LONG-LEAD FORECASTING OF PRECIPITATION AND WHEAT YIELDS IN SASKATCHEWAN USING TELECONNECTION INDICES

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ABSTRACT

Teleconnections among the central, east equatorial Pacific, the Pacific/North American (PNA) pattern, and Southern Oscillation (SO) and monthly precipitation, monthly temperature, and spring wheat yields in Saskatchewan are examined. When sea surface temperatures in the central equatorial Pacific are warmer than the air temperatures (strong El Niño) there is an upward flux of water vapour into the atmosphere, convection, heat released by condensation, a strengthening of the westerlies and a vitalization of the Hadley circulation. When sea surface temperatures are colder than the air temperatures (strong La Niña) in the central equatorial Pacific it produces the opposite influence on atmospheric processes. Composite analysis reveals that El Niño and La Niña are the primary modulators of the Pacific/North American pattern and movement of surface cyclones across the western continent. Correlation and composite analyses indicate that between 1950 and 1998 warmer than normal sea surface temperatures in the central and east equatorial Pacific during the winter and early spring (El Niño) are associated with cooler and wetter conditions during the May through July period in Saskatchewan and higher wheat yields. Conversely cooler than normal sea surface temperatures in the central and east equatorial Pacific during the winter and early spring (La Niña) are associated with hotter and drier conditions during the May through July period in Saskatchewan and lower wheat yields. The relationship appears to be strongest for the Brown soil zone and weakest for the Black soil zone in Saskatchewan.

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This project was undertaken at the advanced age of 50 after having correctly forecast June and July precipitation over the Canadian prairies in 1998 with a lead time of four and a half months using a technique developed by Dr. Khandekar, Jeff Babb and myself. To quote Jerome Namias "forecasting real climatic events is exciting and convincing" suggesting that one has some understanding of cause and effect, has a reliable forecasting tool and may have hit "paydirt."

May those reading this thesis find it a source of some enlightenment.

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ACRONYMS

CCA- canonical correlation analysis

CWB- Canadian Wheat Board

EAJET - Eurasian Jet Teleconnection Index

ENSO- El Niño/Southern Oscillation

NAO - North Atlantic Oscillation Index

NCAR- National Center for Atmospheric Research

PNA- Pacific North American Teleconnection Index

PT- Pacific Transition Teleconnection Index

QBO- Quasi-Biennial Oscillation Index

SD - standard deviation

SLP- sea level pressure

SO - Southern Oscillation

SOI- Southern Oscillation Index

SST - sea surface temperature

SSTA - sea surface temperature anomaly

CHAPTER 1

INTRODUCTION

The El Niño/Southern Oscillation (ENSO) event of 1982/1983 had fascinating and compelling climatic and economic consequences with both negative and positive impacts around the world. Rasmussen (1984) noted that October 1982 marked the onset of El Niño conditions off the Ecuador/Peru coast. In southwestern Ecuador and northwestern Peru rainfall records were shattered during the nine-month period between October 1982 and June 1983. This period marked the most prolonged and catastrophic El Niño visitation ever recorded in the region, exceeding the great El Niños of 1925 and 1891. Glantz (1996) tallied the economic damage in different parts of the world as a result of the droughts and floods associated with the 1982/83 El Niño. Drought costs in southern Africa, Australia and India were U.S. $1 billion, $3 billion and $150 million respectively. In the United States, storms in the Mountain and Pacific states caused U.S. $1.1 billion in damage. Flooding in the Gulf states caused U.S.$1.1 billion in damage. On the other hand an extremely mild winter in 1982/83, likely caused by El Niño, meant an energy saving of U.S. $500 million to the U.S. In South America, drought damage in southern Peru and western Bolivia was estimated at U.S.$240 million while flood damage in southern Brazil, northern Argentina and eastern Paraguay was estimated at U.S.$3 billion. The locations of the four Niño regions, in the equatorial Pacific, are shown in Figure 1.1.

The positive and negative impacts of the 1982/83 ENSO event on world grain production have been described by Garnett and Khandekar (1992). They noted a sea-surface warming at Niño-3 in early 1982, reaching a maximum of 3.0°C above normal in

December of that year. Sea surface temperatures (SSTs) at Niño-3 then cooled 0.6°C over an eight month period from 1.3 °C above normal in December 1982 to 0.7°C above normal during August 1983. Weather conditions in the summer of 1982 favoured corn production in the U.S. Corn Belt and the Canadian and U.S. spring wheat production regions, but reduced Indian rice and Russian spring wheat production. September to November of 1982 brought good rains to the Argentinian wheat region, but precipitation was drastically reduced in the Australian wheat-growing region. The summer of 1983 favoured Indian rice and Canadian and U.S. spring wheat-growing regions, while production shortfalls occurred in the U.S. Corn Belt and Russian spring wheat growing regions. The U.S. Corn Belt drought of 1983 resulted in an actual crop shortfall of four billion bushels from the previous record in 1982. At a value of U.S. $2.50 per bushel of corn it was considered to be a U.S. $10 billion corn drought. The period September to November 1983 brought favourable precipitation to the Australian wheat regions but unfavourable conditions to the Argentinian wheat-growing region.

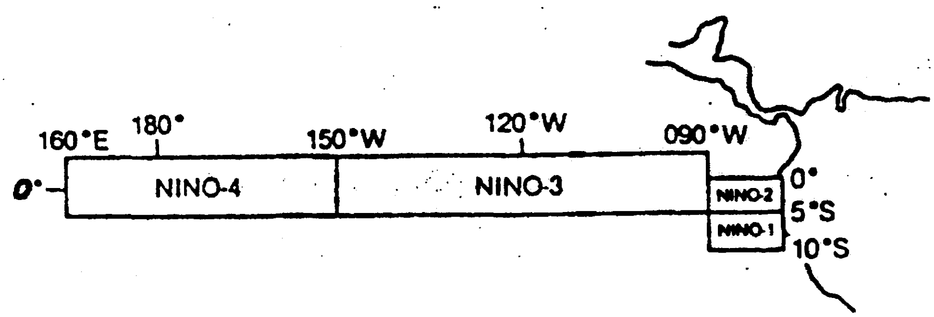


Figure 1.1 Locations of Niño-1, Niño-2, Niño-3 and Niño-4
(Data source: Climate Diagnostic Bulletin, 2000)

Garnett and Khandekar (1992), Shabbar *et al.* (1997), Garnett *et al.* (1998a), and Hsieh *et al.* (1999) found that when SSTs in the central and eastern equatorial Pacific were above normal during winter and early spring (El Niño), precipitation over the Canadian prairies was above normal during the months of June and July which favoured wheat production. Conversely, when SSTs in the central and eastern equatorial Pacific were below normal during winter and early spring (La Niña), precipitation over the Canadian prairies during the months of June and July was below normal and wheat yields were reduced. Garnett and Khandekar (1992) demonstrated that El Niño was a " friend" to spring wheat growing on the Canadian prairies. They found a modest correlation ($r = 0.4$) between Niño-3 SSTAs during June-August and spring wheat yields over the Canadian prairies for the period 1967-1990. Garnett *et al.* (1997) further substantiated this relationship when they found a four-month lag correlation ($r = 0.6$) between Niño-3 SSTAs in April and July rainfall on the Canadian Prairies. April SSTAs explained about 36% of July rainfall variability over the Canadian prairies for the period of 1964 to 1996, suggesting that when April SSTAs at Niño-3 are positive the Canadian prairies are wetter than normal in July.

The ENSO influence on winter weather in Canada has been well documented (Ropelewski and Halpert, 1987, 1989a, 1989b; Kiladis and Diaz, 1989). The impacts of El Niño and its counterpart La Niña on Canadian temperature and precipitation patterns have been described in two recent studies (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997). In general, El Niño usually brings warmer and drier winters to western Canada, while La Niña usually brings colder and wetter winters to this region.

It is hypothesized that El Niño is associated with cool, wet summers on the Canadian prairies, while La Niña is associated with hot, dry summers. The possibility of testing this hypothesis for weather and wheat yields in Saskatchewan's three main soil zones was one of the motivations for undertaking this study. Saskatchewan's wheat-producing region is large enough to be suitable for teleconnection-related research.

1.1 Literature review of large-scale circulation and precipitation

In the early part of the 20^{th} century, Sir Gilbert Walker demonstrated the existence of a planetary seesaw in sea level pressure (SLP) between the eastern and western equatorial Pacific region, which has become known as the Southern Oscillation (SO). The SO was discovered through his efforts in forecasting the Indian monsoon. An early synthesis of results was published in 1923 and 1924 (Walker 1923, 1924; Rasmussen, 1984). An index of the SO, called the Southern Oscillation Index (SOI), describes the strength of the Walker Circulation; it represents the difference in SLP between Tahiti and Darwin and results in clockwise circulation from 80°W to 160°E with a return flow at 150 mb. The concept of the SO refers to the barometrically recorded exchange of mass along the complete circumference of the globe in tropical latitudes. A positive SO is indicative of a strong Walker Circulation and strong trade winds. An intensifying Walker Circulation also provides an increase in the east-west temperature contrast that is a cause of the Walker Circulation in the first place. A weak Walker Circulation occurs with a decrease in the strength of the trade winds, weakening the equatorial upwelling such that the eastern Pacific becomes warmer and supplies heat to the atmosphere above. The

Walker Circulation normally strengthens between the winter and summer seasons (Bjerknes, 1969).

Groissmayr (1929) suggested that the Indian monsoon influenced the weather of the Canadian prairies. His study, based on earlier work by Walker (1923,1924), described a technique, based on teleconnections and statistics, to forecast prairie winter temperatures with a lead-time of 3-9 months. He found that weather in Argentina, Egypt and India had an “enormous” influence upon Canadian winters many months later. He further suggested that a similar methodology could be applied to forecasting other seasons in Canada.

The recognition of the relationship between El Niño and the SO has been attributed to Jacob Bjerknes (1969), who demonstrated an intimate link between events in the Pacific Ocean and the SO. The linking of El Niño and the SO into the El Niño/Southern Oscillation (ENSO) phenomenon was viewed as persuasive evidence that the ocean plays the role of the flywheel in the ocean/atmosphere climate engine and is responsible for the extraordinary persistence of the SO from season to season. Bjerknes hypothesized that the normal SST gradient between the relatively cold eastern equatorial Pacific and the huge pool of warm water in the western Pacific-Indonesian region gives rise to a great east/west circulation cell in the plane of the equator. Dry air gently sinks over the cold waters of the eastern Pacific and flows westward along the equator as part of the southeast trade wind system, driven by the westward “push” arising from higher surface pressure in the east and lower pressure in the west. A return flow is found in the upper troposphere, thus closing the two-dimensional circulation pattern. A sharp drop in the SOI signals a relaxation in the pressure gradient that drives the Walker Circulation near the earth's surface. The trade winds become weak during El Niño, and with the negative values of the SO the easterly flow in the western Pacific collapses, and by July the average wind on the equator between 137°E and 170°E is from the west representing a weak Walker circulation.

