Trends and Changes in Extreme Weather Events:

An assessment with focus on Alberta and Canadian Prairies

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SUMMARY

This report examines recent studies on trends and changes in extreme weather events in Canada and assesses these studies in the context of global warming. The assessment suggests that extreme weather events (hot spells, extreme precipitation events, thunderstorm/tornadoes and ice storms) do not show an increasing trend anywhere in Canada, or over the Canadian prairies at this point in time. On the Canadian prairies, extreme cold spells and winter blizzards are definitely on the decline during the past 40 years. In the higher latitudes of the northeast, from Baffin Bay to Labrador, extreme cold spells have increased in the last 50 years. The total precipitation has increased everywhere in Canada but this increase is mainly due to increase in low to moderate intensity events. The Canadian prairies have experienced drought conditions during the mid-1980s and more recently during 1998/99 and in 2001. These drought patterns appear to be primarily governed by the phase of the ENSO (El Nino-Southern Oscillation) cycle. Canada as a whole is not getting hotter, but less cold. Canada as a whole is getting a little wetter. On the Canadian prairies, low intensity precipitation events have increased in the last 50 years, and for Alberta, summer precipitation has increased by about 10 per cent. Thunderstorms and tornadoes are not increasing on the prairies at this point in time.

There is a considerable variability (and uncertainty) in many of the climate model projections of extreme weather occurrences, particularly in regard to the timing of the occurrences. Based on the careful evaluation of available studies, it appears that the likelihood of increased incidences of extreme weather events during the next ten to twenty years over any region of Canada is very small at this time.

The present database in Canada, with respect to several extreme weather events like thunderstorms (with or without tornadoes), severe windstorms, hail and lightening is not adequate for assessment of long term trends and changes. Many of these extreme weather events have been monitored and suitably archived only during the last 25 years or so. A few studies reported recently suggest that some of the extreme weather events like severe tornadoes and windstorms may have declined in frequency, following the dust bowl years of the 1920s and 1930s over the Canadian prairies. In higher latitudes, the Canadian database on extreme precipitation and stream flow is also inadequate for long-term trend analysis. There is a definite need to critically assess the available data and develop special techniques for assessing long-term trends in many of the extreme weather elements.

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1.0 INTRODUCTION

1.1 Global Warming and Extreme Weather: A Brief Overview

The Intergovernmental Panel on Climate change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Development program (UNEP) in 1988. The IPCC is now recognized as a prime source of scientific and technical information on climate change and its environmental and socioeconomic impacts. The first assessment report on climate change was completed by the IPCC in 1990. In its second assessment reports (three in all) published in 1996, the IPCC identified increasing concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the earth's atmosphere as a result of increasing human activity world-wide, and its possible link to the increasing mean surface temperature of the earth, or global warming as is now popularly known (IPCC, 1996). The IPCC reports (1996) also discussed in detail the possible adverse impact of global warming on present and future climate as the Earth's mean temperature continues to rise with increasing human activity in the future. Some of the adverse impacts that have been publicized following the 1996 IPCC reports are: increase in the number of tropical storms (hurricanes and typhoons) and their intensity, increasing frequency of extreme weather events like tornadoes, floods or droughts, higher maximum temperature, and more hot days over nearly all land areas. Since the publication of the IPCC 1996 reports, a large number of studies have been reported in recent literature; many of these studies deal with analysis of past climatic data. The thrust of most of these observational studies is to assess if the past climatic data and recent large-scale as well as regional-scale extreme weather events indicate any variability that can be associated with possible climate change that, in turn, can be linked to global warming. The global warming/extreme weather link is being increasingly mentioned at present in news media and in informal scientific commentaries.

The IPCC Third Assessment Report (TAR) has been recently published (IPCC, 2001). The report of the Working Group I covers the current understanding of the basic science of climate change and reinforces the earlier findings re: increasing concentrations of greenhouse gases and most of the observed warming of the last fifty years being attributed to human activities. The report further identifies certain changes that have occurred in important aspects of climate, with specific reference to *more frequent warm episodes of ENSO (El Nino/Southern Oscillation) phenomenon since mid-1970s and frequency and intensity of droughts increasing in parts of Asia and Africa.* The TAR also identifies certain extreme weather and climate events, and obtains estimates of confidence in observing these changes in the latter half of the 20^{th} century and in the 21^{st} century. These estimates of confidence for various weather and climate events are provided in Table 1.

Table 1 Estimates of confidence in observed and projected changes in extreme weather and climate events

Confidence In observed Changes (latter half of the 20th century)	*Changes in Phenomenon*	*Confidence in Project Changes (during the 21st century)*
Likely (66-90% chance)	**Higher maximum temperatures and more hot days over nearly all land areas**	Very Likely
Very Likely (90-99% chance)	**Higher minimum temperatures, fewer cold days and frost days over nearly all land areas**	Very Likely
Very Likely	**Reduced diurnal temperature range over most land areas**	Very Likely
Likely over many areas	**Increase of heat index over land areas** *	Very Likely over most areas
Likely over many Northern Hemisphere mid-to high latitude land areas	**More intense precipitation events**	Very Likely over many areas
Likely in a few areas	**Increased summer continental drying and associated risk of drought**	Likely over most mid-latitude continental interiors. (Lack of consistent projections in other areas)
Not observed in the few analyses available	**Increase in tropical cyclone peak wind intensities**	Likely over some areas
Insufficient data for assessment	**Increase in tropical cyclone mean and peak precipitation intensities**	Likely over some areas

*Heat Index: a combination of temperature and humidity that measures effects on human comfort

According to the table above, extreme weather events that are of concern to most Canadians would be the occurrence of higher maximum temperatures and associated 'hot spells' in summer, more intense precipitation events and associated flooding, especially in urban and coastal areas, and increased summer drying and associated risk of drought over the Canadian prairies, the most drought-prone region of Canada. The possibility of higher minimum temperatures and fewer cold and frost days would be considered a welcome event, and in most situations a beneficial event over most regions of Canada.

1.2 Global Warming and Extreme Weather: Media and Public Perception

Climate change and extreme weather have arguably become the most important environmental issues at present and are often referred to in news media and in environmental policy discussions. Worldwide incidences of severe weather events are more often reported in the news media at present than they were reported ten or twenty years ago. According to Unger (1999), television viewers in the USA are three times more likely to see a story on severe weather today than they were only 30 years ago. In Canada, news items regarding release of regional or national Government reports, as well as release of IPCC reports on climate change, have received front-page coverage and bold headlines in the past five years. Examples of some of the headlines: Climate Change in Canada: A bleak forecast (*The Toronto Star, November 24, 1997)*; Weather worse than it used to be: Scientists (*The Toronto Star, May 8, 1998);* Canadians warned to brace for more extreme weather (*National Post, November 15, 1999).* Besides news media, some of the Canadian Government documents have also projected a global weather/extreme weather link. For example, Figure 1.1 shows the first page of a Government of Canada poster on Climate Change, which has been released for public dissemination. According to this poster, warmer temperatures for Canada would mean more severe weather events like droughts, winter storms and tornadoes, flooding and erosion in coastal areas.

These headlines and warnings about more frequent occurrences of severe weather events in Canada have created a perception among most Canadians that with increasing mean surface temperature there will be increasing incidences of severe weather events like winter blizzards, droughts/floods, thunderstorms/tornadoes and heat waves. Recent studies using observational data over various regions of Canada do not appear to support the generally held perception that severe weather events have increased in Canada. The recent report (IPCC, 2001) categorically states that no systematic changes in the frequency of tornadoes, thunder days or hail events are evident in the limited areas analyzed. Thus, there is a mismatch between the popular perception about the impact of global warming on extreme weather and observation.

Khandekar (2000) has examined the question of change in intensity and/or frequency of extreme weather events on a global as well as on a continental scale, and has concluded that the results are conflicting and a definite link between global warming and extreme weather does not appear to emerge at this point. With increasing awareness of the issue of climate change and its future socioeconomic impact in Canada, there is a need to analyze all the studies reported so far and to assess if there are indeed any increasing/decreasing trends in extreme weather events.

1.3 Scope and Purpose of the Present Study

The present report is an assessment of studies on extreme weather events in Canada, and evaluates trends and changes in these events with a focus on the province of Alberta and the Canadian prairies. The study will examine recent studies published on trends and changes in basic weather elements like precipitation, temperature, etc., and will also make additional analysis of available data (if necessary) to assess these trends and changes. The report will also examine some of the well-known extreme weather phenomena in Canada like blizzards, droughts/floods, thunderstorms and tornadoes. Some of the recent extreme weather events (e.g. Ice Storm 1998, Red River Flood 1997, Saguenay Flood 1996) will also be examined in the context of global warming and climate change.

An assessment of changes in trends in these weather elements and weather phenomena is presented in the following chapters.

Figure 1.1 A Government of Canada poster on climate change and extreme weather

2.0 EXTREME WEATHER: PRECIPITATION AND TEMPERATURE

2.1 Introduction

Precipitation and temperature are the most basic and perhaps the most ubiquitous weather elements which have maximum impact on almost all strata of the Canadian society. Significant changes in day-to-day precipitation and temperature values are easily noticed by people living in mid-latitude countries. Canadians are generally interested in knowing about precipitation and temperature changes as these changes can affect their day-to-day lifestyles (e.g., driving patterns and road safety; clothing requirements, etc.). The most significant changes that would be of interest and concern to Canadians would be 1) increasing or decreasing frequency of 'hot spells' during the relatively short summer season and 'extreme cold spells' during the generally long winter season in Canada, and 2) increasing or decreasing incidences of 'heavy' precipitation during winter and summer seasons in particular. Increase in minimum temperature in winter or decrease in maximum temperature in summer is generally greeted as a welcome change and can also be considered as economically beneficial for most regions of Canada (e.g. less house-heating costs in winter or less air-conditioning costs in summer).

There have been several studies reported in recent literature on Canadian precipitation and temperature trends and changes. Similar studies on precipitation and temperature changes over the conterminous USA have also been reported in recent literature. These studies have provided a closer look at these basic weather elements over USA and Canada, and have identified some interesting patterns of change in precipitation and temperature structure over the last one hundred years. These studies are reviewed and several findings are assessed and presented below:

2.2 Precipitation

Precipitation is perhaps the most difficult climatic variable in the context of the present global warming debate. Precipitation can vary irregularly with space and time and hence needs to be carefully analyzed before any conclusions on trends and changes can be made. Secondly, precipitation data coverage over a given area and its high inter-annual variability can make trend analysis a difficult problem. Despite these problems, several studies have been reported and some of these are summarized below:

An often-quoted study for documenting the impact of global warming on changing precipitation pattern is the analysis of Karl and Knight (1998) showing an increasing trend in the percentage contribution of the upper 10^{th} percentile of daily precipitation to the total annual precipitation, area-averaged across the conterminous USA (see Figure 2.1a). This figure is based on all available rain gauge data over the conterminous USA for the period 1910-1990. For comparison linear trends in mean seasonal precipitation, area-weighted over the contiguous USA, reported in another recent study (Groisman et al., 1999) are also shown in Figure 2.1b. Karl and Knight (1998) study is based primarily on the data from about 200 US Historical Climate Network stations, while Groisman et al. use US Climate Division database which routinely assimilates precipitation data from approximately six to eight thousand sites over the contiguous USA. Figure 2.1a clearly shows an increasing trend in "heavy daily precipitation" events across USA

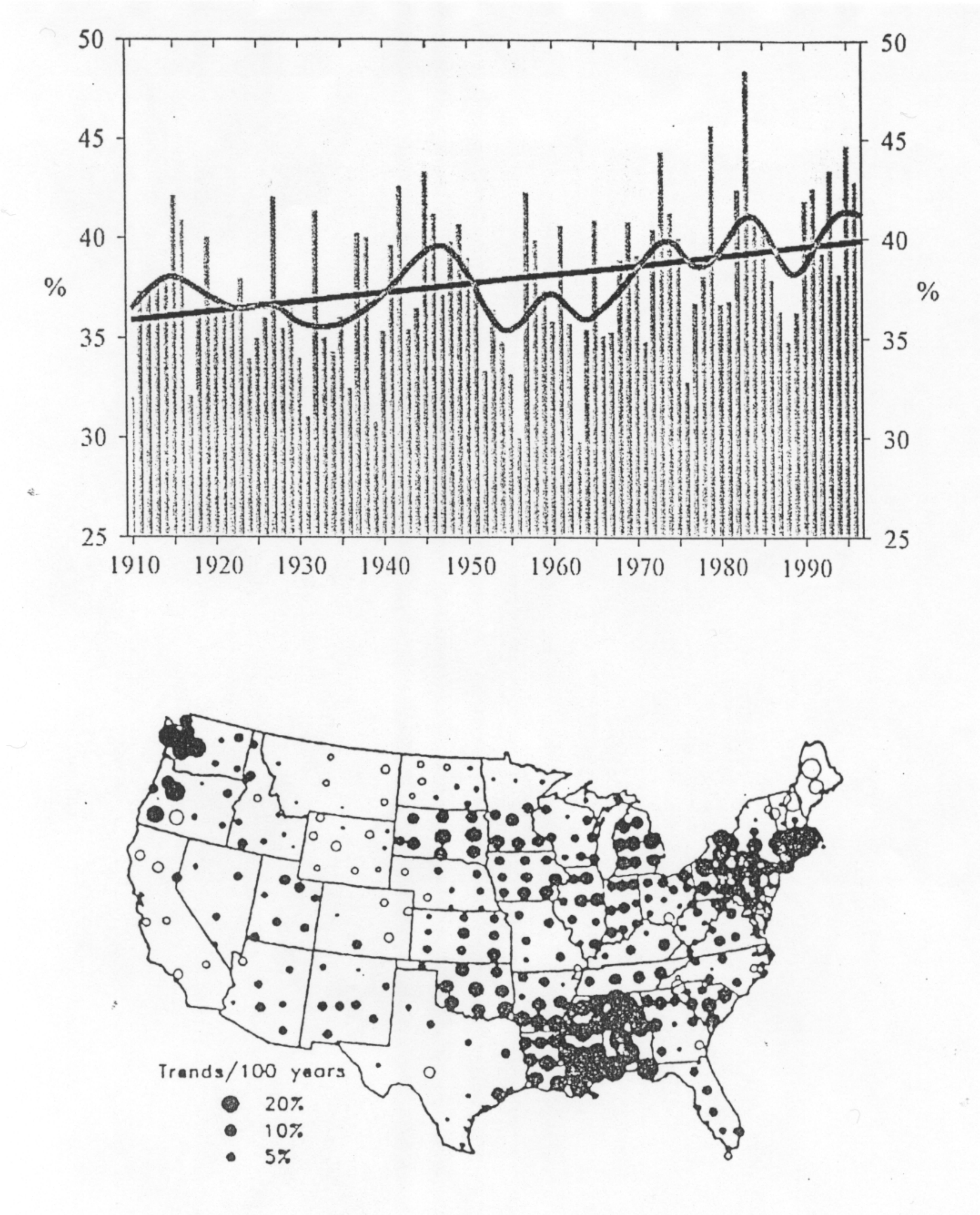


Figure 2.1 Top (a) – Increasing Trend in Percentage Contribution of Upper 10th Percentile of Daily Precipitation Events to Total Annual Precipitation, Area-Averaged, Across USA (from Karl and Knight, 1998). Bottom (b) – Precipitation Trends Across USA (from Groisman et al., 1999)

as a whole, while Figure 2.1b shows increasing as well as decreasing precipitation trends across various regions of USA. The southeastern USA, especially the Gulf States (Alabama, Mississippi and Louisiana) show strong increasing trends, while a large area of southwestern USA and the American prairies and states just south of the Canadian border, show a decreasing trend in mean seasonal precipitation. These two figures suggests that the increasing trend in heavy precipitation events across USA as a whole, may be primarily coming from southeastern and northeastern US states where linear trends in annual precipitation have increased by 20 percent or more at some locations. The increasing precipitation trend in the southeastern US states can be accounted in part as hurricane-induced precipitation with more land falling of hurricanes in the latter half of the 20th century than in the first half (O'Brien, et al., 1996). Also the impact of a gradual southeastward movement of the primary storm tracks over North America (Hayden, 1999) and changing thunderstorm activity (Changnon, 2001) in the southeastern states may be a contributing factor for increasing precipitation trends and consequently for increasing contribution from upper ten percentile of daily precipitation events for the entire conterminous USA. More discussion on changes in storm tracks and in thunderstorm activity will be presented in later chapters.

For Canada, several studies on precipitation patterns have been reported in the last five years; notable among these are three studies prepared and reported by researchers at Environment Canada. In a comprehensive paper by Mekis and Hogg (1999), the fraction of precipitation falling in heavy (90th percentile) events is shown to have decreased by over 4% since 1910, over the southern regions of Canada (south of 55N). At more northern stations (north of 55N), this fraction has increased by 5%, but this increasing trend is based on a shorter data set, 1945-1995. Figure 2.2a shows the decreasing and increasing trends in heavy precipitation for northern and southern regions of Canada, while Figure 2.2b shows the spatial distribution of this trend over the entire country. In a follow-up study (Zhang, Hogg and Mekis, 2001) spatial and temporal characteristics of heavy precipitation over Canada (excluding the high arctic north of 70N) are examined and several precipitation characteristics are analyzed in details. The study defines heavy rainfall and snowfall events for each station and season separately by identifying a threshold value that is exceeded by an average of three events per year. Annual and seasonal time series of heavy events are obtained by counting the number of exceedances per year. The study uses 51 evenly distributed stations each with more than 50 years of data with majority of stations having data from 1900 to 1998. Several interesting conclusions are drawn in this important study of heavy precipitation in Canada, including the following:

- The decadal variability is the dominant feature in both the frequency and the intensity of extreme precipitation events over Canada.
- For the country as a whole, there appears to be no identifiable trends in extreme precipitation during the last century.
- The observed increase in precipitation totals in the twentieth century was mainly due to the number of small to moderate events of precipitation.

