8	*
Thunder Bay	1.0		1.5		2.2	*
Terrace Bay/Schreiber	0.1		0.3		0.6	
Red Lake	misg		0.6		1.3	
Cameron Falls	-0.7(1924-43)		0.2		1.2	*
Geraldton	misg		-1.5	*	-0.7	
Growing Season (May - Sep.)						
Kenora	15.0		14.8		15.6	
Fort Frances	14.9		14.2	*	15.1	
Mine Centre	14.9		14.6		15.0	
Dryden	14.6		14.5		14.9	
Sioux Lookout	14.1		13.9		14.6	
Thunder Bay	12.9		13.5		13.8	*
Terrace Bay/Schreiber	12.2		11.6		11.8	
Red Lake	misg		14.2		14.1	
Cameron Falls	12.3(1924-43)		12.9		13.4	*
Geraldton	misg		12.3		12.7	
Autumn (Sep. – Nov.)						
Kenora	4.0		4.4		4.0	
Fort Frances	4.3		4.5		4.3	
Mine Centre	4.0		4.8		4.2	
Dryden	3.6		4.1		3.3	
Sioux Lookout	3.0		3.7		3.1	
Thunder Bay	4.2		5.0		4.4	
Terrace Bay/Schreiber	3.6		4.1		4.1	
Red Lake	misg		3.6	*	2.5	
Cameron Falls	3.4(1924-43)		4.5		4.0	
Geraldton	misg		2.8		2.2	

The fall season (October to November) does not follow the pattern of the other seasons. The average of 1971-1998 is cooler than earlier periods at most locations. No obvious spatial or temporal pattern is readily apparent (Table 4.3).

4.3 Comparison of Monthly and Seasonal Variability for the Defined Time Periods

Standard deviations (σ) were calculated and then summarised by month and season. Winter σ values were always higher than those of other seasons and summer σ values were usually the lowest. This is a typical finding for middle North America (Environment Canada 1982).

The middle period, 1944-1970, consistently had less variability than the other periods. This was nearly always the case in individual months and in all seasons, but the numerical differences were not large in spring, the growing season and fall (not shown). However, the winter season showed considerably reduced variance in the middle period (Table 4.4) compared to the early and recent period.

Table 4.4 Standard deviation of winter mean temperatures by period.

	Standard Deviation (°C)		
Station	1916-1943	1944-1970	1971-1998
Kenora	4.3	3.4	4.1
Fort Frances	4.1	3.4	4.3
Mine Centre	4.0	3.5	4.1
Dryden	4.3	3.5	4.1
Sioux Lookout	4.3	3.5	4.1
Thunder Bay	3.5	3.2	3.5
Terrace Bay/Schreiber	3.4	3.2	3.7
Red Lake	misg	3.6	4.1
Cameron Falls	3.7(1924-1943)	3.5	4.5
Geraldton	misg	3.6	3.9

4.4 Trends in Mean Maximum and Minimum Temperatures

The positive change in daily mean temperatures (T_{mean}) detailed above is due to increases in both minimum temperature means (T_{min}) and maximum temperatures (T_{max}) during the 83-year period. The T_{min} increase makes up a greater proportion, 60 to 75%, of the increase in T_{mean}. The air temperature usually declines overnight (the T_{min} often occurs just after sunrise) with the consequence that milder nighttime temperatures, on average, occur in recent decades. The ramifications for frost occurrence during the growing season are obvious, but there are other potential implications in the growing season and other seasons. An example of the relationship change in proportion and the overall increases of the T_{max} and T_{min} is featured in Figure 4.5. Changes at individual stations are summarised in Table 4.5.

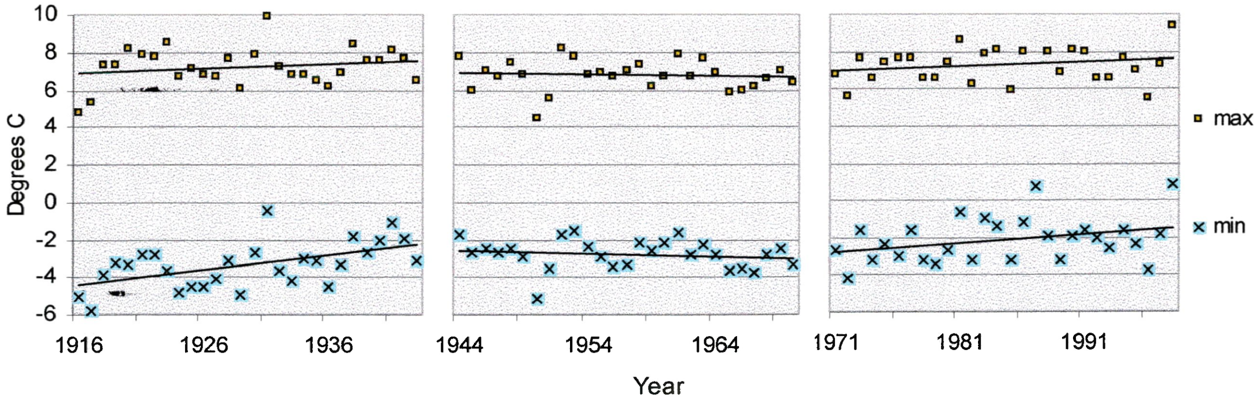

Figure 4.5 Kenora annual maximum and minimum temperatures means: 1916-1943, 1944-1970 and 1971-1998.

Table 4.5 Linear trends in annual T_{max} and T_{min} temperatures (°C): 1916-1943,1944-1970 and 1971-1998 ($\alpha \leq 0.05$ is indicated by *). Trends for Fort Frances 1916-1970 are derived from unadjusted Town data. The Thunder Bay 1916-1943 trends are based on the Port Arthur site.

Station	Average Annual Temperature Change(° C/year)					
	1916-1943		1944-1970		1971-1998	
	Max	Min	Max	Min	Max	Min
Kenora	0.023	0.080*	-0.008	-0.016	0.024	0.049*
Fort Frances	0.033	0.026	-0.012	0.008	0.042	0.060*
Mine Centre	0.064*	0.003	-0.040*	0.052*	0.016	0.031
Dryden	0.028	0.051*	-0.038	0.041	0.033	0.039
Sioux Lookout	misg	misg	-0.004	-0.050	0.033	0.058*
Thunder Bay	0.015	0.087*	-0.016	-0.019	0.023	0.021
Red Lake	misg	misg	misg	misg	0.026	0.003

4.5 Change in the Diurnal Temperature Range

Trends in both T_{max} and T_{min} variables can have implications for vegetation and many other features of the landscape. The numerical difference between these variables can also be used to quantify tendencies in the daily range of temperature. Figure 4.6 illustrates a relatively rapid decline in the DTR followed by minor fluctuations from the 1940s to the present.

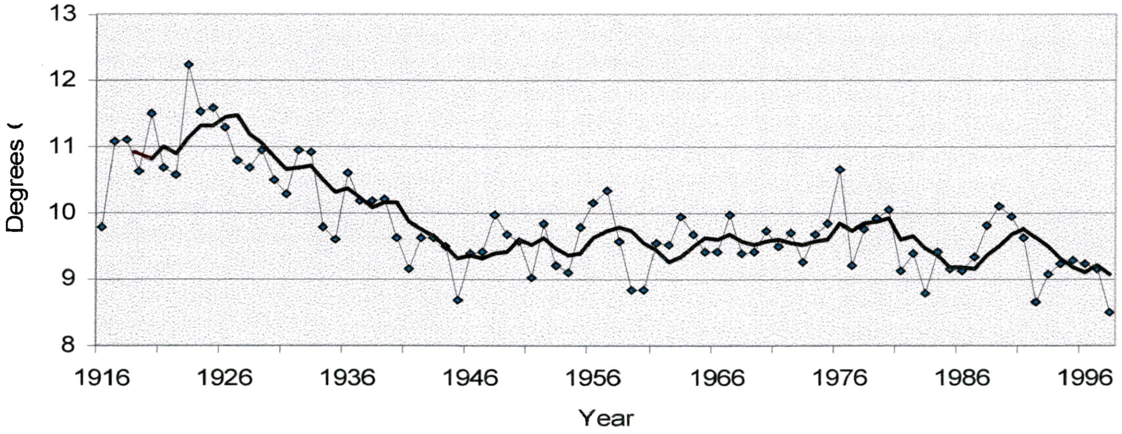

Figure 4.6 The diurnal temperature range with a 5-year moving average at Kenora, 1916-1998.

A more moderate decline in the DTR occurs at other sites in the early period (see Table 4.6). No consistent regional pattern is apparent in the later periods.

Table 4.6 Linear trends in the DTR (°C): 1916-1943,1944-1970 and 1971-1998. ($\alpha \leq 0.05$ is indicated by *).

	Average Annual Temperature Change(° C/year))		
Station	1916-1943	1944-1970	1971-1998
Kenora	-0.057*	0.008	-0.025
Fort Frances	0.007	-0.020	-0.018
Mine Centre	-0.015	-0.092*	-0.016
Dryden	-0.024	-0.085*	0.010
Sioux Lookout	misg	0.047	-0.025
Thunder Bay	-0.015	0.004	0.003

4.6 The Frequency of Selected Temperature Extremes in the Growing Season

Analyses of extreme temperatures were confined to sites with long-term observations. The Mine Centre and Dryden stations have observations during all the defined periods but many daily readings were missing in the 1916-1943 period and precluded direct comparison with later periods. These incomplete records and other early site records suggest the frequency of temperatures ≥ 30° C and < 0° C during the growing season was higher than during the period 1944-1970. Little change occurred at regional locations in the number of days with temperatures ≥ 30° C in the period 1944-1970 (see Figure 4.7). Most sites had slight increases in the final decades of the 20th century but this was not a regional feature.

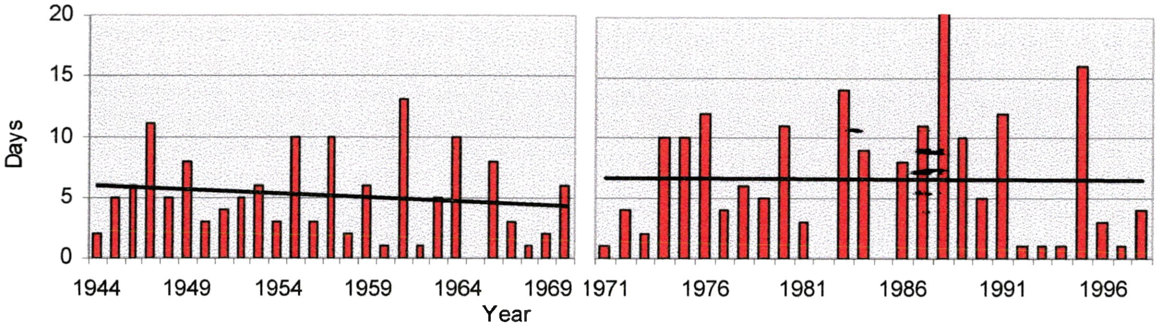

Figure 4.7 Days during the growing season at Kenora with maximum temperatures ≥ 30° C: 1944-1998.