Bjerknes (1969) hypothesized that regular monitoring of the temperature of the tropical east Pacific was indispensable for long-range forecasting in North and South America. Garnett *et al.* (1995) indicated that many studies since then have substantiated the validity of this hypothesis. A major problem facing forecasters is having sufficient foreknowledge of the detailed evolution of SSTAs in the central and east equatorial Pacific (Newman, personal communication). The Niño-4 region of the Pacific is near the warmest water in the Pacific Ocean and a source of great energy, especially if the water is warmer than normal for an extended period of time and SSTs are higher than the air temperature as described by Bjerknes (1969). Under these conditions the maximum upward transfer of moisture takes place with intensive convection bringing the moisture to the level of condensation in towering shower clouds. These conditions result in a large flux of sensible and latent heat from the ocean to the atmosphere and lead to wetter than normal conditions in the equatorial central Pacific. Bjerknes (1966) revealed that the great positive water temperature anomaly observed along the Equator in the central and eastern Pacific from November 1957 to February 1958 was accompanied by an increase in the strength of the mid-latitude westerlies and vitalization of the Hadley circulation. La Niña has the reverse influence. Garnett *et al.* (1995) show that during La Niña there is a greater tendency for ridging along the west coast, leading to dry conditions over western Canada, while during El Niño there is a greater tendency for troughing on the west coast and wetter conditions over the Canadian prairies. The ENSO phenomenon is now a well-known climatic forcing function constituting the largest single source of inter-annual climatic variability on a global scale. ENSO effects are wide-ranging and often severe, and they have attracted the attention of scientists worldwide (Diaz and Markgraf, 1992).

The Pacific North American teleconnection pattern (PNA), defined by Wallace and Gutzler (1981), is a derivative of ENSO. The original four-point index describing this pattern is a measure of the 70-kPa flow pattern over the eastern Pacific and North America. It is a linear combination of the normalized 70-kPa height anomalies in metres (z^*) at four locations as given by the following equation:

$$PNA = \frac{1}{4}[z^*(20°N, 160°W) - z^*(45°N, 165°W) + z^*(55°N, 115°W) - z^*(30°N, 85°W)$$

The respective locations are near Hawaii, over the North Pacific Ocean, over Alberta, Canada, and over the Gulf Coast region of the United States. When the flow over this region is zonal, the index value is negative and when the flow is meridional, the index value is positive. A strong Walker Circulation, positive SOI (La Niña), is generally conducive to meridional flow over the PNA region and the transport of hotter and drier air to Saskatchewan. Conversely a weak Walker Circulation, negative SOI, (El Niño) is generally conducive to zonal flow over the PNA region and the transport of cooler and wetter air. The latter scenario is more favourable for the transport of cooler and wetter air favouring wheat yield prospects during the most critical month of July.

Romolo (1998) found a relationship between the PNA pattern and April and May precipitation on the Canadian prairies. Strong zonal flow prior to and during the spring months was conducive to high precipitation over the Canadian prairies while meridional flow brought drier conditions. He showed how meridional flow during the months of April and May diverts storms away from the prairie region.

The work of Groissmayr (1929), Walker and Bliss (1932), Khandekar (1991), Garnett and Khandekar (1992), and Webster (1995) suggested the Indian monsoon plays an active role in the global climate system. Khandekar (1991) hypothesized that a combination of Eurasian snow cover, Indian monsoon performance and ENSO influences can help trigger El Niño and La Niña events 12-15 months later. The combined influence of the Indian monsoon and ENSO is a greater source of interannual climatic variability on a global scale than ENSO alone (Khandekar, personal communication).

Several investigators suggest a basic climatic forcing mechanism. Berlage (1966) examined the role of the Quasi-Biennial Wind Oscillation (QBO) and raised the question of whether the QBO influences ENSO or ENSO influences the QBO. The QBO is often referred to as the stratospheric wind reversal. Van Loon and Labitzke (1988) postulated that solar activity influences the QBO. Gray *et al.* (1992) speculated that the QBO plays a role in triggering ENSO events, depending on the season and state of the "Warm Pool" near Australia. Lau and Sheu (1988) indicated that there is phase-locking between the QBO, the annual cycle and the ENSO phenomenon. It seems plausible that the solar radiation influences the QBO which in turn influences ENSO with phase-locking of the annual cycle, the QBO and the ENSO phenomenon depending on the state of the "Warm Pool".

1.2 Literature review of prairie temperature, precipitation and wheat yield forecasting

The greatest droughts on the Canadian prairies in the past 50 years, 1961 and 1988, have occurred concurrently with a surplus monsoon in India (Garnett *et al.*, 1998b). When precipitation over all of India is greater than 110% of normal for the period June-September, it is considered to be a surplus monsoon. When precipitation over India is less than 90% of normal for this period, it is considered to be a deficit monsoon. Garnett and Khandekar (1992) noted that the greatest global droughts since 1975 have occurred a year after a deficit Indian monsoon, with a surplus Indian monsoon the following year. Examples include 1975 in the former Soviet Union and 1983 and 1988 in the United States Corn Belt. Hence, high risk situations for the Canadian prairies are those in which the monsoon is likely to be surplus (Garnett, *et al.* 1998b). Garnett and Khandekar (1992) suggested that if the monsoon appears as if it is going to be a surplus, it raises the risk of a drought in the U.S. Corn Belt and to some extent in the Canadian prairies. Khandekar and Neralla (1984) and Khandekar and Garnett (1992) show that 1988, 1961 and 1970 were years of surplus monsoons in India. These years were also the first, second and fifth hottest June-Julys in Saskatchewan for the 1950-1998 period. Garnett and Khandekar found an inverse concurrent correlation of $r = -0.59$ between Indian rainfall and U.S. corn yields for the period 1967-1990. During the 1930s, when dust bowl conditions prevailed in North America, there were no deficit monsoons but three surplus monsoons in India (Khandekar and Neralla 1984; Knox, personal communication). During the 1980s there were three deficit monsoons and two surplus monsoons in India, while the Canadian prairies had significant droughts in 1984, 1985 and 1988.

Because of this link, there is value in assessing the potential impact of the Indian monsoon circulation on North American agriculture by monitoring the main forcing functions that govern the performance of the Indian monsoon and anticipating how the Indian monsoon will perform each year. For example, a lack of Eurasian snow cover in the winter months, westerly stratospheric winds during June, July and August, and La Niña conditions during the June, July, and August would pose some drought threat to North America. North America is more drought prone during La Niña. (Tannehill, 1947; Bell, personal communication).

Two of the most severe decades for drought over the Canadian prairies were the 1930s and 1980s. A comparison study by Nkemdirim and Weber (1999) reported that nine of the eleven years from 1929 to 1939 inclusive were drought years compared to six out of eleven from 1979 to 1989. The longest runs were four years for the 1930s and three for the 1980s. The territorial size under mild to extreme drought was 16% larger in the 1930s than in the 1980s, the area impacted by extreme drought was 10% more during the 1980s. A diminished strength of west winds suggested that many of the droughts of the 1980s might have been linked to the numerous blocking highs observed that decade. They found the 1980s was the warmest decade of the 20th century over the prairies; the 1930s was the second warmest decade.

Forecasting June and July temperatures over the Canadian prairies has been carried out using a regression equation developed by Garnett *et al.* (1998a). It revealed a fit including cross validation utilizing six variables that explained 65% of the temperature variation over the Canadian prairies during June and July. A forecast of June-July temperature may provide an indication of precipitation amounts during June and July, especially if it appears that the June-July period is likely to be extremely cool or hot. The very cool summers of 1992 and 1993 were cooler than forecast, probably due in part to the residual effect of the Pinatubo Volcano eruption in 1991. Stowe *et al.* (1992) described the aerosol optical thickness between latitudes 20°S-30°N following the eruption. Their analysis shows that: the volcanic aerosol injected into the atmosphere June 15, 1991 circled the earth in 21 days and covered about 42% of the earth's surface area after two months. In January 1992, they suggested that the globally averaged net radiation at the top of the atmosphere might be reduced by about 2.5 W m^{-2} (cooling effect of at least 0.5°C) once the aerosol was distributed globally over the next two to four years.

Garnett *et al.* (1998a) described a technique using an accumulated PNA index to provide guidance in forecasting summer temperatures over the Canadian prairies. The technique shows whether or not there is a 70-kPa ridge developing over the North American continent. This technique provided excellent general guidance as to Saskatchewan's June and July temperature four out of the five summers between 1994 and 1998. Also developed was a time-step composite related to the persistence of SSTAs at Niño-3, which was helpful in forecasting June and July precipitation over the Canadian prairies during 1998 and 2000. This composite captures the persistence of SSTAs at Niño-3 by summing the SSTAs beginning in September nine months before the June-July period. In 1998, this technique correctly forecast the 114% of normal precipitation that occurred in June and July of that year and the drought problems that occurred from Texas to southern Alberta in 2000. The drought damage in the U.S.A. in 2000 was estimated at

U.S. $ 4.5 billion (LeCompte, personal communication).

However, this technique was unsuccessful for forecasting Canadian prairies dryness in the westcentral Canadian prairies in 1999. Heavy timely rains were received in that region during the June-July period. In 1999 a U.S. $1.0 billion-dollar drought occurred along the Appalachians between Texas and southern Ontario (Garnett, 2000). The flow over the PNA region was strongly zonal and may have been a factor in the drought being confined to the vicinity of the Appalachian Mountains. This composite indicates that the likelihood of experiencing a drought over the Canadian prairies is remote following an El Niño winter. Garnett *et al.* (1998a) found that five variables (PNA in September, PNA in April, Niño-3 in October, Niño-3 in February, and Niño-3 in May) appear to shift mean June and July precipitation. Their regression analysis explains about 45% of the precipitation variation in June-July.

The explanatory power of this regression equation might be improved by including such factors as the SST gradient of North Pacific SSTs as described by Bonsal (1991), or a measure of the strength and position of the Pacific High as noted by Tannehill (1947) and Chakravarti (1972). Tannehill (1947) described the influence of the Pacific and Bermuda Highs on precipitation amounts and distribution in the United States. He showed that in almost every national (U.S.) dry year the Pacific High is expanded and suspected that this was caused by cold water in the Pacific. He concluded that the Pacific High largely controls the amount of rain precipitated over the U.S. while its distribution to some extent is determined by the Atlantic High and its extension the Bermuda High.

Quiring and Blair (2001) have explored other teleconnection indexes for possible inclusion in a regression equation for improving the explanatory power and lead-time in forecasting wheat yield in Saskatchewan. They concluded that for summer precipitation, North Pacific and North Atlantic teleconnections were the most influential. More specifically related to June and July precipitation, the July Pacific Transition (PT), the June Eurasian jet (EAJET) and the April North Atlantic Oscillation (NAO) were the individual variables that exerted the most effect on crop yields. The link between the PT and crop yields arises through its effect on July and August precipitation in southwestern Saskatchewan. The negative phase of PT is associated with below normal heights in the mean pressure ridge over the northwestern U.S. If the negative phase is strong, it will contribute to higher than normal precipitation over the northwestern U.S. and southwestern Canada including Saskatchewan. Conversely, a positive phase is associated with above normal heights in the mean pressure ridge and therefore below normal precipitation over the study region. The EAJET is primarily a measure of the intensity of the westerlies over the North Atlantic. The EAJET may influence the location and intensity of storm tracks over North America and has its greatest influence on northern Saskatchewan crop districts. The NAO also manifests itself through changes in the jet stream and storm tracks over the North Atlantic, as well as causing modifications in the mean configuration of zonal and meridional heat transport. Its influence is greatest in northern Saskatchewan crop districts.