A couple of interesting diagrams from the Zhang et al. (2001) study are presented here. In Figure 2.3 (top) are shown 11-year moving averages of annual time series of average number of heavy events per location over Canada, while Figure 2.3 (Bottom) shows trends in nationally averaged normalized percentiles of annual daily precipitation. Figure 2.4 shows trends in

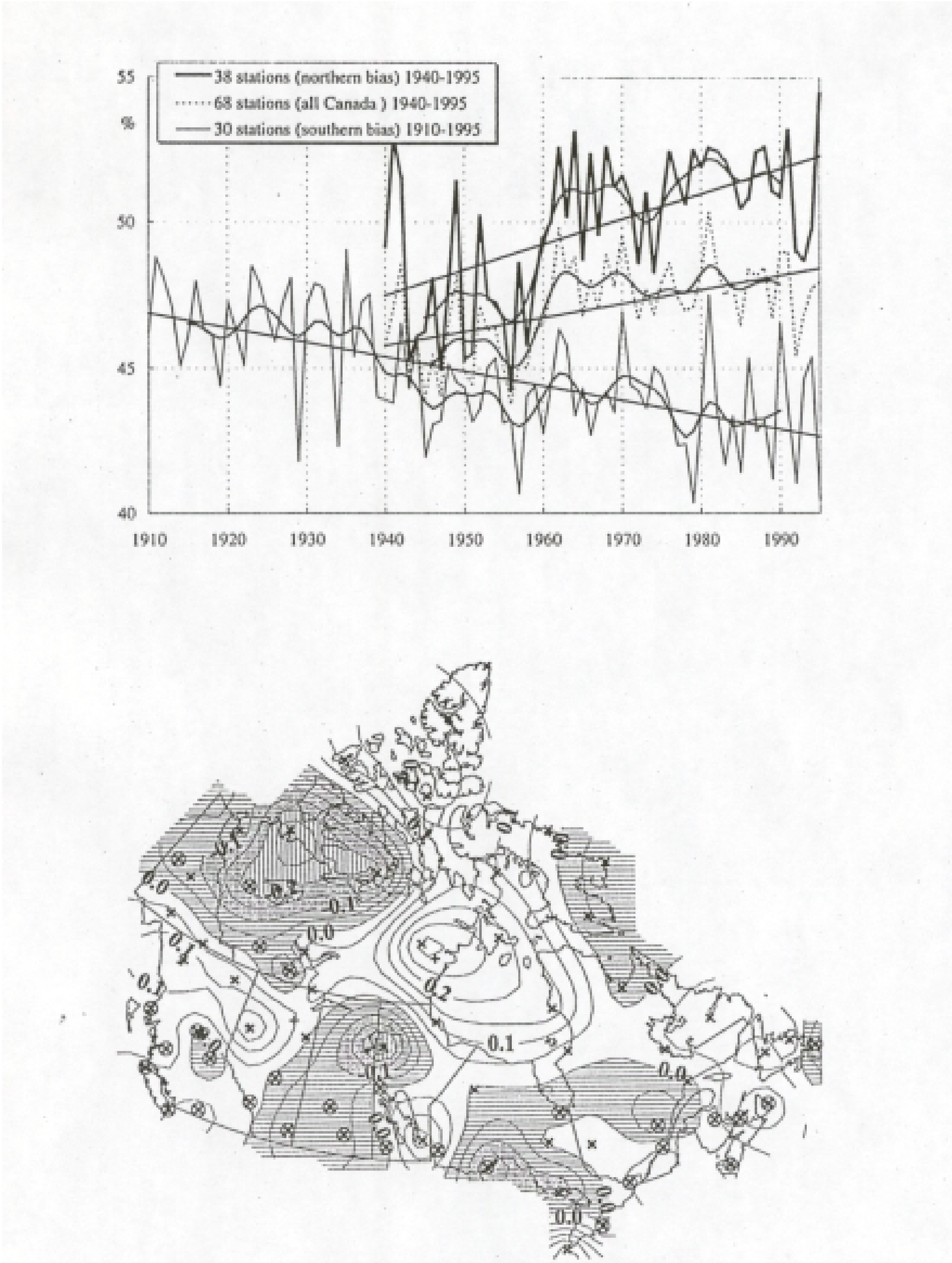


Figure 2.2 Top – Inter-annual variation of fraction of annual precipitation falling in "heavy" events for Canada. Bottom – Spatial trend in fraction of annual precipitation falling in "heavy" events (>90th percentile). Negative values are hatched (from Mekis and Hogg, 1999)

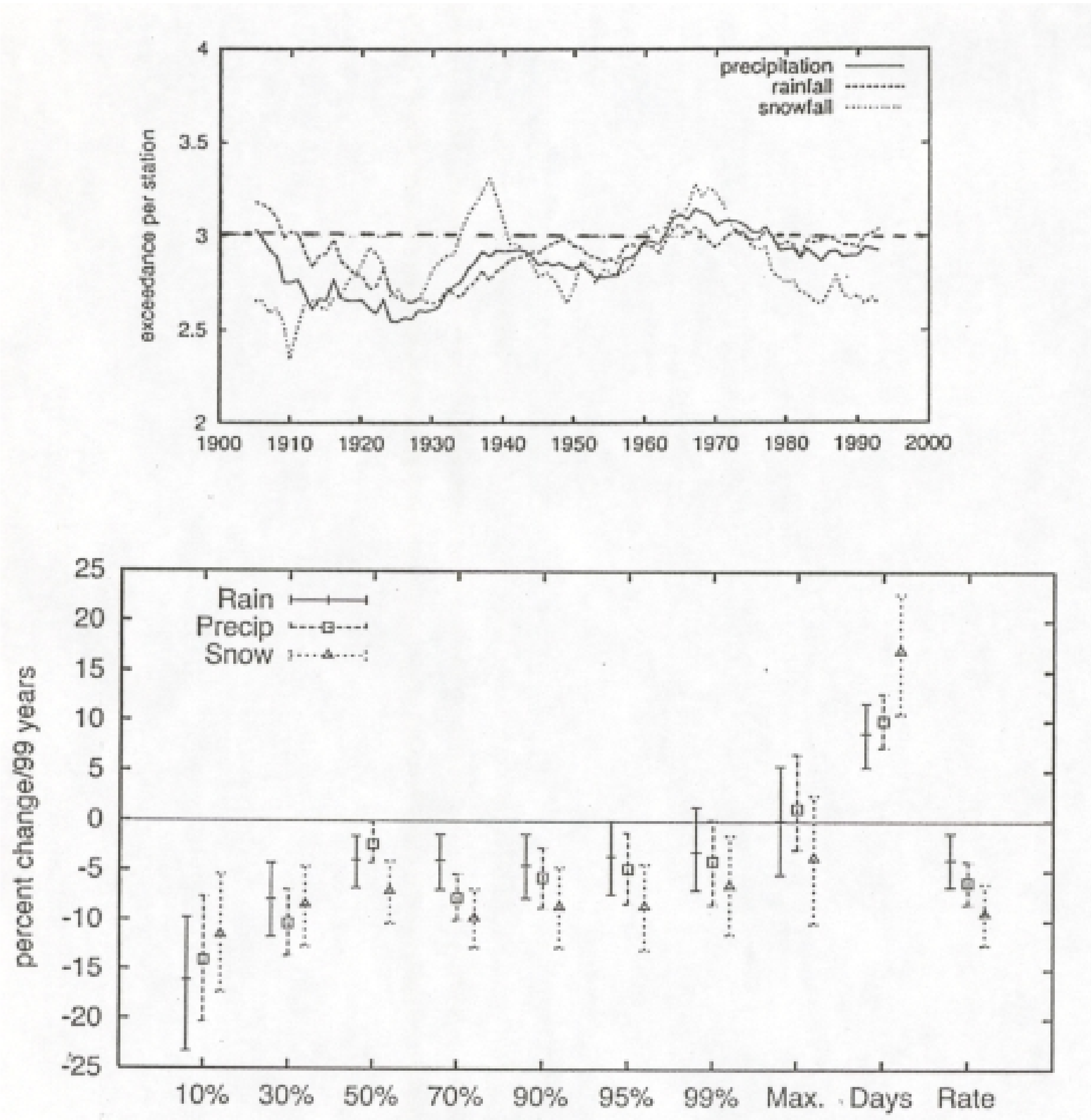


Figure 2.3 Top – Eleven-year moving averages of annual time series of average number of heavy events per location over Canada south of 70°N. Bottom – Trends in nationally averaged normalized percentiles of annual daily precipitation (units: percentage change per 99 years). The 95% confidence intervals are provided. Trends in annual maximum values of precipitation, number of days with precipitation and average precipitation rates are also shown. Trend significant at 5% level if its 90% confidence interval does not cross zero line (Zhang et al., 2001)

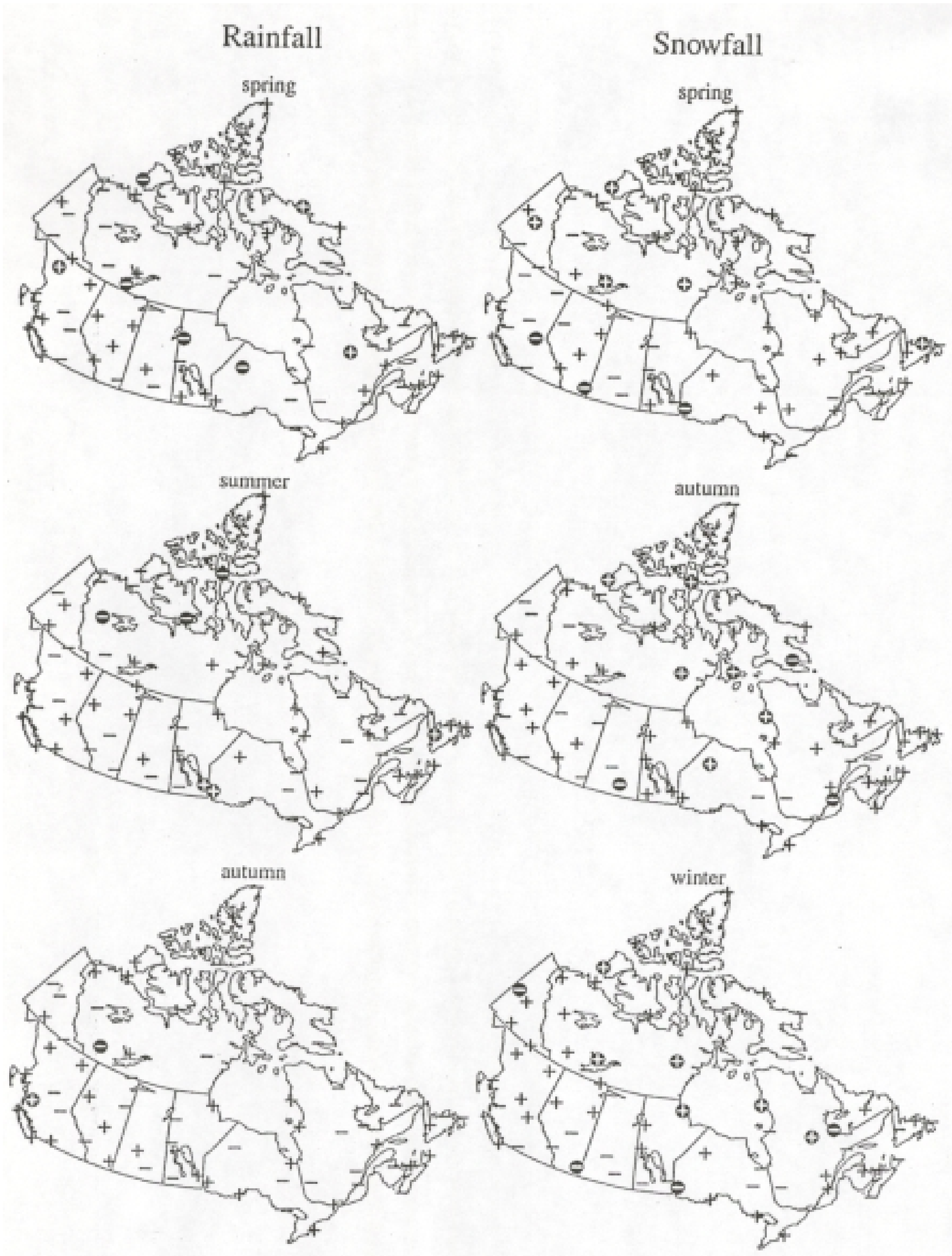


Figure 2.4 Trends in fraction of rain (left) and snow (right) falling in heavy events for the period 1950-1998 (+/- signs indicate positive/negative trends. Significant trends marked with filled circles (Zhang et al., 2001)

different regions of Canada in the fraction of rain or snow falling in heavy events for the period 1950-1998. Several important observations can be made from these figures relating Canadian precipitation variability and characteristics: 1) average number of heavy rainfall or snowfall events do not show any significant long term trends; there are however, important decadal changes, rainfall index was low during the 1915-1950 period compared to other periods; since about 1970s, the total precipitation index (rainfall and snowfall) shows a steady decline; 2) significant increase in the number of days with precipitation (both rain and snow) associated with significant decrease in the in the average rate of precipitation over the country, and 3) trends in heavy rainfall or snowfall events do not show any consistent positive or negative trend in any region; in northern regions (Northwest Territories, for example), winter and spring precipitation appears to be on the increase.

Focusing on Alberta and the prairie region, two studies reported recently are of relevance. A study by Akinremi et al. (1999) finds an increase in the number of precipitation events on the Canadian prairies, but this increase is mainly due to increase in the number of low-intensity events (precipitation amounts in the 0.5 to 5.0 mm range). The study (by Akinremi et al.) further concludes that precipitation events are not getting more intense on the Canadian prairies**,** a conclusion which is reinforced in the Zhang et al. 2001 study for the entire country. Akinremi et al., further document a significant increase in the amount of precipitation over the prairies during the last 75 years (1920-1995) and this increase is found to be mainly due to increase in the rainfall amounts. Another study by Shen (1999) for the province of Alberta finds the total precipitation showing an upward trend from the 1920s to present with the increase to be about 38 mm or about 9 percent of the normal precipitation. According to Shen (1999), July precipitation for Alberta shows an increase of about ten percent. July rainfall is considered to be an important parameter for the growing season (Garnett, Khandekar and Babb, 1998).

In summary, precipitation amounts have generally increased over most of the country, however this increase is primarily due to increase in the number of low intensity (small to moderate) events. There is no identifiable trend in extreme precipitation events anywhere in Canada at this point in time.

2.2.1 Droughts and Floods

Droughts can have a significant impact on the Canadian prairie region which is the most drought-prone region of Canada (Maybank et al., 1995) and is also the most important grain growing region in Canada. East of the prairie region in central and eastern Canadian provinces, drought is a rare occurrence and is not considered as a major threat. The mid-west and northwestern inland regions of North America are identified as the most drought-prone regions where some of the worst droughts have occurred in the thirteenth and sixteenth century (Woodhouse and Overpeck, 1998). During the last one hundred years, the most severe droughts in the prairies were during the 1920s and the 1930s which are well known as the “dust-bowl” years of North America. The recurrent droughts of the dust-bowl years led to the creation of a Canadian Government Agency called PFRA- Prairie Farm Rehabilitation Agency in 1937 (Nemenishan, 1998; Sauchyn and Skinner, 2001). The main aim of creating PFRA was to help the prairie farmers with agricultural and weather related expertise. The recurring droughts of the dust bowl years were probably caused by unusual changes in atmospheric circulation patterns during the rapid warming of the Earth's mean surface temperature in the 1920s (Fu et al., 1999). According to Rasmusson (1988), we have yet to understand why the climate of North America was so anomalous during that particular period from the 1920s through the 1930s.

A commonly used drought index is the Palmer Drought Severity Index (PDSI), which is calculated using precipitation, air temperature and soil moisture at a location. For the prairies, PDSI values have been calculated at a number of locations and Figure 2.5 shows the time series of normalized PDSI values for three summer months (June-July-August) at selected locations in southeastern Alberta and southwestern Saskatchewan. High negative values (less than -3.0) indicate severe drought conditions, while high positive values (greater than +3.0) indicate wet conditions. Figure 2.5 reveals several moderate to severe drought years during the decade 1930-1940; this figure also reveals some of the recent drought years, namely 1984/85, 1988, 1998, 2000/01, with 1988 being the worst drought year in the recent 15-year period over the Canadian prairies. Although the drought driving forces are not completely known at this point in time, recent studies (Garnett and Khandekar, 1992; Nemenishan, 1998) have now identified the phase of the ENSO (El Nino-Southern Oscillation) cycle as the important driving mechanism. The 1988 drought was most certainly associated with the cold (La Nina) phase of the ENSO which followed immediately after the 1987 El Nino (warm phase). The recent drought of summer 2001 which may have caused an economic shortfall of about five billion dollars is now attributed (see Garnett, 2002) to the lingering cold (La Nina) phase which has continued to dominate the SST (Sea Surface Temperature) patterns over the equatorial belt of the Indo-Pacific region since mid-1998. In Figure 2.6 are shown seasonal march of areally-averaged composite standardized precipitation anomalies over southern Canada for El Nino/La Nina events. This composite shows that following an onset of El Nino (La Nina), precipitation decreases (increases) significantly during the winter months over the prairies and has a small secondary increase (decrease) later during the summer months. With such a precipitation pattern, it is now recognized that El Nino (La Nina) events are generally related to the increase (decrease) of precipitation over the Canadian prairies. According to the most recent assessment of the SST pattern (Climate Diagnostics Bulletin, 2002), the ENSO cycle is now entering into an El Nino phase which may provide more precipitation over the prairies during the summer months of 2002 (Garnett, Khandekar and Babb, 1998). Based on a preliminary analysis (as of November 2002), the rainfall over the prairies was significantly below normal during June and July, the rainfall was close to normal during September 2002. However, this late rainfall was of little value for crops.

In summary, the drought is an extreme weather event and can inflict a devastating impact on the socio-economic conditions of the Canadian prairies which have experienced some of the worst recurring droughts during the 1920s and the 1930s. Based on the current understanding of the drought driving forces and the atmospheric and oceanic circulation patterns of the last few years, it is concluded that the drought patterns of the last 25 years were governed primarily by the ENSO phase and that future drought events over the Canadian prairies will be governed, primarily by a combination of ENSO and PNA (Pacific North American) atmospheric flow patterns. The linkage of the present global warming and future drought occurrence on the prairies is not established at this point in time (Khandekar, 2001).