Generally there were no consistent trends exhibited by different stations in the number of extreme maximum (≥30° C) days. All stations show a negative linear trend in the number of days with frost, i.e. minimum temperatures < 0° C (except Thunder Bay with no change). Kenora (Figure 4.8) is representative of the majority of regional records.

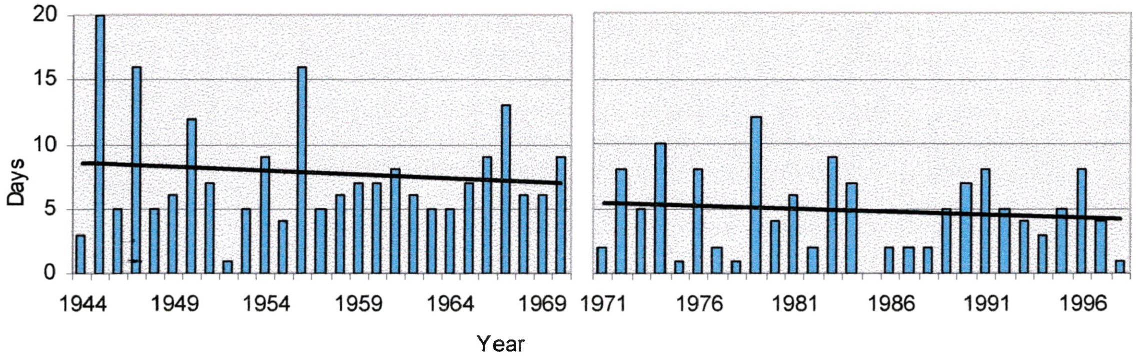

Figure 4.8 Days during the growing season at Kenora with minimum temperatures <0° C: 1944-1998.

4.7 Climate Spectra

Spectral frequency analyses revealed that similar cycles were recurring in the temperature data for the different stations. This is not unexpected due to the high correlation of temperature fluctuations for stations within a geographic region. The most predominant cycles were noted for each time period.

1916-1998

The annual mean temperatures for all long-term stations were analysed for 1916-1998. These analyses established that certain frequencies were present at most (or all) seven sites in varying powers. The most consistent and strongest cycles were 3-5 years in length.

1916-1949 and 1950-1998

A biennial cycle (just over two years) was present in both periods at all sites. It was the second strongest signal at many sites in 1916-1950. In the period 1950-1998, this ranking changes and it becomes the most prominent signal at all stations except Fort Frances (see Table 4.7). Visual inspection of the time series plots suggests that this prominence is not consistent throughout the period. It becomes a dominant feature in the early 1970s and persists during the rest of the period.

Table 4.7 Comparison of spectral cycles in 1916-1949 and 1950-1998. The most prominent cycle (highest power) for each time period is shaded.

Station	1916-1949 (34 years) (years/cycle)					1950-98 (49 years) (years/cycle)					
Kenora	16.5		4.1	3	2.2	24.5				3.3	2.1
Fort Frances	16.5	5			2.2	24.5	7.0				2.1
MineCentre			4.1	3	2.2				4.5	3.3	2.1
Dryden	16.5		4.1		2.2	24.5		6.1		3.3	2.1
SiouxLookout	16.5			3.3	2.2	24.5			4.9	3.3	2.1
ThunderBay		6		3	2.2		8.2			3.3	2.1
Terr/Schreib	16.5			3	2.2	24.5				3.3	2.1

1916-1943, 1944-1970 and 1971-1998: January and July

The focus was further defined to examine the coldest and warmest months. Several of the same cycles were present in winter and summer as evident when Table 4.8a and 4.8b are compared. In the first period a 6.8-year cycle predominated in January and a higher frequency of 2.5 years in length was most pronounced in July. During the second period the higher frequency (2.3 years/cycle) was the most predominant for both January and July. In the third period, the most prominent frequency in winter was consistently a 2.8-year cycle and in summer a 7.0-year cycle dominated.

Table 4.8a January spectra in three periods. The most prominent cycle (highest power) for each time period is shaded.

Station	1916-1943 (28 years)			1944-1970 (27 years)			1970-98 (28 years)		
	(years/cycle)			(years/cycle)			(years/cycle)		
Kenora	6.8	3.9	2.1	13.5	3.9	2.3		5.6	2.8
Fort Frances	6.8	3.9	2.1	13.5	3.9	2.3		5.6	2.8
MineCentre	6.8	3.4	2.1	13.5	3.9	2.3		5.6	2.8
Dryden	6.8	3.4	2.1	13.5	3.9	2.3		5.6	2.8
SiouxLookout	6.8	3.4	2.1	13.5	3.9	2.3		5.6	2.8
ThunderBay	6.8	3.4	2.1	13.5	3.0	2.3	14.0	5.6	2.8
Terr/Schreiber	6.8	3.0	2.3		3.0	2.3		5.6	2.8

Table 4.8b July spectra in three periods. The most prominent cycle (highest power) for each time period is shaded.

Station	1916-1943 (28 years)				1944-1970 (27 years)				1970-98 (28 years)			
	(years/cycle)				(years/cycle)				(years/cycle)			
Kenora	6.8	3.4	2.5		9.0	5.4	3.0	2.3	7.0	4.7		2.3
Fort Frances	9.0	3.9	2.5	2.1	9.0	5.4	3.0	2.3	7.0	4.7		2.3
MineCentre	6.8	3.4	2.5	2.1	9.0	5.4	3.0	2.3	7.0	4.7		2.3
Dryden	6.8	3.4	2.5	2.1	9.0	5.4	3.4	2.3	7.0	4.7		2.3
SiouxLookout	6.8	3.4	2.5		9.0	5.4	3.0	2.3	7.0	4.7		2.3
ThunderBay	6.8	3.9	2.5		9.0		3.9	2.3	7.0	4.7	3.5	2.5
Terr/Schreiber	6.8	4.5	2.5		9.0		3.9	2.3	7.0	4.7	3.5	2.5

Visual inspection of the Dryden January and July series (Figure 4.9) generally showed similar patterns of temperature variation until the early 1970s. There were alternating periods of higher frequency variation (2-3 years) and periods of mid- frequency variation (5-8 years).

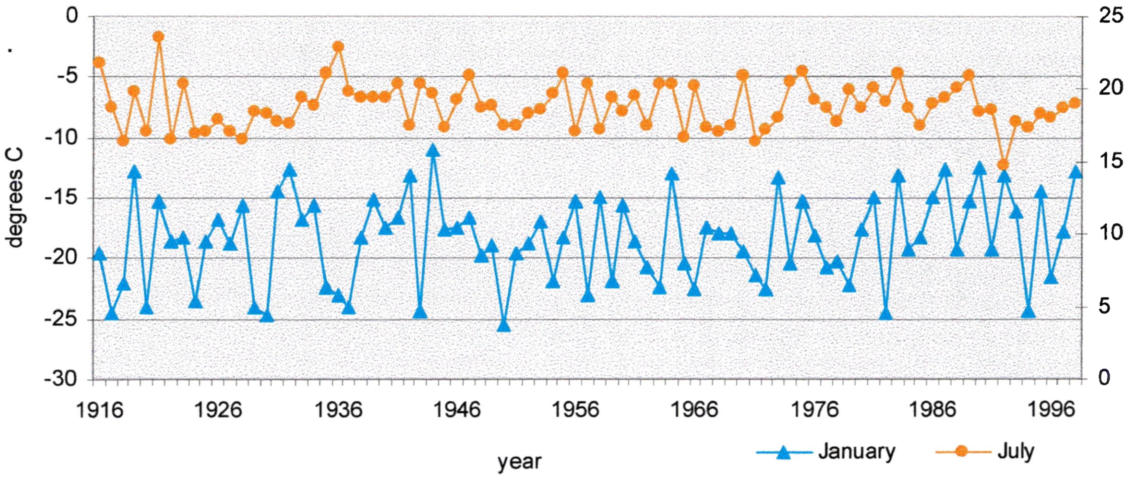

Figure 4.9 Dryden January and July mean temperatures: 1916-1998.

All stations roughly demonstrated this pattern:

1916 to early 1920s - ~ biennial cycle
mid 1920s to early 1950s - ~ seven-year cycle
mid 1950s to mid 1960s - ~ biennial cycle
late 1960s to early 1970s - ~ seven-year cycle.

The mid frequency (5-8 year) cycles for the July series between the 1920s to the 1950s were not well defined. These periods did not correlate with the time periods associated with the annual temperature trends. After the mid 1970s the July and January series differ: in January there is a nearly biennial cycle which continues until 1998, while in July, a seven-year cycle predominates until the end of the period. The strength of the January signal contributes to the predominance of a biennial cycle in the annual temperatures after 1970-1978.

4.8 Linear Trends in Rainfall

Precipitation is not a continuous variable and typically is not normally distributed spatially or temporally. This feature, combined with difficulties with accurate measurement (discussed in earlier chapters), limits procedures for estimating missing values. The available long-term climate records of rainfall are confined to the southern portion of the region.

Most of the annual precipitation in NWO occurs as rain (not shown). Although it is possible to have moderate rain events in the winter season (December – February), such occurrences are rare, and usually confined to stations near Lake Superior. The transition months of March, April, October and November generally have a combination of snow and rain. Approximately 80% of the annual total rain occurs during the growing season (May – September) in much of the region. Higher rain totals during October and November, especially at sites adjacent to Lake Superior, reduce this ratio slightly.

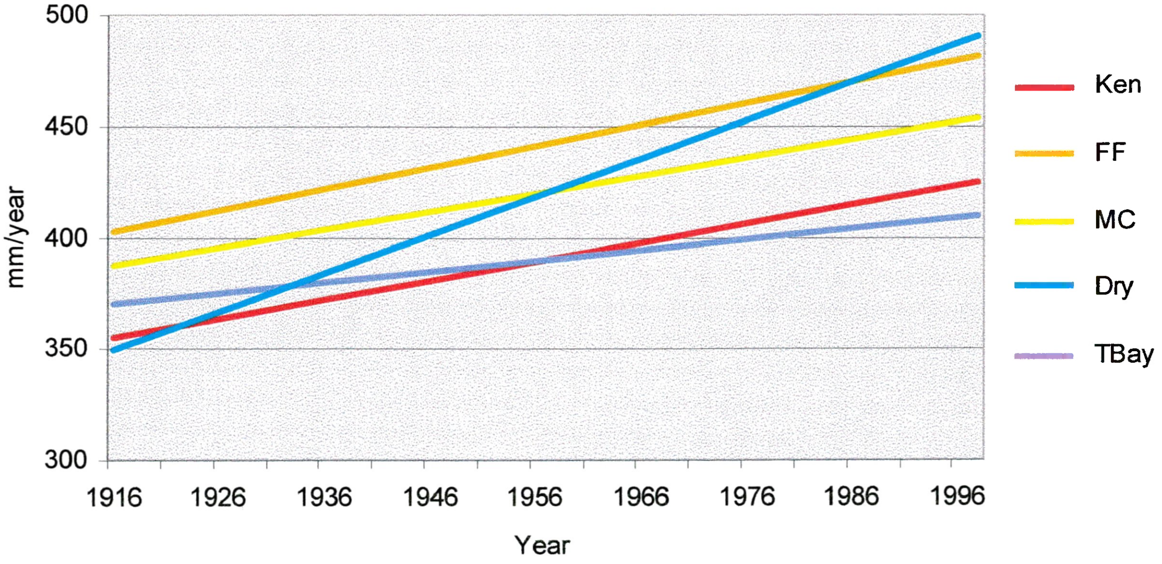

Figure 4.10 Growing season rainfall trends of five southern sites: 1916-1998.

