CANADIAN PRAIRIE DROUGHT:

A CLIMATOLOGICAL ASSESSMENT

Alberta Environment

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SUMMARY

This report presents a climatological analysis of Canadian prairie droughts based on 20th-century data. The report further analyzes the driving forces of drought and develops an empirical technique for monitoring and predicting future droughts. The climatological analysis suggests that droughts of varying intensity and duration have occurred on the North American prairie regions for many centuries, long before instrumental records became available. Analysis of tree-ring data reveals that some of the worst droughts occurred on the North American prairies in the 13th and 16th centuries. Droughts of single- or multi-year duration have occurred on the Canadian prairies throughout the 20th century. Some of the severest droughts occurred during the 1920s and 1930s, a period often referred to as the dust bowl years. The recent droughts of the 1980s and late 1990s are comparable to some of the droughts of the dust bowl years.

Large-scale atmospheric circulation patterns, primarily driven by the SST (sea surface temperature) distribution over the equatorial Pacific as well as over the central and eastern North Pacific, appear to be the most important drought driving forces. The cold (La Nina) phase of the SST distribution in the equatorial Pacific and its persistence appears to be the most important precursor for drought occurrence on the Canadian prairies. The SST pattern over the central and eastern North Pacific plays an important but secondary role in the development of circulation patterns conducive to spring and summer drought on the Canadian prairies.

The first half of the 20th century experienced several persistent droughts that lasted for several consecutive years. It is possible that some of the early 20th-century prairie droughts were driven by the anomalous climate that prevailed over North America before and during the dust bowl years. Some of the well-known droughts (e.g., 1916/17, 1936/37) may have been activated by solar forcing. Some of the single-year droughts (1961, 1988) may have been influenced, in part, by remote forcing from the Asian monsoon system. There does not appear to be any link between recent droughts and the observed warming of the earth's surface.

Appropriate monitoring of various large-scale atmospheric/oceanic indices can provide useful guidance for forecasting future drought with a lead time of three to four months.

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ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

1.1 A Brief Overview Of Drought In North America

Droughts have been recurrent events in North America throughout the period of instrumental measurements of the last 100 to 150 years. An analysis of tree ring data, well before the instrumental measurement period, indicates that North America has experienced droughts for many centuries over in the past (Fritts, 1965; Landsberg, 1975;1982). In the book *North American Droughts* (Rosenberg, 1978), a listing of major drought periods from the 13th century to the 1950s is deduced from tree ring data in the mid-western state of Nebraska in the U.S. This list identifies 12 droughts lasting 10 years or longer, three lasting 20 years or longer, and the longest drought, lasting 38 years, is inferred to have occurred toward the end of the 13th century. In a recent paper, Woodhouse and Overpeck (1998) present an overview of 2000 years of drought variability in the central U.S. and document several major droughts in the 13th and 16th centuries.

In the 20th century, some of the most significant and persistent droughts over the U.S. and Canadian prairies were during the 'dust bowl' years of the 1920s and 1930s. The drought years of 1919–21, 1929–31, and 1936–37 have been well identified, especially in southeastern Alberta and southwestern Saskatchewan. This region of the Canadian prairies is part of the well-known Palliser triangle (named after the British explorer, Captain John Palliser), which is part of the Great Plains of North America. As discussed later, the years 1910–1940 saw generally reduced precipitation, especially during the growing season (April–June), over many locations in and around the "dry belt" of the Palliser triangle. The dust bowl years of the 1920s and 1930s have been followed other single-year droughts, for example, 1961 and 1977. The last 25 years have seen a couple of multi-year droughts in the mid-1980s and more recent droughts in 2001 and 2002.

The recurring droughts during the dust bowl years led to the creation of a Canadian government agency called the Prairie Farm Rehabilitation Administration (PFRA) in 1937 (PFRA, 1998; Sauchyn and Skinner, 2001). The main role of the PFRA was to assist prairie farmers with agricultural and weather-related expertise to help mitigate the impacts of drought.

Unlike most other natural disasters, prairie drought is not generally associated with catastrophic injury and death. However, prairie droughts have had disastrous impacts on Canada's grain industry and on environmental and socioeconomic conditions in the prairie provinces. Typically, a drought can affect an area of one million square kilometres (~260 thousand square miles) on the Canadian prairies and can last for several weeks to months. Some of early 20th-century droughts lasted for several years in a row during which mean precipitation was below normal for several consecutive seasons over various locations on the Canadian prairies. The single-year droughts of 1961 and 1977 were widespread and characterized by significantly reduced precipitation at a number of locations on the prairies for several months in each of those two years.

Drought affects not only the multi-billion dollar grain industry, but other sectors of the prairie economy as well. According to the Canadian government's *Discussion Paper on Drought in*

Western Canada, the 1977 drought in western Canada cost over $100 million in additional electric power generation costs, $20 million in unanticipated fire-fighting charges, $10 million in emergency federal and provincial drought programs, plus losses in tourism and costs of additional water treatment. The recent drought of 2001 was adjudged to be the third most severe drought in the last 50 years and produced an estimated shortfall of $4 billion in grain revenues (Garnett, 2002). Besides the economic losses, a drought can cause considerable social impact on the prairie farmers as well as other inhabitants. The social, economic, and political impacts of drought in the mid-western U.S. have been discussed succinctly by Rosenberg (1978).

1.2 Purpose and Scope of the Present Study

A number of studies on Canadian and U.S. prairie droughts have been reported in recent years: notable among these are studies by Maybank et al., 1995; Sauchyn and Skinner, 2001; Woodhouse and Overpeck, 1998; and Trenberth et al., 1998. These and numerous other studies reported in the last 25 years or more have helped document single- and multi-year droughts of the 20th century. A few of the studies (e.g., Diaz, 1983; Stockton and Meko, 1983) identified certain cyclical patterns in drought occurrences. These cyclical drought occurrences were linked to solar influences through sunspot cycles in a number of studies reported in the 1970s and 1980s, including studies by Currie (1984, 1990, 1991). Studies by Mitchell et al. (1979) and others suggest 11-year and 22-year cycles in the occurrence of droughts in a long series of rainfall data on the American prairies. Some of the notable droughts of the dust bowl years, for example, 1917, 1931, and 1937, appear to have been linked to the Hale sunspot activity as analyzed in a number of studies by Currie and others. Despite these studies, the mechanisms of recurring droughts of the 1920s and 30s are still not fully understood. According to Rasmussen (1988), "we have yet to understand why the climate of North America was so anomalous during that particular period from the 1920s through 1930s."

Since the publication of seminal papers by Bjerknes (1966, 1969), there have been a large number of studies on the impacts of ENSO (El Nino–southern oscillation) on North American weather and climate. For the Canadian prairies, studies by Garnett and Khandekar (1992), Shabbar and Khandekar (1996), Shabbar, Bonsal and Khandekar (1997), among others, have shown the impacts of ENSO and its warm and cold phases on the temperature and precipitation patterns over southern Canada and, in particular, on grain yields on the Canadian prairies. In a few recent studies (Mantua et al., 1997; Garnett, Khandekar and Babb, 1998; Garnett, 2002), some of the large-scale atmospheric and oceanic flow patterns like ENSO, PNA (Pacific North American), PDO (Pacific decadal oscillation) are recognized as having significant influences on winter and spring weather on the Canadian prairies and possibly on summer precipitation and drought occurrence. In another recent study (Castro et al., 2001), the SST (sea surface temperature) patterns in the equatorial Pacific and in the eastern North Pacific were found to influence large-scale atmospheric flow patterns which, in turn, can produce dry and wet years in the North American summer monsoon and drought or flood conditions on the U.S. and Canadian prairies.

The purpose of the present study is to identify the major drought years (single- or multi-year) of the 20th century and analyze these drought years in the context of large-scale atmospheric and oceanic circulation patterns. Such an analysis is aimed at providing an improved understanding of the driving forces behind drought. Based on this understanding, a simple empirical procedure is proposed to predict and monitor an oncoming drought on the Canadian prairies with a lead time of three to six months.

The recent drought years on the prairies, in particular 2001 and part of 2002, have prompted suggestions that these drought conditions may be linked to the global warming/climate change issue that is being debated extensively in the scientific community as well as in news media (e.g., IPCC, 2001; Khandekar, 2000, 2002). The present study undertakes a specific analysis of droughts of recent years in the context of the large-scale global warming and climate change issues.

This report is arranged as follows: Chapter 2 presents analytical descriptions of some of the major droughts of the 20th century. In Chapter 3, drought driving forces and mechanisms are discussed. An analysis of recurring droughts of the 20th century in the context of large-scale flow patterns and indices is presented in Chapter 4, followed by a brief outline of an empirical procedure for monitoring and predicting a future drought event. The findings of the study are summarized in Chapter 5.

2.0 PRINCIPAL PRAIRIE DROUGHTS OF THE 20TH CENTURY: ANALYTICAL DESCRIPTIONS

Introduction: In this chapter, some of the principal droughts (either single- or multi-year) of the 20th century are identified and discussed briefly in terms of their impacts on agriculture and the socioeconomic structure on the Canadian prairies. In keeping with the primary focus of this study, the emphasis will be on the major persistent droughts. It may be mentioned here that the neighboring provinces, namely British Columbia to the west and Ontario to the east, have also experienced drought conditions of varying intensity in conjunction with a prairie droughts. This chapter primarily analyzes the severity of droughts on the prairies, but with occasional reference to British Columbia and Ontario since the driving forces of drought and the associated large-scale atmospheric flow patterns have definite impacts on these provinces as well.

2.1 The Palliser Triangle: The Most Drought-Prone Region of the Prairies

As mentioned in Chapter 1, some of the most severe droughts on the prairies occurred during the dust bowl years of the 1920s and 1930s. The first two decades of the of the 1900s experienced drought conditions in certain years or, in some cases, in multiple years; e.g., the years 1904–11 and 1917–19 appear to have had multi-year droughts, especially in the Palliser triangle area and also in south-central Alberta between Red Deer and Calgary. The Palliser triangle area, shown in Figure 2.1 (top), is probably the most drought-prone region of the Canadian prairies. Within this region is the so-called 'dry belt', considered to be one of the driest areas of Canada with average annual precipitation of only about 300 mm. The Palliser triangle also extends into the U.S. Great Plains as far south as Nebraska. The dry belt suffered a multi-year drought from 1917 to 1926 when rainfall was very uneven—years with adequate rainfall preceded and followed by years with very little rain. The uneven nature of prairie rainfall is discussed below.

Figure 2.2 shows rainfall variation for Medicine Hat (southeastern Alberta) during the early grain growing season (April–June) together with annual rainfall totals. This figure can be used to identify some of the multi-year droughts that occurred during the first four decades of the 20th century. Medicine Hat, located in the heart of the Palliser triangle, reflects the drought intensity in this drought-prone region of the prairies. It also reflects generally dry conditions in adjacent regions of Alberta as well as in the neighboring province of Saskatchewan and, to a lesser degree, southern Manitoba. For example, Swift Current (about 100 km east of Medicine Hat) shows multiple years of the 1904–09 and 1917–19 periods as generally dry years, but with varying drought intensities as measured by the well-known Palmer Drought Severity Index (PDSI) (Palmer, 1965).