Hsieh *et al.* (1999) correlated Pacific Ocean SSTAs for the months of December, January, February, March, April and May with spring wheat yields over the prairies. They developed a new teleconnection index to use in forecasting spring wheat yield.

Their study showed that during winter and spring, the SSTA in the north Pacific stretched diagonally from the Gulf of Alaska to the Philippine Sea and displayed a three-cell pattern of alternating negative–positive-negative correlation with wheat yield. To indicate the strength of the 3-cell pattern in the SSTA field in the North Pacific they used 4° by 4° grids centered at:

(A) 152°W, 58°N (northern Gulf of Alaska, 1st cell)

(B) 160°W, 46°N (2nd cell)

(C) 152°W, 26° N (northeastern centre of 3rd cell)

(D) 140°E, 18°N (southwestern centre of the 3rd cell)

The detrended SSTA at each grid was then normalized by its standard deviation. The teleconnection index (TI) was constructed from these normalized SSTAs:

$$TI = -SSTA\ (A) + SSTA\ (B) - SSTA\ (C) - SSTA\ (D)$$

The correlation between TI and wheat yield were: $r = 0.41$ (January), $r = 0.56$ (February), $r = 0.63$ (March), $r = 0.62$ (April) and $r = 0.43$ (May). The analysis was based on 27 years of data and the correlations were significant at $p \leq 0.02$ assuming a two-tailed test.

Hsieh *et al.* (1999) found that June and July rainfall explained 36% of spring wheat yields variation. Babb *et al.* (2001) found that July rainfall on the Canadian prairies accounted for 36% of the yield variance and was the biggest single determinant, followed by June precipitation, which explained 8% of the variance. June is a period of vegetative growth and July is the month when grain development occurs. These studies confirmed the importance of July precipitation as a determinant of yield.

In terms of upper air flow pattern, troughing along the west coast is conducive to wet conditions on the Canadian prairies during the summer months while ridging on the west coast is conducive to dry conditions as described by Bonsal and Lawford (1999). Handler (1983) indicated that the onset of high SSTs (El Niño) in the east equatorial region of the Pacific is associated with a southerly displacement of storm tracks during the summer months, which favours the U.S. corn crop and Canadian spring wheat crops. The onset of low SSTs (La Niña) in the east equatorial Pacific conversely can be associated with a northerly displacement of storm tracks. A more southerly jet is favourable for drawing moisture from the Gulf of Mexico and from the Pacific Ocean, the two primary moisture sources for the Canadian prairies as found by Chakravarti (1972).

Dey (1977; 1982) incorporated some synoptic analyses by devising a weather-typing scheme to classify anomalously wet and anomalously dry summers, by analyzing the daily 50-kPa maps and subjectively selecting three weather types, which are common to the Canadian prairies. These types are: Wr (ridge dominant), Wt (trough dominant), and Wz (zonal flow). He concluded that the Wr synoptic type is associated with drier than normal conditions on the prairies, while Wt and Wz conditions are associated with wetter than normal periods on the prairies. The Wr pattern is similar to the positive PNA pattern and Wt and Wz patterns are representative of the negative PNA pattern. Weather typing as suggested by Dey (1973) may prove helpful in predicting the timing of precipitation, but this approach is beyond the scope of this thesis.

The size and shape of the circumpolar vortex, as related to the annual cycle, has relevance in the forecasting of precipitation as suggested by Peterlin *et al.* (1988), Lau and Sheu (1988), and Webster (1995). The annual march of the principal storm track, and the size and shape of the circumpolar vortex which contains the cold air pool that sits over the northern hemisphere, should not be ignored in seasonal forecasting (Garnett, 1986). From spring to summer this cold air pool diminishes in size, as the jet stream migrates northward and then it expands again between summer and winter. The vortex tends to shrink with zonal flow and expand with meridional flow in its annual advance and retreat. The contraction and expansion of the vortex is related to the Index Cycle described by Namias (1950). Peak rainfalls associated with the alignment of ridges and troughs from the central Pacific to central North America are dependent on whether the flow is zonal or meridional. The Canadian prairies and U.S. Corn Belt share the principal storm track and there are a number of predictable peak rainfall periods in these regions associated with the northward advance of the storm track (Garnett, 1986).

Bonsal and Lawford (1999) found that the average number of dry spells on the Prairies associated with El Niño events is significantly higher than for non-El Niño events, with this relationship occurring during the second summer following a mature El Niño. El Niño events are associated with a persistent North Pacific SSTA pattern consisting of anomalously cold water in the east-central Pacific which induces a ridge on the west coast the following summer. The ridging pattern is associated with dryness over the prairies. The pattern of North Pacific SSTAs changes during La Nina events because of a different influence on the Aleutian Low. The key factor in the formation of the North

Pacific sea surface temperature gradient is the Aleutian Low, which tends to be more intense during El Niño than La Niña.

A study by Stone *et al.* (1996) in Australia is noteworthy. Based on individual analyses of 5000 locations worldwide with more than 70 years of monthly data, their system provides rainfall probability distributions three to six months in advance, and is simple enough to be incorporated into present management systems. Their prediction system is based on the identification of lag-relationships between values of the Southern Oscillation Index (SOI) and rainfall probabilities many months later. At Goondiwindi, Australia, for example, a rapid fall in the SOI in the April/May period signals a reduced rainfall probability for the period June-August. It provides a quantitative measure of the ENSO cycle and future rainfall for various parts of the world. For example, they reveal 60-70% probabilities of exceeding median rainfall for the August-October period in Saskatchewan associated with an SOI 'consistently negative' in June/July. This method is capable of providing rainfall probabilities for June and July for main surface synoptic stations for the Canadian prairies by late May (Stone, personal communication).

A comment is required on different forecasting methods. Empirical-statistical approaches are still considered the most reliable. Huang *et al.* (1996) and Pan and Van den Dool (1998) report the following accuracies of different techniques: statistical 21%, climate optimum normal 15% and coupled ocean-atmosphere models 5%. This study was done over a five year period over large regions of the Northern Hemisphere in a comparison of actual versus predicted data points. This thesis utilizes composite and correlation analyses, which are empirical-statistical techniques. Namias (1978) stressed the importance of a balanced approach utilizing statistics and synoptics for making good, practical progress in long-range forecasting and states that empirical-statistical approaches would lead the way. More sophisticated canonical correlation analysis (CCA) techniques for forecasting seasonal climate have been developed by Shabbar and Barnston (1996) and Shabbar and Khandekar (1996).

1.3 Summary of literature review

There are a number of known climatic forcing functions directly relevant to the performance of the Indian monsoon, namely: Eurasian snow cover, the QBO, and ENSO as described by Garnett and Khandekar (1992). The Indian monsoon itself plays a role in the global system especially in years when there is a surplus or deficit monsoon. Several teleconnection indices have been developed to use in forecasting weather and wheat yield variations on the Canadian prairies. A simple accumulation of values of the PNA index in the fall months has proven useful in determining whether a 70-kPa ridge is developing over North America, which has utility for forecasting June and July temperature over the Canadian prairies. Berlage (1966), Van Loon and Labitske (1988), Lau and Sheu (1988), and Gray *et al.*(1992) suggest that solar activity influences the QBO and that there may be interaction between the QBO, the annual cycle of the circumpolar vortex and ENSO events.

There are now a variety of analytical tools ranging from composite analysis to global circulation models with which to tackle the forecasting problem. Many of the older approaches have proven to be the most reliable. Garnett *et al.*(1998a) show that up to 65% of the temperature variation during June and July over the Canadian prairies can be explained by using two teleconnection indexes and multiple regression analysis. The explanatory power of these models could be improved by adding other physically sound teleconnection indices to the regression scheme.

1.4 Climatic factors determining wheat yields

Spring wheat in Saskatchewan is usually planted during May and harvested between mid-August and late-October. It requires approximately 100 days to mature and is usually harvested 7-10 days after it reaches maturity (Saskatchewan Agriculture and Food, 1998). The general growth stages of the crop are tillering, stem extension, heading and ripening (Figure 1.3). Greatest water use and vegetative growth occurs during stem extension, heading and flowering. King (1987) indicates that stem extension usually occurs during June while heading and flowering takes place in July.

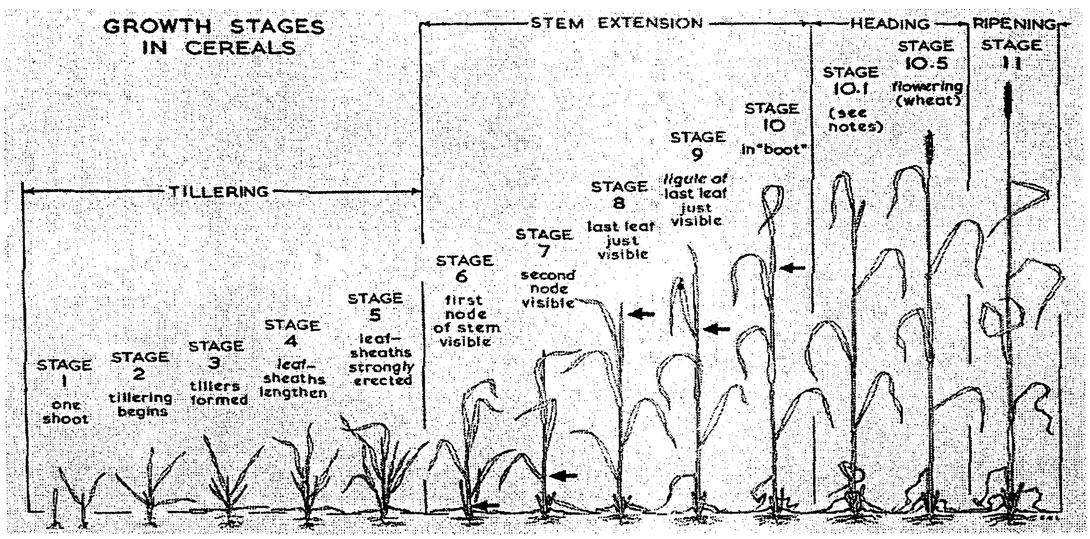


Figure 1.3 Growth stages in cereals (Peterson,1965)

The head of the main stem usually emerges first, followed in turn by heads of the tillers in the order of their origin. After the emergence of the head, the uppermost internode usually continues to lengthen until the head is raised seventy-five millimetres above the upper-most sheath. It is during the heading and flowering stage that heat and dryness have the greatest impact on yield and quality (King,1987).

Cole and Matthews (1923) noted a strong correlation between grain yield and the amount of water removed from the soil of the North American Great Plains. They concluded that crop water usage is derived from that stored in the soil at the time growth begins supplemented by rain during the growing period. The more water that is used by the plant the higher the yield. The nature of the relation between water use and yield was also influenced by soil conditions, such as soil texture.