Growing season rainfall has increased in the 1916-1998 period at all stations with statistically significant increases at Fort Frances and Dryden (Figure 4.10 and Table 4.9). The seasonal totals for Fort Frances (Figure 4.11) suggest that record began in a drier time with much of the increase taking place in the early decades.

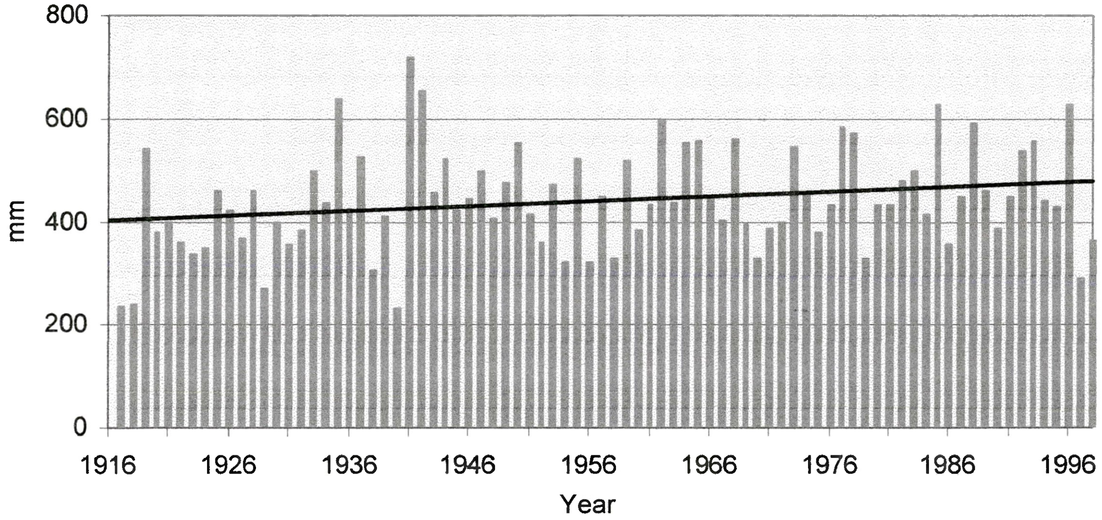

Figure 4.11 Average growing season rainfall for Fort Frances: 1916-1998 (linear trend line shown).

Table 4.9 Trends in growing season rainfall. Significance levels of $\alpha > 0.05$ are not listed.

Station	Years	Avg. Ann. Change (mm/yr)	Significance Level	Total Change (mm)
Kenora	1916-1998	0.9		71.0
Fort Frances	1916-1998	1.0	0.05	79.6
Mine Centre	1916-1998	0.8		67.1
Dryden	1916-1998	1.7	0.001	140.4
Sioux Lookout	1939-1998	0.1		7.2
Thunder Bay	1916-1998	0.5		39.6
Terr/Schreiber	1917-1998	3.3	0.001	191.8
Red Lake	1965-1998	0.6		19.4
Cameron Falls	1924-1997	1.4	0.01	105.7
Geraldton	1968-1997	2.1		63.7

4.9 Comparison of Average Growing Season Rainfall in the Periods

The time periods assigned to summarise temperature change and averages do not describe annual or growing season rainfall particularly well. Nevertheless, the rain averages listed in the time periods of Table 4.10 show that all locations have increasing annual growing season totals (in stations that span more than one period).

Table 4.10 Average annual growing season rainfall in three periods. Means with a '*' are significantly different than means of both other periods.

Station	Average Growing Season Rainfall (mm)		
	1916-1943	1944-1970	1971-1998
Kenora	375.5	380.5	413.1
Fort Frances	416.6	448.3	460.7
Mine Centre	396.2	426.9	437.7
Dryden	381.1	410.8	467.2*
Sioux Lookout	misg	410.8	410.9
Thunder Bay	372.1	392.3	404.6
Terr/Schreiber	364.2*	442.1	460.9(to 97)
Red Lake	misg	misg	459.6
Cameron Falls	461.3(25-43)	560.0	587.1(to 97)
Geraldton	misg	misg	412.8(to 97)

4.10 Number and Intensity of Rainfall Events

4.10.1 Frequency of rain events during the 20th century

Almost all stations recorded an increase in the number of rain days (≥0.6 mm) during the growing season (see Table 4.11). This increase follows a similar pattern to the increase in total amount of rainfall as displayed in Table 4.10. Again, all stations had increases except Sioux Lookout.

Table 4.11 Average number of rain days (≥0.6 mm) during the growing season in three periods. Incomplete periods are detailed. Periods with non-consecutive missing seasons are shaded and years available are indicated.

Station	Average Growing Season Rain Days		
	1916-1943	1944-1970	1971-1998
Kenora	38	49	51
Fort Frances	46	49	53
Mine Centre	48	50	55
Dryden	44	53	69
Sioux Lookout	misg	54	54
Thunder Bay	47	49	51
Terr/Schreiber	44 (17-43)	44 (15 yrs)	63 (23 yrs)
Red Lake	misg	50 (64-70)	52
Cameron Falls	48 (25-43)	55	69 (to 97)
Geraldton	misg	misg	58 (to 97)

4.10.2 Examination of heavy-rainfall events

At first glance the increase in growing season rainfall detailed above would seem to compensate for higher evaporation as a result of higher temperatures. The daily rainfall database was examined to compare the intensity characteristics of the three time periods. Only trivial differences were present in daily totals <30 mm. The frequency of events of ≥30 to 39.9 mm at sites south of latitude 50° did not change but increased slightly north of this latitude. Many stations had a higher frequency of heavy (≥40 mm) rain events (Table 4.12). The Fort Frances record is graphed in Figure 4.12 as an example of this feature.

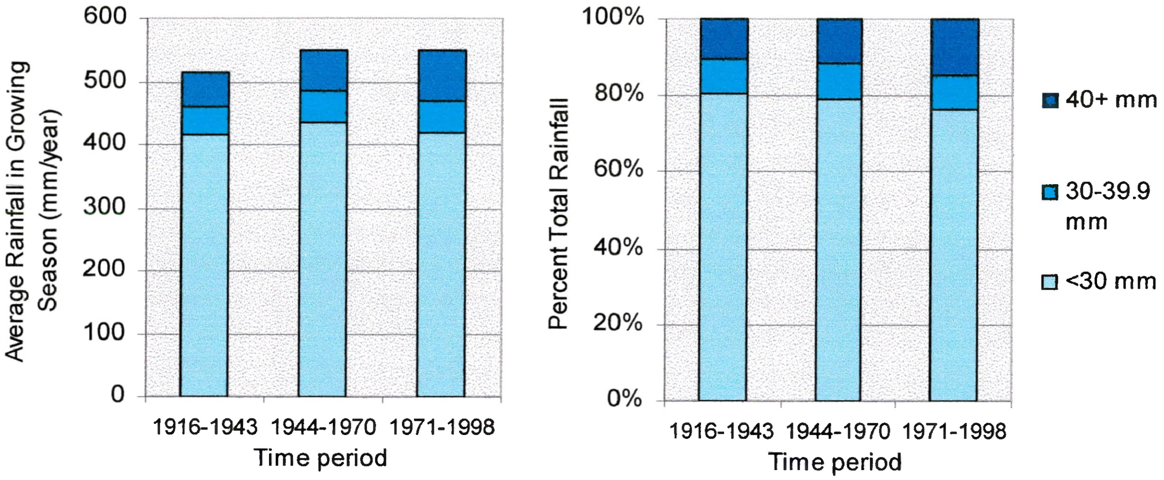

Figure 4.12 Major rain events at Fort Frances; totals and percent of annual average rainfall in selected time periods.

The increase in rain events >40 mm was a consistent regional feature when station duration permitted comparison (Table 4.12). It is also possible at some stations that increases in rainfall in the greater-than-40mm category are due to increased amounts for individual events.

Table 4.12 Percentage of rainfall (≥40 mm) of average annual rainfall in the three periods.

Station	% Heavy Rainfall (>40 mm)		
	1916-1943	1944-1970	1971-1998
Kenora	8.7	9.9	10.7
Fort Frances	10.7	11.7	14.8
Mine Centre	8.6	10.7	11.3
Dryden	8.8	4.2	7.7
Sioux Lookout	Misg	5.4	5.4
Thunder Bay	7.0	9.5	9.6
Terr/Schreiber	9.4	11.8	Misg
Red Lake	Misg	Misg	5.0
Cameron Falls	5.0(1925-43)	6.0	7.9
Geraldton	misg	misg	6.7

4.11 Trends in Annual Snowfall

The amount of snow and snow-cover can have many implications for boreal species. Gates (1993) discusses some of the insulation properties of snow and the protection afforded to vulnerable root systems. Reduced snowcover and early melt followed by extreme minimum temperatures can contribute to species decline. The melting of accumulated snow provides moisture for plant growth and marks the advent of forest fire potential. For example, with the Canadian Forest Fire Weather Index System, the calculation of fire danger in spring begins on the third day after the snowcover has melted (Canadian Forestry Service 1984).

Five longer-term snowfall series were examined and analysed. All of these records contained a decline from the early 1960s to the late 1990s. The Sioux Lookout and Kenora declines were statistically significant. The annual totals and trends of these stations are displayed in Figure 4.13 and Table 4.13.