Besides the first two decades of the 1900s, the 1920s and the 1930s experienced some of the more severe drought years, in particular the 1930s, which have come to be known as the dust bowl years of the U.S. and Canadian prairies. The most severe drought years of this period were 1929–31 and 1936–37. According to Sauchyn and Skinner (2001), 1936

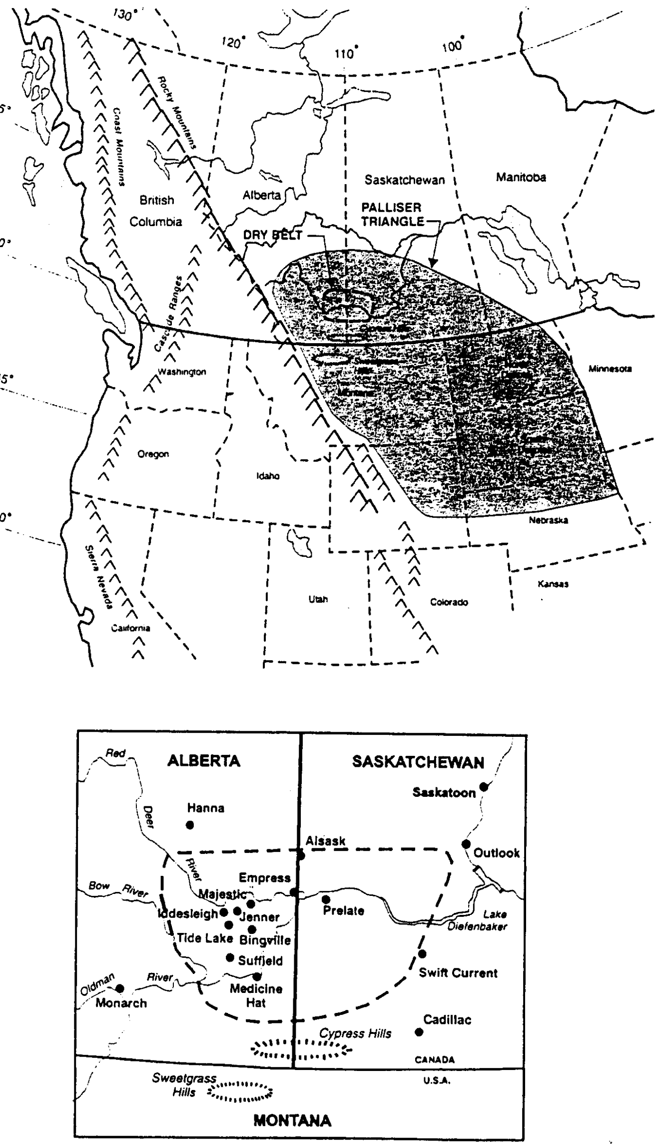

Figure 2.1 **(Top) The Palliser triangle region of the North American Great Plains, named after the British explorer John Palliser. (Bottom) The dry belt of southwestern Saskatchewan and southeastern Alberta, one of the most drought-prone regions on the Canadian prairies.**

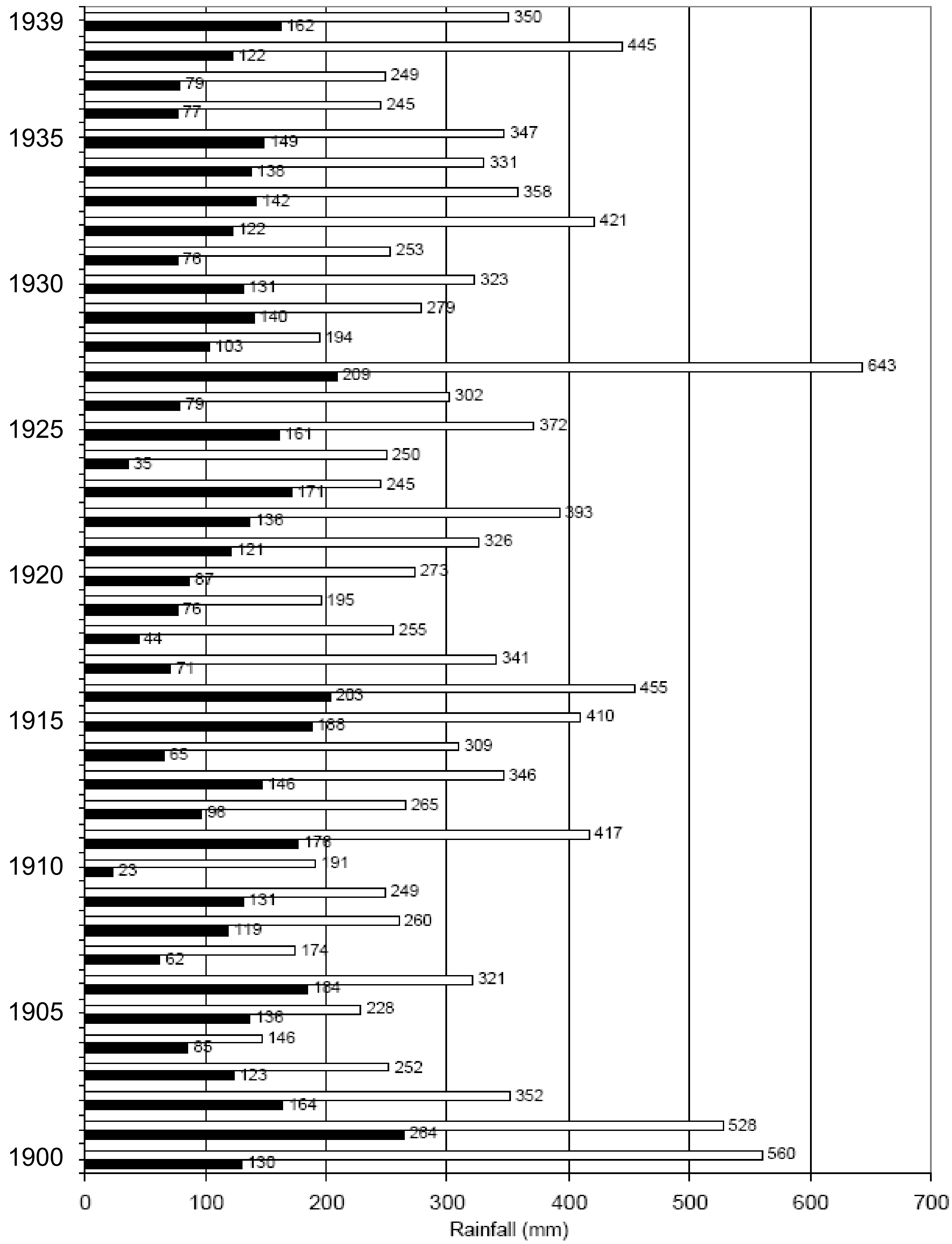

Figure 2.2 Growing season (April–June, shaded bars) and total annual precipitation in millimeters recorded at Medicine Hat, Alberta for the years 1900–1939

(adapted from Nemanishen, 1998)

and 1937 were probably the most severe drought years on the Canadian prairies in the 20th century. Once again, the Palliser triangle area suffered multi-year droughts during 1920–24, 1929–31, and 1936–40.

2.2 Successive Drought Years Identified using PDSI Values

The PDSI takes into account the soil moisture, rainfall, and temperature at a given location and can be computed using basic weather variables like temperature and precipitation. Calculation of PDSI and its use in determining the severity of drought is discussed in a technical report by Palmer (1965). A large number of papers and reports have been published since Palmer's report and several papers in the recent literature have discussed the utility of PDSI for determining the extent and severity of drought (for example, Heim, 2002). The PDSI is now generally interpreted as providing a good indication of a meteorological drought at a given location and over a given time period. Besides the PDSI, there are several other indices, for example, SPI (standardized precipitation index) and DAI (drought area index), that are used to define drought severity. The utility of some of these indices is discussed in a couple of recent papers (Heim, 2002; Keyantash and Dracup, 2002). The present study is aimed at understanding primarily the meteorological aspect of prairie drought and the PDSI appears to be a suitable index for such an analysis.

Monthly PDSI values at various locations on the Canadian prairies were made available by Walter Skinner of Environment Canada. Using these values, years of recurring drought for each of the three provinces were identified. Typically, a PDSI value of –3.0 or lower represents a moderate to severe drought condition while a value –4.0 or lower represents an extreme drought condition. Using these criteria, several multi-year droughts were identified and these years, together with their seasonal PDSI values, are shown in Figures 2.3 through 2.5.

A number of interesting features of the recurring droughts on the Canadian prairies are revealed in these figures. Southeastern Alberta and southwestern Saskatchewan, as mentioned earlier, are the most drought-prone regions of the prairies and show moderate to extreme droughts occurring throughout the 20th century, but especially during the first half of the century and, in particular, during the dust bowl years (1920s, 1930s, and part of the 1940s). Two locations, Medicine Hat and Swift Current, are representative of drought conditions in the Palliser triangle. Both locations show recurring droughts during the first half of the century, some of them lasting from five to eight years in succession. The years 1936–40 were severe drought years as indicated by strongly negative values of PDSI, particularly in southern Saskatchewan. Elsewhere, the droughts persisted from two to four years in general and were less severe (as measured by PDSI) than in the Palliser triangle region. The period 1945–1980 appears to have experienced fewer and also less severe drought occurrences, while the frequency of drought appears to have increased during the recent 1980–2001 period. Drought intensities in the more recent years (1999–2001) appear to have been greater in the western half of the prairies, especially in Alberta and parts of Saskatchewan. In general, the province of Manitoba experienced fewer and less severe droughts than the other prairie provinces during the 20th century.

The recurring droughts in the early part of the 20th century (i.e., 1904–11; 1917–22) were most severe and persistent in central and southeastern Alberta and southwestern Saskatchewan. These years also saw significantly reduced precipitation at several locations in British Columbia and northern Ontario. The recent droughts of 1999–2001 were not severe in central Manitoba, but drought impacts were widespread and felt in many locations from Vancouver to Ottawa.

The PDSI values also reveal some years that were associated with surplus precipitation (rain or snow) as indicated by positive values of PDSI for several months in a given year. In particular, the years 1927 and 1933 show high positive values of PDSI while some of the intervening years like 1929–31, appear to have been severe drought years. Also the recent years 1992–94 and 1996 show surplus precipitation at many locations on the prairies and also in British Columbia and southern Ontario. These years will be examined closely to assess some of the drought driving forces that can be identified using suitable indices of large-scale circulation patterns.

Notable among the single-year droughts are the years 1961 and 1977, both of which were years of widespread drought on the Canadian prairies. The 1961 drought may have been influenced by remote forcing from the Asian monsoon region; this aspect will be discussed in some detail later. The 1977 drought appears to be linked to the widespread drought on the American prairies and elsewhere in the U.S. (Felch, 1978).