Hopkins (1935) investigated the influence of precipitation during the autumn, winter and spring months on wheat yield. He concluded that yields are markedly influenced by factors such as precipitation during the autumn, winter and spring months prior to sowing. Hopkins observed that low temperatures during the initial stages of growth are associated with reduced yields, probably because low temperatures adversely affect germination and tillering.

Lehane and Staple (1965) found, for southwestern Saskatchewan, that stored moisture was as effective in accounting for variability in wheat yield as growing season weather conditions. Clay soils hold more moisture than coarser-textured soils, and crops on clay soils out-yield those on fine sandy loam by 0.34 t/ha on average. Because of drought tolerance, crops on clay soils exhibited more economical use of soil moisture throughout the growing season.

Robertson (1974) concluded that weather accounted for 73% of the wheat yield variation at Swift Current. The contribution of various weather factors to final yields were as follows: Conserved moisture at the start of the growing season 14%, May precipitation 12%, June precipitation 26%, July precipitation 9% and August precipitation 11%. Robertson (1974) pointed out the advantages of a factorial model, as compared to a multiple regression model, in which several elements for different months are all additive. With the factorial model, yield is built over time, depending on the vigour of the plant at each stage. His model demonstrated that weather conditions that affect potential yield at an earlier stage of growth have a bearing on how weather will establish yield at a later stage of development. The yield potential created at each growth stage is highly dependent on weather conditions. Weather elements such as temperature and radiation were considered to be modifiers of yield and other elements, such as rain and evaporation, were considered to be a budget process, which adds to or reduces yield. Moisture is the discrete limiting factor with temperature and radiation either speeding up or slowing down the evapotranspiration process and the amount of water the plant uses. Thus, the general form of Robertson's factorial yield weather model is to add rainfall to the estimate of yield for the preceding crop development period and to modify this sum by functions of temperature and radiation. Robertson's factorial approach more closely simulates the climatic influence on the physiology of the wheat plant and plant processes than many statistical approaches.

Based on evaporation pan ratios, King (1987) described cereal crop development versus water use per week under conditions of adequate soil moisture supply. Table 1.1 shows the water use per week in millimetres during June, July and August for the Brown, Dark Brown and Black soil zones of Saskatchewan. In all three soil zones the greatest water use was during July with the least water use occurring during June. He concluded that the first critical growth stage was tiller initiation and development, which occurs during May. Moisture stress during this stage will result in yield reduction that cannot be overcome by optimum conditions during later growth stages.

Table 1.1 Approximate cereal crop water usage per week (mm) for Saskatchewan soil zones

Month	Week 1	Week 2	Week 3	Week 4	*	Total Water Use
			Brown soil zone			
June	15	20	30	35		
July	40	50	50	50	50	515
August	45	45	40	30	15	
			Dark Brown soil zone			
June	10	15	25	35		
July	40	45	45	45	45	455
August	40	40	40	20	10	
			Black soil zone			
June	10	15	20	30		
July	35	40	40	40	40	395
August	35	35	15	15	5	

* Remaining days

after: Saskatchewan Water Corporation (1987)

The second critical stage is flowering which occurs in July. The effect of moisture stress is not as severe as at tillering but the critical period is more sharply defined. There are no second chances at this stage, if a flower aborts then that amount of potential yield is lost. King (1987) suggested that moisture conditions during tillering determined the number of heads formed while moisture conditions during flowering determined the number of kernels in each head. Both are critical to yield. King's work emphasizes the importance of July climate in the determination of wheat yield. Greatest water usage occurs during July in Saskatchewan during the flowering stage. The least amount of water use occurs in June with the second highest occurring during August.

Methods of predicting wheat yields range from statistical approaches (Haun, 1974; Baier, 1977; Stewart and Dwyer, 1990) to crop simulation models (Raddatz, 1989; and Walker, 1989). Even though the dynamic nature of the crop simulation models may appear preferable to statistical models, both techniques are constrained by insufficient foreknowledge of future weather, especially precipitation. Drought losses sometimes exceed 50%. Losses due to pests and insects in Saskatchewan have been estimated at 3-15%. Crop losses caused by pests, diseases, nutrient limitations and catastrophic events are, however, not as costly in the long run as those due to drought. (Williams *et al.*1988).

Chipanshi *et al.* (1999) calculated water stress indices for wheat over five stages of development; these included emergence, terminal spikelet, vegetative growth, ear growth and grain filling. In Figure 1.3 emergence applies to stage 1, terminal spikelet initiation to stage 5, vegetative growth to stages 6 to 10, ear growth to stages 10.1 and 10.5 and grain filling to stage 11. He found water stress reduced grain yield during ear growth followed by vegetative growth and grain filling at three locations in Saskatchewan. Water stress early in the season did not impact grain yield significantly but was more critical during vegetative growth and ear growth, which coincided with the establishment of the crop's reproductive elements. Water stress, for example, interferes with the pollination process, impairing the potential for grain development.

Assuming the crop germinates, the most weather critical growth periods are tillering and flowering. Moisture stress during these growth stages has the greatest impact on yield and protein content of wheat. Hence, the value of being able to anticipate climatic extremes during July is of special importance.

1.5 The economic value of long-lead forecasting

Saskatchewan is the largest spring wheat-producing province in Canada producing 38% of the country's total wheat (Statistics Canada, 1998). During the 1995-1999 period Canada produced an average of 26.4 million tonnes of wheat of which 10.2 million tonnes were grown in Saskatchewan (Statistics Canada, 1999). The dollar value of the Saskatchewan wheat crop each year based on 10.2 million tonnes produced during 1995-1999 was Can. $1.65 billion based on an average price for the 1993-1997 period of Can. $162 per tonne. Saskatchewan's wheat production is essentially rainfed and very susceptible to drought. Early warning of extreme climate variation during the summer months, especially July, is therefore of considerable value to the agricultural economy.

The value of the crop in three low-production years (1984, 1985 and 1988) was estimated at Can. $1.4 billion compared to Can. $2.3 billion in three high-production years (1986, 1990 and 1996), a difference of Can. $ 0.9 billion dollars (Saskatchewan Agriculture and Food, 1998). During recent decades the area under wheat has varied from 5.48 to 6.96 million hectares (27%), while yield varied from 1.34 t/ha to 2.19 t/ha (160%) for low-yielding versus high-yielding versus years. Fluctuation in production during these years can be related to variation in precipitation and temperature during June and July (Saskatchewan Agriculture and Food, 1998). In the low-yielding years precipitation during May-July averaged 46 mm or 77% of the long term mean, while during the high-yielding years precipitation averaged 72 mm during May-July or 120% of the mean. June 1988 was the hottest for the 1950-1998 period and further contributed to reduced yield that year. These data emphasize the potential economic value of being able to forecast temperature and precipitation during the key growing period of June-July when the greatest risk a farmer faces each year is the weather. Farm prices and cost of inputs are factors which vary each year, however the dollar value associated with production changes associated with variable climate is the most dominant.

The impact of the 1988 drought on agriculture provides a classic example of society's vulnerability to such events. It resulted in a 12% decrease in Canada's agricultural production and is estimated to have caused a direct production loss of $3.3 billion (in 1998 Canadian dollars) (Wheaton *et al.,* 1992; Statistics Canada, 2000).

Canada is a supplier of high-quality high-protein wheat, which is marketed through the Canadian Wheat Board (CWB), Canada's sole marketer of wheat and barley for export from the Canadian prairies. The Canadian Western Red Spring (CWRS) grading system contains a protein segregation system that allows Canada to offer both No.1 CWRS and No.2 CWRS at two and sometimes three levels of guaranteed protein content (Canadian International Grains Institute, 1993). The protein segregation system has three objectives:

1) to improve Canada's precision and flexibility in meeting world market demands for wheat of milling quality, 2) to identify the protein content of high grade wheat as early in the marketing process as possible, and 3) to return the market value of the protein of high-grade wheat directly back to the producer. Guaranteed protein content, together with Canada's strict varietal control, assures consistency of baking performance year

after year. Higher protein content means higher quality for milling purposes (Canadian International Grains Institute, 1993).

There is an inverse correlation between wheat yield and protein content. Cool, wet Junes and Julys produce high yields and low protein, while hot, dry conditions during June-July produce low yields and high protein (Anderson and Eva, 1939). With bread wheat classes the correlation between grain yield and protein is about $r = -0.3$. The magnitude of the coefficient varies quite widely, depending on growing location, climate (mainly rainfall and temperature during the growing period), husbandry and a variety of other factors. The relationship translates into an increase in protein content of 0.5% for each 5% reduction in yield (Williams, personal communication).

Customers of the CWB pay a premium for high protein wheat. Ultimately the quality of the crop is dependent on weather conditions between planting and the end of harvest. The CWB forward sell grain six to twelve months into the future, so the longer lead this organization has on the size and quality of the year's crop, the better the CWB is able to perform this function. With greater foreknowledge of the size and quality of the crop, this organization can be more or less aggressive in the market place for purposes of maximizing sales volume and extracting the best price for their stakeholders, the wheat producers of western Canada (Stacy, personal communication).

Duvenaud (1995) described the interest that wheat producers have in weather during the growing season. Each spring farmers have to decide whether or not they are going to plant, and if so, what they are going to plant. The availability of accurate season-long forecasts for grain growing regions would assist producers in making decisions as to the allocation of farm inputs, especially fertilizers, which adds value to the farm economy. Seasonal forecasting has a role in grain marketing because weather is the big determinant of crop prices. Every weather forecast is a price forecast. Farmers make pricing decisions from the time new crop contracts start trading until the last of the crop is sold. Farms are small businesses with a big annual inventory risk: markets are variable and can be volatile.

Duvenaud (1995) further indicated that farmers off-load part of the risk either on the futures markets or with forward contracts. Off-loading costs money. Pre-selling provides farmers with insurance against prices dropping at the cost of future price rises. Unencumbered ownership of any commodity is an asset that farmers like to retain, but this is weighted against the risk and cost of financial exposure. The decision for most farmers is not whether to hedge, rather it is to what extent to hedge. In this decision, a seasonal forecast can help determine what percentage of the expected crop is to be forward sold. A reliable seasonal forecast can provide an indicator about future prices. Any edge on the market is worth money in grain futures.

1.6 Statement of research

This thesis further tests the "El Niño, La Niña prairie moisture" link suggested by Khandekar and Jones (1995) in which they hypothesized that, on the Canadian prairies:

1. El Niño years are generally associated with higher than normal precipitation during spring and early summer.
2. La Niña years are generally associated with drier conditions during spring and early summer.

This study seeks to test the above claims especially with reference to June-July temperature and precipitation in Saskatchewan. The primary concern is the ability to anticipate climatic extremes during the critical July growing period for wheat. Secondary focus is placed on the climatic impacts of May and June on yield and protein content.

Since the mid 1980s the CWB has been using a plant growth simulation model for forecasting grain yields as described by Walker (1989). This model assumes that climate is a totally random process. Climate is periodic rather than random by nature, and ultimately a teleconnection-based model will be required to provide lead-time estimations of precipitation, temperature, yield and quality 3-6 months prior to the critical June-July period for spring wheat (Khandekar, personal communication).