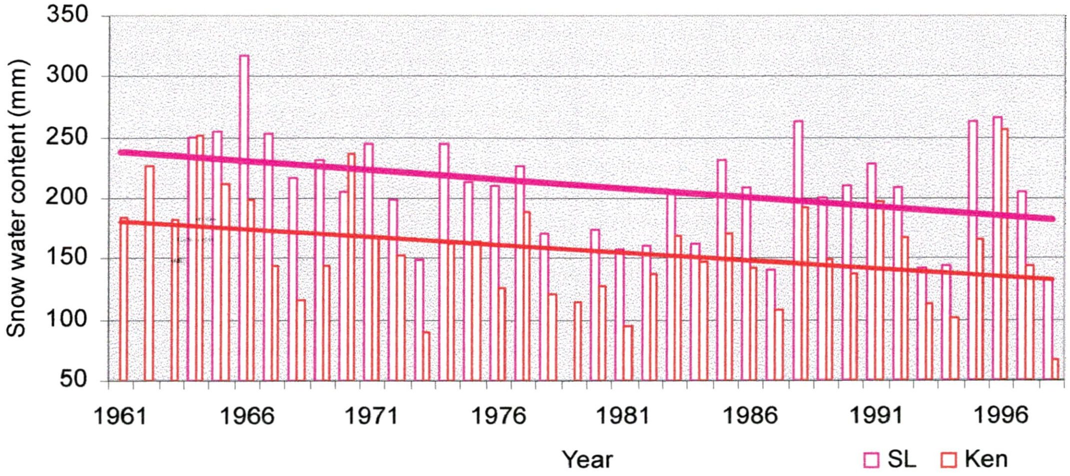

Figure 4.13 Annual snowfall (water content) of Sioux Lookout and Kenora, 1961-1998.

Table 4.13 Annual snowfall (water content) at available stations. Significance levels of $\alpha > 0.05$ are not listed. Significance for Pickle Lake was not calculated because of considerable missing data.

Station	Years	Avg. Ann. Change (mm/yr)	Significance Level	Total Change (mm)
Kenora	1961-1998	-1.30	0.05	-49.4
Sioux Lookout	1964-1998	-1.51	0.05	-52.9
Thunder Bay	1961-1998	-0.49		-18.7
Red Lake	1965-1998	-1.19		-40.5
Pickle Lake	1965-1998	-2.0		-74.7

The changes in proportion of precipitation falling as snow were examined for Kenora, Sioux Lookout and Thunder Bay. Kenora and Sioux Lookout show a decreasing trend over the period 1961-1998. Kenora (Figure 4.14) shows ~10% decline in the amount of precipitation falling as snow over the period. Sioux Lookout and Thunder Bay have only minimal declines in this proportion.

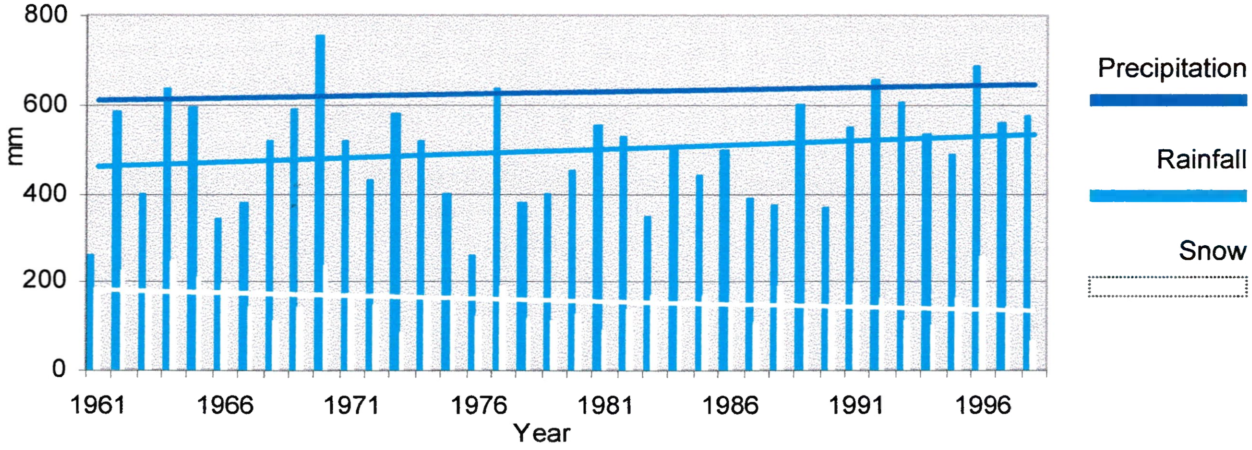

Figure 4.14 Annual totals of rain and snow and linear trends at Kenora 1961-1998. Total precipitation trend is shown for comparison.

The decline in annual snowfall could be a consequence of temperature, i.e. a higher surface air temperature results in precipitation falling and recorded as rain rather than snow. The spring and autumn seasons were assessed in an attempt to isolate a change of state in precipitation during the transition seasons. Trends and difference of means t-tests were calculated for stations with precipitation records that spanned the periods 1944-1970 and 1971-1998. Kenora and Thunder Bay had significantly less snow in the spring with no significant change in rain amounts. The trends were similar at other sites, but snowfall declines were not statistically significant at $\alpha < 0.05$. In autumn there were no significant changes in rain and snow.

DISCUSSION

The results of this study show some significant trends in temperature and precipitation during the 20th century in NWO. The nature and magnitude of these changes are broadly consistent with observed change in southern Canada and in the NH. Some of the observed and predicted trends could contribute to increased disturbance frequency and repositioning of boreal vegetation. Are the beginnings of such consequences already detectable? This kind of question is likely in the same league as discussion about flood frequencies and the incidence of hurricanes, events with potentially major consequences but without simple cause and effect answers. This chapter summarises many of the 20th century climatic trends in the region and examines some implications for the 21st century.

5.1 Construction of a Homogeneous Regional Climate Data Base

Meaningful analyses of surface climate variables like temperature and precipitation at the regional scale require homogeneous time-series of long duration. Changes in instrumentation, station environments, schedules of observation and site location often introduce discontinuities that obscure or exaggerate temperature and precipitation trends. All of the longer climatological records in NWO have one or more of these inhomogeneities.

Each station used in this study received individual assessment and adjustment. Earlier series were adjusted to conform to current site conditions. Almost all of these stations required a combination of two or more climate records. Only the Dryden records were combined without adjustment. Summaries, trends, and other climatic features were calculated using this adjusted database.

5.2 Summary of 20th Century Climatic Trends in Northwestern Ontario

All available records from 1916 to 1998 show a warming trend in reasonable agreement with the pattern of temperature change in the NH. The average increase in T_{mean} in NWO was 1.1° C (an average of available stations with no areal weighting), nearly double the average increase for the globe and the NH, but consistent with predictions of higher rates of change in higher latitudes and mid-continent locations (EC 1995; IPCC 1996). The T_{min} contributed approximately 70% of the increase. This, and a more modest positive trend in the T_{max}, resulted in a decline of the DTR. The most pronounced warming in T_{mean} took place in the spring season (average 1.9° C) with winter (1.6° C) and the growing season (0.5° C) also featuring some temperature increase. Virtually no change took place in the autumn season (0.2° C).

Much of the annual rainfall in NWO, more than 80% at the majority of sites, falls during the growing season (May to September). Annual and growing season rainfall from 1916 to 1998 has increased at all sites (statistically significant at several). These higher totals are due to increased summer rainfall.

Other seasons have little change. An increase in heavy rain events (≥40 mm), typically during the summer months, took place at almost all stations (the exception was Dryden).

At the five stations that measure the water content of snowfall using the Nipher snow gauge (1961-1998), there has been a decline. Most other stations using basic snow-ruler method of measurement feature this decline of recent decades and also suggest a negative trend from 1916 to 1998. The snow-ruler method has not changed during this time (von Storch 1995) but some caution should be applied when comparing these two systems of measurement. It appears that most of the decline in snow, and hence a decrease in total precipitation, occurs in the winter and spring months. Little or no change in precipitation is apparent in the autumn totals.

The temperature did not increase at a constant rate during the 20th century. Two epochs of increase were separated by a slight decline. Many variables associated with temperature varied through these periods (Table 5.1).

Table 5.1 Comparison of temperature trends in the defined periods. All available station series are used to calculate averages. No form of areal weighting is used.

	Average Annual Change (°C/yr)		
Variable	1916-1943	1944-1970	1971-1998
Annual T_{mean}	0.038	-0.013	0.026
Annual T_{max}	0.033	-0.017	0.028
Annual T_{min}	0.049	0.002	0.037
DTR	-0.025	-0.034	-0.010

5.2.1 1916 to 1943: An extended period of warming

The longer records in the region strongly implied that these 28 years between 1916 and 1943 were part of a longer warming trend that commenced one or two decades earlier. The T_{mean} increase was about 0.8° C. On average there appeared to be a more pronounced increase in T_{min} compared to T_{max} with a consequent decrease in the DTR. Monthly, seasonal and annual T_{mean} had high variability. Spectral analyses suggested that cycles of 6.8, ~3.4 and ~2.1 years were present in winter and summer. The more prominent cycle in the winter was 6.8 years. In summer, the most pronounced cycle was 2.5 years.

5.2.2 1944 to 1970: A relatively benign period?

A slight decline (generally) in T_{mean} took place in the region. The average change in T_{mean} was –0.2° C with all seasons cooler except the autumn which, on average, was 0.5° C warmer. The annual temperature decrease in this period was mainly a function of a lower T_{max}. Hence, the DTR continued to decline. Little change was noted in the occurrence of daily temperatures $\geq$30° C at most sites. The occurrence of days with frost in the growing season declined at most sites. A prominent biennial cycle, 2.3 years, was present in winter and summer.

The first use of the term "benign" (that I know of) to describe the 1940s to circa 1970 was by McTaggart-Cowan (director of Environment Canada) in 1973. The term, in a somewhat different context, was used by Baker et al. (1993). They reviewed the agricultural implications of an extended time, 1937-1973, in their examination of favourable climate. This benign period is approximately coincident with a general decline in the NH surface temperatures. This time is one of lower summer temperatures and reduced variability (see Tables 4.3 and 4.4), but also has increased growing season precipitation as evident in Table 4.10. More rainfall and slightly lower T_{max} resulted in reduced moisture stress and less fire activity (Natural Resources Canada, 1997). These were likely favourable decades for the southern boreal forest.

5.2.3 1971 to 1998: warming and variability

The average increase in T_{mean} was about 0.7° C with contributions from T_{max} (40%) and T_{min} (60%). These warming trends also featured increased variability that was greatest in the winter but present in all months and seasons. The increase in the T_{max} did not translate into more days of $\geq 30°$ C in the region. Frost events (in the growing season) declined, a continuation from earlier periods.

Spectral analysis of this period indicated a departure from earlier patterns. Before 1971 the January and July T_{mean} series had similar frequencies but with variation in strength. After 1970, the predominant summer frequency changes to 7.0 years/cycle. The January pattern maintains a biennial pattern established around 1958.