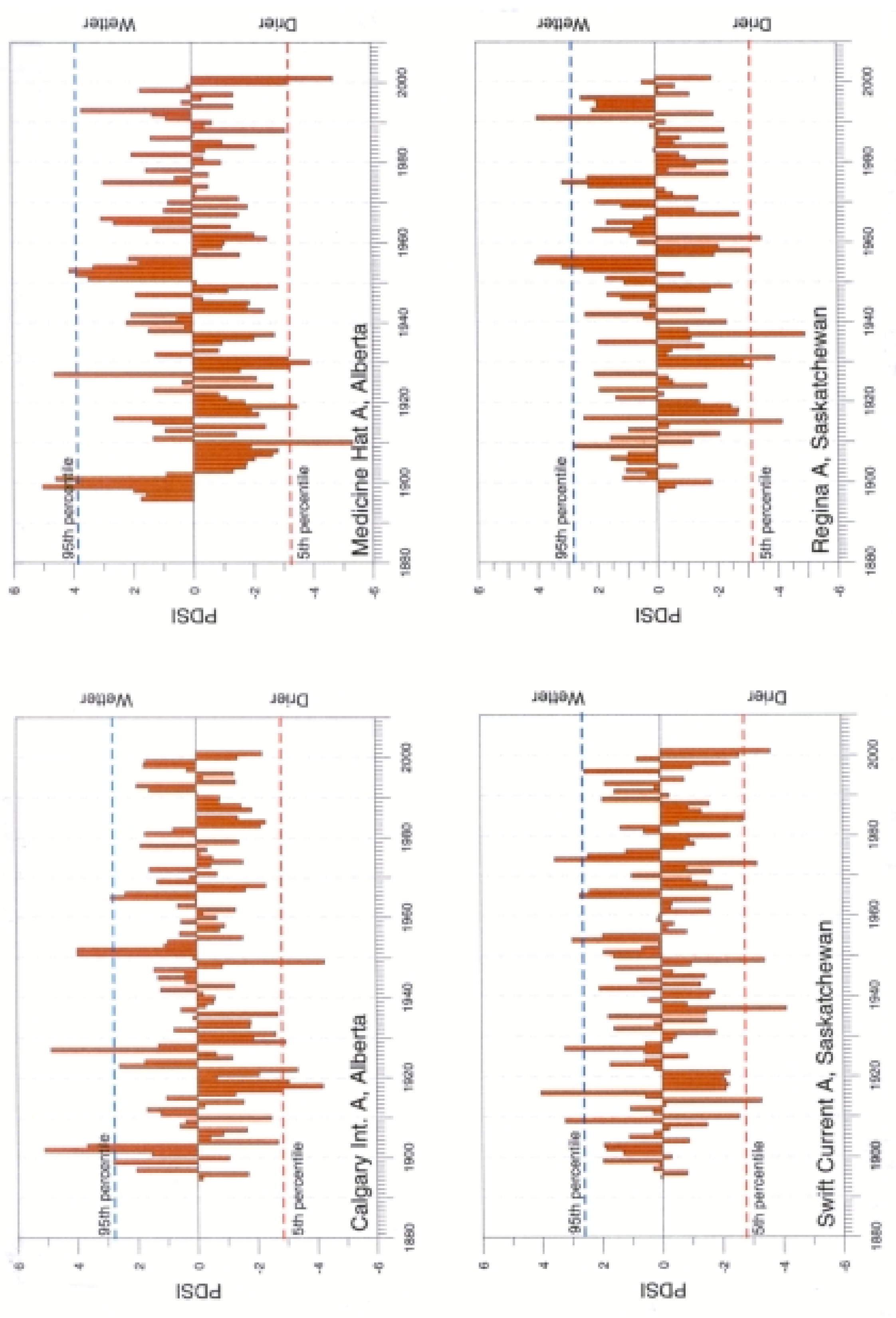


Figure 2.5 Values of PDSI (Palmer Drought Severity Index) at selected locations on the prairies (source – Walter Skinner, Environment Canada)

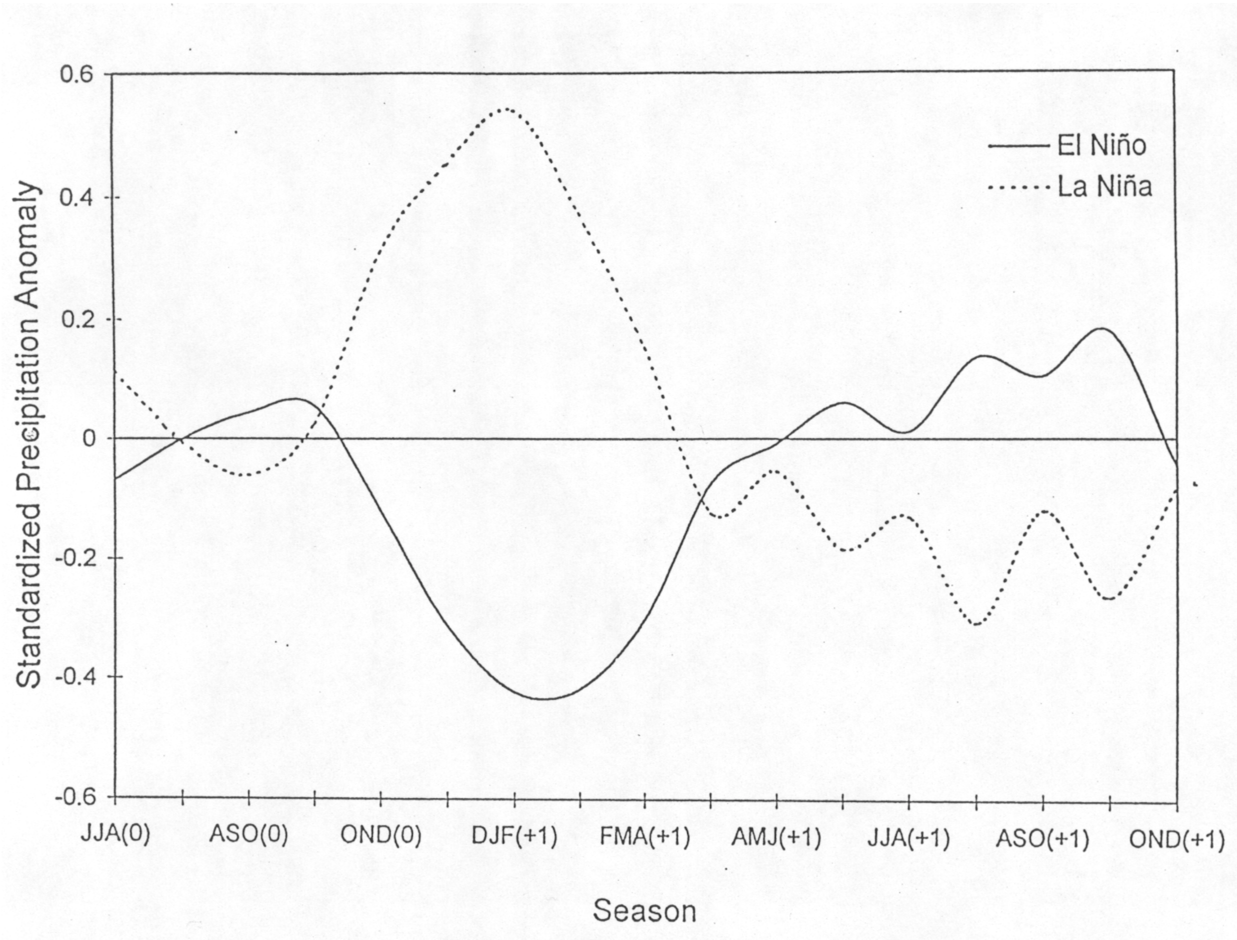


Figure 2.6 Seasonal march of the areally-averaged composite standardized precipitation anomalies over southern Canada from June-July-August (JJA) of the El Nino/La Nina onset year JJA(0) to OND(1) of the following year with respect to the onset. Data used 1900-1990 (Shabbar, Bonsal, Khandekar, 1997)

Floods in Canada are typically associated with intense rain events, ice jams and snow melt. When viewed in a global context, floods in Canada tend to be less dramatic and less hazardous than in other parts of the world (e.g. Monsoon-induced floods in southeast Asia; hurricane or typhoon induced floods in USA or in the western Pacific). In Canada, floods associated with intense rain events are typically local in nature and occur frequently in coastal regions of British Columbia during fall and winter season or in southern Ontario and Quebec during summer thunder showers. Floods associated with rivers and river ice jams occur during spring and are common in eastern Canada (New Brunswick and Quebec) and in northern Ontario. Floods associated with synoptic to sub-synoptic meteorological events are rather rare in Canada. The most devastating flood in Canada was associated with Hurricane Hazel (October 1954) which traveled as an upper-air low pressure trough over southern Ontario and produced extensive flooding in and around Toronto resulting in the death of 79 people and damage exceeding 100 million dollars. In the last six years, the Saguenay region flood in July 1996 and the Manitoba Red river flood in April 1997 are well publicized and extensively documented. These two flood events will be discussed in more details in a later Chapter.

A *Rainfall Frequency Atlas for Canada* prepared by Environment Canada (Hogg and Carr, 1985) shows that all provinces and the northern regions of Yukon and the NWT have recorded one or more intense rainfall events (rainfall exceeding 25.4 mm or 1 inch). The maximum 1-hr rainfall values across Canada varied from 28 mm to 96 mm while the maximum 1-day rainfall values varied from 91 mm to 489 mm with Yukon and NWT recording the lowest maximum values while British Columbia recording the highest value (489 mm in one day). On the east coast, some of the intense rainfall events are associated with the passage of a hurricane moving typically along a southwest-northeast trajectory. Some recent examples of heavy rainfall events are during the passage of hurricane Felix (August 1995) and hurricane or tropical storm Gabrielle (September 2001). On the west coast, Pacific storms (often known as Pine-Apple express since the storm develops east of Hawaii Islands) can bring torrential rains and localized flooding in Vancouver-Victoria area during the fall and early winter season.

Focusing on the prairies and the province of Alberta, the maximum rainfall events (1-hr as well as 1-day events) for Alberta suggest that the province can have intense rainfall on 1-hr as well as on 1-day time scale. Among the intense rainfall events over the prairies are the ‘largest’ summer storm (Environment Canada “Storm Rainfall in Canada” Document) in June 1973 when over 80 mm rain fell over more than 300,000 km^2 of Alberta in one day and a more recent rainfall event in Saskatchewan during the summer of 2000 when over 375 mm rain fell in just eight hours! Among the less intense rain events are a number of heavy downpours in Winnipeg during July and August of 1993, the year of the US mid-west summer floods, which also extended into parts of the Canadian prairies (Lawford et al., 1995, and Kunkel et al., 1994). For Alberta, most of the heavy rainfall events are generally associated with convective activity from late spring through the summer season. Most of these heavy rainfall events are short-lived and are not a major threat in terms of flooding. A closer look at Figure 2.4 shows increasing trend for heavy summer precipitation for northern Alberta, while for central and southern Alberta the trend for heavy rainfall events is negative.

In summary, major flooding on a scale like in a Monsoonal climate zone is almost non existent in Canada. Localized flooding associated with heavy rainfall activity is common on east as well as on west coast and in regions with frequent summer convective activity (e.g., Alberta, southern Ontario and western Quebec). However, there does not appear to be any increasing or decreasing trend in localized or regional flooding anywhere in Canada nor on the prairies, at this point in time.

2.3 Temperature

Temperature is a robust weather element and unlike rainfall, has much smaller spatial variability at a given location; further, mean temperature at a given location has much smaller inter-annual variability than rainfall and as such trend analysis of mean temperature at a given location can be assessed more accurately for detecting climate change. For a northern country like Canada with large mean temperature changes between coastal and inland locations especially during the long winter season, a knowledge of temperature trend and extreme variations is important.

The present global warming debate is built upon the fact that the Earth's mean surface temperature has been steadily rising as documented in a number of studies by Jones and his coworkers at the Climate Research Group in East Anglia, UK (Jones, 1994; Jones et al., 1999). Besides these, a large number of other studies have also been reported in recent literature on surface temperature trends and projections of future climate and temperature changes. The most recent IPCC report (IPCC, 2001) presents the mean surface temperature variation over the last 140 years as shown here in Figure 2.7a; in Figure 2.7b is shown the mean surface temperature variation for the Northern Hemisphere over the last 1000 years. These two figures suggest a rather steep increase in the mean surface temperature variation in the recent 25-year period, about 0.3C for the Earth as a whole and about 0.5C for the Northern hemisphere.

The mean surface temperature trends over various regions of Canada are reported in a recent comprehensive study by Zhang et al. (2000) and Figure 2.8 shows these temperature trends for maximum and minimum temperature based on data for the period 1950-1998. Several interesting features of the mean surface temperature structure over Canada are summarized by Zhang et al. For the purpose of present discussion it is sufficient to note that there are two distinct temperature patterns, a warmer trend for mean temperature over a large area of western Canada extending from the US border (~49°N) to western Arctic (~70°N) and a cooler trend over a sizable area of eastern Canada extending from Northern Ontario to Newfoundland in the south to Baffin bay in the north (~70°N). Further, the mean maximum temperature has warmed by more than 3°C in some regions of western Canada while the mean maximum has cooled by more than 2°C in some northeastern regions of Canada. On an annual basis, both the maximum and minimum temperature show increasing trend in the west and decreasing trend in the east.

In the context of the present study, it is instructive to consider the impact of the present warming trend on temperature extremes over various regions of Canada with particular reference to the prairie provinces. Specifically it is of interest to find out if the winter season over the prairies is getting colder or the summer season is getting hotter. Part of the answer is provided in Figure 2.8. To get a better perspective on the extreme temperature structure over Canada and over the prairie provinces, it is instructive to analyze some of the results from a more recent

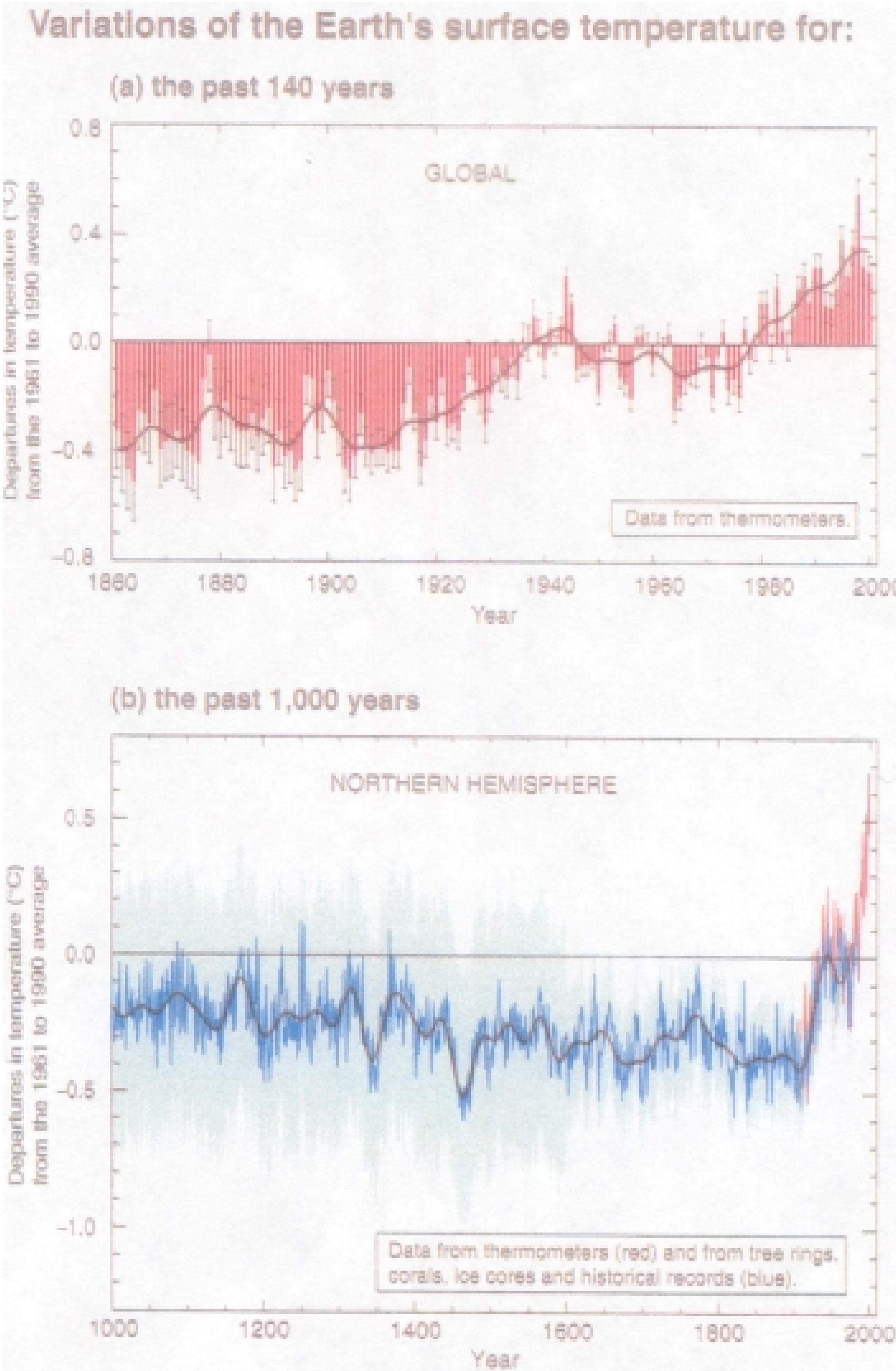


Figure 2.7 Variation of the Earth's surface temperature (a) Global (1860-2000) and (b) Northern Hemisphere (1000-2000) (IPPC, 2001)