1.7 Thesis objectives

This study expands on the work of Garnett and Khandekar (1992) and Garnett *et al.* 1995, 1997, 1998a) and is aimed at forecasting major temperature and precipitation extremes that can affect the yield and quality of Saskatchewan's spring wheat crop. It utilizes teleconnection indices of predictive value. This study has three objectives:

1) To gain an understanding of the strength and nature of the relationship between the El Niño/Southern Oscillation phenomenon and June and July temperatures, precipitation, and wheat yield in Saskatchewan.

2) To investigate the effect of antecedent zonal versus meridional flow over the Pacific North American region on summer temperature, precipitation and wheat yield in Saskatchewan.

3) To develop a conceptual model of how El Niño/La Niña modulates upper level flow, and then influences May through July temperature and precipitation and wheat yields in Saskatchewan.

CHAPTER 2

STUDY AREA, DATA SOURCES AND ANALYSIS

This chapter has three sections. The first defines the study area and discusses the factors that led to its selection, the second describes the data requirements, sources and collection and the third discusses the techniques used in the analysis, which include correlation analysis, composite analysis, and case studies.

There is a large amount of literature relating to climate prediction over the Canadian prairies utilizing factors, such as, sea level pressure (SLP), east equatorial Pacific SSTs and the 50-kPa flow pattern. Ample SLP, SSTA, and 50-kPa data exist for the central and east equatorial Pacific and Pacific North American regions. Similarly temperature, precipitation, and yield data are available for the spring wheat-growing region of Saskatchewan.

2.1 Study area

The study area consists of the three principal soil zones, the Brown, Dark Brown and Black soil zones as shown in Figure 2.1. It is a fertile region for growing spring wheat but is highly sensitive to the vagaries of climate during the summer months. More than 26.6 million hectares of this region is devoted to farming (Fung 1999). Its size, similarity in climate, sensitivity to drought and dependence on a few major crops make it is suitable for teleconnection related research. Yields are highest in the more fertile Black soil zone and lowest in the more arid Brown soil zone (Saskatchewan Agriculture

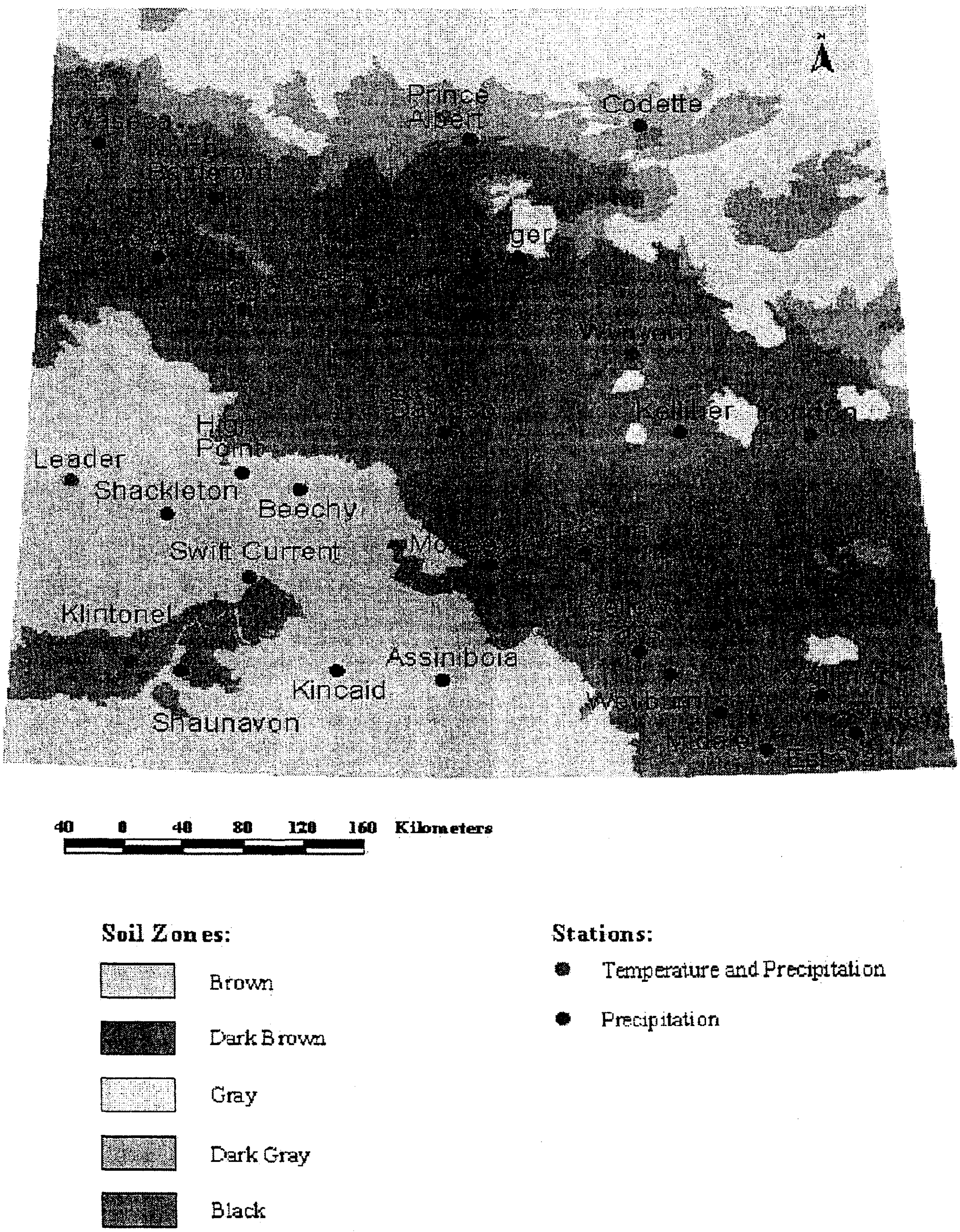


Figure 2.1 Saskatchewan soil zones and climate stations
(Data sources: Environment Canada, 2000, Saskatchewan Agriculture, 1998).

and Food, 1998). The major soil zones are as described by Chipanshi *et al.*(1999) and Saskatchewan Agriculture and Food (1998). Forested lands of low agricultural potential and lower temperatures bound this region to the north. The western border is with Alberta, the eastern border with Manitoba and the southern boundary with the U.S.A.

The area chosen for SST analysis is the east and central equatorial Pacific Ocean, specifically the Niño-3 and Niño-4 regions shown in Figure 1.1. The Niño-3 and Niño-4 regions were selected as being likely predictors of precipitation anomalies in Saskatchewan, as implied in previous studies, such as those by Bjerknes (1966, 1969) for North America and Garnett and Khandekar (1992), Garnett *et al.* (1998a), Hsieh *et al.* (1999), and Babb *et al.* (2001) for the Canadian prairies.

The study area chosen for upper-air analysis is bounded by the four points of the Pacific North American Teleconnection index as defined by Wallace and Gutzler (1981). The index is a linear combination of the normalized height anomalies at four locations. The standardized geopotential height anomaly is at 50-kPa level. The respective locations are near Hawaii, over the North Pacific Ocean, over Alberta, Canada and over the Gulf Coast region of the United States.

The PNA index is positive during months with strong ridging at the 50-kPa level over western Canada and negative with zonal flow at this level. The PNA index is commonly used to characterize the flow during the winter months. In this thesis it is used to describe conditions during eleven months of the year, with particular reference to the fall and winter seasons antecedent to the growing season. PNA values at the 50-kPa level are used because these data are available for the period 1950-1998 whereas 70-kPa data are only available from 1964. It was considered important that certain drought years such as 1961 be included in this study.

2.2 Data requirements, sources and collection procedure

The period of study chosen for this investigation was 1950 to 1998 because SOI, SSTA, PNA, spring wheat yield, temperature and precipitation data were available for this period. The precipitation and temperature data for 30 precipitation and 15 temperature stations were obtained from Environment Canada (Canadian Monthly Climate Data and 1961-1990 normals). The stations were assigned to crop districts and the crop districts then assigned to soil zones. SOI and SSTA data were provided by the Climate Prediction Centre while the upper air data were obtained through the Atmospheric Sciences Department of the University of Washington and the National Centre for Atmospheric Research (NCAR). Yield data were provided by the Saskatchewan Department of Agriculture and Food. The data were used in subsequent correlation and composite analyses.

2.2.1. Southern oscillation index (SOI)

The SOI was originally defined by Walker and Bliss (1932) and is represented by the difference in standardized sea-level pressure between Tahiti (17°33'S, 149°37'W) and Darwin (12°24'S, 130°52'E); seasonal values for the period 1950-1998 are presented in Figure 2.2. The seasons were defined as fall (September-November), winter (December-February), spring (March-May) and summer (June-August). A strongly negative SOI indicates El Niño conditions, and a strongly positive SOI indicates La Niña conditions. A positive SOI is indicative of a strong Walker circulation while a negative SOI is indicative of a weak Walker circulation.

SOI data were obtained for the period 1950-1998 from the Climate Prediction Centre. The mean, standard deviation, maximum and minimum values were calculated for each month. Extreme values of the SOI ranged from 2.9 in November 1974 to –4.6 in February, 1984. The highest monthly variability was in February when the standard deviation was 1.48. The lowest standard deviation was 0.85 during June. The mean monthly values of the SOI reveal a strengthening of the Walker circulation from the winter to spring to summer months, similar to what was found by Bjerknes (1969).

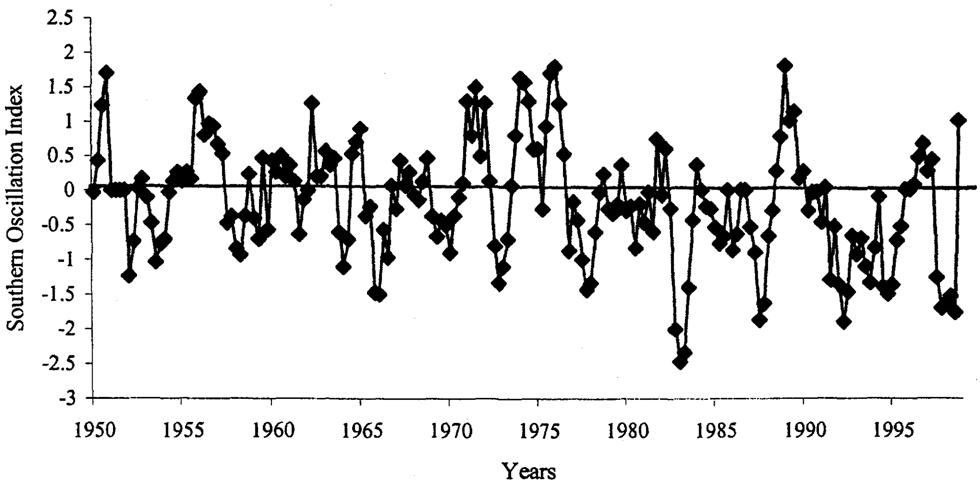


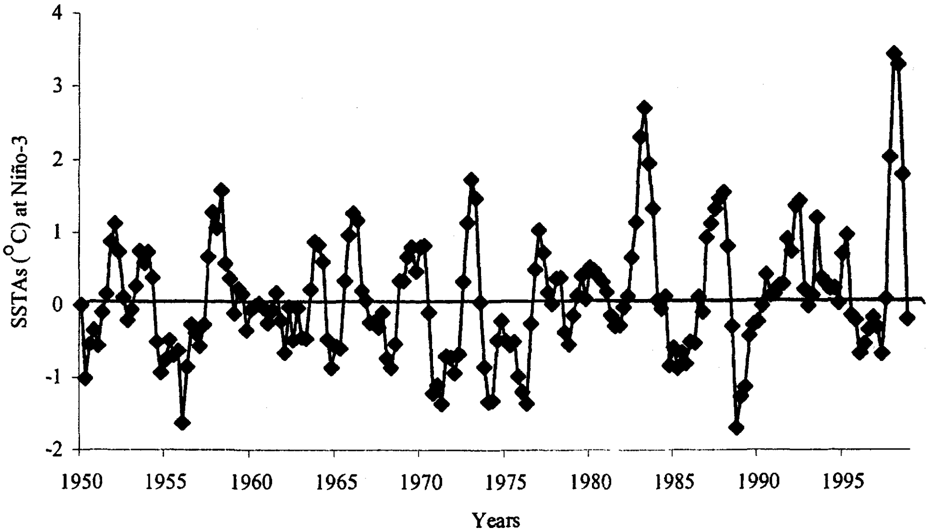
Figure 2.2 Seasonal values of the Southern Oscillation Index 1950-1998
(Data source: Climate Prediction Centre, 2000)