5.2.4 Rain and snow

There was an increase in annual rainfall through the period 1916-1998. On average there was an increase of about 60 mm, though the range was considerable at different stations (an increase from 7 to over 100 mm). At first appearance this increase seems to be a confirmation of the theoretical relationship between a warmer world and an enhanced hydrological cycle (IPCC 1996). The relationship is not so simple, however. The annual amounts of rainfall and temperature have little correlation and the annual and seasonal rain amounts did not follow the periodic temperature trends.

A trend of increased rainfall is apparent from 1916 in the western stations but appears to begin ~1926 in stations near Lake Superior. Phillips and McCulloch (1972) noted that a shift to increased precipitation took place in the Lake Superior basin at this time. The increase in annual regional precipitation appears to level off in the 1990s. Rain is rare during the winter months (especially at sites distant from Lake Superior) in all periods. Little change in average rainfall is evident in the spring and fall months. Virtually all the increase in annual rainfall is due to change during the growing season. There are limited data but the contribution of heavy rain events (≥ 40 mm) increased throughout the entire period.

There was considerable interannual variability in annual and growing season rainfall. There was a slight decline in variability during 1944-1970 at about half of the stations that may have contributed to the benign climate of this period.

The increased rainfall contribution to annual precipitation amounts has been offset by a regional decline in annual snowfall amounts (water content) of an average of 35 cm (decrease ranges from 19 to 75 cm). Given the trend toward warmer temperatures, especially in the spring season, one may assume that precipitation might have been falling as rain when temperatures were near the freezing/melting threshold. However, the spring rainfall amounts, which remained essentially the same, do not support this hypothesis.

The proportion of precipitation falling as snow (water content) decreased (Kenora) but only minimally in two of the three stations examined (Thunder Bay, Sioux Lookout). General conclusions would require more data but given the trend of decreased snowfall and increased rainfall, one would expect that the proportion would generally be declining.

5.2.5 Statistical tests of temperature trends

The linear model provides an indication of the overall trend and is a common way of analysing climatological time series (Clark and Hosking 1988). Analysis of the residuals can reveal some of the limitations of the linear model and the confidence in estimates of the slope and the y-intercept.

Linearity

A single line does not capture the changes in the temperature trends within the period 1916-1998, i.e. the two periods of warming separated by a cooling phase. A higher-order polynomial would better capture the trend (e.g. Figure 3.1).

Homoscedasticity

A plot of the residuals against year (1916-1998) indicates that the variance is greater at the beginning and the end of the period; similar to the standard deviations summarised in Table 4.4. This variability reduces the confidence level of the linear estimates.

Normality

Visual inspection of frequency plots of the residuals confirmed nearly normal distributions, consistent with other findings of normality in temperature (Jones and Hulme 1995; von Storch 1995).

Independence

Analyses of time series often encounter problems with autocorrelation, i.e. a preceding value influences a subsequent value(s). The linear estimates from the least-squares method are unbiased, but the confidence interval is large and results in an overestimation of statistical significance. It is interesting to note that medium-frequency natural climatic cycles such as the El Niño Southern Oscillation (ENSO) may contribute to this problem. Some researchers have used cycles like ENSO as explanatory variables (e.g. Zheng et al. 1997).

In this study, the Durbin-Watson test was used to test for first-order autocorrelation in the residuals of significant trends (Clark and Hosking 1988). This test indicated that there was no significant degree of first-order correlation in the series of most stations. At Mine Centre and Thunder Bay the test was on the borderline between positive first-order autocorrelation and indeterminacy, suggesting reduced confidence in the trends at these stations. More-sophisticated statistical analyses are possible to determine more representative confidence intervals (Zheng et al. 1997; Zhang et al. 1999).

Another approach is to assign a higher level of α in determining whether or not the linear trend is to be considered significant (von Storch 1995). The linear trend at Mine Centre was highly significant ($p = 0.001$) and at Thunder Bay ($p = 0.01$), suggesting that the trends were not due to chance or autocorrelation.

5.3 Comparison of Temperature Findings with Other Research

5.3.1 Environment Canada

The findings of this study were compared with an earlier (EC) study (Gullett and Skinner 1992) for the Northeast Forest region. The average T_{mean} for the Northeast Forest region, which includes this study area, also shows a significant warming of 0.5°C over the years 1895-1991.

The trends were directly compared to adjusted station summaries from 1916-1995 for a number of NWO stations: Kenora, Fort Frances, Mine Centre, Sioux Lookout (1930-1995) and Thunder Bay. The linear trend results for T_{mean} and T_{max} were similar. All trends for T_{mean} showed a positive slope; the average difference between the adjusted EC series and those of this study was 0.002 °C/year or 0.19 °C over the 80-year comparison period. With T_{min}, the magnitude of positive change is generally greater in the EC findings. This is mainly a result of an adjustment applied to recorded T_{min} values at principal stations from 1962 onward to compensate for a change in observation time (discussed earlier).

5.3.2 Adjacent regions

In the Prairies, directly west of the NWO study area, Herrington et al. (1997) identified the same overall pattern of warming until the 1940s, cooling until the 1970s and accelerated warming in the 1980s. Zhang et al. (1999) noted that the greatest magnitude of warming in Canada (1900-1995) had occurred in the

Prairies (annual T_{mean} increase of 1.5° C) with spring having the most pronounced warming.

In eastern Minnesota, south of the study area, Skaggs et al. (1995) found a temperature trend of +0.013° C per year, identical to the NWO average, and similar indications of variability in the periods defined in this study.

5.3.3 Other related research

Zhang et al. (1999) reported that in southern Canada T_{min} has increased more than the T_{max} in all seasons (1900-1995). Thus, the DTR has declined throughout the 20th century. The greatest proportion of this decline took place prior to the 1950s. In this study, only two of four 4 stations (Kenora and Thunder Bay), for which the DTR could be determined from 1916-1998, showed a similar pattern. The decrease in the DTR seems to be present for much of the 20th century in many areas of the world (Easterling et al. 1997).

The increase in annual precipitation and summer rainfall is in general agreement with the findings of Zhang et al. (1999) for NWO and with Karl et al. 1996) for an adjacent area of the United States. A decline in winter precipitation (almost totally in solid form in NWO) also has been noted by Zhang et al. (1999). They detail a decrease in spring snowfall but a net increase in spring rainfall over the period 1900-1995. The period 1950-1995 is reported to have a decline in total spring precipitation of approximately 10%. This study did not demonstrate a change in the spring rainfall in the period 1916-1998. This difference may be due to adjustments for inhomogeneities applied to the rainfall data by Zhang et al.

(1999). The data were further interpolated and gridded data were used. In this study only raw archived precipitation data were utilised.

The increase of heavy rain events (detailed in Table 4.12) agrees well with Karl et al. (1996) and Karl (1997). However, Mekis and Hogg (1999) questioned whether the threshold of 2 inches (50.8 mm) has application in Canada because of the decrease in intensity of extreme events with increasing latitude. They selected a threshold of >25 mm and noted a decrease at most stations, including most of the study area in this research. These differences may be due in part to different thresholds and categories but, in any case, require more research because of the importance of extreme precipitation events in regional emergency planning. In addition, changes in the frequency of such events may lend insights into rates of climate change.

5.4 Northwestern Ontario in the Context of 20th Century Global Climate Change

Many of the features of temperature change in the NWO region have been consistent with observed changes in the NH. The topography of the region can influence regional trends but mesoscale change takes place because of external influences. The events that contribute to the annual and seasonal changes have most of their character initiated considerable distances from NWO. Delivery takes place via global atmospheric circulation systems.

It is still occasionally argued that 20th century warming could be a phase of a longer climate cycle and, as a corollary, little need to plan for the future

(Michaels 1988; Koch 1996). However, no known natural cycles can account for the changes observed, according to Stocker and Mysak (1992). The 20th century, in perspective with recent centuries, is illustrated in Figure 5.1.

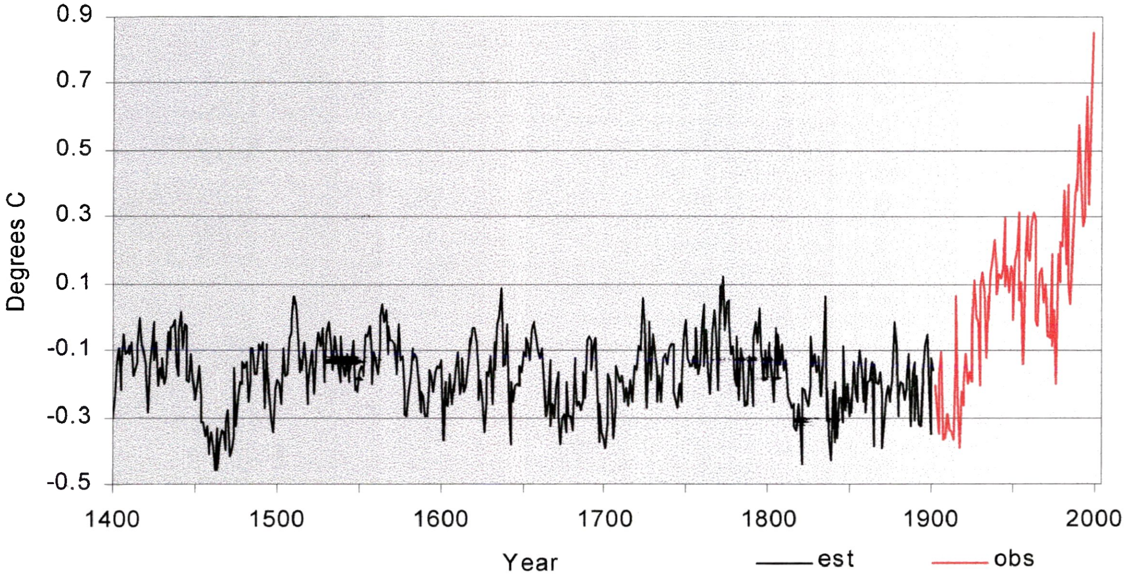

Figure 5.1 Northern Hemispheric Annual Mean Temperature: 1400-1998. The estimated values were determined from proxy data and the observed values were based on instrument records. Source: Mann et al. 1998.

Twentieth-century climate change is a result of a combination of natural and anthropogenic influences. It is prudent to learn as much as possible about the components to understand and cope with climate change in the 21st century.

5.4.1 Natural components

Variation of solar radiation is an obvious area for investigation but the detection of climatic forcing as a result of changes in solar radiation is not straightforward. The sun's energy in the 20th century has varied by only 0.1% during the 11-year sunspot cycle (IPCC 1996) which is not sufficient to cause the warming observed in the 20th century. Other longer-term solar variations have been detected, but in the 20th century, these result in only minor fluctuations in radiative forcing (Shine et al. 1996; Tett et al. 1999).