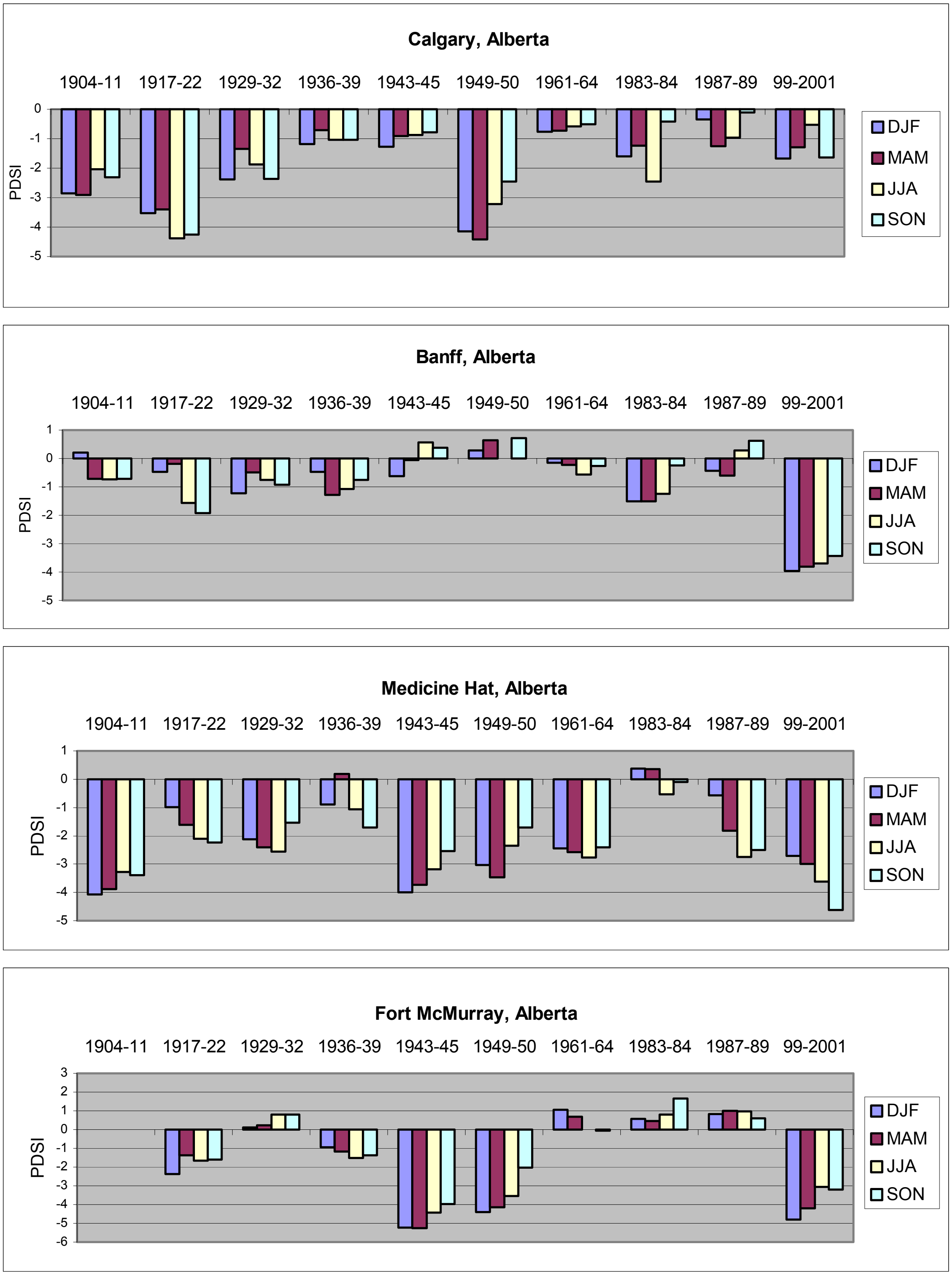

Figure 2.3 Seasonal variations in PDSI values at Calgary, Banff, Medicine Hat, and Fort McMurray, Alberta during years of recurring drought of the 20th century.

Each colored bar represents the average PDSI value for a designated three-month period averaged over the years indicated. Months are denoted in the legend by their first letters. PDSI values below –3 indicate moderate to severe drought.

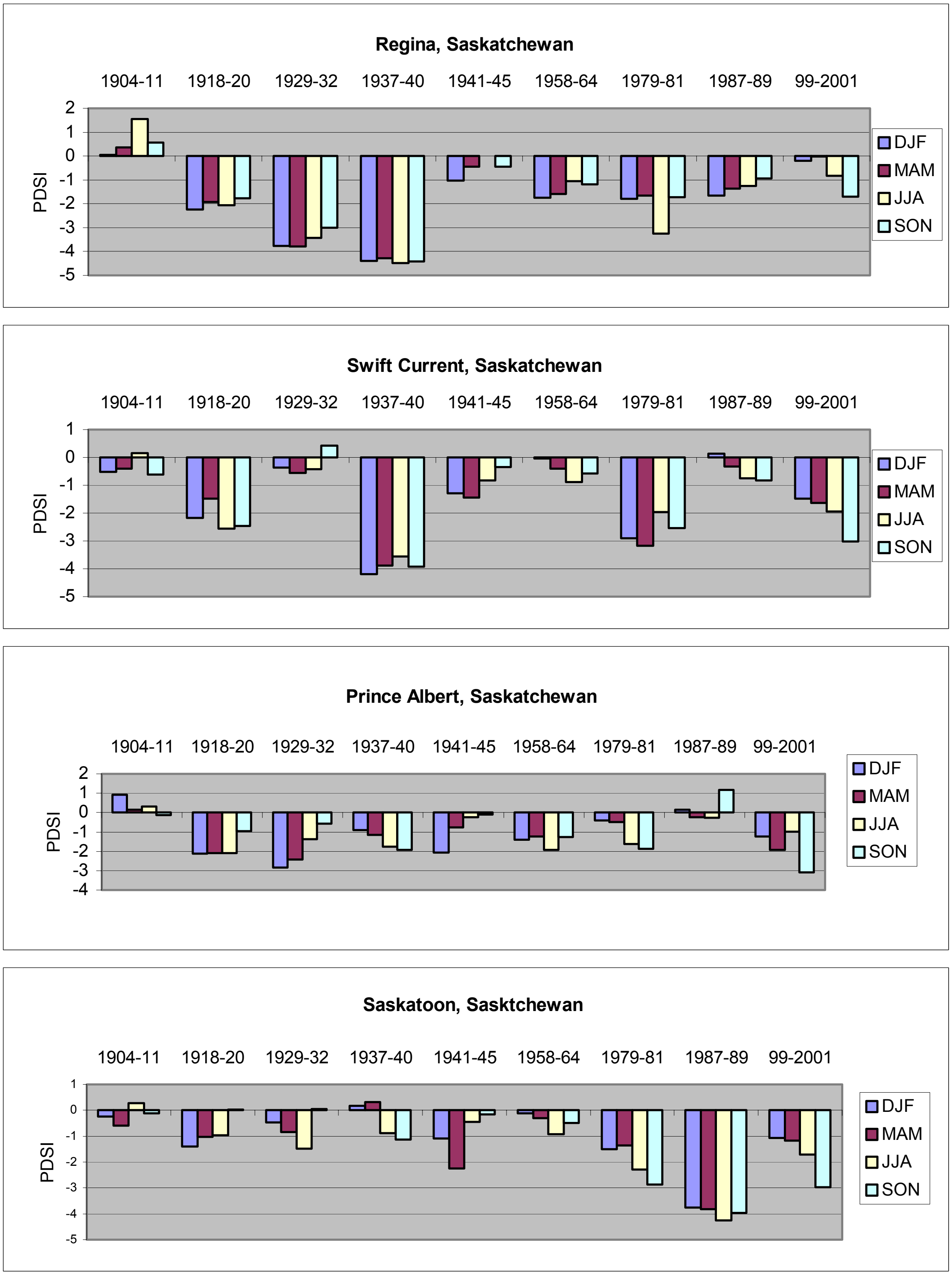

Figure 2.4 Seasonal variations in PDSI values at Regina, Swift Current, Prince Albert, and Saskatoon, Saskatchewan during years of recurring drought of the 20th century.

Each colored bar represents the average PDSI value for a designated three-month period averaged over the years indicated. Months are denoted in the legend by their first letters. PDSI values below –3 indicate moderate to severe drought.

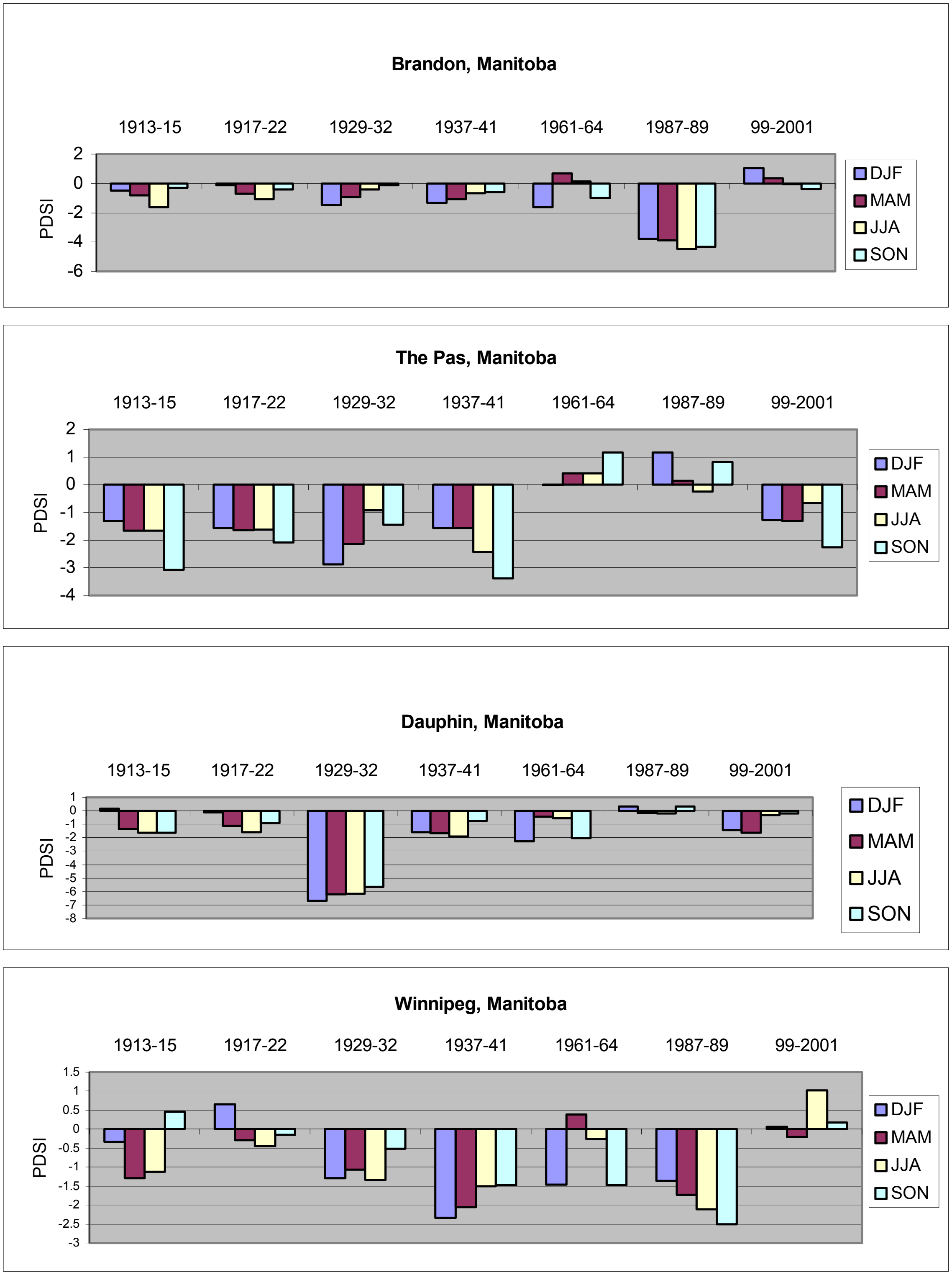

Figure 2.5 Seasonal variations in PDSI values at Brandon, The Pas, Dauphin, and Winnipeg, Manitoba during years of recurring drought of the 20th century

Each colored bar represents the average PDSI value for a designated three-month period averaged over the years indicated. Months are denoted in the legend by their first letters. PDSI values below –3 indicate moderate to severe drought

2.3 Socioeconomic Impact of Prairie Droughts

As mentioned earlier, even during extended droughts there has never been a direct and immediate threat of large numbers of deaths among humans, although the lack of drinking water has sometimes led to acute problems in the care of livestock. Extended droughts have, however, had disastrous socioeconomic impacts in terms of severe disruption of grain, food, and water supplies and have also had serious impacts on the Canadian economy. The early drought years of the 1920s and 1930s caused considerable hardship to a large number of farming communities on the prairies and even threatened the survival of the southern prairies as a viable economic region. The impact of recent droughts has been considerably softened through appropriate adaptive measures and management of available resources, owing, in part, to the efforts of PFRA and other agencies. Nevertheless, economic impact of drought can still be significant and requires mitigating actions by various levels of government.