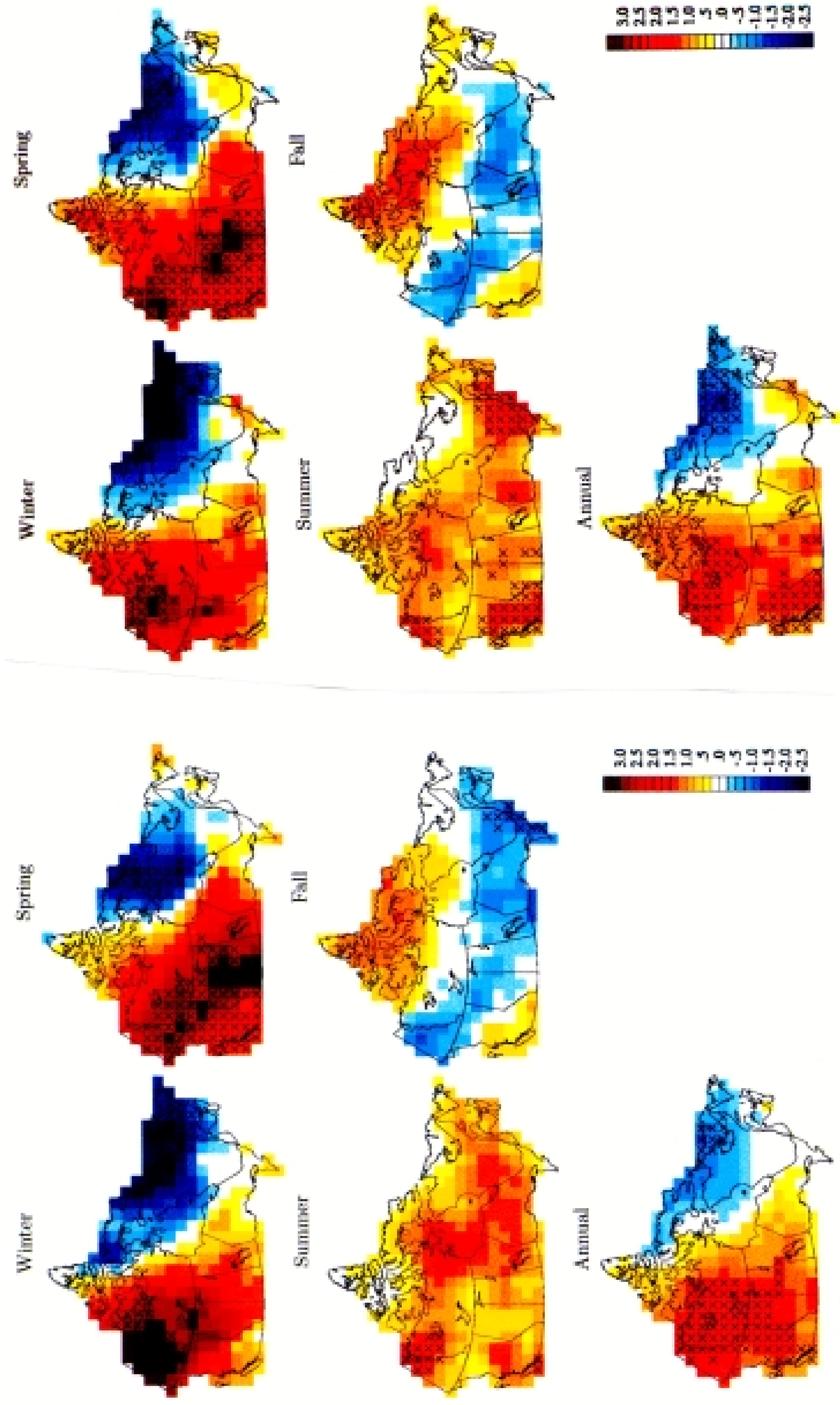


Figure 2.8 Left – Trends in daily maximum temperature from 1950-1998, over Canada. Unit: °C per 49-yr period. Grid squares with significant trends (at 5% level) are marked by crosses. Right – Trends in daily minimum temperature for various seasons (Zhang et al., 2000)

study by Bonsal et al. (2001). In Figure 2.9 (top) are shown average standardized anomalies over southern Canada (below 60°N) for the 5^{th} percentile of daily minimum temperature during winter and the 95^{th} percentile of daily maximum temperature during summer. In the bottom part of the same figure, are shown percentage occurrence (by decade) of the five lowest annual minimum and the five highest annual maximum daily temperatures recorded at 82 stations over southern Canada for the period 1910-1998. Several interesting features of the temperature structure have been summarized by Bonsal et al. For the purpose of present discussion, two important aspects of the temperature structure need to be emphasized: 1) the minimum temperature has been steadily rising throughout the 20^{th} century (although there is evidence of inter-annual and inter-decadal variability), and 2) the maximum temperature while showing inter-decadal variability in the first half of the 20^{th} century, shows no evidence of a long-term trend in the latter half of the century. Of particular interest is the fact that a steady rise in the minimum temperature and almost no rise in the maximum temperature has helped reduce the diurnal temperature range (maximum-minimum) and thus helped reduce the mean temperature variability in recent years. Also of interest is the fact that some of the highest maximum temperature values were recorded in the 1930s and in early 1940s. These two aspects of the temperature structure are revealed in details in Figure 2.10, which shows trends in daily minimum and maximum temperature over southwestern and southeastern Canada from 1910 to 1998. The figure shows how the minimum temperature has increased in almost all months in the southwest (southern prairies and British Columbia) as well as in the southeast (eastern Quebec, New Brunswick and Nova Scotia) regions of the country with a couple of notable exceptions: for the prairies, the minimum temperature shows significant cooling during November, while for the eastern provinces, the minimum temperature has decreased over a short duration in January. The maximum temperature on the other hand, has increased over the prairies during the winter and spring, but has dramatically decreased during the peak of the summer season while showing some increase again in late summer. In the east, the maximum temperature shows increasing and decreasing pattern without suggesting any consistent trend in any one season in particular. As summarized by the authors (Bonsal et al.), "Canada is not getting hotter, but 'less cold'; in particular, minimum temperature has increased significantly over western Canada while maximum temperature has decreased a little during the peak summer months." This translates into warmer winters and slightly cooler summers in general for most regions of Canada. This aspect of climate change is discussed in additional details in the following section.

2.3.1 Extreme Hot and Cold Spells

A possible impact of climate change on extremes of temperature (hot or cold) in a particular season is of concern to most Canadians. According to the IPCC 2001 projections of climate change, *higher maximum temperature and more hot days, also increase of heat index over nearly all land areas is likely to be observed in the latter half of the* 20^{th} *century* (see Table 1). It is instructive to examine the historical temperature data of past selected periods and compare these datasets against the recent ten years (1990-2000) which have been adjudged to be among the warmest in the last one hundred and fifty years (IPCC, 2001). The study of Bonsal et al. (2001) suggests that some of the hottest years over the Canadian prairies were possibly during the 1920s and 1930s, which are often known as the dust bowl years of the North American prairies. A close examination of the temperature dataset from 1910 through 1940 suggests that many individual years (eg. 1914, 1917, 1920, 1926, 1936, 1937) show higher mean maximum

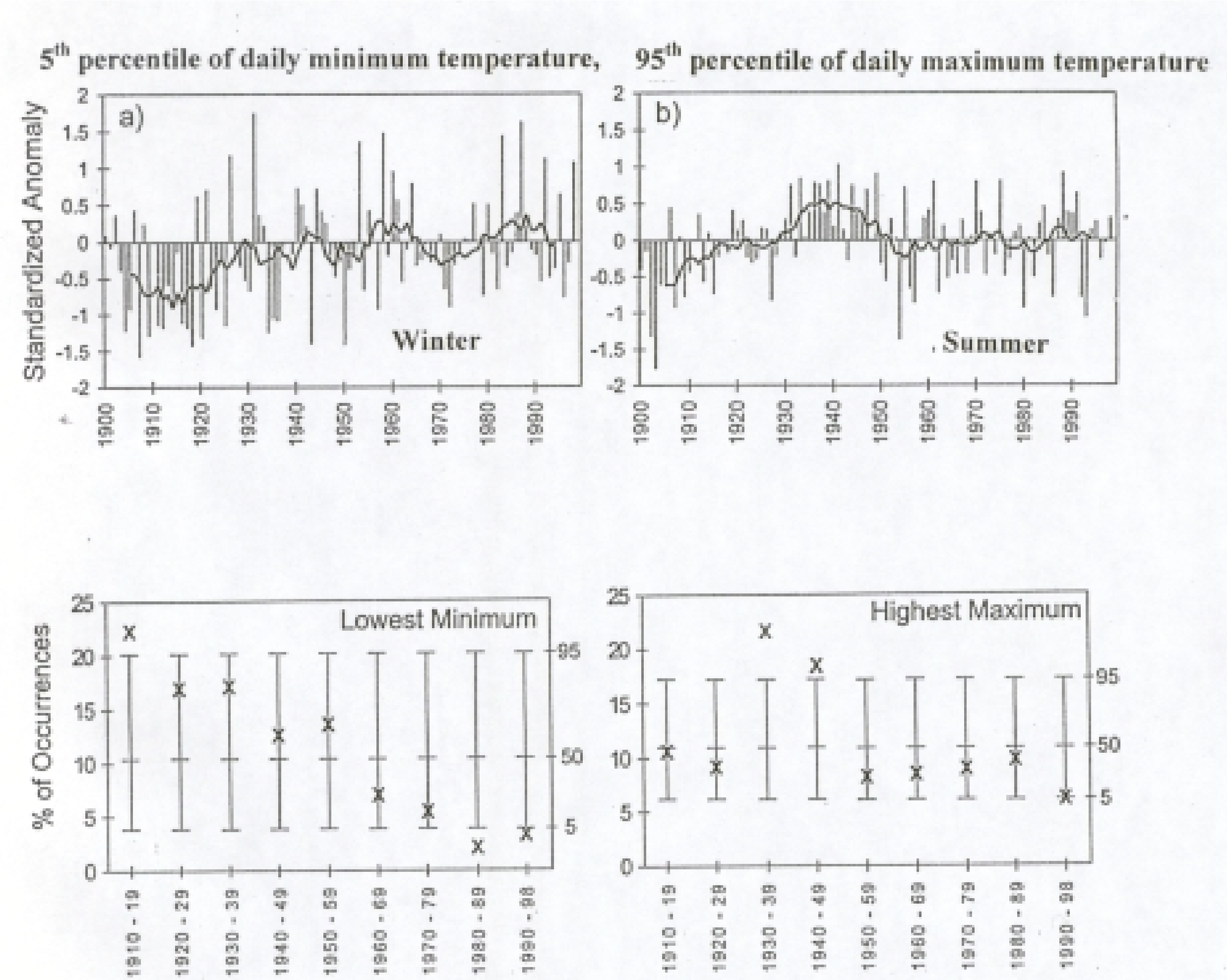


Figure 2.9 Top – Average standardized anomalies over southern Canada (south of 60°N) for the 5th percentile of daily minimum and for the 95th percentile of daily maximum temperature. Continuous solid lines represent the 10-year running means. Bottom – Percentage occurrence (by decade) of the five lowest annual minimum and the five highest annual maximum daily temperature recorded at 82 stations over southern Canada for the period 1910-1998. Observed percentages are denoted by an x. Error bounds displaying the 5th, 50th and 95th percentiles for each decade (determined by a statistical permutation procedure) are also shown (Bonsal et al., 2001)

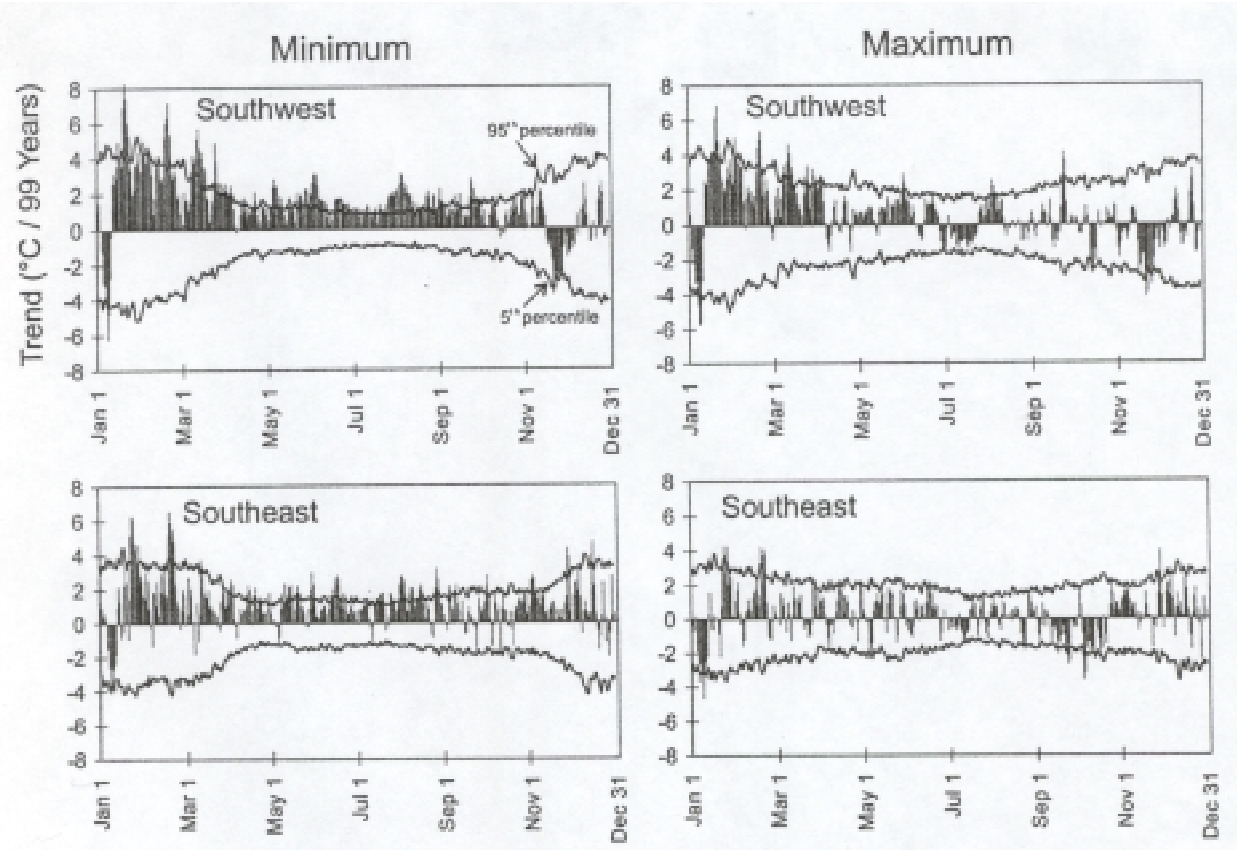


Figure 2.10 Trends in daily minimum and maximum temperature over southwestern and southeastern Canada from 1900 to 1998 (°C/99 yr). The 5th and 95th percentiles of the trends are also shown (Bonsal et al., 2001)

temperature in the summer months (June, July, August) than some of the warmest years of the 1990s. To examine this aspect further, mean maximum temperatures for the three summer months were calculated for different decades of the dust bowl years at selected prairie locations and the values are shown in Table 2. These mean temperature values are compared against the corresponding values for the recent two decades, namely 1980-89 and 1990-99. The table values reveal two interesting aspects of the extreme temperature structure during the 20th century over the Canadian prairies: The decades 1910 through 1940 are among the hottest decades over the prairies, with 1930-39 being the hottest decade of the 20th century. The recent two decades, although hot are not the hottest and the mean maximum temperature appears to show a small decreasing trend in the last ten years. Table 3 shows that the second quarter (1925-1949) of the 20th century had the maximum number of hottest days on the prairies; for the last quarter (1975-1999) of the 20th century, most of the hottest days occurred during the decade 1981-1989.

In another recent study (Knappenberger et al., 2001) the daily temperature trend over the conterminous USA has been analyzed for the 20th century and it is concluded that some of the hottest summers in the USA were during the early part of the 20th century, namely during the years 1910-1940, the dust bowl years over North America which were dominated by anomalous and as yet unexplained weather and circulation patterns. In Figure 2.11 is shown a news item on the heat wave in Toronto during the period 5-12 July 1936, which was probably the hottest summer month in Canada in the 20th century. During that heat wave of July 1936, a total of over 1100 people died in Canada as a result of heat exhaustion with over 200 deaths in southern Ontario.

Table 2 Decadal mean maximum summer (Jun-Aug) temperature values at selected locations on the prairies

		Past decades			Recent decades	
Province	***Location***	***1910-1919***	***1920-1929***	***1930-1939***	***1980-1989***	***1990-1999***
Alberta	Calgary	22.0	22.4	23.2	22.1	21.4
	Fort McMurray	21.5	21.9	23.0	22.3	22.5
	Lethbridge	23.9	23.9	24.6	24.3	23.7
	Medicine Hat	26.0	26.1	26.7	26.1	25.3
Saskatchewan	Estevan	24.7	25.1	27.2	26.3	24.6
	Prince Albert	22.6	23.0	23.6	23.4	22.9
	Regina	23.8	24.3	25.9	25.3	24.2
	Saskatoon	23.2	24.0	24.9	24.5	23.7
Manitoba	Brandon	24.7	24.3	25.9	25.5	24.5
	Dauphine	23.4	23.9	24.9	24.3	23.5
	The Pas	21.2	21.6	22.6	22.4	21.3
	Winnipeg	24.5	24.8	25.6	25.1	24.5
Average over the Prairies		**23.5**	**23.8**	**24.8**	**24.3**	**23.5**

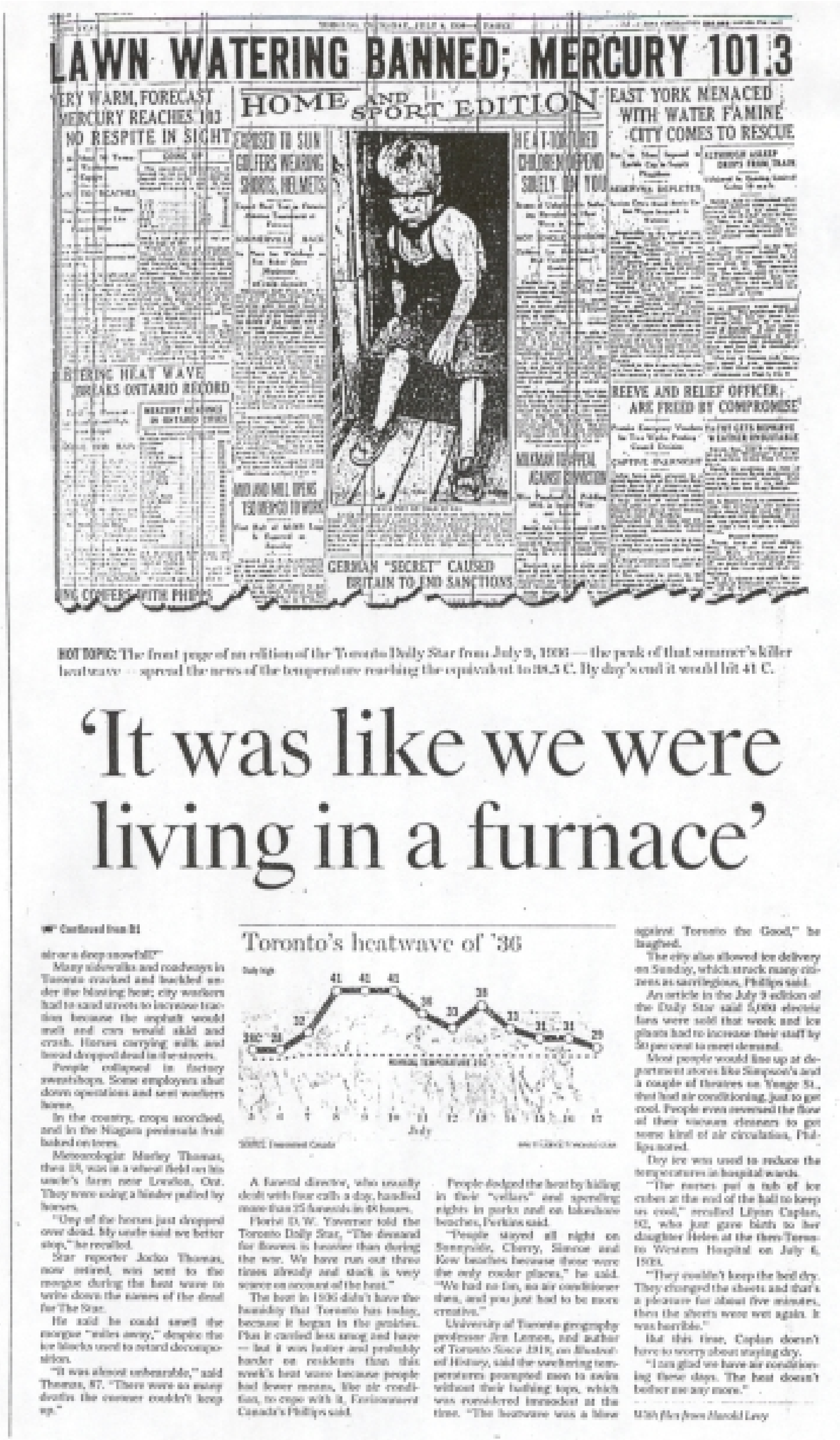
Table 3 Hottest days (temperature > 38 °C) at selected prairie locations during the four quarters of the 20th century

Province	***Location***	1900-1924	1925-1949	1950-1974	1975-1999
Alberta *	Fort McMurray	-	1	-	-
	Medicine Hat	5	22	9	5
Saskatchewan	Estevan	1	12	3	17
	Indian Head	4	17	1	-
	Prince Albert	-	1	-	1
	Regina	5	8	-	5
	Saskatoon	3	9	2	6
	Swift Current	1	7	-	1
Manitoba	Brandon	13	9	3	4
	The Pas	-	-	-	-
	Winnipeg	-	5	-	3

*Note: Calgary, Edmonton, Lethbridge & Slave Lake have no days over 38 °C.