Volcanic activity can inject aerosols into the stratosphere. Major eruptions can cause large, though temporary, negative radiative forcing (IPCC 1996). The 20th century, when compared to recent centuries, has been relatively free of major volcanic eruptions. The exception is Pinatubo, in the Philippines, which erupted in 1991. The aerosol veil placed in the stratosphere by this eruption caused a dip in global and NWO regional temperatures in 1992 and 1993. The impact of this eruption in NWO was considerable. Summer months were much cooler than 1961-90 normals throughout the region.

Cyclical patterns seem apparent in virtually any time series of temperature or precipitation. They tend to decay or be overtaken by other semi-periodic patterns. Nevertheless, certain climatic features are associated with them and there is potential to predict future weather and climate patterns. The following may have connections with weather and climate events in NWO:

- El Niño and the Southern Oscillation (ENSO). This is the best known cyclical pattern, receiving considerable attention in the media. This source of climate variation in the equatorial Pacific Ocean is distant from NWO but changes in sea surface temperature (SST) and pressure patterns result in teleconnections that contribute to temperature and precipitation anomolies around the world. It is an important source of interannual climate variation in NWO. There are three phases of ENSO:

1) El Niño, a warm phase that usually results in mild winter temperatures in NWO (and much of southern Canada);
2) La Niña, a cool phase with less consistent consequences than with the El Niño phase. Pronounced effects (cooler than normal winter temperatures and above normal snowfall) of La Niña are experienced in NWO approximately five winters out of ten (Flannigan 2000);
3) A normal phase with little obvious impact in NWO.

A more thorough examination of the ENSO process is given by Bigg (1995) and, for a review of impacts in Canada, see Shabbar and Khandekar (1996).

- Quasi-Biennial Oscillation (QBO): As the name suggests, this is a cycle of approximately two years (von Storch 1995) with related changes in the direction of stratospheric winds (Christoforou and Hameed 1997).
- Pacific North American (PNA): This is a longer frequency cycle (23-35 years) discussed in some detail later.

5.4.2 Forcing due to human practices (emissions, tropospheric aerosols, land use)

It is generally assumed that anthropogenic forcings (AF) played a relatively insignificant role prior to the 1940s (IPCC 1996), although Tett et al. (1999) argued that the human signal is detectable and significant from 1906 onward. They suggested that the warming in the early decades was caused by cycles of natural internal variability (ocean atmospheric interactions) and steadily increasing AF. Increased solar activity made a detectable though minor contribution.

The anthropogenic contribution of GHGs has increased incrementally since 1800. The rate of increase became exponential during the benign period (1944-1970). The decline in NH temperature in this period seemed to contradict the GHG warming premise. It generated discussion of *feedbacks* and the possibility that the warming of the recent decades was only a temporary interruption of the *Little Ice Age* (Lamb 1966; Wahl and Lawson 1970). Discussion of an impending ice age was featured in the media.

The retrospective explanation of these decades of cooling is that aerosols from human industry in combination with natural cycles resulted in cooling in the NH. The cooling was not global in extent; a slight warming occurred during most of this period in the SH (Parker et al. 1994). This difference is thought to be due to a much greater production of aerosols in the NH versus the SH.

Much of the resumed warming trend of recent decades, a global increase of 0.25° C, has been due to AF, although solar irradiance could have made a contribution (up to 0.125° C) to the warming (Tett et al. 1999). Anthropogenic forcing could affect and probably does affect, 'natural' cycles i.e. ENSO, PNA, Arctic Oscillation (Corti et al. 1999) which makes it difficult to separate the attributed causes - natural or anthropogenic - of climate change.

5.5 Evidence of 20th Century Climate Change in the Boreal Forest of Northwestern Ontario

Figure 5.1 forcefully suggests that the temperature trend of the 20th century is a major departure from previous centuries. A logical expectation could be that the boreal ecosystem would exhibit signals in response:

1) Accelerated growth may result from warmer temperatures and more GS rainfall. In addition, higher atmospheric concentrations of CO_2 may enhance photosynthetic and growth rates (Gates 1993), although with less effect than in more southerly climates (Herrington et al. 1997).

2) Disturbance is an integral processes of the boreal forest and likely to contribute to shifts in the south and north transition zones and change in species distribution within. Weather and climate variables have some direct and many indirect interactions with various types of disturbance in the boreal forest. For example, air temperature, precipitation (and its absence) and wind can be applied to predict fire behaviour. Usually the variables are indirect and more complex; e.g. insect survival and persistence can be a function of certain temperature thresholds and other features such as winter snow depth (Gates 1993).

Fire disturbance has increased in the circumpolar boreal forest when the 1980s and 1990s are compared with the 1950s and 1960s (Stocks et al. 1998; Zimov et al. 1999). The annual area burned has increased by about 250% (Zimov et al. 1999). A similar increase is noted for Canada (Natural Resources Canada 1997; Stocks et al. 1998) and Figure 5.2 suggests that Northern Ontario is part of this pattern.

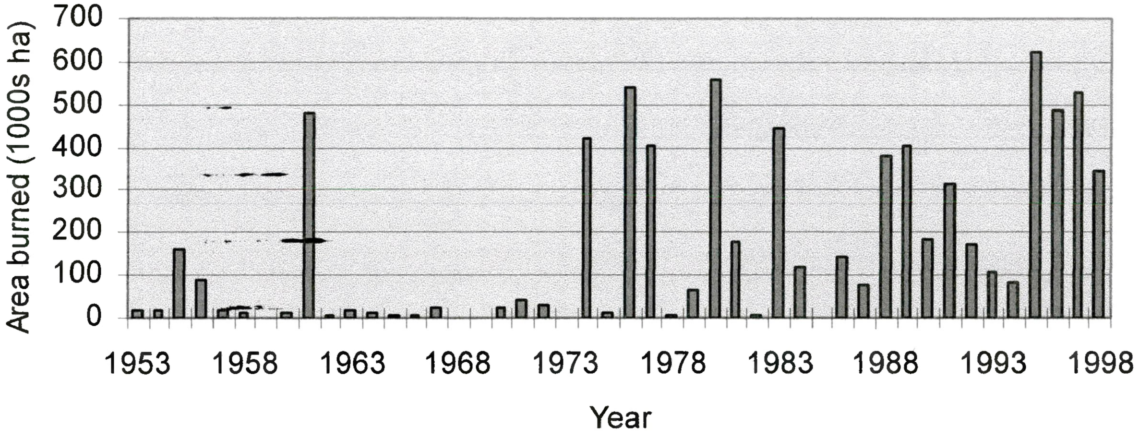

Figure 5.2 Forest area burned in Northern Ontario during 1953-1998. Sources: Flannigan 2000; Wintle 2000.

This increase may not be as remarkable as it appears. It could be a function of better measurement, notably satellite observation that began in the 1970s (Stocks et al. 1998). Decades of fire suppression with related fuel build-up may have also contributed (Duinker 2000). However, new technologies in lightning detection and satellite observation have enabled rapid detection, and rapid suppression methods have also improved.

The results of this study are consistent with different fire regimes in the benign and the most recent warming period. More years in recent decades have had warmer winters with reduced snowfall followed by warmer spring temperatures. These factors likely resulted in an accelerated snowmelt (not investigated in this study). Spring rainfall has not increased and, although there has been a pronounced increase in growing season rainfall, it has been more variable. Such conditions increase the potential for drier fuels in the fire season.

If this is followed by certain local weather conditions, especially drought and winds events, increased fire activity is a likely result (Flannigan et al. 2000).

5.6 Can 20th Century Cycles Provide Clues for 21st Century Climate in Northwestern Ontario?

The temperature trends and variability of the three periods in the 20th century may be indicative of one or more lower frequency cycle(s). If such cycles could be more precisely defined, there is potential to anticipate associated features with phases of cycles in the 21st century. The decadal temperature trends, and some associated features, discussed in this paper may be part of the PNA pattern, first identified by Wallace and Gutzler (1981). They connected North Pacific SSTs and associated atmospheric patterns that produced teleconnections with upper air ridges and troughs and “centres of action” over NA. Extending this work, Minobe (1997) presented evidence of a 50-70-year oscillation of the PNA. Individual regimes are 23~35 years in length. He identified this pattern from the 1700s to the present using proxy and instrument data. The most recent “high” phase, a negative anomaly of pressure in the Pacific and a positive anomaly of pressure over western NA, began in 1976. My examination of NWO climate series has revealed decadal patterns similar to other parts of central North America and southern Canada, reinforcing that the changes are not generated in NWO (though some of the noise may be).

The timescales of the PNA and the more frequent ENSO cycle are quite different but there is evidence that certain phases share some SST patterns

(Zhang et al. 1998). It has been observed that more (less) El Niño (La Niña) events have taken place since the mid-1970s (Bigg 1995; Timmermann et al. 1999). In this study the winter/summer spectral patterns in the period 1971-1998 were different, whereas in earlier periods they showed a similar pattern. A possible explanation is that the winter time-series was reflecting the increased frequency of the El Niño phase of ENSO.

There is potential to use the teleconnections between the dynamics in the Pacific and the surface weather experienced in NWO. There is increasing confidence that Pacific SSTs, pressure indices and the resulting upper-level atmospheric patterns can be used for long-range forecasting (e.g. Shabbar and Khandekar 1996). Recent work by Flannigan et al. (2000) found high correlations between SST in the North Pacific and forest area burned from British Columbia to Quebec. The relationship between regional fire disturbance and patterns in the Pacific Ocean needs to be explored and defined. Seasonal forecasting could be utilised to plan and allot resources for fire management.

5.7 Future Impacts of Regional Climate Change on the Boreal Forest

Models that reproduce the warming of recent decades are in general agreement that significant climate change will occur in the next 50 and 100 years. The annual release of GHGs of human origin doubled between 1965 and 1995 (US Dept of Energy 1998). Another doubling is predicted by the year 2020. Intuition suggests that AF is becoming more dominant in the climate change process. Current GCMs simulate the climate of the 20th century at a continental scale reasonably well and there is increasing confidence in scenarios for the 21st century (IPCC 1996). The future could contain surprises that will mitigate human input (surprises are possible in the other direction too), but decade-to-decade climate change is most likely.

Climate change has the potential to change the limits, productivity and other qualities of the boreal forest in NWO. It has been suggested by Emanuel et al. (1985) that the boreal forest could disappear (in Canada), but any major change could be disruptive for the landscape and the economy of the region. It is impossible for boreal species to be able to adjust to such rapid change in predicted temperatures with natural regeneration and migration processes (Gates 1993). Schwartz (1992) noted that the average rate of migration was 10 to 40 km per century during the warming (a lower rate than current warming predictions) that followed the last glacial age. He added that the modern landscape, fragmented by cutting practices, transportation rights of way and other land-use practices, would likely reduce these potential rates.

Disturbance plays a fundamental role in the natural range, health and processes such as succession in the boreal forest (Herrington et al. 1997). The boreal forest, especially the southern transition, will be vulnerable to increased frequency of disturbance related to higher temperatures in combination with other meteorological and biotic variables.