The grain and agri-food industry on the Canadian prairies is now a significant component of the Canadian economy and a moderate to severe drought can inflict various levels of economic impact on the population in general. The Canadian prairie region is one of the world's major agricultural areas, producing about 25 million tons of wheat and over 45 million tons of grain including wheat, oats, barley, and canola (Canadian Wheat Board, 2001). As mentioned earlier (Garnett, 2002), the drought of 2001 resulted in an economic shortfall of $4 billion or more and required supportive measures from various governments. A close inspection of grain yield numbers reveals a similar shortfall in total yields during 1961 and 1977, both being severe drought years.

Chapter Summary: Based on a suitable drought index, the years of persistent drought on the prairies during the first half as well as during the latter half of the 20th century have been identified. Some of the drought years in the early part of the 20th century were also years of reduced rainfall at many locations in British Columbia and northern Ontario. The drought years of 1999 through 2001 appear to have been widespread in their impact from the west coast to central Canada, including parts of Ontario. The present analysis has also helped identify years of no drought or years with surplus precipitation.

The socioeconomic impact of prairie drought has been discussed briefly in terms of shortfalls in grain yields and resulting economic losses. Other important socioeconomic impacts are water shortages, increased energy consumption, the increased risk of forest fires, and the need for rehabilitation of farming communities. Many of these socioeconomic impacts are outside the scope of the present study.

3.0 THE DRIVING FORCES OF DROUGHT: UNDERSTANDING THE DROUGHT MECHANISM

Introduction: Several studies reported in the last 25 years or so have attempted to analyze North American prairie droughts and have linked a number of factors to the onset and evolution of single- or multi-year droughts. In a series of papers Namias (1960, 1966, 1978, 1982, 1983) analyzed droughts in various regions of U.S. and Europe and provided a partial explanation of the drought mechanism. In his 1983 paper "Some causes of the United States Drought", Namias (1983) states that *the immediate drought-producing mechanism almost always involves persistent and persistently recurrent subsidence of air(approximately a few hundred meters per day) which results in compressional warming and lowered relative humidity. Thus in warm-season droughts over the Great Plains of the United States, heat waves usually accompany drought and cloud development is retarded.* Namias further states that there are almost always multiple causes of drought in a given region of the U.S. and elsewhere, and while drought may be easily attributed to regional pressure and wind systems, physical understanding must include larger-scale atmospheric teleconnections and interactions between the atmosphere and abnormalities at its lower boundary, such as variation in sea surface temperatures, snow and ice cover, and the character of soil and its moisture content.

Many of the ideas mentioned above have been studied in greater detail in recent years and an improved understanding of the drought driving forces and the general mechanism of drought in the U.S. and Canadian prairie regions has been achieved. In the following discussion, we analyze some of the drought-related studies reported for the Canadian and American prairies.

3.1 Canadian Prairie Droughts and Large-Scale Circulation Patterns

Some of the notable studies on Canadian prairie droughts are those of Dey and Chakravarty (1976), Dey (1982), Bonsal et al. (1993), Bonsal and Lawford (1999), and Nkendirim and Weber (1999). The earlier studies of Dey and Chakravarty identify the presence of a mid-tropospheric ridge centered over the prairie provinces leading to extended dry spells and precipitation deficits during the summer season. The study of Bonsal et al. extends this idea and tries to develop a causal relationship between SST patterns over the North Pacific and extended dry spells over the Canadian prairies. Bonsal et al. find a certain configuration of SST pattern—anomalously cold water over an area between 140 and 160W longitude and centered around 30N latitude in conjunction with anomalously warm water off the coast of northern British Columbia—as favorable for the development of a mid-tropospheric ridge over the prairies. This ridge development, according to Bonsal et al., leads to extended dry spells and drought during the summer season. The conceptual SST pattern proposed by Bonsal et al. is shown in Figure 3.1. In a more recent study, Bonsal and Lawford (1999) examine the roles of El Nino and La Nina in the occurrence of extended dry spells over the Canadian prairies.

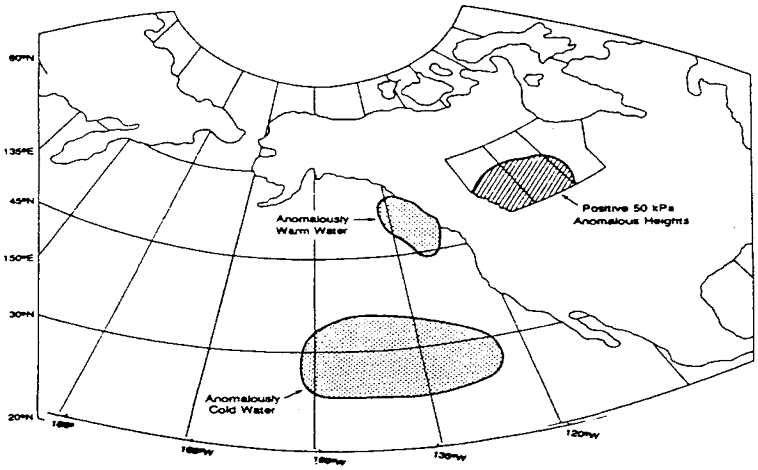

Figure 3.1 Schematic diagram showing the typical SST (sea surface temperature) pattern in the North Pacific Ocean and the typical 500-hPa (50-kPa) anomaly pattern over the Canadian prairies associated with extended dry spells during the spring and summer (from Bonsal et al., 1993).

The influence of large-scale atmospheric and oceanic flow patterns on Canadian prairie weather and climate and specifically on prairie grain yields has been reported in several studies in the last 10 years or so (Handler, 1990; Garnett and Khandekar, 1992; Garnett, Khandekar, and Babb, 1998; Bonsal, Zhang, and Hogg, 1999; Garnett, 2002). These and other related studies (Shabbar and Khandekar, 1996; Shabbar, Bonsal, and Khandekar, 1997) have shown that, in general, El Nino (La Nina) events in the equatorial eastern Pacific are associated with drier (wetter) winter months immediately following these events and wetter (drier) spring to summer months on the Canadian prairies. This analysis has also led to a hypothesis, now generally accepted, that El Nino and La Nina play important roles in Canadian prairie agriculture. Handler (1990), Garnett and Khandekar (1992), Hsieh et al. (1999), and others have shown that, in general, rains and grain yields (corn in the U.S. and wheat in Canada) are higher during the summer following an El Nino event while rains as well as grain yields are lower in the summer following a La Nina event. The linkage between El Nino/La Nina and prairie drought will be discussed in greater detail in Chapter 4. The study by Bonsal, Zhang, and Hogg (1999) analyzes variability in summer precipitation amounts on the prairies and attempts to link this variability to large-scale atmospheric flow patterns and to mid-tropospheric (500-hPa) trough/ridge formation at the beginning of the summer season over the prairies. A schematic from Bonsal et al. (1999) shown in Figure 3.2 shows the composite northern hemisphere 500-hPa circulation patterns associated with the driest and wettest May and June on the Canadian prairies.

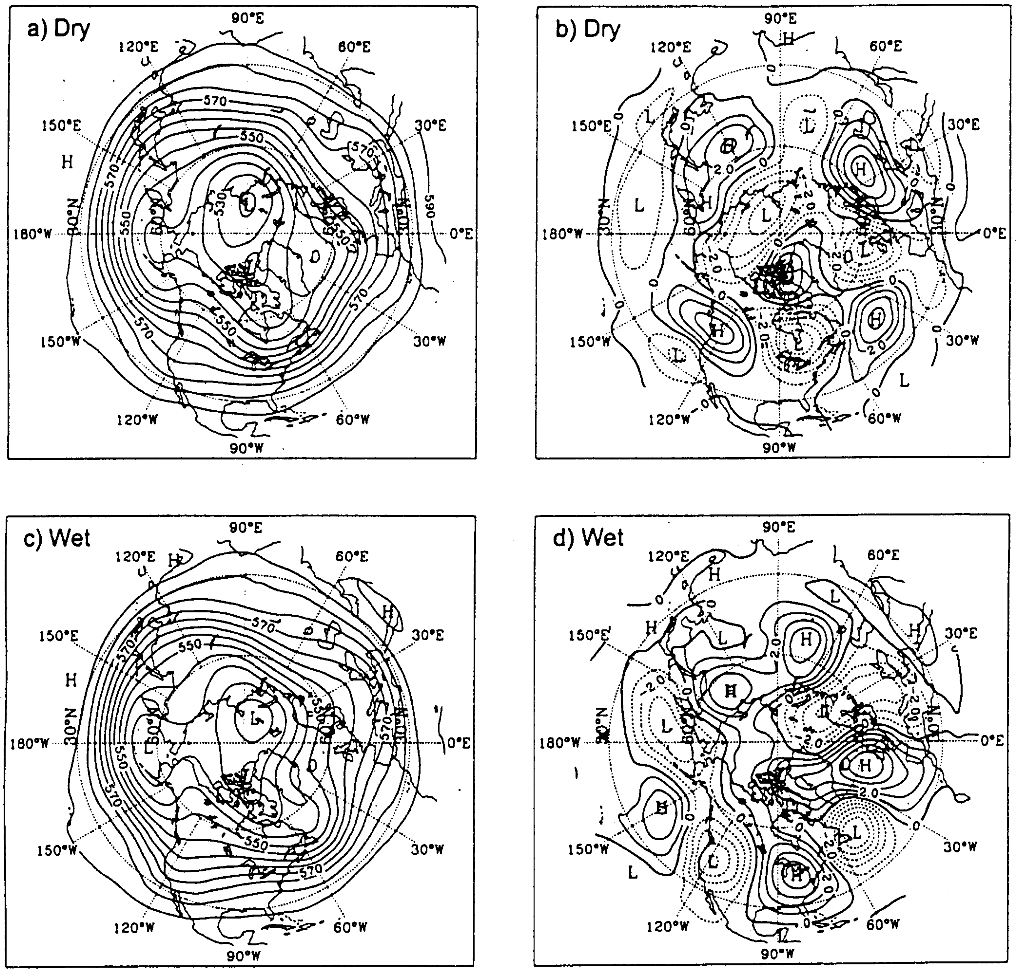

Figure 3.2 Composite northern hemisphere 500-hPa patterns associated with driest and wettest spring months (May and June) on the Canadian prairies from 1946 to 1996.