Extreme cold spells of long duration (several days in a row) can be discomforting and stressful for most residents in Canada. The Canadian prairie provinces are known for their long winter season with occasional extreme cold spells when the minimum temperature goes down to -25°C or lower. A recent study (Shabbar and Bonsal, 2002) examines trends in winter (Jan-Feb-Mar) season cold and warm spells in different regions of Canada using high quality data at 210 locations for the period 1950-1998 (Vincent, 1998). Several interesting findings of this study have been summarized by the authors (Shabbar and Bonsal). For the purpose of the present discussion, some of the important findings are: the duration and frequency of cold spells have decreased on the prairies while they have increased in eastern Canadian provinces during the last fifty years. The central region of the country (Ontario, Quebec) display in general, mixed insignificant trend in cold spells. The majority of the country is associated with a significant increase in winter warm spells both in frequency and duration.

Chapter Summary: The most dramatic impact of Global Warming on the temperature structure over the prairies is a definite warming of the mean temperature over the last fifty years. This warming is primarily due to the increase in the minimum temperature especially during the winter season. Interestingly, the maximum summer temperatures appear to show a downward trend suggesting that 'hot spells' during summer months may be declining. For Alberta, the mean temperature structure and its trend can be suitably displayed in a schematic prepared by Chaikowski (2000) and shown here in Figure 2.12. As discussed earlier, Alberta as a whole has warmed up by 1 °C to 3 °C during the winter season, has cooled a little during the summer season while the fall season has become cooler by 1 to 2 °C. Extreme cold spells have decreased while warm spells have increased in winter months in Alberta.



LAWN WATERING BANNED; MERCURY 101.3

HOME AND SPORT EDITION

VERY WARM, FORECAST MERCURY REACHES 103 NO RESPITE IN SIGHT

EXPOSED TO SUN GOLFERS WEARING SHORTS, HELMETS

HEAT-TORTURED CHILDREN DEPEND SOLELY ON YOU

EAST YORK MENACED WITH WATER FAMINE CITY COMES TO RESCUE

BLISTERING HEAT WAVE BREAKS ONTARIO RECORD

REEVE AND RELIEF OFFICER ARE FREED BY COMPROMISE

GERMAN "SECRET" CAUSED BRITAIN TO END SANCTIONS

HOT TOPIC: The front page of an edition of the Toronto Daily Star from July 9, 1936 — the peak of that summer's killer heatwave — spread the news of the temperature reaching the equivalent to 38.5 C. By day's end it would hit 41 C.

'It was like we were living in a furnace'

Continued from B1

air or a deep snowfall?"

Many sidewalks and roadways in Toronto cracked and buckled under the blasting heat; city workers had to sand streets to increase traction because the asphalt would melt and cars would skid and crash. Horses carrying milk and bread dropped dead in the streets.

People collapsed in factory sweatshops. Some employers shut down operations and sent workers home.

In the country, crops scorched, and in the Niagara peninsula fruit baked on trees.

Meteorologist Morley Thomas, then 18, was in a wheat field on his uncle's farm near London, Ont. They were using a binder pulled by horses.

"One of the horses just dropped over dead. My uncle said we better stop," he recalled.

Star reporter Jocko Thomas, now retired, was sent to the morgue during the heat wave to write down the names of the dead for The Star.

He said he could smell the morgue "miles away," despite the ice blocks used to retard decomposition.

"It was almost unbearable," said Thomas, 87. "There were so many deaths the coroner couldn't keep up."

Toronto's heatwave of '36

A funeral director, who usually dealt with four calls a day, handled more than 25 funerals in 48 hours.

Florist D.W. Yavorner told the Toronto Daily Star, "The demand for flowers is heavier than during the war. We have run out three times already and stock is very scarce on account of the heat."

The heat in 1936 didn't have the humidity that Toronto has today, because it began in the prairies. Plus it carried less smog and haze — but it was hotter and probably harder on residents than this week's heat wave because people had fewer means, like air conditioning, to cope with it, Environment Canada's Phillips said.

People dodged the heat by hiding in their "cellars" and spending nights in parks and on lakeshore beaches, Perkins said.

"People stayed all night on Sunnyside, Cherry, Simcoe and Kew beaches because those were the only cooler places," he said. "We had no fan, no air conditioner then, and you just had to be more creative."

University of Toronto geography professor Jim Lemon, and author of *Toronto Since 1918, an Illustrated History*, said the sweltering temperatures prompted men to swim without their bathing tops, which was considered immodest at the time. "The heatwave was a blow against 'Toronto the Good,'" he laughed.

The city also allowed ice delivery on Sunday, which struck many citizens as sacrilegious, Phillips said.

An article in the July 9 edition of the Daily Star said 5,000 electric fans were sold that week and ice plants had to increase their staff by 50 per cent to meet demand.

Most people would line up at department stores like Simpson's and a couple of theatres on Yonge St., that had air conditioning, just to get cool. People even reversed the flow of their vacuum cleaners to get some kind of air circulation, Phillips noted.

Dry ice was used to reduce the temperatures in hospital wards.

"The nurses put a tub of ice cubes at the end of the hall to keep us cool," recalled Lilyan Caplan, 92, who just gave birth to her daughter Helen at the then Toronto Western Hospital on July 6, 1936.

"They couldn't keep the bed dry. They changed the sheets and that's a pleasure for about five minutes, then the sheets were wet again. It was horrible."

But this time, Caplan doesn't have to worry about staying dry.

"I am glad we have air conditioning these days. The heat doesn't bother me any more."

With files from Harold Levy

Figure 2.11 News story on the heat wave in Toronto, July 5-17, 1936 (The Toronto Star, August 9, 2001)

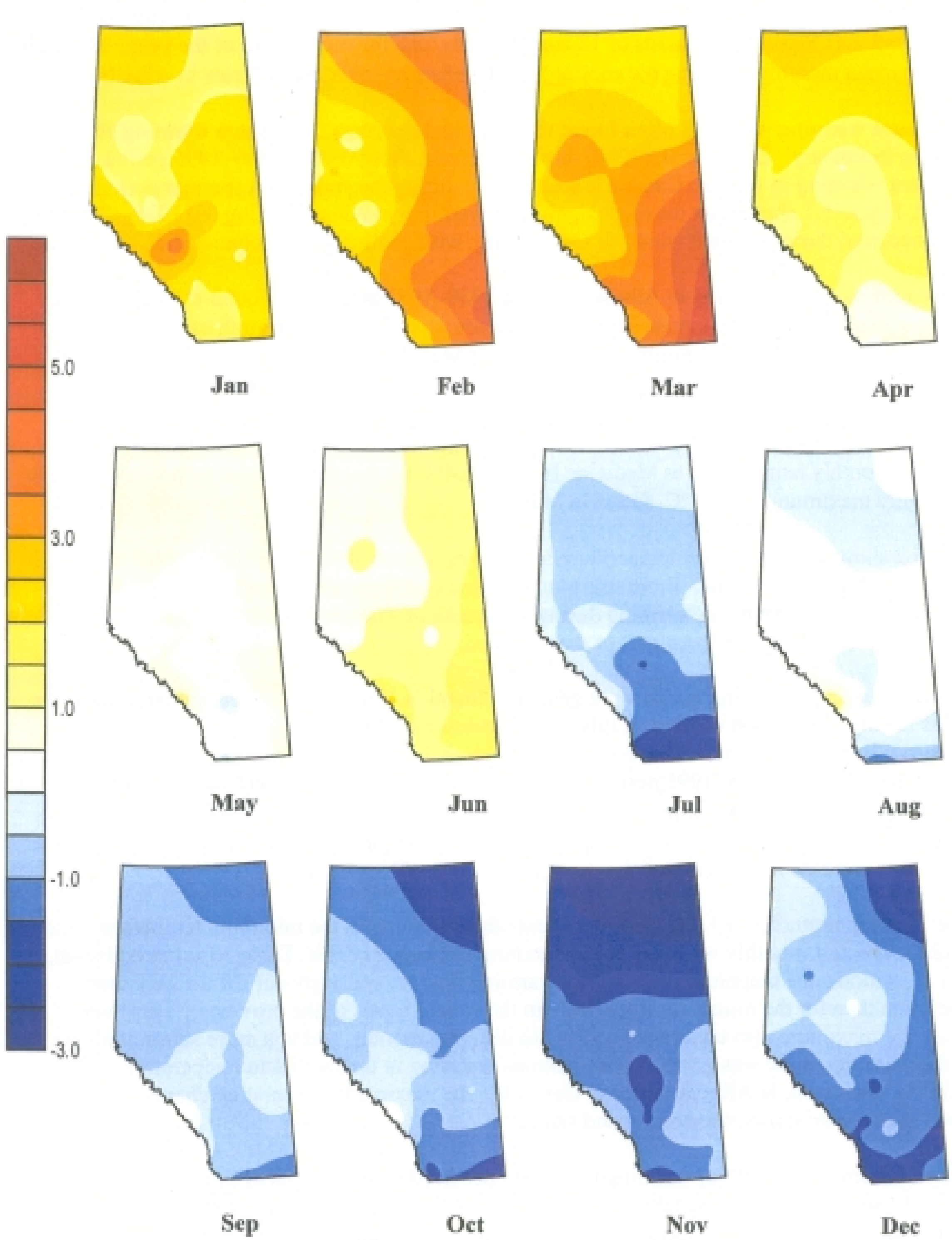


Figure 2.12 Monthly mean temperature change over Alberta in °C during the 58 year period, 1938-1995 (Chaikowsky, 2000)

Precipitation amounts have increased in general over most regions of Canada, but this increase is mainly due to increase in low intensity precipitation events. There is no trend in extreme precipitation events anywhere in Canada. Over the prairie provinces, the precipitation amounts (rain as well as snow) have decreased in the last couple of years, but this decline appears to be related to the cold phase of the ENSO cycle. There does not appear to be a decreasing trend in the precipitation amount on the prairies at this point.

3.0 EXTREME WEATHER: THUNDERSTORM, TORNADO, HAIL, WIND

3.1 Introduction

Thunderstorms and associated tornadoes are among the most violent of the weather phenomena that affect a large region of USA and Canada and can inflict extensive damage and loss of life. In the USA, thunderstorms occur primarily in the mid-western states of Kansas, Missouri and Oklahoma and in the Gulf States of Texas, Louisiana Alabama and Florida. The mid-western thunderstorm and severe convective activity zone often extends into the southern Canadian prairies which experience the maximum number of thunderstorms in Canada on an annual basis. Another area of significant thunderstorm/tornado activity in Canada is the region of southern Ontario, parts of northern Ontario and western Quebec. In eastern Canadian provinces, thunderstorm and tornado is a rare occurrence and is therefore not of particular consequence as an extreme weather hazard.

Climatologically, the summer months of June, July and August are considered the most important months for thunderstorm activity in southern prairies as well as in southern Ontario and in Quebec. A severe thunderstorm, under appropriate environmental conditions, can produce a tornado vortex at its base which can inflict considerable property damage as well as loss of life (see for example, Etkin et al., 2001). Some of the noteworthy thunderstorm and tornado incidences in Canada in the last 20 years are: Barrie (ON) tornado, 31 May 1985; Edmonton (AB) tornado, 31 July 1987; Pine Lake (AB) tornado, 14 July 2000 and Aylmer (QC) tornado, 4 August 1994. The Edmonton tornado of July 1987 is considered to be the deadliest (27 deaths) and the costliest tornado incident in Canada with an estimated damage cost of ~250 M dollars (Charlton et al., 1998).

The presence of hail in a thunderstorm cell is again dependent upon local and regional environmental factors like surface topography and mean temperature at the base of a thunderstorm. In Canada, hail fall activity is primarily associated with two prairie provinces, Alberta and Saskatchewan. Several important studies have been reported on Alberta hailstorms (see for example, Renick and Maxwell, 1978). An intense thunderstorm infested with large hail stones can inflict severe damage to property and residential areas in general and in particular to agricultural crops during the grain growing season in southern prairies. Associated with thunder and hail is a downburst phase which can produce strong winds at the surface level. The occurrence of strong winds in conjunction with thunderstorms and tornadoes and its damage potential is another example of impact of extreme weather events on the Canadian society.

3.2 Thunderstorms and Tornadoes

In the context of the present study, we consider first the climatology of thunderstorm/tornado occurrences in Canada and the USA and their inter-annual variability based on reported studies: A climatology of tornado occurrences in Canada has been prepared and reported by Newark (1984); this has been updated by Etkin (1995) who has prepared a scatter plot of tornado occurrences in Canada as shown in Figure 3.1 (top). This figure highlights two primary regions of tornado activity in Canada, namely southern Ontario and the three prairie provinces, these two regions reporting about 60 tornadoes per year (Etkin et al., 2001). For comparison, the tornado climatology in the USA is also shown in Figure 3.1 (bottom). For the conterminous USA, the majority of tornado occurrences are in the US mid-west and the south central region of Oklahoma/Texas, which is well known as the 'Tornado Alley' where up to 10 tornadoes occur over a 10,000 mi^2 (~26000 km^2) area on an annual basis. According to Grazulis et al., (1993), several hundred to a couple of thousand tornadoes are reported and/or recorded in the USA on an annual basis, while a significant number of tornadoes do not get reported or recorded for a variety of reasons, like tornadoes occurring on the western plains and in rural areas, poorly formed and 'weak' tornadoes and tornadoes associated with gust fronts and other shear zone tornadoes which have a convergent rotation but may not be connected to the base of a thunderstorm. The tornado season in Canada is typically during the three summer months (June-August), while in the USA the tornado season is much longer, typically five to seven months.

Several important studies on Canadian tornado activity have been reported in the last fifteen years (Raddatz and Hanesiak, 1991; Paul, 1995; Hage, 1987, 1994; Etkin, 1995; Etkin et al., 2001). The spatial and inter-annual distribution of tornado frequency for Alberta and Saskatchewan using an extensive dataset from 1880-1998 has been prepared in a couple of studies by Hage (1994, 2002) and are presented in Figure 3.2 (a, b). The top of Figure 3.2 shows the spatial distribution for the two prairie provinces and identifies two important centers of tornado activity, one south of Edmonton and the other in and around Regina. The bottom part of the Figure shows the inter-annual variation of tornadoes for the period 1880-1998. Several interesting features of the severe thunderstorm and tornado activity can be noted. There is an increased tornado activity during the dust bowl years of the prairies, from 1910 through 1926/30, a definite decline in the activity between 1940 through 1975, a rapid increase beginning late seventies through early eighties and a declining trend since about 1990. Hage has made an assessment of all available data on severe windstorm and convective activity collected using newspaper reports and community history books which contain windstorm information on a farm-by-farm basis from well over several thousand farms. According to Hage (2002), *the increased tornado count after about 1975 is attributed to increased public awareness, through scanning of local daily and weekly newspapers and the establishment by Environment Canada of networks of hundreds of volunteer severe weather observers in each province.* A similar rise in observed tornado count has been reported in the USA and is attributed to increased public awareness and reporting of tornado occurrence, and not due to actual increase in tornado activity in the USA (Forbes and Bluestein, 2001).

Another recent study on tornado climatology in Canada (Etkin et al, 2001) discusses the tornado statistics since 1980 when the Environment Canada observing network was established. According the Etkin et al., about 60 tornadoes are reported annually in Canada, more than 60 percent of which are reported in the three prairie provinces. The largest number of reported tornadoes is of the weak (F0 on the Fujita scale) category, while very few tornadoes (less than 5) of the strongest categories (F4 and F5) have been reported in Canada in the last 25 years. The three prairie provinces have reported about 650 tornadoes during the period 1980-1997. Figure 3.2 from Hage (2002) yields a total of about 580 tornadoes in the two provinces Alberta and Saskatchewan during the same period namely 1980-1997, while another recent study

Figure 3.1a Locations of known tornadoes over Canada, 1916-1992 (Etkin, 1995)

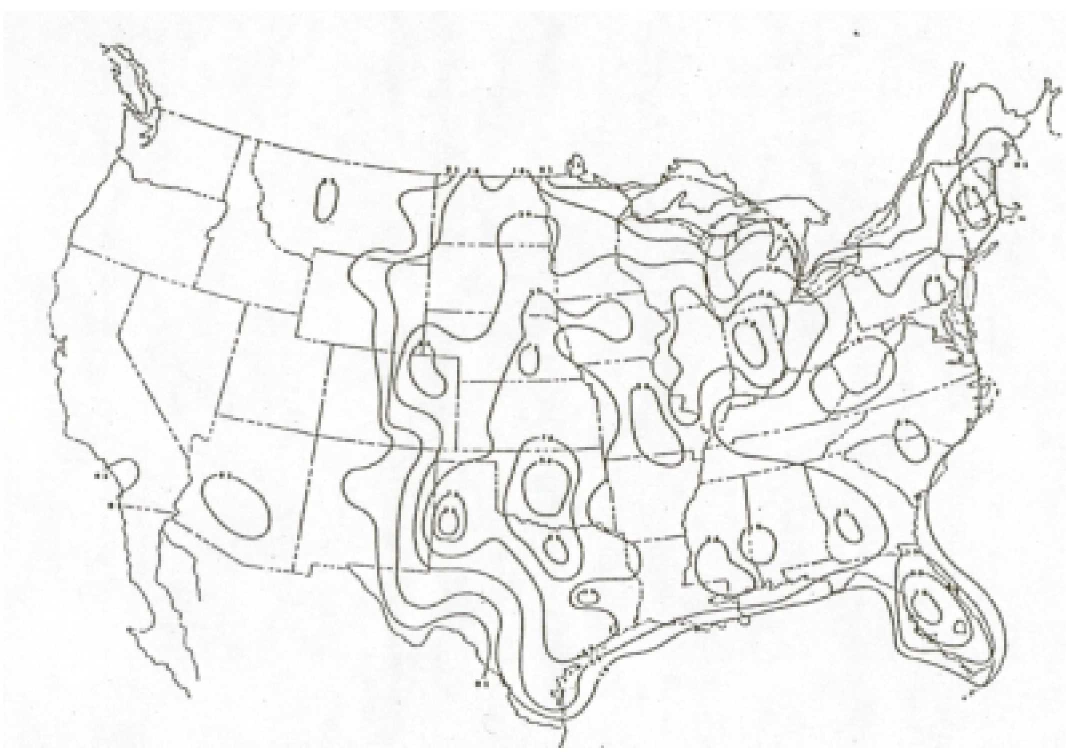


Figure 3.1b Average annual tornado incidence per 10,000 mi^2 (25,900 km^2) over conterminous USA (Grazulis et al., 1993)