5.7.1 Fire

A number of studies predict a significant increase in fire activity in the boreal forest (Flannigan and Van Wagner 1991; Stocks et al. 1998; Zimov et al.

1999). Higher fire frequency would favour species best able to take advantage of the changing fire regime. Other factors such as fire intensity, seasonal time of occurrence and growth stage of species could affect distribution (Weber and Flannigan 1997). The qualitative change graphed in Figure 5.2 is in relative agreement with other regions. It seems like an excessive response to the findings of this study, i.e. the climate has not changed enough to justify such a response. However, Weber and Flannigan (1997) noted that the incidence and magnitude of future fire activity is unlikely to be a simple progression in step with atmospheric warming. Feedbacks and other interactions could result in further increases in fire activity. Figure 5.2 needs to serve as a warning.

5.7.2 Blowdown

Wind events that result in uprooting of whole trees or snapping of stems are not unusual in NWO and often result in areas of extreme fires and complicated salvage operations (Flannigan et al. 1989). Higher winds aloft have been observed (with radiosonde weather balloon launches) in recent decades which may be related to increasing temperature between the troposphere (+0.3° C) and the stratosphere (-0.6° C) (IPCC 1996). This change may be a factor in blowdown disturbance if stronger winds are also experienced at the surface; Flannigan et al. (1989) discussed physical mechanisms that may bring winds associated with a jet stream to the surface.

5.7.3 Insect and disease

Climate directly influences insects and pathogens of the boreal forest by affecting population and range. For example, Cerezke and Volney (1995) suggested that frost in late spring contributed to declines in spruce budworm populations. A prolonged outbreak of spruce budworm infestation in NWO (~1985 to the late 1990s) may have been related to reduced frost events in late spring as would be implied by the findings of this study. In the future, insects and pathogens may become additional agents of accelerated change in the boreal forest, a result of non-linear and possibly unexpected interactions (Flannigan, 2000).

5.8 Adaptive Strategies

Much of the forest industry in Ontario is dependent on timber harvesting in the boreal forest. It is the largest industry in the north of the province and failure to adapt to change is likely to have grave economic consequences. Planting, rotations and other aspects of forest management, by default, involve planning for a future climate (Pollard 1991). However, there are many uncertainties about the dimensions of climate change (notably at the regional scale) and the effects on boreal species. More research is needed to gauge responses to various components of climate change.

Climatic variables have been linked to forest productivity and planning for many decades in Ontario. Research by Hills (1960) combined ranges of vegetation with parameters of mean annual temperature, length of growing season, seasonal precipitation and topography. Hills' site regions, and comparable works, are typically based on climatology in the form of 30-year normals, e.g. Canadian Climate Normals 1961-1990 (Environment Canada 1992). In times of transitional climate, this process likely mismatches future harvest and climate. For example, planting in the year 2000 with a planned rotation of 60 years assumes the climate of ~1976.

A more-complete comprehension of past extremes and a framework to monitor future events is likely to contribute to improved understanding and more-robust planning. A climate-extremes index (Karl et al. 1996) could be designed to monitor regional change. Such an index could be based on maximum and minimum temperatures, precipitation features, strong wind events and other extremes that are specific to NWO.

Work by Mackey and Sims (1993) combined GCM temperature projections (1.5 x CO_2 and 2 x CO_2) with a Geographical Information System to locate future domains of several boreal species. This method has considerable potential to assist with matching planting sites with suitable species. Mitigation of climate-related forest decline could be accomplished with more-intensive silviculture practices (Duinker 1990). Climate change may reduce the effectiveness of some silviculture procedures. For example, Towill (1999) reported a decline in the effectiveness of plantings in the Kenora/Red Lake area, possibly caused by a warmer growing season and reduced soil moisture.

Planning for the future of forest management in Northwestern Ontario almost certainly involves the retreat of the boreal forest and replacement with species that are suited to a transitional climate. Policies are needed that 1) address the fundamental cause of the problem, 2) mitigate the consequences, and 3) adapt to the most probable outcome(s) but do not exclude other scenarios. Planning for the mid-21st century (and beyond) is a daunting task and accurate prediction of the future has a poor track record. This is not to suggest that a leap of faith is necessary. The past relationship between GHGs and climate is understood from paleoclimatic and historical investigations. Atmospheric concentration of CO_2 has increased by 30%, and CH_4 by 145%, when compared to pre-industrial times (IPCC 1996). There is evidence of change within the boreal forest (Schindler et al. 1990) associated with observed regional climate change that is consistent with increased GHGs. Climate/forest ecosystem modelling provide projections of what is to come with further increases in GHGs. Combining trends based on human behaviour with the physics of land, water and atmospheric interactions are certain to generate surprises. However, inaction because of uncertainty (Hengeveld 1990), with avoidance of planning for forests, ecosystems and related human endeavours, is not a practical course for policy-makers.

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APPENDIX A

A.1 Station Histories and Adjustments

Fort Frances

Observations at Fort Frances began in 1892, but there are interruptions of years in duration until 1917. Records were kept at the Town location until 1995. The Airport site was opened in 1976 and has records to the present. Five km separate the two sites and the elevation is the same (343 m above msl).

The temperature means of the missing town months (2%) were estimated using the same procedure detailed for Kenora. Mine Centre (60 km NE) and Emo (35 km W) monthly means and standard differences were used. The missing Airport values were calculated from Town temperature means.

Unlike the Kenora situation, there were enough years in common (19) to allow a direct comparison of sites. The standard differences between the stations were calculated. The Town site monthly means were warmer than the Airport location in all months with the annual mean temperature being 0.9° C higher. The Town location was adjusted to conform to the Airport.

The precipitation records of the sites were combined without adjustment. During the years of parallel observation, missing months were filled in using the Town record.

Mine Centre

Mine Centre has a lengthy record (83 years) and is relatively complete, with the exception of years 1977-1986 where 23 months are missing. One site change, in 1986, is listed (Environment Canada 1989). There was no discontinuity detected and no adjustments were made. The 23 months, and 11 others, were estimated using the SDs between Mine Centre and Fort Frances, Dryden and Atikokan (when available).

Dryden

The original Dryden station has observations for 1914-1925 and 1926 until closure in August, 1997. No site changes or adjustments are listed for this record. Observations commenced at the Airport in December, 1969. The elevation is 413 m above msl, 31 m higher than the original site.

The temperature means for months of the missing years, 1925 and 1926, and four other months, were estimated using Kenora and Sioux Lookout.

Monthly and annual mean temperatures were compared for the 28 simultaneous years of observations. The values were almost identical and the r^2 correlation was 0.98 or 0.99 for all months. The two time series were combined without adjustment because no inhomogeneities were found.

Precipitation of the common years was compared and no obvious difference between the stations was apparent. The two records were combined.

Sioux Lookout

The Sioux Lookout record was constructed using three records. The original station operated from 1914 to 1932, the second from 1931 to 1938 and the Airport from 1938 to the present. These sites are in close proximity, separated by less than 5 km, and have similar elevations. The Airport is 390 m above msl.

The entire year 1928 is missing. The monthly mean temperatures was estimated using Dryden data (75 km to the SW).

There are 29 months of common observations from the original and second stations. This common period only allows a comparison of two or three seasons and Dryden data were added to the comparison. The relationship between all these sites is broadly consistent (no inhomogeneities), but some of the intermediate station values are warmer than would be expected (only six years used).

Thunder Bay

The Thunder Bay record was constructed using the original Port Arthur site (1877-1935), two intermediate sites, and the Airport time series (1941 to the present). The Airport site is 10 km to the SW of the original location and 199 m above msl. There are no times of simultaneous observations at these sites.

A previous examination of the Thunder Bay temperature series (Saunders 1995) suggested several discontinuities in the record. A comparison of Duluth and the Port Arthur revealed a decrease in the differences of the monthly and annual means that begins abruptly in January, 1902. A comparison with the nearest parallel record (Savanne) also suggested a shift to warmer readings at the Port Arthur site. Derived MSDs were calculated using the same procedure detailed in Table 2.2 (for Kenora). The stations used are listed in Table 2.3.

Table A1.1 Station records used to estimate and standardise the Thunder Bay record. The following neighbouring stations were used for comparison and estimating adjustments for the two major time series and the intermediate years in the Thunder Bay record.

Station	Years of observation	Latitude (°)	Longitude (°)	Distance from Thunder Bay Airport (km)
Duluth	1871-1959	46 40	92 08	282
Savanne	1892-1946	48 58	90 12	94
Kakabeka	1909-1977	48 24	89 37	21
Grand Marais	1913-1998	47 48	90 21	106
Quorn	1915-1960	49 25	90 54	155
North L.ake	1921-1941	49 25	90 34	64

Schreiber/Terrace Bay

Observations at the Schreiber station began in 1886, with relatively continuous records from 1909 to 1975. The Terrace Bay record is comprised of two sites, the first on a paper mill property and the second, at the Airport, less than one km to the north. The Terrace Bay stations are located 12 km east of Schreiber. All the sites are 3 or 4 km north of Lake Superior.

Three years of simultaneous observation allowed a brief comparison of sites. The monthly means were close with no obvious seasonal differences. No stations with similar siting were available for further comparison and testing of homogeneity. The averaged annual means were identical. Aguasabon (1950-1972), a station 11 km ESE of Schreiber, was used to estimate some missing temperature means for Schreiber.

Red Lake

The Red Lake archived data contain two main problems. 1) The years 1945 to 1957 have considerable missing data and the years 1958 to 1963 are entirely missing. 2) Three site changes of location and elevation are listed (Environment Canada 1989).

The Red Lake temperature series were assembled with the following stages:

1) Monthly mean temperatures for 1939 to June, 1945 and 1964 to 1998 were entered as reported in the Environment Canada archives.
2) In the years 1945 – 1949, 45% of the monthly means were missing. Standard differences and r^2 correlations between Red Lake and Kenora, Dryden and Sioux Lookout were calculated for the years 1939 – 1945. Estimates of the missing values were made with the procedure detailed for Kenora.
3) In the years 1950 – 1957, 70% of the monthly means were missing. Observations began in 1950 at Ear Falls, located 62 km SE of the Red Lake site. Standard differences and r^2 correlations between Red Lake and Ear Falls, Kenora, Dryden and Sioux Lookout were calculated for the years 1964 – 1970 and estimates calculated for missing months.
4) The same method was used to estimate means for the period 1958 – 1963 when observations were discontinued at the Red Lake station.

No attempt was made to assemble precipitation series prior to 1965. Limited confidence should be used conclusions based on data from Red Lake.