Top (a,b): Circulation and anomalies for dry cases. Bottom (c,d): Circulation and anomalies for wet cases (from Bonsal et al., 1999).

The NAO (North Atlantic oscillation), an important large-scale oscillation, was first identified by Sir Gilbert Walker in his pioneering studies (in the early 1900s) on the correlation between the Indian monsoon and worldwide weather elements. The NAO has been studied extensively in several recent papers (e.g., Hurrell, 1995; Hurrell and van Loon, 1997) and is now recognized as having a definite impact on temperature and precipitation patterns over eastern Canada (Wettstein and Mearns, 2002). This impact is believed to extend occasionally into central Canada and the eastern prairies. Some of the possible impacts of the NAO on prairie weather will be discussed later in the context of developing a simple empirical technique for monitoring and predicting deficit/surplus precipitation seasons on the prairies. In the last 25 years, studies have identified several other large-scale atmospheric circulation patterns and defined them in terms of certain measurable indices. Notable among these studies are those by Wallace and Gutzler (1981) defining the PNA (Pacific North American) atmospheric flow pattern and by Mantua et al. (1997) identifying and defining the PDO (Pacific decadal oscillation).

In an attempt to utilize some of the large-scale atmospheric and oceanic indices, Garnett (2002) and Garnett et al. (1998) developed a simple technique to analyze the impact of accumulated values of selected indices on the summer temperature and precipitation patterns over the prairies. Using a database of 32 years (1965–1996), Garnett et al. (1998) obtained composites of accumulated PNA and SST indices, which appear to have forecasting skill with a lead time of 3 to 4 months for monitoring temperature and precipitation patterns over the Canadian prairies. Two such composites are shown in Figure 3.3, one with the accumulated PNA index and the other with the SST index. In both these composites, the indices were accumulated for about 10 months before the summer season (or the grain growing season) on the prairies. As can be seen from Figure 3.3, the composites provide distinctly different profiles for the hottest and coldest summers or for driest and wettest summers based on the 32-year data set. In a more recent study, Garnett (2002) found that accumulated values of Nino-4 SST values provide a useful indication of dry or wet conditions during the grain growing season in Saskatchewan. More discussion on the development of simple empirical forecasting techniques is presented in the next chapter.

3.2 Impact of Sunspot Cycles on Prairie Drought

As mentioned earlier, several studies, notably by Currie (1990, 1991), have linked solar activity to drought occurrence on the U.S. prairies and the Great Plains in general. Some of the severe drought years, notably 1917 and 1937, have been linked to sunspot cycles of 11 or 22 years. As an example, Figure 3.4 shows the cyclic variation in precipitation records from the mid-western U.S. state of Illinois. This figure suggests that the cyclical variation of dry and wet years on the western plains of the U.S. can be explained using epochs of maximum and minimum solar tidal forcing (M_N) of the atmospheric luni-solar cycle. As pointed out by Namias (1983), however, no satisfactory explanation or physical mechanism for a possible link between sunspot cycles and a specific atmospheric flow pattern leading to a drought or a wet season has been developed so far.

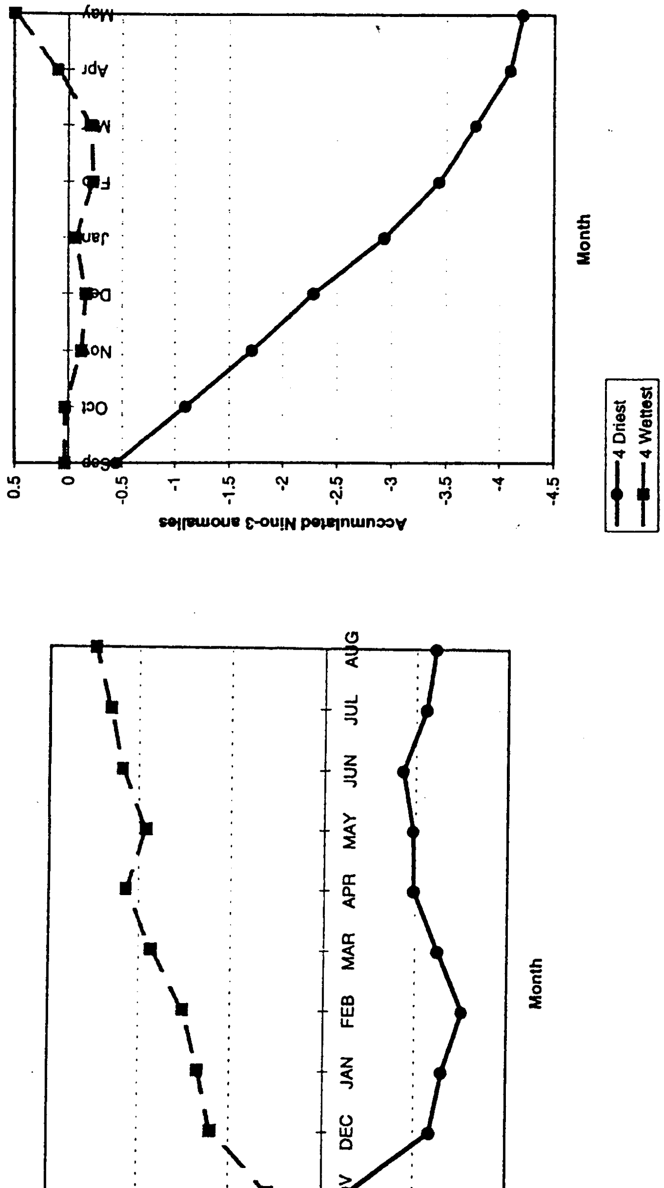

Figure 3.3 (Top) Composite of accumulated PNA index values for four hottest (1970, 1987, 1988, 1989) and four coldest (1969, 1985, 1992, 1993) June–July periods on the Canadian prairies. (Bottom) Composite of accumulated El Nino index values for four driest (1967, 1974, 1979, 1985) and four wettest (1970, 1971, 1991, 1993) June–July periods on the Canadian prairies.

Data used: 1965–1996 (from Garnett, Khandekar and Babb, 1998).

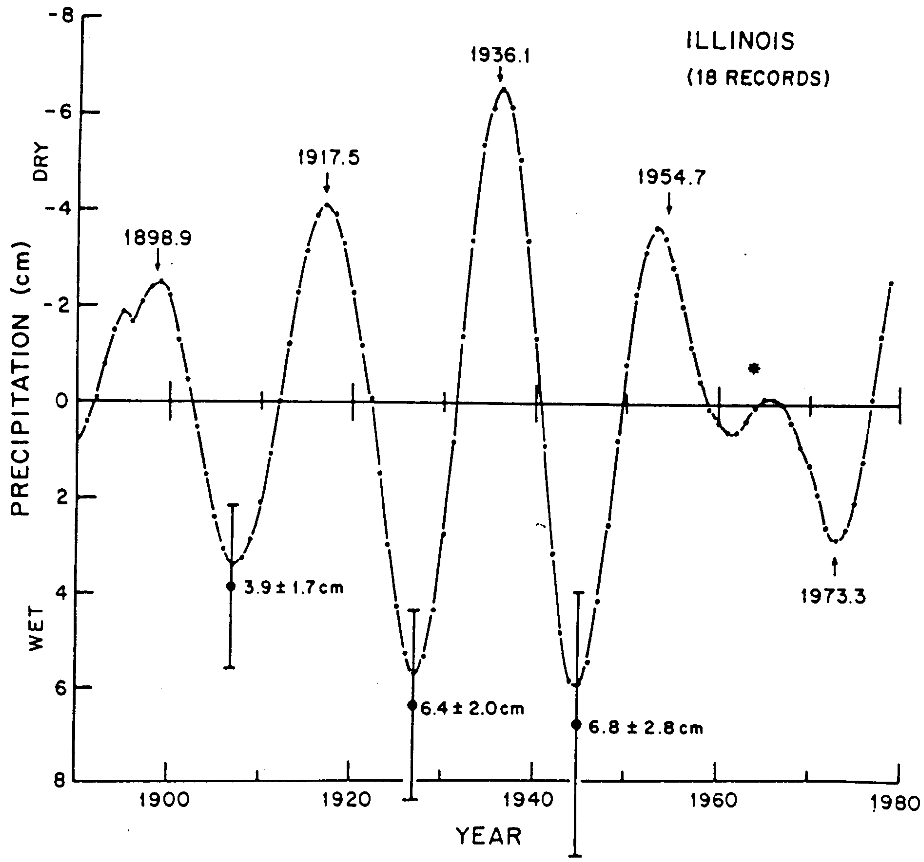

Figure 3.4 Cyclic variation of precipitation at 18 stations in Illinois using a maximum entropy spectrum analysis

The downward-pointing arrows and associated dates (1898.9, 1917.5, 1936.1, and 1954.7) mark epochs of maximum solar tidal forcing M_N of the atmosphere. The epochs are highly correlated with minima in luni-solar-induced precipitation and, by extension, to drought years in the U.S. mid-west (from Currie and O'Brien, 1990)

In a number of papers by Currie, impressive correlations between sunspot cycles and precipitation at selected locations in the U.S. corn belt and vicinity were presented. However, the lack of a plausible explanation based on atmospheric flow patterns makes the sunspot-drought connection elusive at this time, although several empirical procedures have appeared in American and Canadian farm newsletters and almanacs suggesting the use of sunspot cycles for predicting drought conditions.

The climatic anomalies of the early years of the 20th century and, in particular, during the dust bowl years (1920s and 1930s) are still not fully understood by meteorologists. Recent climate modeling efforts in the context of the ongoing global warming debate have included the influence of varying solar flux to simulate the rapid warming of the surface of the earth during the years 1910–1940 (for example, Meehl et al., 2003). Several other recent studies (Lean, Beer, and Bradley, 1995; Lean and Rind, 1998) have now identified changing solar radiation as an important mechanism of climate change. It is possible that some of the extreme droughts of the dust bowl years were triggered or made worse by solar flux variability. We discuss implications of solar flux variability for drought monitoring and prediction in Chapter 4.

3.3 A Review of Some Recent Studies

In the last 10 years, several important studies have been reported, notably those of Mo et al. (1997) and Trenberth and Guillemot (1996). on the drought of 1988 and the flood of 1993. These two years represent diametrically opposite summer weather patterns over the mid-western regions of Canada and the U.S. These and a few related studies have provided an improved understanding of the dramatically different flow patterns that can produce a drought (like that in 1988) and a flood (like that in 1993) over the North American Great Plains. A more recent study by Castro et al. (2001) analyzes the relationship of the North American monsoon to tropical and North Pacific SST patterns. The North American monsoon, a summer season of rains beginning in the southwestern state of Arizona and extending northward to the mid-western states along the U.S./Canada border does influence Canadian prairie weather during the grain-growing season. These studies have provided useful insight into the mechanisms responsible for drought. In a recent study on the cause of the 1930s dust bowl, Schubert et al. (2003) document presence of negative SST anomalies over the tropical Pacific and the North Pacific during the interval 1932–38. These authors suggest that a colder equatorial and north Pacific may be a precursor to recurring drought conditions on the prairie regions of North America.