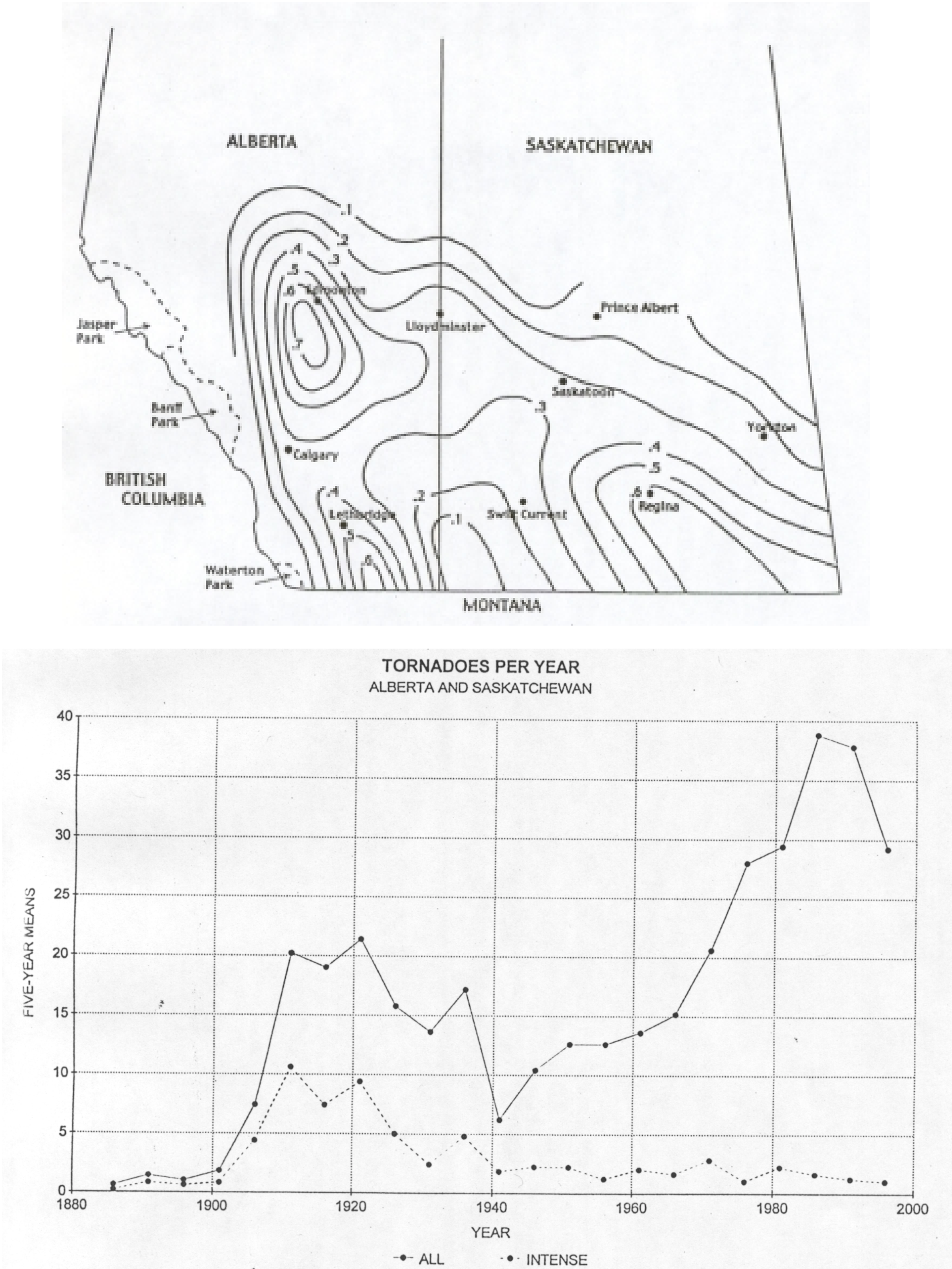


Figure 3.2 Top – Average annual tornado incidence per 10,000 km2. Bottom – Five-year averages of annual tornado count for Alberta and Saskatchewan. Data: 1880-1998 (Hage, 2002)

(Cummine and Noonan, 2001) obtains a total of about 480 tornadoes for the three prairie provinces during the period 1982-2000. The inter-annual variation of tornado count for the three prairie provinces as determined by Cummine and Noonan is shown in Figure 3.3. This tornado count obtained by Cummine and Noonan appears to be on the lower side when compared with the number obtained by Hage. This difference in the tornado count is attributed to the way the tornado statistics are collected, tornado days (by Cummine and Noonan) versus actual number of tornadoes (by Hage).

It is interesting that that the tornado count in the 1990s is in general on the decline in western Canada and in particular in Alberta. This decline in tornado activity can be interpreted in terms of the decadal mean maximum temperature variation as shown in Table 2. The mean maximum temperature shows a definite decline during the decade 1990-1999 and this reflects in the declining tornado activity which has been linked to the general global warming in a few recent studies (Etkin,1995; Etkin et al.,2001) as well as in IPCC documents and related newspaper and media accounts. It is instructive to note that the tornado activity over the Canadian prairies is directly related to the regional mean temperature at the surface level and the thermodynamic stability of the prairie atmosphere during the summer months. Additionally, the impact of boundary layer and the anthropogenic vegetation transformation on the deep convection over the Canadian prairies has been recently identified and discussed in a couple of studies by Raddatz (1998, 2002). In view of this, it is argued here that the thunderstorm/tornado activity of the prairie region is more directly related to the mean surface maximum temperature over the prairie region and not to the global mean surface temperature changes. Also the impact of boundary layer transpiration and agricultural practices (Raddatz, 2002) may further augment thunderstorm and convective activity over the prairies. At this point in time, there does not appear to be any emerging trend either increasing or decreasing in thunderstorm and tornado activity over the prairie provinces in general and over Alberta in particular.

3.3 Hail

The hail activity which is inherently associated with severe thunderstorm activity over the prairies is another extreme weather event which has been examined here in the context of global warming. The formation of hailstones in a thunderstorm is a complex phenomenon, primarily governed by regional topography and synoptic-scale processes which initiate deep convection. The foothills of southern Alberta and western parts of Saskatchewan are the regions most prone to hail fall activity on the Canadian prairies. In southern Ontario and occasionally in western Quebec, hail activity is sometimes associated with severe summer weather. For the purpose of present study, the following discussion will be confined to the prairie provinces only.

There are only a limited number of studies on hail climatology in Canada that have been reported in open literature. Among the early studies are those of Paul (1967) and Wojtiw (1975) which provide spatial and temporal analysis of hail fall occurrence in central Alberta over a 15-year period from 1957 through 1973. Among the recent studies are those of Smith and Yau (1993) and Smith et al. (1998) which have analyzed data from about 1975 through 1985. Based on these and a few other studies, a spatial distribution of hail frequency in Canada is shown in Figure 3.4. This figure identifies the most important regions for hail activity in western Canada,

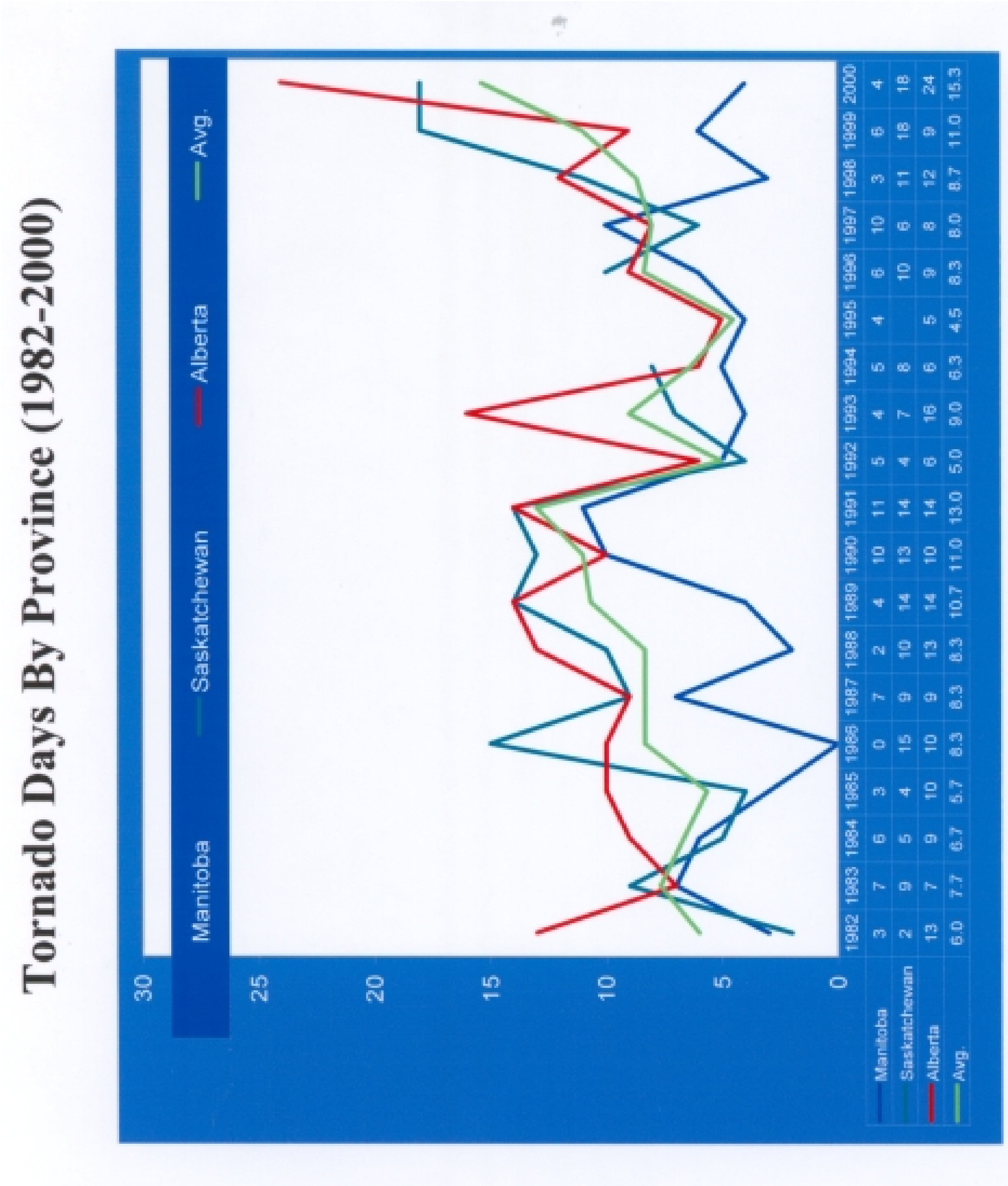


Figure 3.3 Tornado days by province (1982-2000) (Cummine and Noonan, 2001)

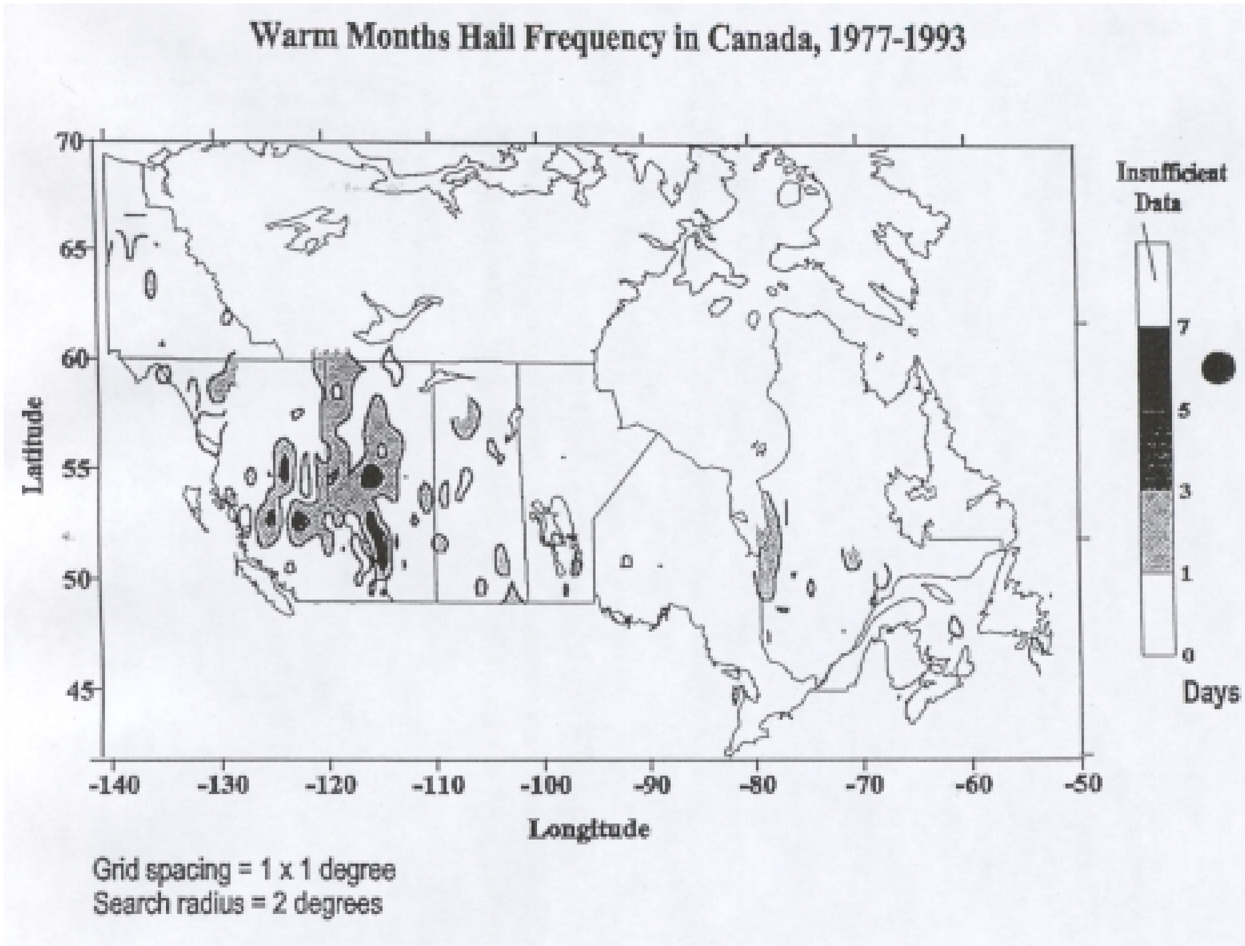


Figure 3.4 Spatial distribution of hail occurrence in Canada, 1977-1993 (Dennis Dudley, Environment Canada)

namely central British Columbia, central Alberta and western and southern Saskatchewan. Elsewhere in Canada, hailfall activity is only spotty and not of particular significance.

The study by Smith et al. (1998) analyzes daily hail reports from Alberta for the years 1957-1985 and obtains an average of about 50 hail days for central Alberta, a hail day being defined as a day with one or more reports of hail within a 24-hour time span. The study further reveals significant year-to-year variability in the number of hail report and documents more hail activity during the years 1957-1972 than the years 1973-1985. No specific explanation is offered for the year-to-year variability in the hailfall activity. Other studies on hail activity, referred to above, do a brief analysis of inter-annual variability but offer no specific mechanism for the variability.

For the conterminous USA, several studies on hail climatology and long-term fluctuations in hail activity are reported, notably by Changnon and his coworkers (e.g. Changnon, 1978, 1998; Changnon and Changnon, 2000; Changnon and Hewings, 2000). A recent study by Changnon and Changnon (2000) has analyzed screened record of 66 first order stations in the conterminous USA over a hundred-year period (1896-1995). The study reveals five types of distributions of hail activity across the USA. In one distribution, typical of US mid-western states, peak hail activity was revealed during the period 1916-1935 and a general decline thereafter to 1976-1995. The study further analyzes linear trends in hail activity and obtains an upward trend for the mid-western states and a downward trend south of the Great lakes and for the US Gulf coast states. Another recent study (Changnon and Hewings,2000) finds a definite decline in the average number of hail days in the conterminous USA during the period 1950-1997.

In summary, hail activity in Canada and in the USA shows significant year-to-year variability and sharp regional differences in trends, either increasing or decreasing. For Alberta and Saskatchewan, two provinces with maximum hail activity in Canada, there is no increasing or decreasing trend in hail activity at this point in time. For the conterminous USA, a definite decline in hail activity is revealed for the last 50 years.

3.4 Wind

Incidences of extreme wind and associated damage to residential areas and farmlands are typically reported during severe convective activity (thunderstorm/tornado), either on a local scale or along a frontal boundary with a sharp temperature discontinuity. Examples of wind damage to buildings and residential areas during severe thunderstorm/tornado activity are reported and analyzed in a large number of wind engineering studies. Studies by Fujita and his coworkers have documented damage to farmlands along a characteristic cycloidal path during tornado outbreaks in the mid-western US states (Fujita, 1966; Fujita et al. 1967). Outside of thunderstorm and tornado, extreme winds are experienced during the passage of a hurricane in southeastern USA or in eastern Canada and during the passage of a sharp cold front with gust winds associated with intense pressure gradient.

In Canada, extreme winds are generally associated with summer severe convective activity and with severe winter storms and blizzards. Several studies referenced in this report have analyzed (extreme) winds associated with specific case studies of severe convective activity or winter storms; however, very few studies reported so far have made any systematic analysis of inter-annual variability of wind speed and associated trends. The most comprehensive studies on extreme winds and windstorms in Canada are reported by Hage (1994, 2001), both these studies pertaining to the two prairie provinces Alberta and Saskatchewan. In his 1994 study Hage has compiled a climatology of tornadoes and other destructive windstorms for Alberta covering a period 1879-1984. In his recent study Hage (2001) has complied windstorms, tornadoes and lightening fatalities for Saskatchewan covering the period 1880-1984. In both these studies, Hage has made an extensive analysis based on newspaper reports, community and prairie farm newsletters and other documents as well as available instrument data. In a more recent study Hage (2002) has documented this inter-annual variation of windstorms and intense winds in a schematic as shown in Figure 3.5. This figure shows a peak in the windstorms during the period 1920-1940, a period associated with the dust bowl years in the prairies. Associated with the windstorms, high values of wind speed appear to peak out during the decade 1910-1920 following which there is a steady decline in the occurrence of intense winds on the prairies. This inter-annual variability of windstorms and intense winds seem to resemble in some ways to the inter-annual variability of tornadoes (Hage, 2002) over the prairies. Once again, the incidences of extreme winds appear to be associated with the decades 1910-1940, the period with anomalous circulation and flow patterns over North America. There appears to be a generally declining trend for windstorms and extreme winds over the prairies over the recent years.