2.2.2 Niño-3 sea-surface temperature anomaly (SSTA) data

The seasonal variability of Niño-3 SSTAs for the 1950-1998 period is shown in the upper part of Figure 2.3. The lowest monthly SSTA was in June of 1988 when the Niño-3 SSTA was –2.1°C, while the highest SSTA was in December of 1998 when the Niño-3 SSTA was +3.8°C. Monthly standard deviations in surface water temperatures varied from 1.14°C in December to 0.64°C during March-April. Niño-3 was included because it is larger than Niño-4 and has more energy associated with its fluctuations. Niño-3 makes up a large body of water, half the size of Canada in geographical extent, and is subject to huge energy changes associated with fluctuations in SSTs.

2.2.3 Niño-4 sea surface temperature anomaly (SSTA) data

The seasonal variability of Niño-4 SSTAs is shown in the lower part of Figure 2.3. On a monthly basis the greatest monthly negative SSTA (–1.67°C) occurred in October, 1955 and the greatest positive SSTA occurred in November, 1987 (1.53°C). The monthly standard deviation ranged from 0.48°C in June to 0.79°C in December. The Niño-4 region was chosen for investigation because of speculation that it may provide a longer lead-time for forecasting precipitation and hence yield. The Niño-4 region warms before Niño-3 with a weakening of the trade winds and initiation of El Niño and cools off later than Niño-3 with a strengthening of the trade winds associated with La Niña.



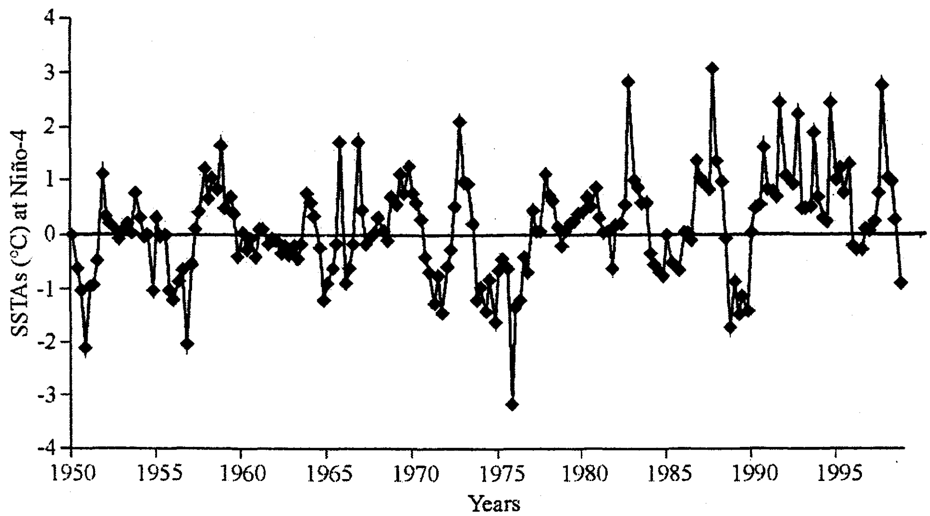


Figure 2.3 Seasonal variation of SSTAs at Niño-3 (top) and Niño-4 (bottom), 1950-1998 (Data source: Climate Prediction Center, 2000).

2.2.4 Upper level Pacific North American (PNA) teleconnection index data

Monthly values of the PNA index were multiplied by 100 to remove the decimal place. The strongest meridional flow was in March of 1983 when the index value was 229, and the strongest zonal flow occurred in January of 1950 when the index was -250. The SD varied from a high of 1.03 in January to a low of 51 in July. To show the variation of the PNA index on a seasonal basis, monthly values averaged as fall (September to November), winter (December to February), spring (March-May) and summer (June-August). A plot of the variation of seasonal values of the PNA index is shown in Figure 2.4. Periods of zonal and meridional flow are evident in Figure 4.

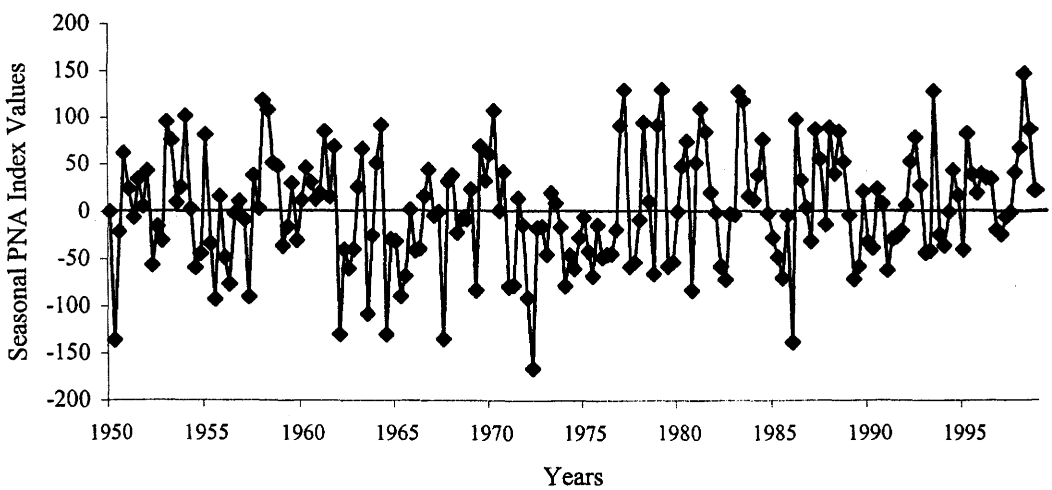


Figure 2.4 Seasonal variation of the PNA index, 1950-1998,
(Data source: University of Washington, 2000, Monthly PNA values multiplied by 100 to remove the decimal place in published data)

During the 1970s for example, zonal flow dominated while during the 1980s meridional flow was more prevalent. Nkemdirim and Weber (1999) describe the heat and dryness of the 1980s compared to the other decades.

2.2.5 50-kPa height and height anomaly charts

50-kPa chart heights anomalies and height anomaly data were obtained from the National Center for Atmospheric Research in Boulder, Colorado. These charts show the alignment of ridges and troughs from 180°W over the Niño-4 region of the central equatorial Pacific to Saskatchewan in Western Canada and the movement of weather systems during 1951 and 1988 years of extreme El Niño and La Niña during the months of May through July.

2.2.6 Precipitation data

Seven, twelve and eleven climate stations are located in the Brown, Dark-Brown and Black soil zones, respectively: these have the most complete monthly precipitation data during May, June and July (Figure 2.1, Appendix A). Mean monthly precipitation for the three soil groupings were calculated for the months of May, June and July. The precipitation dataset contains 4416 values of which there were 123 (3%) missing values. These missing values were filled using a gridded dataset created by Environment Canada and a technique developed by Alaka and Elvander (1971) and Hogg *et al.* (1997). This procedure uses statistical optimal interpolation and employs a "first quess" field and interpolates only departures from climatology of the relevant field. Hogg *et al.* (1997) shows its effectiveness in interpolating precipitation in data sparse, strong-relief regions.

In agricultural Saskatchewan the wettest month is June, with a mean precipitation amount of 73.3 mm, followed by July with 59.7 mm and May with 42.9 mm. The driest and wettest Mays, Junes and Julys were in 1967 and 1991; 1967 and 1991; and 1961 and 1993, respectively. Precipitation is most variable in June, with a SD of ± 26.5 mm., followed by July with a SD of ± 20.3 mm and May with a SD of ± 16.0 mm. The annual variation in June-July precipitation as a fraction of normal is shown in Figure 2.5.

2.2.7 Temperature data

The hottest month on average in agricultural Saskatchewan is July with a mean temperature of 16.8°C, followed by June with 15.5°C and May with 10.2°C. The hottest and coldest Mays, Junes and Julys during the study period were: 1988 and 1974; 1988 and 1951; and 1960 and 1972 respectively. Temperature was most variable in May with a SD of $\pm$ 1.44°C followed by June with a SD of $\pm$ 1.32°C and July with a SD of $\pm$ 1.02°C. The variation in June-July temperature and precipitation versus year are shown in Figure 2.5.

2.2.8 Wheat yield data

Spring wheat yield data for the period 1950-1998 by crop district were obtained from Statistics Canada and Saskatchewan Agriculture and Food for twenty crop districts in Saskatchewan for the period 1950-1998. The location of these crop districts is shown in Figure 2.6. The annual variation of provincial wheat yield is shown in Figure 2.7.

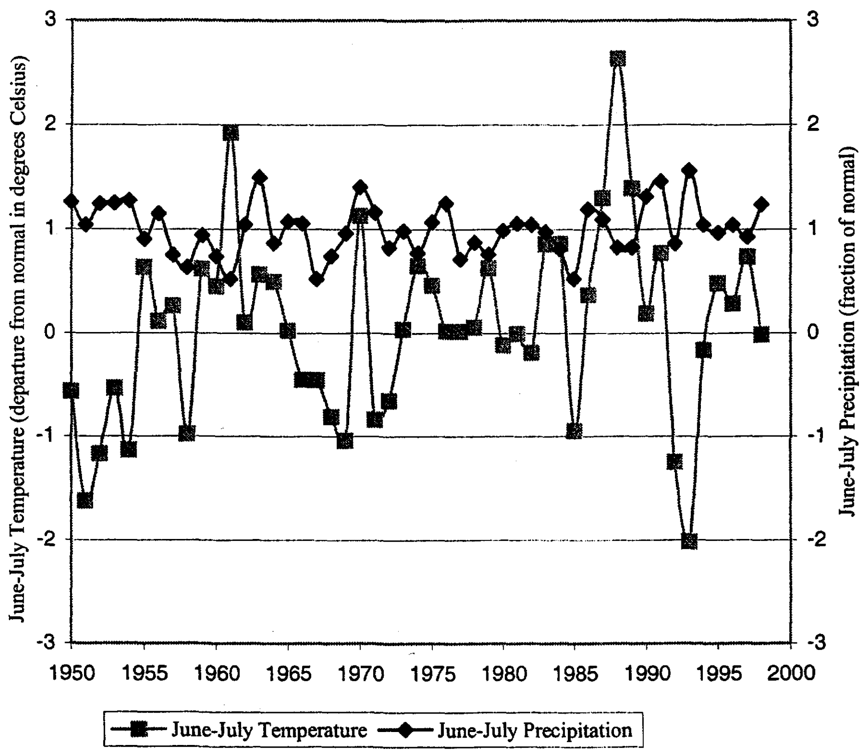


Figure 2.5 Variation from 1950-1998 mean for June and July precipitation and temperature In Saskatchewan. (Data source: Environment Canada, 2000)(Temperature is a deviation from the mean and precipitation a fraction of the mean to show inverse relationship).