Based on the discussion above, a conceptual model showing a schematic of large-scale flow patterns that could produce dry or wet summer seasons over the mid-western plains of Canada and the U.S. is presented in Figure 3.5. This model, based on the study by Castro et al. (2001), also includes the ridge/trough pattern of mid-tropospheric flow documented by Bonsal et al. (1999). In addition, the model incorporates remote forcing from the Asian monsoon region as a possible (additional) forcing mechanism for dry or wet summers on the U.S. and Canadian prairies. This conceptual model represents a significant improvement in the understanding of the impact of SST patterns of the equatorial Pacific and the central and eastern North Pacific on the atmospheric flow that governs dry or wet conditions over western Canada. The use of this model together with various indices representative of SST distribution in the Pacific is discussed in the next chapter.

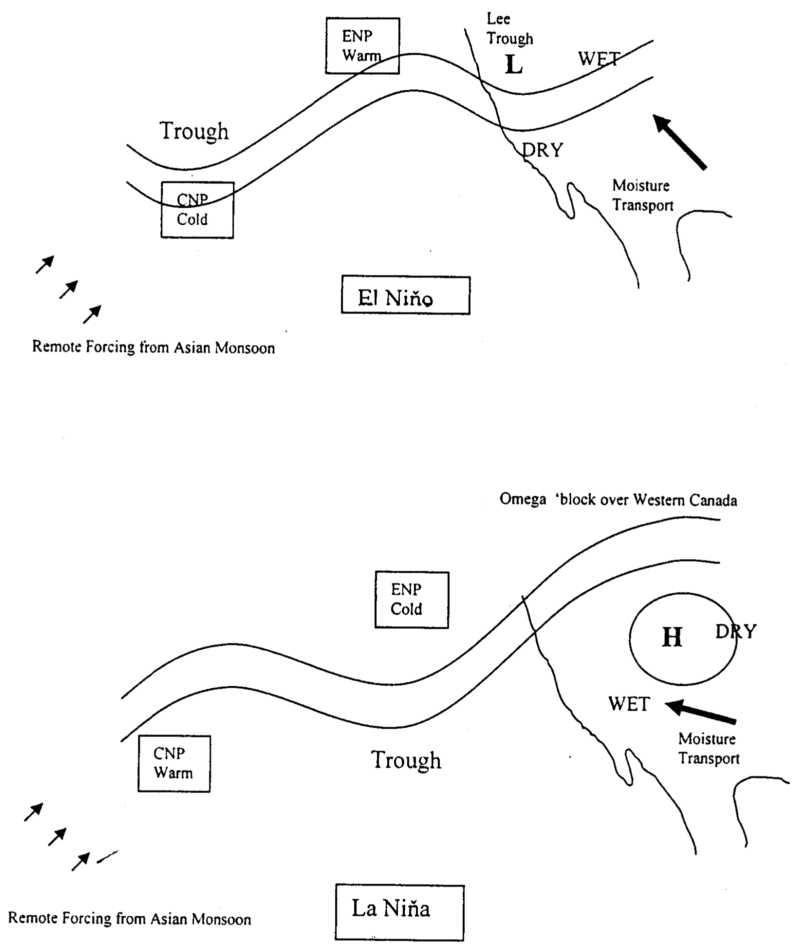

Figure 3.5 Conceptual model of large-scale atmospheric flow for a wet (top) and dry (bottom) summer on the Canadian prairies in conjunction with SST patterns over the equatorial Pacific and North Pacific

The wet summer is preceded by an El Nino event while the dry summer is preceded by a La Nina event in the equatorial Pacific and central and eastern North Pacific. CNP - central North Pacific; ENP - eastern North Pacific (adapted from Castro et al., 2001).

3.4 Drought Occurrence in the Context of Global Warming

The current debate on global warming and its possible impact on future climate has prompted suggestions that drought frequency on the Canadian prairies could increase in the future. This issue is complex and requires an in-depth assessment and analysis of long-term data on temperature and precipitation. In the context of the present study, an analysis of the PDSI values on the prairies has been done with respect to various periods of the 20th century. As mentioned earlier, drought frequency on the prairies was elevated during the period 1910–1940 and in particular during the dust bowl years, typically defined as the 20-year period from 1920 through 1940. A striking feature of this period was the recurrence of droughts lasting for periods of three or more years. During the second half of the 20th century there were a few notable single-year and two-year droughts like those in 1961, 1963/64, 1980/81, and 1988/89. During the early to mid- 1990s there were no major droughts, while the years 1992–94 and 1996 were generally associated with surplus rainfall over the prairies as well as in parts of British Columbia and southern Ontario. The droughts that occurred in 1999–2001 were severe in many parts of the prairies as well as in central and northern Ontario. The uneven rainfall distribution during the years 2002 and 2003 on the prairies cannot therefore be interpreted as either drought or wet years.

When the dry and wet years of 20th century are analyzed in the context of the observed warming of the earth's surface (see IPCC, 2001; Khandekar, 2000), it is tempting to argue that the recurring droughts in the first half of the 20th century may have been linked to the increasing temperature of the earth's surface. However, a careful analysis reveals that the early years from 1910 to 1940 were dominated by an anomalous climate pattern that is still not fully understood. Further, there is evidence that severe droughts have always occurred over the prairies from time-to-time (e.g., 13th and 16th centuries) and that these historical droughts were not linked to warming of the earth's surface. The 1990s, which were adjudged to be the warmest years of the 20th century, did not experience severe droughts, while there certainly were a few good rain years, e.g., 1992–94 and 1996. Thus, a meaningful link between global warming and prairie drought remains elusive at this time.

The droughts on the prairies during the 1980s were primarily governed by the warm and cold phases of the ENSO cycle (Khandekar, 2002) and may also have been linked, in part, to the solar cycle. The most recent drought years from 1999 to 2001 were almost certainly linked to the cold phase of the ENSO cycle. The link between global warming and recent droughts on the prairies, suggested by some of the climate model simulations, is not currently supported by observational evidence.

Chapter Summary: Large-scale atmospheric circulation patterns, which are primarily governed by the SST distribution in the equatorial Pacific and the central and eastern North Pacific, appear to have contributed the principal driving force for recurring drought throughout the 20th century. Drought occurrences during the first half of the 20th century may have been associated with climate anomalies over North America, especially during the dust bowl years of the 1920s and 1930s. The cyclical forcing of solar activity may have triggered or activated some of the well-known droughts of the early 20th century. Some of the individual drought years, like 1961 and 1988, may have been influenced by remote forcing from the Asian monsoon region as suggested in studies by Garnett et al. (1997) and Castro et al. (2001). Any linkage between global warming and drought does not appear to have observational support at this time.

4.0 DROUGHT MONITORING AND PREDICTION USING ATMOSPHERIC/OCEANIC INDICES

Introduction: Based on analysis of droughts on the Canadian prairies, it is now generally accepted that large-scale drought on the prairies of a long duration (a few weeks to several months, or longer) is primarily caused by a certain SST distribution in the equatorial Pacific and the central and eastern North Pacific. Various studies cited earlier have come to assess prairie drought as being linked to a cold phase of ENSO or a La Nina event in the central or eastern equatorial Pacific. A number of studies have identified the weather patterns and anomalies over North America that are generally associated with the El Nino and La Nina phases of the ENSO cycle. It is realized, however, that every El Nino or La Nina event is different from the previous one and that the El Nino and La Nina events can and do produce different and often unpredictable impacts, depending on the interaction of these events with existing atmospheric flow patterns. The weather patterns and anomalies produced by a particular El Nino event also depend on its strength and the way the event develops over the central and eastern North Pacific (Kumar et al., 2001). The interaction of a given El Nino event with atmospheric flow patterns can often be analyzed by simply using representative indices of well-known large-scale atmospheric oscillations and flow patterns. It is now well recognized that these large-scale flow patterns play an important role leading to dry and wet seasons over the Canadian prairies. In an attempt to develop some understanding of the drought mechanism, we now present a brief discussion of some of the indices used to represent large-scale atmospheric flow patterns and how they are related to weather patterns and anomalies over North America.

4.1 Indices of Large-Scale Flow Patterns that Influence North American Weather and Climate

Among the important phenomena that have been identified as influencing North American weather and climate are the ENSO, PDO, NAO, and PNA flow patterns. The indices used to characterize these flow patterns are described below. There may be other flow patterns, such as the AO (Arctic oscillation, which can and does influence weather and climate especially during the winter season over North America), however, in the present context, we will not consider any possible impact of AO on prairie drought.

ENSO: The El Nino–Southern Oscillation, introduced previously, is perhaps the best-known and most analyzed large-scale flow pattern. It has generated a large number of studies in the last 25 to 30 years. The ENSO index is a combination of the SST and SO (southern oscillation) indices, the SO being defined by Walker and Bliss in 1932 while working on seasonal forecasting of Indian monsoon using worldwide weather data. Recent studies by Ropelewski and others (Ropelewski et al., 1987, 1989; Kiladis and Diaz, 1989) have provided important background on the impacts of cold and warm events of the ENSO cycle on North American weather and climate. With respect to the Canadian prairies, it is now generally agreed that El Nino (La Nina) events are followed by warmer (colder) and drier (wetter) winter seasons and possibly wetter (drier) summer seasons, especially the early part of the grain growing season on the prairies (Shabbar and Khandekar, 1996; Shabbar, Bonsal, and Khandekar, 1997). Figure 4.1 shows the seasonal march of areally averaged composite standardized precipitation anomalies for southern

Canada for El Nino and La Nina events. This composite shows that precipitation decreases (increases) significantly during the winter months following an onset of El Nino (La Nina) 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 associated with increases (decreases) in summer precipitation on the prairies. The development and strength of the ENSO cycle is thus an important variable in monitoring and predicting prairie drought.

At present, the ENSO cycle in the eastern, central, and western equatorial Pacific is monitored based on SST index values over four regions, identified as Nino1+2, 3, 3.4, and 4 as shown in Figure 4.2. This figure also shows the variation of the SST index over the four Nino regions for the past 20 years or so. Together with SST pattern, the pressure oscillation of the ENSO cycle is measured in terms of SO, a slowly varying pressure oscillation over the eastern and western regions of the equatorial Pacific.

PNA: The Pacific North American atmospheric flow pattern, first defined by Wallace and Gutzler (1981), is a characteristic and persistent pattern that controls the weather and climate of North America, especially during the winter season. The PNA index is defined in terms of 70-kPa height anomalies and is a representative measure of mid-tropospheric atmospheric flow over the central and eastern North Pacific and North America. A positive value of the index suggests a more meridional flow over the eastern North Pacific and northwestern North America, while a negative value suggests a more zonal flow. These different flow patterns can result in weather and climate anomalies over the Canadian prairies.

The PNA flow pattern is definitely modulated by the warm and cold phases of ENSO. An evolving warm phase in the equatorial central and eastern Pacific produces a more zonal flow and consequently imparts a negative value to the PNA index, while during a cold phase the PNA flow pattern becomes more meridional and the PNA index more positive. Figure 4.3 shows profiles of accumulated values of PNA indices for El Nino, La Nina, and normal years in the equatorial Pacific based on 1950–1998 data. This figure reveals how the PNA flow pattern evolves during El Nino and La Nina events.