From a modeling perspective, the study by Kharin and Zwiers (2000) suggests that changes in extreme wind speed over extratropical land mass and over Canada in particular are expected to be small in future climate projections for the 21st century.

Chapter Summary: Available studies on thunderstorms and tornadoes suggests that there is no increasing or decreasing trend in thunderstorm/tornado activity on the prairies at this point in time. Available data on tornado count show considerable year-to-year variability, but no specific trend. In view of the fact that the mean summer maximum temperature over the prairies has declined during the last decade and further that the vertical wind shear over the prairies during the summer months would be reduced in a warmer future climate (G. Reuter, Univ. of Alberta, Personal communication), the likelihood of intense convective activity is expected to be reduced in the next ten to twenty years. The hail fall activity associated with intense thunderstorms is also likely to be reduced in a warmer future climate. The incidences of extreme winds and associated windstorms appear to be on the decline on the prairies. From a modeling perspective, extreme winds do not appear to be of major concern in a warmer future climate.

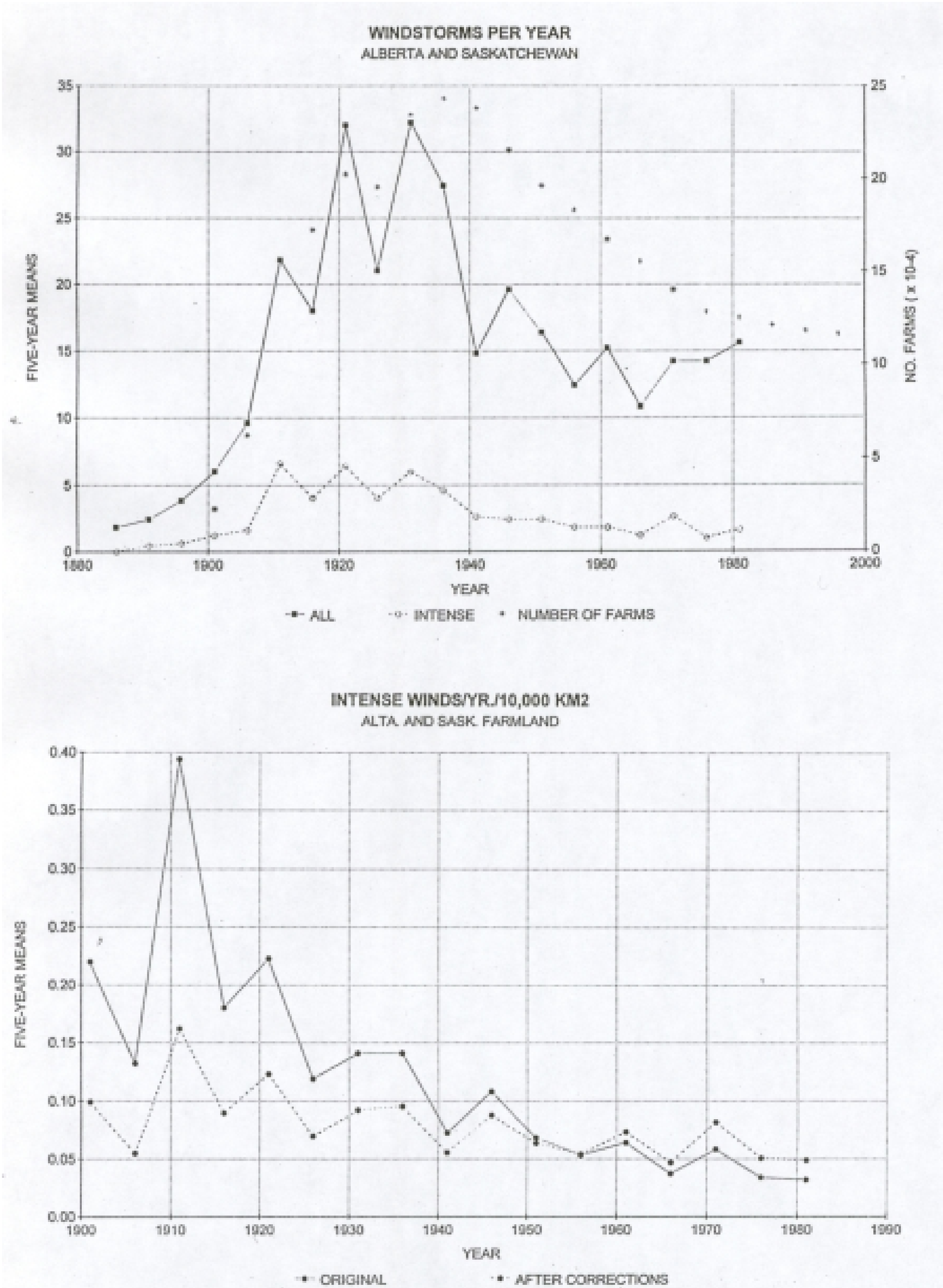


Figure 3.5 Windstorms and intense winds, Alberta and Saskatchewan, 1900-1990 (Hage, 2002)

4.0 EXTREME WEATHER: BLIZZARDS, ICE STORMS AND OTHER LARGE-SCALE STORMS

4.1 Introduction

Among the large-scale extreme weather events that have significant impact on Canada's climate are blizzards in the Canadian prairies, ice storms in eastern Canada and Quebec, and fall and winter coastal storms on the Pacific as well as on the Atlantic coast. The eastern Canadian provinces are also occasionally influenced by tropical cyclones and hurricanes, which normally travel along the warm waters of the Gulf Stream from Sable Island (Nova Scotia) to Avalon Peninsula in Newfoundland. These tropical storms/hurricanes generally impact the Canadian east coast during mid-August through mid-October.

In an earlier report, Khandekar (2000) discussed the inter-annual variation of hurricanes and typhoons in the context of climate change. Khandekar also discussed the east coast winter storms and trends and their inter-annual variability. For the purpose of present study, the discussion here will be limited to winter blizzards, ice storms and sub-synoptic to meso-scale events like the Red River flood (April 1997) and the Saguenay flood (July 1996), these events being often cited as examples of global warming impact on Canadian climate.

4.2 Blizzards

The Canadian prairie blizzards are one of the most extreme weather events and a fact of life for most residents in the prairie provinces. By definition a blizzard is a winter storm having a wind speed of 40 km h^{-1} or more, with snow or drifting snow and a wind chill factor of greater than 1600 Wm^{-2}, lasting for at least four consecutive hours. Over the Canadian prairies, a blizzard is typically developed from two migratory low pressure systems, the Alberta Low and the Colorado Low (Lawson, 1987). The Alberta Low which often develops at the foothills of southern Alberta typically moves east to northeastward and intensifies into a blizzard over Saskatchewan and Manitoba, the two prairie provinces which experience the largest number of blizzards anywhere in Canada.

Several recent studies have examined the mid-latitude storm climate using available data of recent years in an attempt to assess the impact of global warming and climate change on the mid-latitude storm frequency and intensity. Agee (1991) found a 30% percent decrease in the frequency of cyclones over the northern hemisphere; Serreze et al., (1997) while examining trend in winter (October to March) cyclone frequency for the mid-latitude band 30-60°N also found a decrease in cyclone frequency for the period 1966-1993. A more recent study by McCabe et al., (2000) using mid-latitude cyclone data for the period 1959-1997 concludes that for the northern hemisphere winter cyclone frequency has increased in high latitudes and decreased in mid-latitudes, while for both latitude bands, the intensity of cyclones has increased. From a modeling perspective, Lambert (1995) examined the impact of a doubled-CO_2 climate on cyclone activity using a General Circulation Model (GCM) developed at the Canadian Climate Centre in Victoria. Lambert found a significant reduction in total number of cyclones in both the hemispheres but an increased frequency of intense cyclones, most pronounced in the northern hemisphere. According to Lambert, the reduction in cyclone frequency was consistent with a reduction in baroclinicity in the lower troposphere in a warmed climate. The IPCC (1996) document states *"the evidence on change in extra-tropical synoptic systems is inconclusive; there is no clear evidence of any uniform increase"*. The most recent IPCC document, Climate Change 2001 concludes that there is no compelling evidence to indicate that the characteristics of tropical and extratropical storms have changed. The IPCC statements do not appear to reflect some of these recent findings on the mid-latitude storm climate.

In the context of the present study, it is instructive to consider the most recent study by Lawson (2002) and examine some of his findings. Lawson makes a careful analysis of the frequency and intensity of prairie blizzards for the period 1953-1997 using the Canadian Climate Archive database. The intensity of a blizzard is defined in terms of extreme wind speed, extreme low temperature and duration in hours. The blizzard count is carefully determined from the 40-year data period, on an annual basis. The trend in blizzard frequency is determined using a linear trend analysis. In Figure 4.1 are shown the inter-annual variation of blizzards at three selected locations, Regina, Saskatoon and Winnipeg. It may be noted here that none of the locations in Alberta had a sufficient number of blizzard count (as per definition of a blizzard) for a meaningful trend analysis. The figure clearly shows that there is a definite decreasing trend in the number of blizzards in recent years. Further, the intensity of a blizzard event as defined in terms of extreme wind speed, extreme low temperature and duration does not show any trend over the last 40 years. Lawson concludes that the blizzard events on the prairies appear to be diminishing in occurrence and exhibit no trend in the severity of their individual weather elements.

The Canadian prairie blizzards are an important component of the mid-latitude storm systems in northern hemisphere and have a significant impact on the prairie life-style. Lawson's findings appear to be in contrast to several of the news media headlines and commentaries (eg. *Weather getting worse than it used to be)* on Canada's changing climate and to some of the articles on Disaster Loss Reduction Program and on increased insurance cost due to extreme weather events (see for example, Bruce, 2000, and Kovacs, 2001).

4.3 Saguenay (Quebec) Flood, July 1996

The flash flood in the Saguenay region (northeast of Montreal) occurred following an unprecedented heavy rainfall event during 19-21 July 1996, when over 200 mm rain fell over an area of 5000 km^2 in the Saguenay river basin. Synoptically, this severe precipitation event can be traced back to a small low pressure centre over Manitoba with a central sea-level pressure of 1002 mb. As this low pressure system moved northeastward, it deepened rapidly to 979 mb in a 24-hour period between 19 and 20th July 1996. With the deepening of the low pressure system, heavy precipitation occurred between 19-21 July and this resulted in a localized flash flooding, property damage and loss of life.

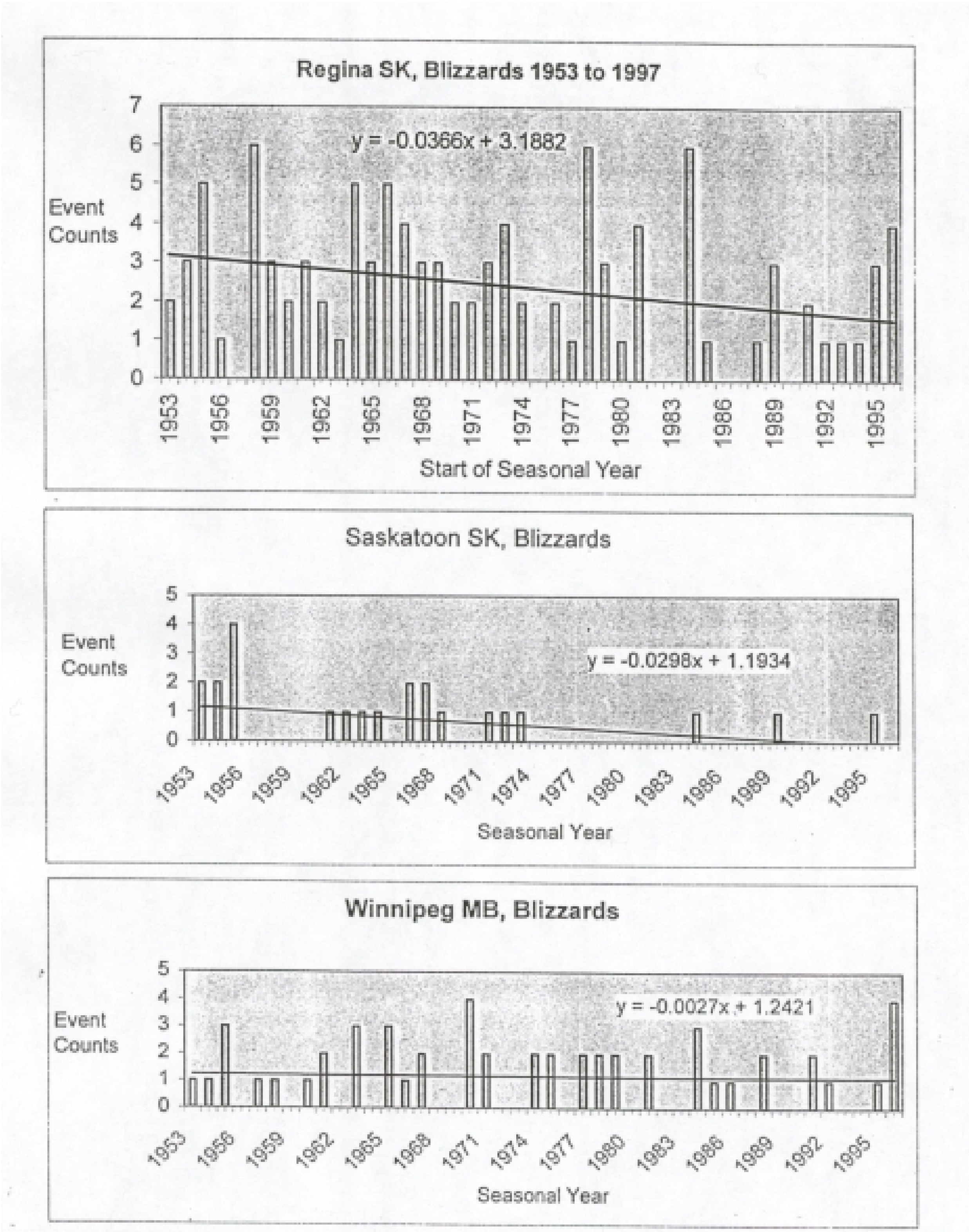


Figure 4.1 Frequency of blizzards at selected locations on the Canadian prairies and linear trend, 1953-1997 (from Lawson, 2002)

In a couple of recent studies (Yu et al., 1997; Wen et al., 2000) the Saguenay region flood has been simulated using a high resolution numerical model with a 10-km grid spacing and the role of land surface schemes and localized topography on the flood potential was investigated. A land surface scheme which included initial soil moisture condition and the vegetation cover provided the best simulation of the heaviest observed rainfall (~275 mm) when the localized topography was also included.

The Saguenay region flood was exceptional although not unprecedented. Noted among the recent urban floods in Canada is the Montreal flood of 14 July 1987 when a summer thunderstorm produced rainfall amounts of well over 100 mm at several rain gauge locations in a matter of only few hours! During the U.S. Mid-western summer floods of 1993, the city of Winnipeg experienced heavy rainstorms during July and August of 1993. During a particularly heavy rainstorm in July 24/25 (Lawford et al., 1995), rainfall amounts of 50 to 100 mm were recorded in a six-hour duration in Winnipeg.

4.4 Red River Flood, April 1997

The Red River, an important river system in the Canadian/American prairies, originates in the hills of Dakotas (USA) and flows northward into Lake Winnipeg about 100 km north of the city of Winnipeg, Manitoba. The river is normally fed by the fall and winter precipitation (rain as well as snow) in the North American prairies and reaches a peak flow level in early spring in and around the city of Winnipeg. Extreme flood levels in and around the city of Winnipeg in 1776 and 1826 have been documented through anecdotal information (Warkentin, 1999). A systematic recording of Red River floods at Winnipeg began in 1875. Following the great flood of 1950, the Royal Commission on Flood Cost Benefit recommended the construction of major flood control works to protect the city of Winnipeg. A Red River Floodway system has been built following the Royal Commission recommendation and this Floodway system went into operation in 1969.

The 1997 Red River flood was the highest recorded in Winnipeg in the 20th century and strained the Floodway control works to near its limit. The peak stages of 1997 flood (which occurred between 25-27 April, 1997) from the US Boundary to the Floodway control structure just south of Winnipeg were 0.6 to 1.5 m higher than for the great flood of 1950 and 1979 (Warkentin, 1997/98). Total damages for the 1997 flood was estimated at around $400 million, while damages prevented by flood control works and emergency diking was estimated to be between 6 and 8 billion dollars.