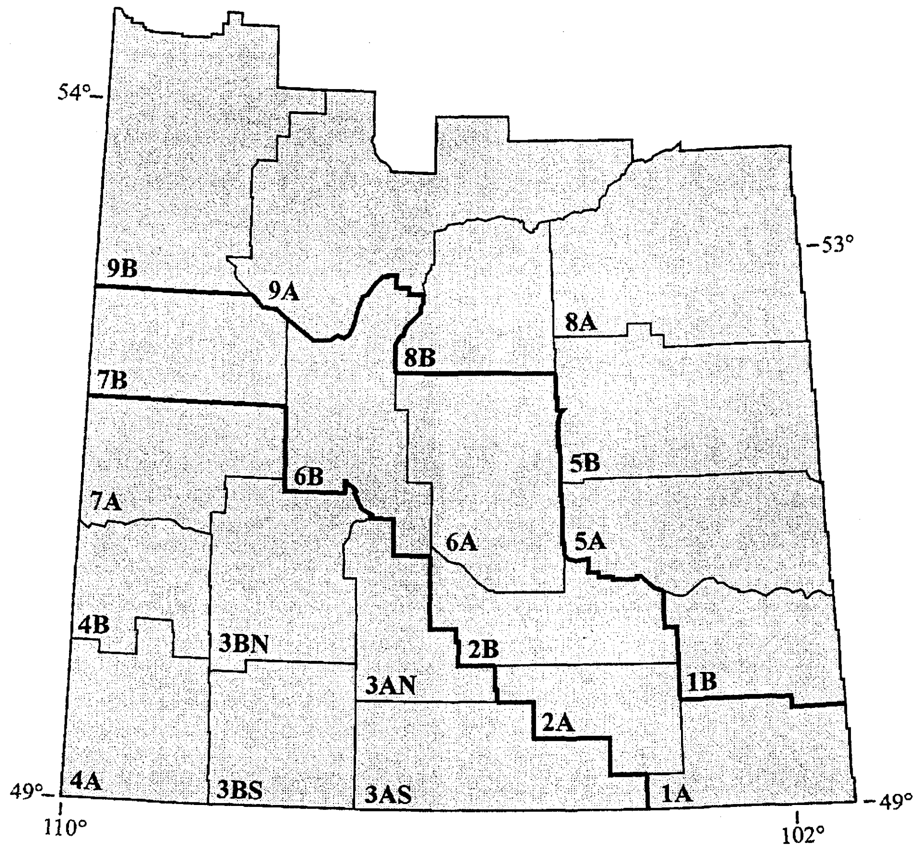


Figure 2.6 Saskatchewan Crop Districts
(Data source: Saskatchewan Agriculture and Food, 1998)

Crop districts 3AS, 3AN, 3BN, 3BS, 4A, 4B and 7A make up the Brown soil zone; 1A, 2A, 2B, 6A, 6B, and 7B make up the Dark Brown soil zone and 1B, 5A, 5B, 8A, 8B, 9A and 9B make up the Black soil zone. Mean values for the included crop districts were used to compute the soil zone statistics.

In terms of soil zones, the highest yield was recorded in the Black soil zone in 1996 with a yield of 2.50 t/ha. The lowest yield was in the Brown soil zone in 1961, with a value of 0.48 t/ha. The second lowest spring wheat yield, by crop district, was in the Dark Brown soil zone in 1954, with a yield of 0.57 t/ha.,a year when extensive rust was reported. The yield variation was essentially the same in each soil zone with a SD of $\pm$ 0.4 t/ha.

The overall average yield in Saskatchewan for the period 1950-1998 was 1.63 t/ha. The SD was $\pm$ 0.46 t/ha with the maximum yield of 2.35 t/ha produced in 1996. The lowest yield for that period was 0.64 t/ha in 1961. Figure 2.7 shows a gradual upward trend in wheat yields since 1950. Also noticeable is a discernible reduction in yield variation in the last decade. This is possibly due to changes in tillage practices, other changes in technology as well as favourable weather conditions.

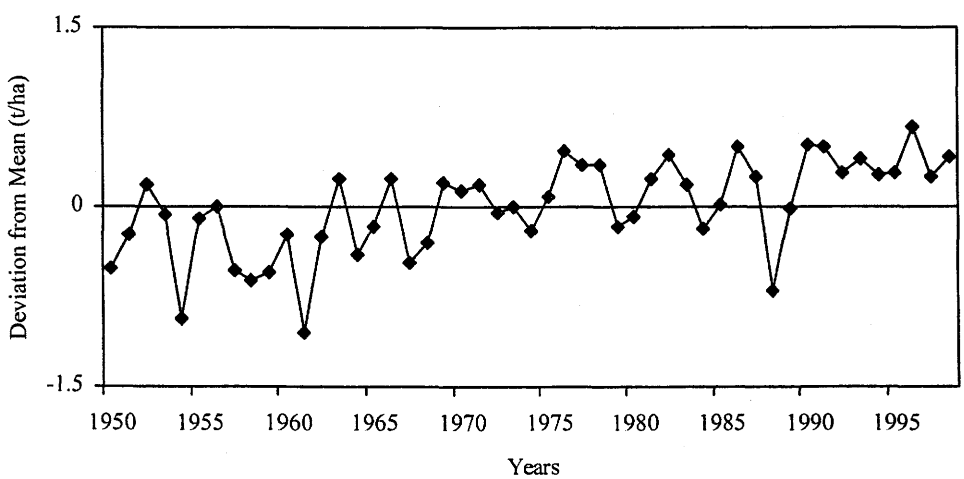


Figure 2.7 Saskatchewan spring wheat yields compared to1950-1998 mean (1.63t/ha) (Data source: Saskatchewan Agriculture and Food, 1998)

2.2.9 Protein data

Mean protein content (%) data for red spring wheat on the Canadian prairies for the period 1950-1998 were obtained from the Canadian Grain Commission in Winnipeg from three different sources. The primary source was notes compiled by Dr. Tipples supplemented by a report by Martins and Hylnka (1969) and the Protein Survey of Canadian Red Spring Wheat (Grain Research Laboratory of the Canadian Grain Commission 1979). The mean protein content for the 1950-1998 period was 13.5 %.

2.3.0 Analysis

This component is comprised of correlation and composite analyses. Eight sets of monthly data were analyzed for the period 1950-1998.

1) Southern Oscillation Index (SOI)
2) Sea surface temperature anomalies (SSTAs) for Niño-3
3) Sea surface temperature anomalies (SSTAs) for Niño-4
4) Pacific North American (PNA) teleconnection index
5) Atmospheric flow data at 50-kPa height
6) Surface precipitation
7) Surface temperature
8) Spring wheat yield

The data were organized in a computer spreadsheet so that correlation and composite analyses could be easily performed between independent variables of SOI, SSTAs, PNA indices and dependent variables of temperature, precipitation and spring wheat yield for Saskatchewan.

2.3.1 Correlation analyses

Correlation analyses were then performed to investigate relationships among:

a) Provincial May, June and July temperature and precipitation vs. wheat yield

b) SOI September through July vs. provincial wheat yield

c) Niño-3 SSTAs September through July vs. provincial wheat yield

d) Niño-4 SSTAs September through July vs. provincial wheat yield

e) PNA September through July vs. provincial wheat yield.

Once done for Saskatchewan's entire grain growing region the same procedure was applied to the three soil zones.

Correlation matrices were also created for yields, June-July temperature and June-July precipitation among the three different soil zones. The purpose of this correlation analysis was to determine the level of coherence of these three variables among the different soil zones.

2.3.2 Composite analysis

In order to assess the possible impact of persistently warmer or colder than normal SSTs in the east equatorial and central Pacific SSTAs on precipitation in Saskatchewan during the months of May through July, summations of SSTAs between January and July were calculated. Summations were started in January to endeavour to detect a clear early warning signal.

1) Niño-3 SSTAs during the six driest, six intermediate and six wettest May-July periods. Intermediate refers to the six years closest to the median value

2) Niño-3 SSTAs during six driest, six intermediate and six wettest Julys

3) Niño-3 SSTAs during six driest, six intermediate and six wettest June-Julys

4) Niño-4 SSTAs during six driest, six intermediate and six wettest May-Julys

5) Niño-4 SSTAs during six driest, six intermediate and six wettest Julys

6) Niño-4 SSTAs during six driest, six intermediate and six wettest June-Julys

To assess the predictive skill of the PNA accumulation for forecasting Saskatchewan temperatures, the following procedures were used:

7) Accumulated PNA values for the six hottest, six coolest and six intermediate Julys. PNA values are summed beginning in September prior to the growing season

8) Accumulated PNA values for the six hottest, six intermediate and six coolest Junes

To assess the behavior of the SOI during various extreme climatic situations and look for some predictive signal, the SOI was plotted for:

9) Six coldest, six moderate and six hottest Julys

10) Six driest, six moderate, and six wettest Julys

2.3.3 Case studies

To demonstate how El Niño and La Niña can affect 50-kPa flow, the El Niño year of 1951 and the La Niña year of 1988 were selected. These years were selected because June 1951 was the coldest June while June 1988 was the hottest for the 1950-1998 period. Temperature and precipitation for the months of June and July were first ranked to reveal: the coldest June (1951), hottest June (1988), coldest July (1972), hottest July (1960), driest June (1967), wettest June (1991), driest July (1961) and wettest July

(1993). The 50-kPa flow for each of these months was examined in light of earlier composite and correlation analyses, especially in relation to trends in SSTAs in the eastern and central equatorial Pacific.

CHAPTER 3

CORRELATION AND COMPOSITE ANALYSES

The correlation and composite analyses of this chapter deal with some of the extreme situations described in Chapter 2. The real value to agricultural users of long-lead forecasting products is receiving an early warning of temperature and precipitation extremes that are likely to impact yield and protein of cereal crops during critical growth stages. The techniques outlined in this chapter have utility for anticipating such climatic extremes, especially during the critical July period.

3.1 Results of correlation analysis

3.1.1 Correlation coefficients of indices vs. yield and July climate

Correlation analysis was performed to determine the influence of May, June and July precipitation and temperature on wheat yield (Table 3.1). It is evident that May, June and July precipitation correlated best with wheat yield followed closely by July precipitation. May and June precipitation was significant but not as important as May, June and July precipitation and July precipitation. Analysis was done with undetrended wheat yields given the gentle slope in the yields series. In future research it may be advisable to detrend the yield series prior to correlation analysis.