PDO: The Pacific decadal oscillation was recently defined in a comprehensive paper by Mantua et al. (1997) and the PDO index is derived using several oceanic indices over different regions of the North Pacific. The PDO maybe viewed as an ENSO-like oscillation exhibiting inter-decadal climate variability. The PDO index is derived as the leading principal component of monthly SST anomalies of the North Pacific Ocean poleward of 20ºN. A positive monthly value of PDO means a warmer SST pattern in the North Pacific while a negative value represents a colder SST pattern. Our analysis suggests that a negative value of PDO in conjunction with a La Nina phase of the ENSO cycle may produce an atmospheric flow leading to drought on the prairies.

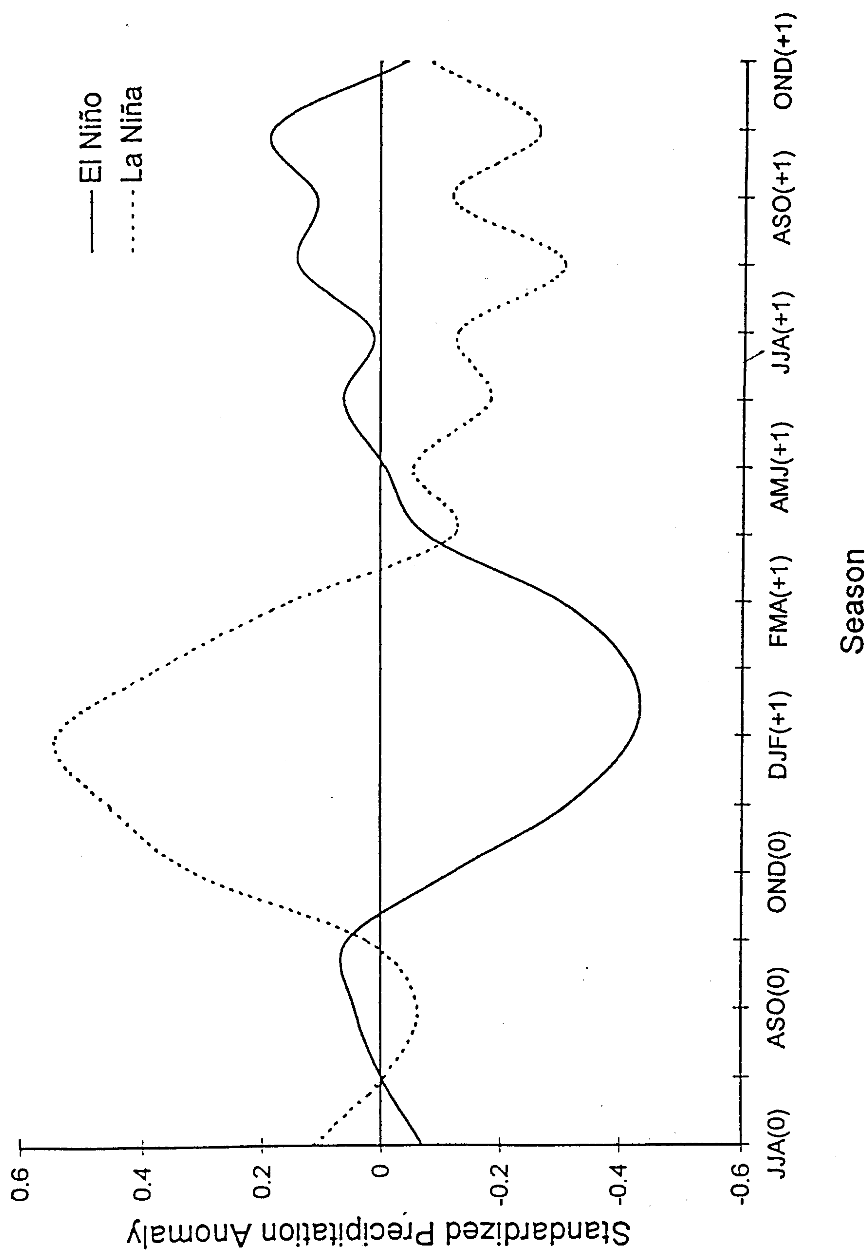

Figure 4.1 Seasonal march of the areally averaged composite standardized precipitation anomalies over southern Canada for June-July-August (JJA) of the El Nino/La Nina onset year JJA(0) to OND(1) of the following year with respect to the onset

Data used: 1900–1990 (Shabbar, Bonsal and Khandekar, 1997).

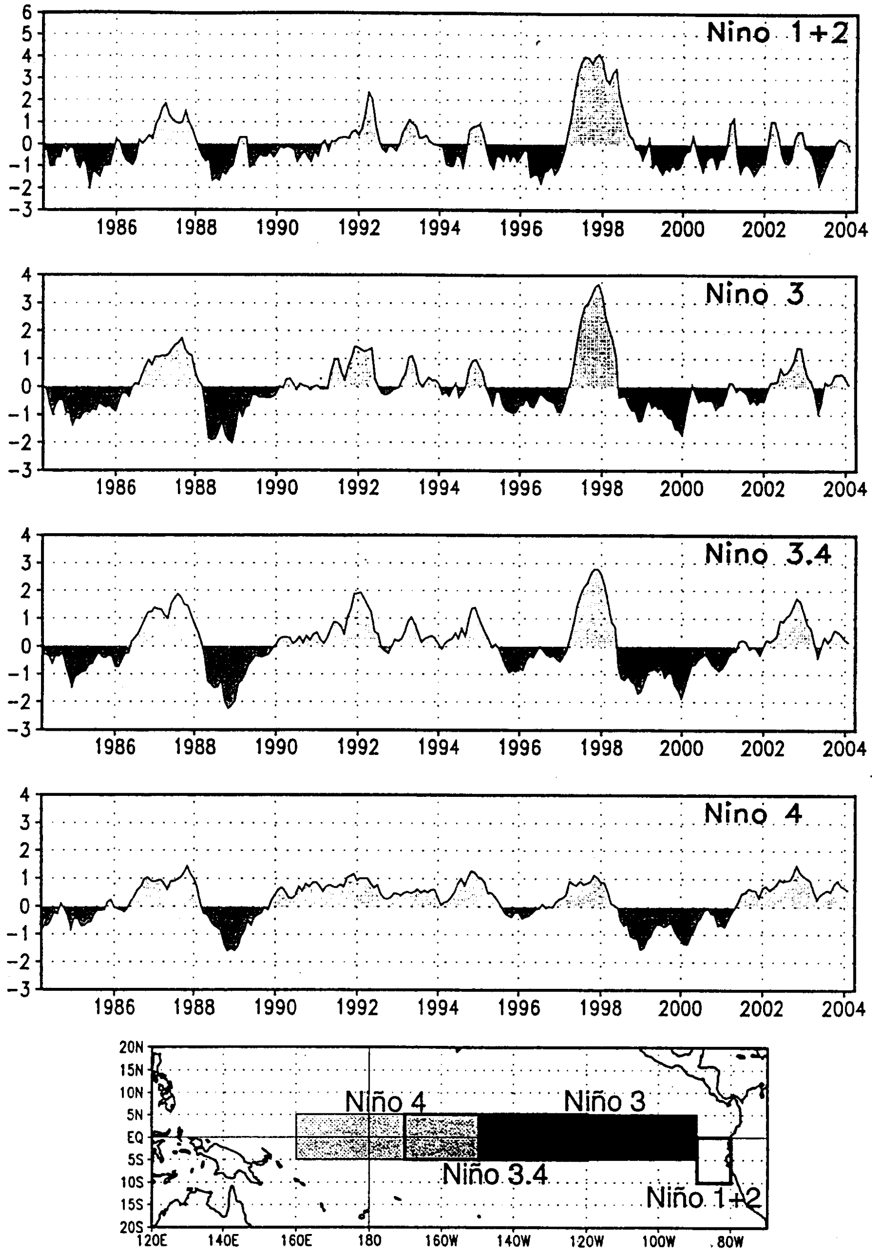

Figure 4.2 SST distribution over four El Nino regions for the past 20 years together with geographical locations and areas covered by the four regions. Negative SST anomalies are shaded, indicating La Nina events.

Note the strong El Nino event from June 1997 through March 1998 (Climate Diagnostics Bulletin, January 2004)

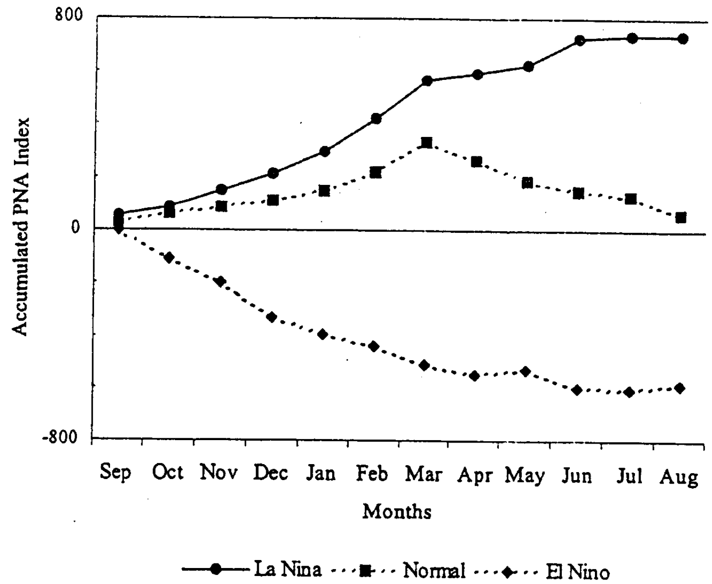

Figure 4.3 Profiles of accumulated PNA index values in El Nino, La Nina, and normal years, 1950-1998

The monthly PNA values are based on a four-point PNA algorithm and are accumulated from the previous September through August of the El Nino/La Nina year (Garnett, 2002).

NAO: The North Atlantic oscillation, first defined by Walker in the early 1900s while working on forecasting of the Indian monsoon, is being studied vigorously at present. It is now realized that the NAO phenomenon influences the mean temperature and precipitation patterns over a large area of eastern North America and also parts of Western Europe (Wettstein and Mearns, 2002). The NAO index is defined as the difference between sea-level pressure at two representative locations over the North Atlantic (e.g., between Lisbon, Portugal and Reykjavik, Iceland) and is indicative of surface pressure oscillation over the North Atlantic. The NAO is now considered to be part of the parent Arctic oscillation (AO), which is a measure of the circumpolar vortex in the northern hemisphere.

The variations of these oscillations (PDO, NAO, and SOI) over a hundred-year period are shown in Figure 4.4. The figure illustrates the slowly varying character of these oscillations and further reveals how they can maintain a certain phase, positive or negative, over several years at a time.

The large-scale atmospheric flow patterns over North America are primarily governed by the SST distribution over equatorial regions as well as over the central North Pacific, with possible influence from the SST distribution in the Indian Ocean (Hoerling and Kumar, 2003). The SST distribution can play an important role in maintaining a certain atmospheric flow pattern over a prolonged period and this in turn can lead to a drought or a wet period over parts of North America and, in particular, the Canadian prairies.