Cameron Falls

Observations at Cameron Falls, a hydro-electric generating station on the Nipigon River, began in 1924. Occasional monthly means are missing, about 3% of the total, throughout the record. A number of station records were used to estimate missing values. In addition to the Thunder Bay temperature time series, which parallels the entire Cameron Falls record, data from several shorter-term stations were used: MacDiarmid (38 km to the N), Abitibi Camps 230 and 300 (approximately 70 km to the W and NW) and Dorion 70 (40 km to the S).

Geraldton

The Geraldton temperature series are a composite of several series. Long Lac, 30 km to the NE, was used from 1929 to 1957. The years 1958 to 1967 were estimated according to the procedure described for Kenora. The stations were Cameron Falls (150 km SW), Manitouwadge (95 km SE) and Nakina (55 km N). Another station, Geraldton Forestry, had some temperature data for part of this period (until 1964), but only occasional monthly means are available. These means were used for comparison with the estimated values, not for any calculations.

Observations commenced in the town of Geraldton in 1968. In September 1981, the instruments were moved to a new location at the Airport (Environment Canada 1989), 6 km to the north. The Airport location is 82 m lower than the previous location (Environment Canada 1989).

Several stations with series that span some or all of these sections in the Geraldton series were used to monitor non-meteorological changes that could be a consequence of the construction. Cameron Falls and Manitouwadge were used, but these records were used to estimate missing data. Kapuskasing, 325 km to the east, was used because it spans all potential discontinuities and was not used in any of the initial estimates.

Limited confidence should be used conclusions based on data from Geraldton.

APPENDIX B

B.1 Annual Mean Temperatures of Additional Stations: 1916-1998

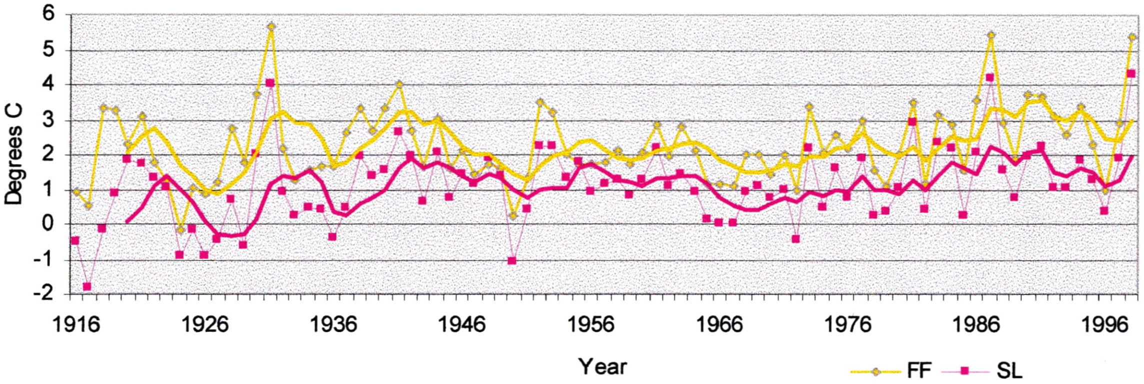

Figure B.1.1 Fort Frances and Sioux Lookout

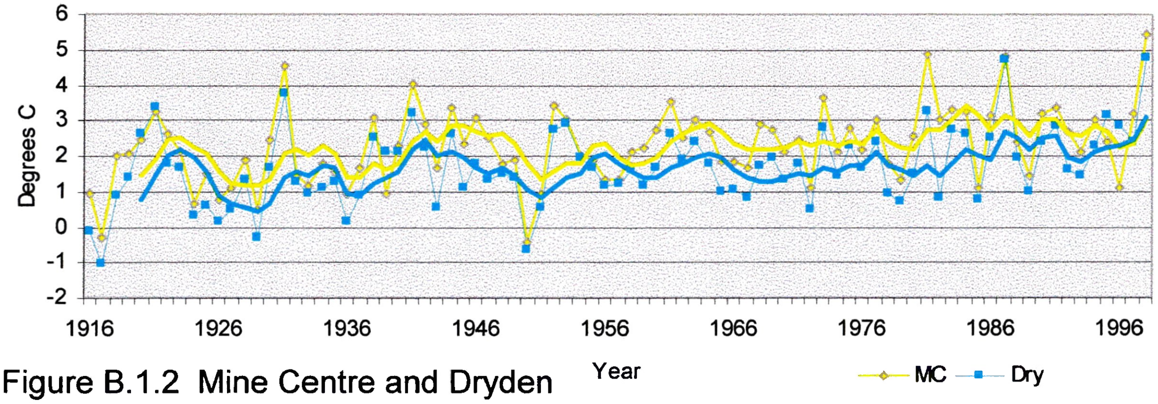

Figure B.1.2 Mine Centre and Dryden

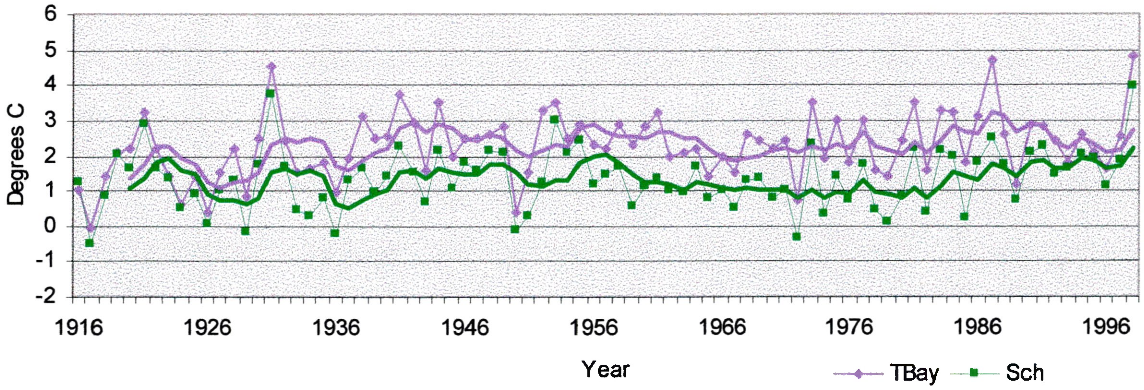

Figure B.1.3 Thunder Bay and Schreiber

B.2 Growing Season Mean Temperatures of Additional Stations: 1916-1998

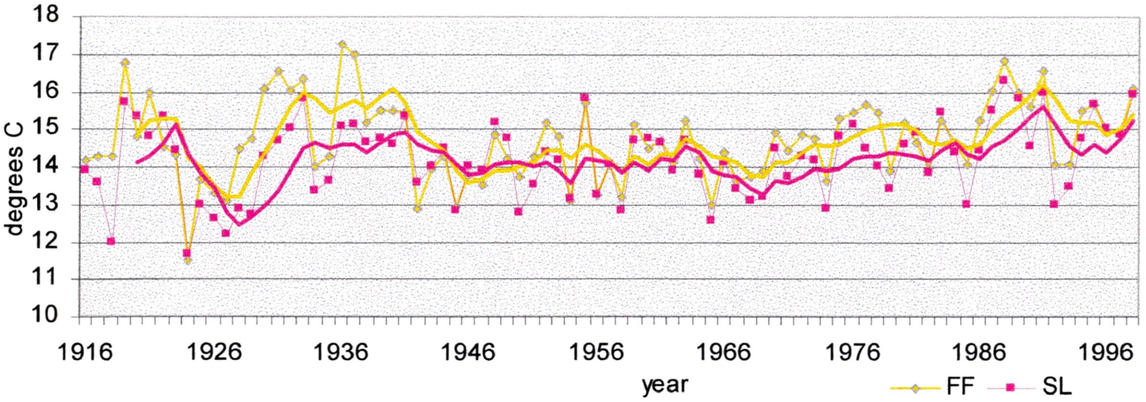

Figure B.2.1 Fort Frances and Sioux Lookout

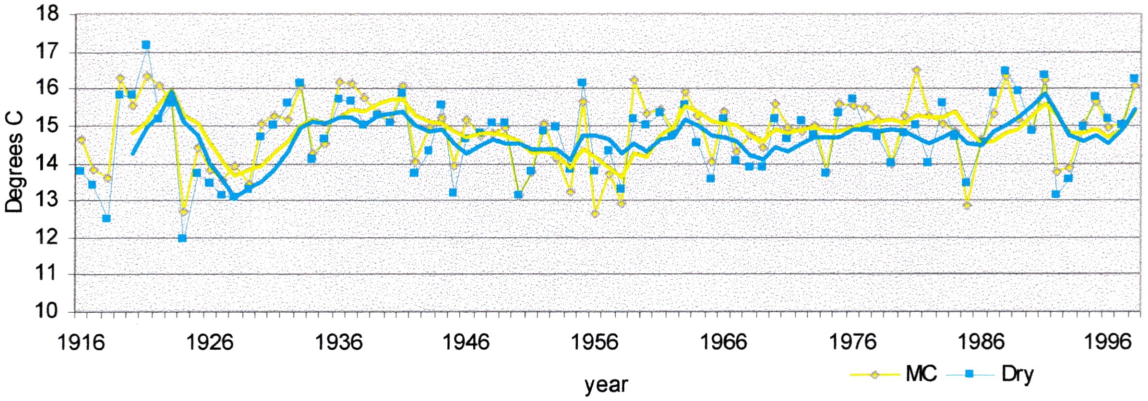

Figure B.2.2 Mine Centre and Dryden

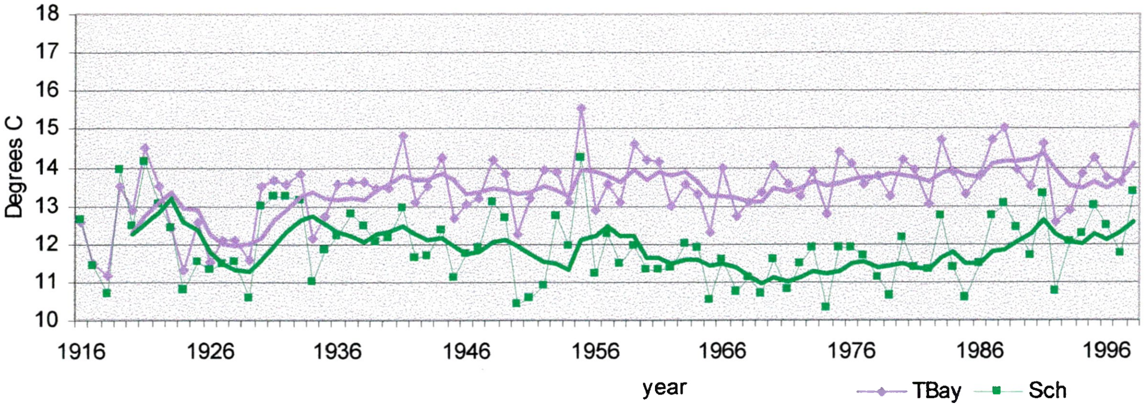

Figure B.2.3 Thunder Bay and Schreiber