A perspective on the 1997 flood in relation to previous floods can be obtained by figures 4.2 and 4.3, which show the Red River watershed and the inter-annual variation of winter and spring precipitation for the Red River watershed. The total winter and spring precipitation in 1997 was slightly higher than in 1950 which was the previous highest value in the 50-year record. For 1997, the winter precipitation in the Red River watershed was over 150 mm which was significantly above normal. The above normal winter precipitation together with the soil moisture saturation over the previous four years and a couple of persistent snow storms early in

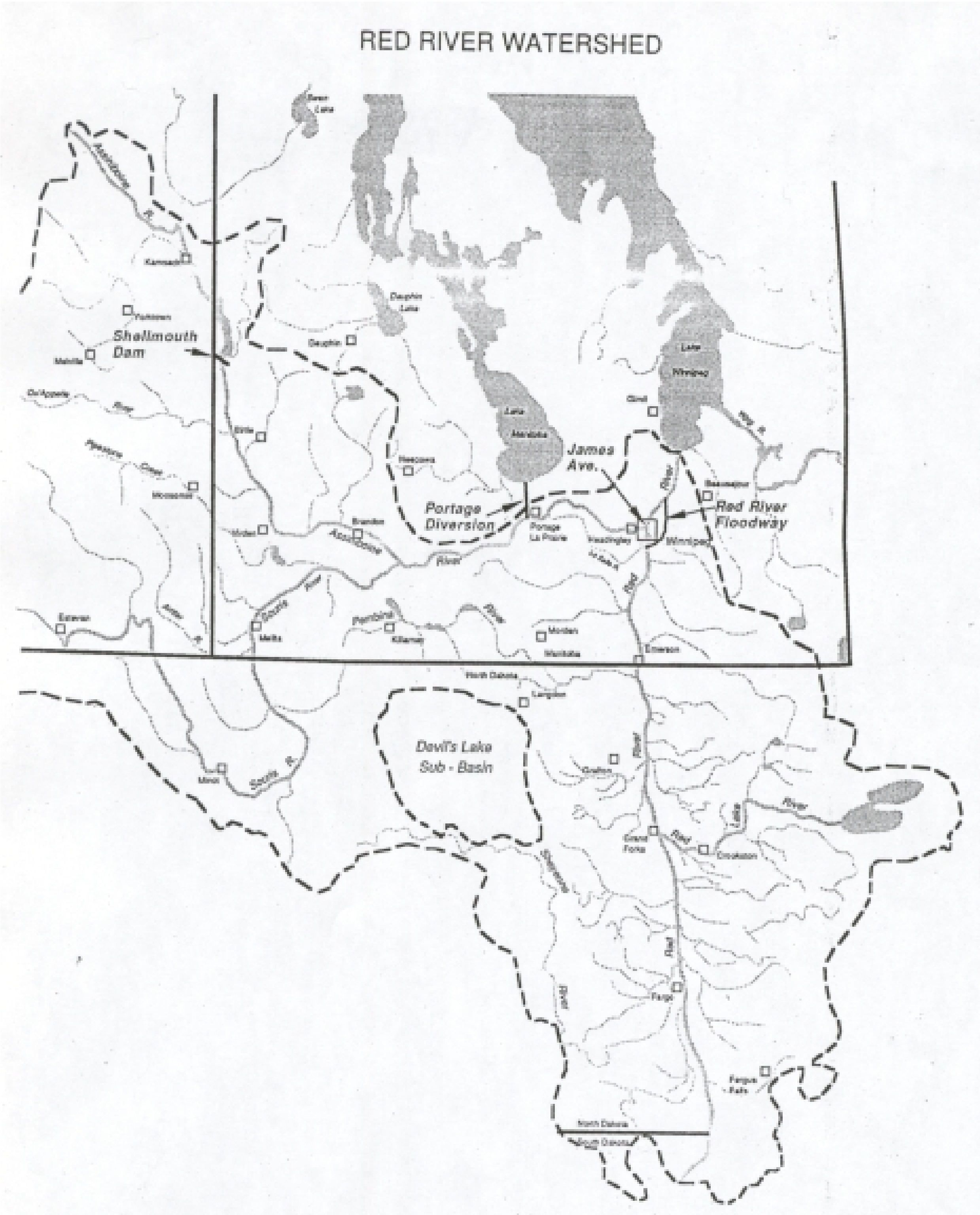


Figure 4.2 Map of Red River watershed from North Dakota to Manitoba (A.A. Warkentin, Manitoba Water Resources, Winnipeg)

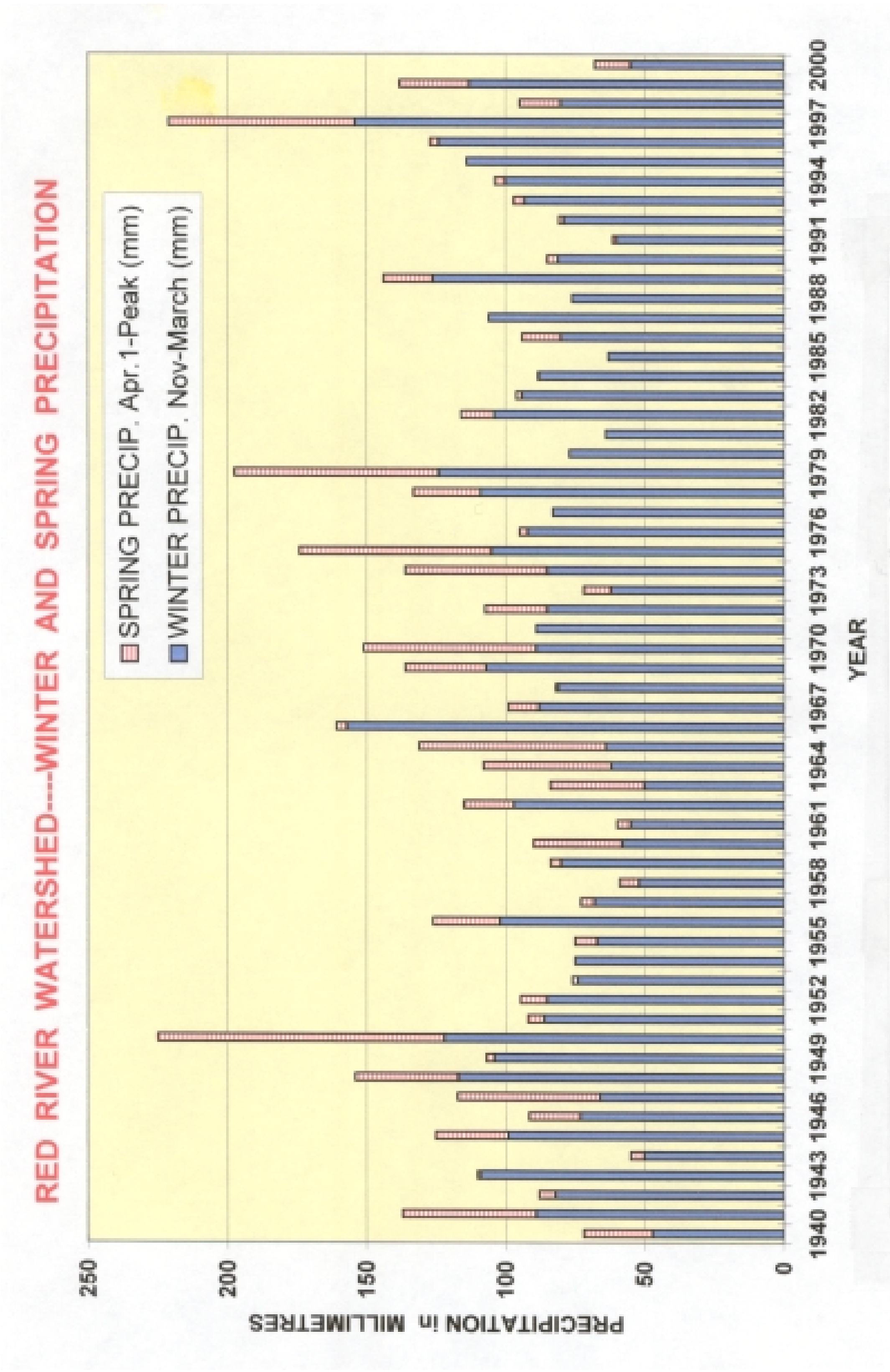


Figure 4.3 Inter-annual variation of winter and spring precipitation over Red River watershed, 1940-2000 (A.A. Warkentin, Manitoba Water Resources, Winnipeg)

April 1997 in southern Manitoba led to the extensive flooding in and around Winnipeg during the third week of April 1997.

The sequence of weather and climatic events that led to the 1997 Red River flooding appear to be part of natural climate variability. There is no discernible global warming signal in the Red River flooding event of April 1997. According to Warkentin (personal communication), the return period of the 1997 Red River flood has been estimated at about 97 years at present. The recent data (1998-2000) of Figure 4.3 do not show any increasing trend for the winter and spring precipitation over the Red River watershed.

4.5 Ice Storms & Freezing Precipitation

Ice storms and associated freezing precipitation is an extreme weather event which can and does occur almost anywhere any Canada (Stuart and Isaac, 1999). The eastern Canadian provinces and the Ontario/Quebec corridor in and around the Ottawa River are the regions associated with maximum occurrences of freezing rain and ice storms. In western Canada, freezing rain occurrences are often reported around the Hudson Bay region during spring and early summer. In the southern regions of the Canadian prairies, ice storm and associated freezing precipitation is not a common weather event and is therefore not considered as a major weather hazard.

The ice storm that hit the Ottawa-Montreal region for a 5-day period in January 1998 is considered one of the costliest natural disaster in Canada with damage estimated in excess of 1 billion dollars. This storm dubbed as “Ice Storm’98” has often been referred to in news media and Canadian government documents as an example of possible impact of global warming on future Canadian climate. A study on the Ice Storm’98 and related storm climatology has been recently reported by Higuchi, Yuen and Shabbar (2000). A brief discussion of the storm morphology and its assessment in the context of the present study is given below:

The ice storm’98 was caused by a combination of meteorological factors, brought together by the strong El Nino event of 1997/98 which has been described in several recent papers (for example, Khandekar et al., 2000; Arun Kumar et al., 2001). An unusual combination of two low-pressure synoptic weather systems occurring in quick succession and aided by the El Nino phase, produced a persistent flow pattern in the area of Ottawa/Montreal, where a significant moisture flux was converging from the Gulf of Mexico along a southerly flow. A high pressure region over northern Quebec helped advect cold air along a southwesterly trajectory into the area. The cold air advection at the surface together with warm moist air from the Gulf of Mexico as well as from the western tropical Atlantic produced a freezing precipitation of between 60 and 100mm in some regions of the area (see Figure 4.4). The persistency of the flow patterns, aided by the extreme warm phase of the El Nino and a favorable phase of the North Atlantic Oscillation (NAO) produced the most intense freezing precipitation event over the Ottawa-Montreal region (Higuchi et al., 2000). A climatological study of ice storms in the Ottawa/Montreal region (Milton and Bourque, 1999) reveals that many of these events are associated with flow patterns as discussed by Higuchi et al., and these ice storms often produce freezing precipitation amounts from 25 to 50mm.

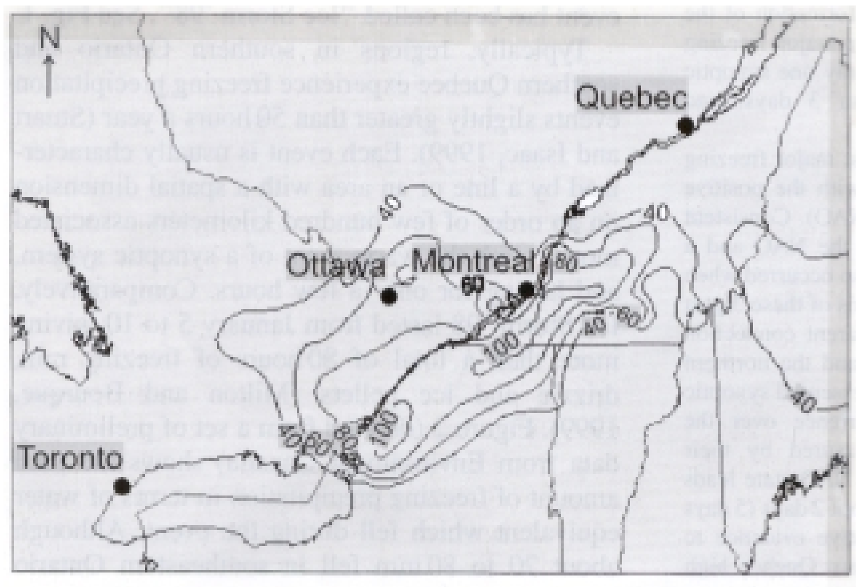


Figure 4.4 Top – Distribution freezing precipitation accumulation in terms of water equivalent in mm, during the Ice Storm 1998, January 5-10 (Higuchi et al., 2000). Bottom – Map of worst-hit areas during Ice Storm 1998 (Maclean's Magazine, January 19, 1998)

In summary, the Ice Storm'98 was the most intense of the several ice storms which have occurred in the Ottawa/Montreal region in the last 30 to 40 years. The unique feature of the Ice Storm'98 was the formation of two low-pressure weather systems in quick succession which were aided by the extreme phase of the 1997/98 El Nino and a favorable phase of the NAO. Based on the recent study by Higuchi et al., and other recent studies on ice storm climatology, it is concluded here that the linkage between global warming and climate change and the development of the Ice Storm'98 has not been established. Further, there does not appear to be any increasing trend in ice storms in eastern Canada at this point in time. For the Canadian prairies, ice storms and freezing rain are not a major concern as extreme weather events.

Chapter Summary: Among the large-scale weather events that have significant impact on the Canadian climate, are the winter blizzards on the prairies, ice storms in Quebec and in eastern Canada, spring floods and summer rainstorms. The winter blizzards are definitely on the decline, in frequency as well as in intensity on the Canadian prairies. The Red River Flood in Winnipeg in 1997, the Ice Storm in Ottawa/Montreal in 1998 and the Saguenay (Quebec) flood in 1996 all appear to be part of natural climate variability and the linkage to the global warming of recent decades has not been established. Large-scale extreme weather events like blizzards, ice storms and floods do not appear to show any increasing trend anywhere in Canada, at this point in time.

5.0 SUMMARY AND CONCLUDING REMARKS

The main purpose of this report is to critically examine recent studies on extreme weather events in Canada and make an assessment on trends and changes in these events in the context of global warming and climate change. According to the terms of reference of this report, the focus of the study is on Alberta and the Canadian prairie provinces. Several findings of this study are listed below:

5.1 Summary of Important Findings

The minimum temperature has increased everywhere in Canada, excepting the extreme northeast region of Labrador and Newfoundland, over the last fifty years. Over the prairies, there has been a significant reduction in extreme cold spells in winter. The maximum temperature has increased during winter and spring over a large region of western and southern Canada extending from Yukon to southern prairies and southern Ontario. The maximum summer temperature has remained unchanged over the last fifty years, while it has declined a little over the prairies during the last decade. *Canada as a whole is not getting hotter, but less cold.*

Total precipitation over Canada as a whole has increased by about 12% in the Twentieth century, however most of this increase is primarily due to low to moderate intensity precipitation events. *There is no identifiable trend in extreme precipitation (frequency or intensity) during the last century.* Over southern Canada south of 60^0 N, the fraction of precipitation falling in “heavy” events has decreased by over 4%, while over north central Canada (north of 60^0 N) the fraction of heavy precipitation has increased by about 5% but this increase is based on a relatively shorter dataset of about 50 years. For Alberta, the annual precipitation has increased by about 10% while the July precipitation has increased by about 12%.

Tornado and associated thunderstorm occurrences appear to be on the increase but this is primarily due to increased awareness and reporting of these events in recent years. A careful assessment of available data indicates that tornado count on the prairies while showing year-to-year variability does not show any increasing trend at this point in time. There is no definitive study available at this time on thunderstorm inter-annual variability over the Canadian prairies.

The frequency and intensity of winter blizzards are on the decline on the prairies during the last forty years. A recently completed study has analyzed inter-annual variation of intense windstorms and associated strong winds on the prairies over a period 1880-1984. The study documents frequent occurrences of windstorms and strong winds during the years 1920-1940, these years being identified by climatologists as the dust bowl years of the prairies. Since the 1940s, there has been a steady decline in the occurrences of windstorms and strong winds on the prairies.

An analysis of droughts on the prairies reveals that some of the extreme and recurring droughts on the prairies occurred during the dust bowl years from 1920s through 1930s. In recent years the prairies have experienced droughts in the mid-eighties and in the last three years or so. An assessment of the drought occurrences suggests that most of the prairie droughts are associated with either a cold phase or a rapid transition from a warm to a cold phase of the ENSO cycle.

The most recent drought of summer 2001 appears to be associated with the cold (La Nina) phase of the ENSO cycle.

An analysis of some of the recent extreme weather events, Saguenay region flood (July 1996), Red River flood (April 1997) and Ice Storm-Ottawa/Montreal (January 1998) suggests that these events are part of natural climate variability. The linkage of these events to the global warming of the recent years is not clear. A further assessment of these and related extreme events suggests that there is no increasing trend in these events over any region of Canada at this point in time.

Extreme weather events (blizzards, extreme cold/hot spells, thunderstorms and associated tornadoes, droughts/floods) do not appear to be increasing on the Canadian prairies at this point in time.

5.2 Extreme Weather and IPCC Projections: Present and Future

The most recent IPCC report (IPCC, 2001) has made estimates of confidence in observed and projected changes in extreme weather events and climate events. According to these estimates (see Table 1), some of the extreme weather events (e.g. higher maximum temperature and more hot days; higher minimum temperature and fewer cold days; more intense precipitation events; increased summer continental drying and associated risk of drought) are likely to be observed in the latter half of the 20th century and very likely to be observed during the 21st century. In the light of what has been summarized above, it appears that many of the IPCC general projections are not reflected in observations over Canada so far. For example, summer months in Canada in general and over the prairies in particular have not become hotter during the 1990s. It is the higher minimum temperature over most regions that has boosted the mean temperature over Canada as a whole and not the summer maximum temperature as has been suggested. Also, precipitation events are not getting more intense anywhere in Canada including the prairies. The estimates of confidence provided in Table 1 for the observed changes in extreme events during the latter half of the 20th century are based on a limited number of studies so far (IPCC, 2001, Ch.9) and do not specifically refer to any Canadian regions. Nevertheless, it is of interest to note that the projections of some of the extreme events are not seen in the trends of observed data of the recent decades over the prairies, as well as over the rest of Canada so far.

Some of the changes in extreme weather events discussed in Table 1 are ‘very likely’ to be observed during the 21st century, although the precise timing of occurrence of these changes remains highly uncertain at this time. An often quoted study (Kharin and Zwiers, 2000) obtains estimates of changes in extreme events for the period 2040-60 and beyond. For climate change assessment over the next two decades, Kharin and Zwiers’ study is of very little utility. Based on an assessment of recent studies on trends and changes, it appears that for Canada and the prairies, the likelihood of increasing incidences of extreme weather events in the next twenty years is rather small.

5.3 Data Gaps and Future Research Needs

For Canada as a whole, several aspects of extreme weather events have not been fully assessed as yet due to unavailability of long period of data and an analysis of their inter-annual variability.

For the Canadian prairies, the database on thunderstorms and tornadoes is inadequate at present. These severe weather phenomena, being much more common in the USA, have been extensively studied using a much larger (and a longer) database that is readily available over many regions of the USA. Two recent studies by Changnon (2001a,b) provide a comprehensive analysis of thunderstorms and associated rainfall, hail and wind damage and their inter-annual variability over the conterminous USA based on one hundred years of data. In Canada, data on thunderstorms and related severe weather activity (tornado, hail, wind) are available on a much shorter time frame, about 20 to 30 years. Further, very few comprehensive studies on inter-annual variability of these severe weather events on regional to smaller spatial scales are available at this point in time.

Another area of data and knowledge gaps is the urban and regional scale flooding and streamflow patterns associated with intense precipitation events in various parts of Canada. A recent study on Canadian stream-flow (Zhang et al., 2001) analyzes available data on stream-flow and obtains a significant decrease in the annual mean flow in the southern part of Canada as a whole. In northern Canada (north of 60°N) where data coverage is sparse, the fraction of heavy precipitation is reported to have increased in recent years; however, shorter length of data and inadequate spatial coverage makes it difficult to assess precipitation impact on stream-flow patterns and on long-term trends. There is a need to improve our database in the north and develop improved understanding of long-term trends in the context of global warming and climate change.

6.0 CONCLUSION

The perception that global warming and climate change would lead to increase in extreme weather events appears to be inconsistent with observation in the Canadian prairies so far. There is need to continue monitoring trends of extreme events, particularly for assessing inter-annual variability of such events on the regional and smaller spatial scales. A recent study for the United States (Changnon, 2002) shows that economic loss values due to weather extremes, when adjusted to societal changes, do not indicate a shift due to global warming. A similar conclusion has been drawn by Pielke, Jr. (2002) while assessing US flood damage against societal wealth. The economic impacts of weather extremes and the linkages to global warming and/or societal changes need to be more accurately assessed for Canada and the prairies.

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