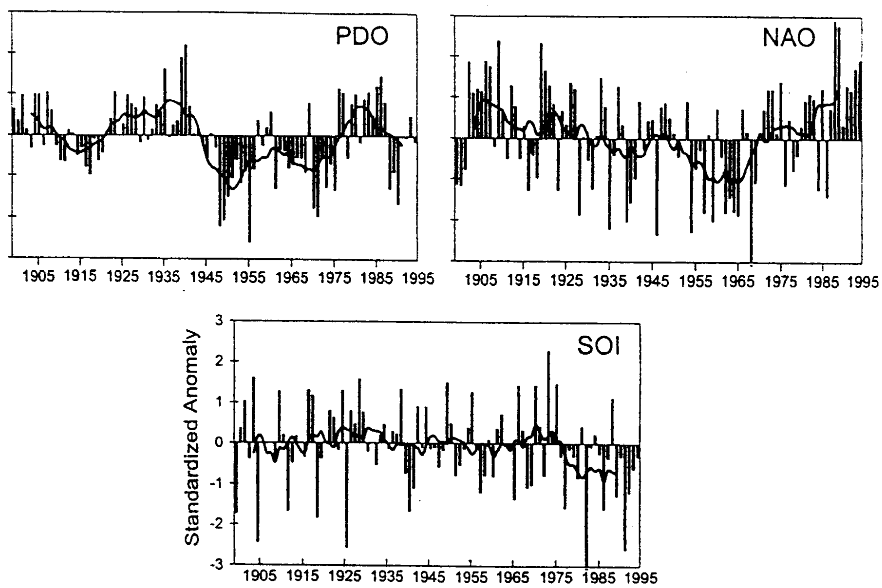

Figure 4.4 Inter-annual variation of standardized values of PDO, NAO, and SOI indices for the season JFM (January-February-March) over the period 1900–1995 (Bonsal et al., 2001).

4.2 Drought and Wet Years in the Context of Large-Scale Indices

Analysis of the indices of large-scale flow patterns in the context of recurring drought years of the 20th century suggests preferential phases of some of these indices in producing drought or wet conditions over the North American prairies. In order to examine this aspect in some detail, mean values of two important indices, the Nino-3 SST anomaly and the PDO index, were calculated for the years of recurring drought identified in Chapter 2. Table 4.1 presents mean values of these indices for the majority of drought years of the 20th century. The Nino-3 region of the equatorial Pacific is the region whose temperature anomalies influence the weather and climate of North America the most. It is of interest to note that the majority of droughts listed in Table 4.1 appear to be associated with negative values of the Nino-3 index, thus strongly suggesting that the presence of a cold (La Nina) phase of the ENSO cycle is an important prerequisite for drought occurrence on the prairies. Besides the cold phase of the ENSO cycle, the SST distribution over the North Pacific as revealed by the PDO index also appears to play an important role in determining the large-scale flow pattern and associated drought conditions.

In Table 4.1, the PDO index appears to be divided about equally between positive and negative values. In an attempt to more closely examine the significance of the central North Pacific in drought occurrence, another index, the NP (North Pacific) index as defined by Castro et al. (2001) is considered here. Mean values of this index for selected intervals of drought and wet years on the Canadian prairies are given in Table 4.2. The dry and wet years were selected based on PDSI values, positive values of PDSI (>1.0) representing wet conditions and negative values (<-1.0) representing dry conditions. It is seen from the table that drought years are generally accompanied by negative values of the NP index while wet conditions are associated with positive values. Of particular interest are the recent drought years 1999–2001 (PDSI values during these years were -3.0 and below at many locations) while the NP index was strongly negative during all seasons. In contrast, the wet years on the prairies, specifically 1978–80 and 1992–94, were associated with positive values of the NP index during all four seasons.

The NP index, developed and used in a recent study by Castro et al. (2001), is defined using a combination of SST anomalies over the central and eastern North Pacific and reflects in some ways the PDO index defined by Mantua et al. (1997). Based on the analysis of drought as well as wet years on the Canadian prairies, the NP index appears to provide a better indication of oncoming drought or wet conditions on the prairies, especially during the grain growing season.

Besides the large-scale indices, prairie drought also appears to be influenced, in part, by the cyclical forcing of solar activity and remote forcing from the Asian monsoon region. The well-known droughts of 1917 and 1937 appear to have been influenced by solar forcing as suggested in several studies by Currie and others. The single-year droughts of 1961 and 1988 appear to have been influenced by remote forcing from the Asian monsoon, both these years being strong monsoon years in India and south Asia (Khandekar and Neralla, 1984). A teleconnectivity between the east Asian summer monsoon and North American atmospheric flow patterns has been suggested by Lau (1992).

Table 4.1 Values of Nino-3 anomalies together with values of PDO index for intervals of drought years

Season →	DJF		MAM		JJA		SON	
Interval	Nino-3	PDO	Nino-3	PDO	Nino-3	PDO	Nino-3	PDO
1904-1911	-0.37	0.25	-0.43	0.15	-0.23	-0.04	-0.24	0.15
1917-1922	-0.31	-0.25	-0.16	-0.35	0.02	-0.46	-0.09	-0.31
1936-1939	-0.30	0.83	-0.32	0.57	-0.55	0.62	-0.06	0.27
1987-1989	0.05	0.72	-0.18	1.00	-0.21	0.94	-0.20	0.47
1999-2001	-1.01	-0.50	-0.26	-0.11	-0.48	-0.86	-0.79	-1.43

Note: DJF: December January February, etc.

Table 4.2 Values of NP index for intervals of drought and wet years

Interval / Season →	DJF	MAM	JJA	SON
1978-80 wet	1.34	1.15	0.91	0.55
1987-1989 drought	-0.36	0.14	-1.53	-0.24
1992-1994 wet	1.77	2.14	1.44	1.84
1999-2001drought	-2.78	-3.21	-1.64	-1.65

4.3 Drought Monitoring and Prediction

The above discussion suggests that suitable monitoring of these large-scale oscillations using appropriate indices could provide techniques for identifying atmospheric flow patterns conducive to a drought or a wet season over a given region. In recent years research has been directed towards monitoring appropriate atmospheric indices to identify an oncoming drought or a wet season. Tadesse et al. (2004) developed a simple procedure for monitoring drought using the data mining technique. The procedure employs drought indices like PDSI and classifies them into seven categories ranging from extremely dry to extremely wet. At the same time, the various atmospheric-oceanic indices are classified according to their numerical values. Using monthly values of the various indices, a step-wise computerized procedure was developed to quantify the severity of a predicted drought or wet condition over a given region.

The empirical technique proposed here uses the logic developed by Tadesse et al. but employs a graphical approach in which accumulated values of various indices are monitored on a monthly basis. This technique is similar to the one developed and used by Garnett et al. (1998) and depicted schematically in Figure 3.3. Based on the discussion above and an analysis of indices (Tables 4.1 and 4.2), the following empirical procedure for monitoring and predicting drought and wet conditions during the summer months on the Canadian prairies is proposed:

1. Examine the monthly SST values over different El Nino regions and ascertain the phase of the ENSO cycle as cold or warm. A strong cold (warm) phase is taken as a predictor of drought (wet) conditions.
2. Examine the values of other indices, PDO, NP, and PNA and determine if cumulative values of these indices suggest a specific positive or negative profile.
3. Based on steps 1 and 2 and using the guidelines provide by Tables 1 and 2, determine if drought or wet conditions are expected to develop over the next few months.
4. Develop a simple numerical index using an appropriate combination of the SST, PDO, and NP indices. The combined numerical index, with an appropriate threshold value, can be used to predict the severity of drought or wet conditions.
5. As an additional guideline, monitor the large-scale atmospheric-oceanic anomalies that determine the Indian/Asian monsoon intensity (Khandekar, 1996). A definitive signal of a weak (strong) monsoon can provide additional qualitative guidance in determining the severity of drought (wet) conditions.

The procedure outlined above is primarily a qualitative approach to drought monitoring and prediction. The steps outlined above can be used in conjunction with monthly PDSI values available for individual locations over the prairies. Numerical values of most of the indices and are readily available on various websites (see Climate Diagnostics Bulletin, 2003) and can thus be monitored conveniently.

It should be noted that only a preliminary outline of an empirical technique is presented here. The outline provided may, however, prove useful in the future development of an operational prediction technique, which could include a multiple regression procedure. This additional developmental work is beyond the scope of the present investigation.

5.0 SUMMARY AND CONCLUDING REMARKS

The purpose of this investigation is to provide a climatological assessment of Canadian prairie droughts based on 20th-century data and to develop an improved understanding of the drought driving forces. Further, an empirical drought monitoring and prediction technique is proposed based on the present understanding of the drought mechanism. Several findings of the study are set out below.

5.1 Summary of Important Findings

The Canadian prairie provinces together with the American prairie region are the most drought-prone regions of North America, where droughts of varying intensity and duration have occurred for many centuries, well before instrumental records became available. An analysis of tree-ring data reveals that some of the worst droughts occurred in the 13th and 16th centuries.

Droughts of single- or multi-year duration have occurred on the Canadian prairies throughout the 20th century. Some of the severest droughts occurred during the 1920s and 1930s, a period commonly referred to as the dust bowl years. The recent droughts of the 1980s and the 1990s are comparable to some of the droughts of the dust bowl years.

Large-scale atmospheric circulation patterns, driven primarily by the SST distribution over the central equatorial Pacific as well as over the central and eastern North Pacific, appear to be the most important drought driving forces. The cold (La Nina) phase of the ENSO cycle over the equatorial Pacific and its continuing presence appears to be the most important precursor for a drought occurrence. On the other hand, the warm (El Nino) phase of the ENSO cycle and its continuing presence in the central equatorial Pacific and the eastern North Pacific is generally associated with surplus precipitation on the prairies during the grain growing season.

The SST pattern over the central and eastern North Pacific plays an important but secondary role in the development of circulation patterns conducive to dry weather and drought onset on the Canadian prairies. Typically, an atmospheric flow pattern identified as an “omega block” is developed over the prairies and, depending on the longevity of this pattern, a drought of moderate to severe intensity is established.

During the warm phase of the ENSO cycle, a specific combination of SST patterns over the central and eastern North Pacific can lead to the development of a quasistationary low pressure system off the west coast of Canada. This low pressure system, accompanied by trough formation in the lee of the Rocky Mountains, can lead to wet conditions on the prairies.

The first half of the 20th century experienced numerous droughts, some of which persisted for several consecutive years. Most of the early droughts appear to have been driven by SST patterns over the central and eastern North Pacific. It is possible that some of the early 20th-century prairie droughts were driven by the anomalous climate that prevailed over North America during and before the dust bowl years.

The impact of solar forcing through sunspot activity has been identified as a possible factor in drought formation and/or drought intensification. Some of the well-known droughts (e.g., 1916/17, 1936/37) may have been activated by solar forcing.

The recent droughts of the mid-1980s and late 1990s were almost certainly induced and maintained by a negative (cold) phase of the ENSO cycle.

There does not appear to be any linkage between recent droughts on the prairies and the observed global warming of the earth's atmosphere. Prairie droughts are forced primarily by the SST patterns over the entire Pacific basin, east of the dateline. Some of the single-year droughts (1961, 1988) appear to have been influenced, in part, by remote forcing from the Asian monsoon system.

5.2 Concluding Remarks

The present report is admittedly a preliminary work on an important aspect of the prairie climatology. There is a definite need to investigate several aspects of prairie drought that are not covered in this report. The simple outline proposed here needs to be developed further in order to provide useful information for smaller regions of the Canadian prairies. There is also a need to closely analyze the spatial variability of drought and its linkage to global as well as regional-scale atmospheric features.

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