A significant inverse correlation was found between July precipitation and temperature. When it is hot in July it is usually dry, and when cool it is usually wet. Later in this chapter a simple empirical summation technique of the PNA index values is described for forecasting temperature during July. A similar summation technique of Niño-4 SSTAs is shown for anticipating July precipitation.

Table 3.1 Correlation coefficients between various climatic parameters and wheat yield

a. Correlation coefficients between late spring and summer climatic elements and spring wheat yield in Saskatchewan

Parameter	Correlation coefficient
May Temperature	0.16
May Precipitation	0.19
June Temperature	0.01
June Precipitation	0.24
July Temperature	-0.25
July Precipitation	0.47 *
May-June Precipitation	0.30 *
June-July Precipitation	0.47 *
May-July Precipitation	0.49 *

b. Correlation coefficients between monthly climatic elements

May Temperature vs. May Precipitation	0.07
June Temperature vs. June Precipitation	-0.12
July Temperature vs. July Precipitation	-0.43 *

c. Correlation coefficients between seasonal sea surface temperature anomalies and yield

Niño-3	September-November	0.05
Niño-3	December-February	0.09
Niño-3	March-May	0.27
Niño-3	June-August	0.26
Niño-4	September-November	0.06
Niño-4	December-February	0.11
Niño-4	March-May	0.25
Niño-4	June-August	0.35 *

* Values greater than 0.28 are significant at the 5% level

The only significant correlation found between SST data and yield is for Niño-4 SSTAs. This suggests that what happens at Niño-4 is more relevant to wheat yields in Saskatchewan than Niño-3 and that the Niño-4 region is likely the better predictor. The composite shown in Figure 3.3 also suggests that the Niño-4 region provides the longest lead or is a better early warning indicator. Other studies by Garnett and Khandekar (1992), Hsieh *et al.* (1999), and Babb *et al.* (2001) indicate significant correlations between Niño-3 SSTAs with Canadian prairie wheat yields. The smaller size of Saskatchewan compared with the entire Canadian prairies may be the reason that Niño-3 was not found to be significant. Based on previous findings between Niño-3 SSTAs and Canadian spring wheat yield, the study of relationships between Saskatchewan wheat yields and Niño-3 SSTAs was not abandoned.

Table 3.2 also shows a correlation between the SOI in April and Saskatchewan wheat yields. A negative SOI (indicative of El Niño) during April favors Saskatchewan wheat yields. This agrees with Garnett *et al.* (1997) who found significant correlations between April Niño-3 and July precipitation on the Canadian prairies. A significant correlation was found between Niño-3 during May, June and July, and Niño-4 during June and July and Saskatchewan wheat yields. Significant correlation is also evident between the PNA index in April and Saskatchewan spring wheat yields: this agrees with Romolo (1998), who found that a positive PNA index during April was associated with dry conditions over the Canadian prairies. Hence zonal flow in April favors spring wheat yields while meridional flow does not. A disadvantage of zonal flow during the April-May period is that it may delay planting which increases the frost risk to wheat in the fall.

Table 3.3 reveals a number of significant correlations providing a predictive signal for July temperature. A positive PNA index during the month of December suggests that July temperature will be warmer than normal. The physical mechanism is unclear. PNA flow is more likely to be meridional during La Niña, which if it persists through the summer months, is likely to cause July to be warmer than normal. Significant negative correlations were found between Niño-4 in May, June and July and July temperature. Colder than normal SSTs in the Niño-4 region are associated with a warmer than normal July in Saskatchewan. Meridional flow during July over the PNA region is associated with a warmer than normal July.

Table 3.2 Correlation coefficients between climatic indices and wheat yield

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Precipitation									0.19	0.24	0.47*
Temperature									0.16	0.01	-0.25
SOI	-0.03	-0.17	-0.13	-0.14	-0.12	-0.22	-0.17	0.37*	-0.14	-0.13	-0.25
Niño-3	-0.01	0.08	0.08	0.05	-0.12	-0.09	0.14	0.23	0.35*	0.28*	0.35*
Niño-4	0.04	0.07	0.06	0.11	0.08	0.11	0.22	0.25	0.25	0.32*	0.35*
PNA	-0.21	0.29*	-0.14	-0.14	0.15	0.05	0.08	0.28*	-0.02	-0.24	-0.12

* 5% level of significance: 0.28

Table 3.3 Correlation coefficients between climatic indices and July temperature

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SOI	0.05	0.08	0.01	0.03	0.02	0.02	0.03	0.25	0.19	0.16	0.34
Niño-3	0.18	0.09	0.01	0.09	0.05	-0.02	0.04	0.05	-0.17	-0.15	0.15
Niño-4	-0.04	0.00	-0.07	-0.06	-0.08	-0.10	-0.16	-0.23	-0.29*	-0.39*	-0.30*
PNA	0.14	0.24	0.07	0.39*	0.12	0.04	-0.01	-0.13	-0.23	0.00	0.41*

* 5% level of significance: 0.28

Table 3.4 Correlation coefficients between climatic indices and July precipitation

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SOI	-0.10	-0.16	-0.2	-0.21	0.08	-0.20	-0.03	0.25	-0.08	-0.20	-0.20
Niño-3	0.00	0.06	0.06	0.08	0.06	0.08	0.22	0.29*	0.31*	0.23	0.21
Niño-4	0.11	0.10	0.15	0.16	0.15	0.22	0.24	0.22	0.24	0.29*	0.29*
PNA	-0.15	0.06	0.13	0.05	-0.17	0.03	0.17	0.19	-0.01	0.05	-0.39*

* 5% level of significance: 0.28

Tables 3.3 and 3.4 show the ENSO influence on July temperature and precipitation. Warmer (colder) than normal Niño-3 SSTs during April and May are usually associated with wetter (drier) than normal weather in July in Saskatchewan. Warmer (colder) than normal SSTAs at Niño-4 during the May June and July period are associated with cooler (hotter) than normal weather in July. This represents a lag of three months and substantiates the findings of Garnett *et al.* (1997). An association was found between SSTs at Niño-4 during June and July and July precipitation. Warmer than normal SSTs at Niño-4 in June and July are associated with wetter than normal weather during July. A greater lead indication was evident with Niño-3 than with Niño-4. Also noteworthy was the correlation between the PNA index in July and July precipitation. This suggests that when the flow over the PNA region is zonal in July, Saskatchewan is usually wet, and when the flow is meridional it is dry.

3.1.2 Correlation coefficients of indices vs. yield and July climate by soil zone

Correlation coefficients were calculated between the four teleconnection indices and precipitation, temperature and wheat yield in Saskatchewan's three major soil zones. Table 3.5 shows that the best early warning indicator of yields in the Brown soil zone is the SOI index in April. Similarly a significant correlation was found between Niño-4 in

April, May and June and Brown soil zone yield. When compared to the other soil zones, the correlations with yield were strongest in the Brown soil zone. Niño-4 appeared to provide a longer and stronger lead than Niño-3 in this soil zone. The correlations in this matrix again confirm that El Niño (La Niña) favors (disfavors) the spring wheat crop in the Brown soil zone.

Table 3.6 shows the correlations between various teleconnection indices and July precipitation in the Brown soil zone. The most interesting finding was between the SOI and Niño-4 in February, and July precipitation in the Brown soil zone. This represents a leading lag of six months. The causal mechanism behind these correlations is uncertain. Significant correlations were found between Niño-3 during April and May, and July precipitation. Above normal SSTs during April and May at Niño-3 suggest a wetter than normal July in the Brown soil zone. A significant correlation was found between the PNA in July and July precipitation. This correlation suggests that zonal flow over the PNA region during July is conducive to wet conditions in the Brown soil zone while meridional flow is conducive to dry conditions.

Table 3.5 Correlation coefficients between climatic indices and yields in the Brown soil zone

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Precipitation									0.22	0.12	0.31*
Temperature									0.07	0.13	-0.25
SOI	-0.03	-0.22	-0.1	-0.16	-0.10	-0.20	-0.14	-0.35*	-0.16	-0.11	-0.24
Niño-3	0.01	0.08	0.10	0.08	0.13	0.13	0.17	0.26	0.32*	0.33*	0.33*
Niño-4	0.14	0.15	0.15	0.20	0.13	0.18	0.27	0.32*	0.32*	0.37*	0.36*
PNA	0.15	-0.21	-0.16	0.06	0.11	0.05	0.15	0.23	0.07	-0.18	-0.21

* 5% level of significance: 0.28

Table 3.6 Correlation coefficients between climatic indices and July precipitation in the Brown soil zone.

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SOI	-0.11	-0.16	-0.23	-0.07	-0.23	-0.29*	-0.14	-0.20	0.16	-0.03	0.03
Niño-3	0.26	0.11	0.15	0.18	0.13	0.18	0.26	0.29*	0.31*	0.23	0.18
Niño-4	0.06	0.04	0.00	0.06	0.10	0.30*	0.25	0.19	0.19	0.19	0.16
PNA	-0.22	-0.16	0.18	-0.06	-0.11	-0.07	0.15	0.18	-0.10	0.10	-0.28*

* 5% level of significance: 0.28

Table 3.7 Correlation coefficients between climatic indices and Dark Brown soil yields

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Precipitation									0.21	0.21	0.48*
Temperature									0.15	-0.09	0.24
SOI	-0.03	-0.22	-0.10	-0.16	-0.18	-0.18	-0.14	-0.35*	0.15	-0.11	0.23
Niño-3	0.24	-0.03	0.07	0.03	0.09	0.08	0.11	0.17	0.32*	0.26	0.24
Niño-4	0.07	0.10	0.08	0.15	0.10	0.11	0.19	0.25	0.26	0.32*	0.35*
PNA	-0.03	0.33*	-0.18	0.07	0.14	0.05	0.04	0.23	-0.24	-0.20	-0.16

* 5% level of significance: 0.28

Table 3.8 Correlation coefficients between climatic indices and July precipitation in Dark Brown soil zone

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SOI	-0.04	-0.13	-0.19	-0.14	-0.06	-0.24	-0.06	-0.17	-0.06	-0.21	-0.11
Niño-3	-0.08	-0.13	-0.19	-0.01	-0.01	0.00	0.18	0.28*	0.30*	0.26	0.24
Niño-4	0.06	0.04	0.00	0.06	0.10	0.15	0.23	0.26	0.26	0.31*	0.36*
PNA	-0.13	-0.19	0.03	0.05	-0.11	0.13	0.19	0.18	0.00	0.07	-0.11

* 5% level of significance: 0.28

Table 3.7 indicates that strong zonal flow over the PNA region in October is usually favourable for growing conditions for spring wheat in the Dark Brown soil zone the following summer. A correlation also exists between the SOI in April and yield. SSTAs at Niño-4 in June and July are similarly correlated with wheat yields. These are consistent with the correlations found between Niño-3 and Niño-4 and July precipitation in the Dark Brown soil zone shown in Table 3.8. These findings corroborate those of Garnett *et al.* (1997) and Garnett *et al.* (1998a).

Table 3.9 reveals a correlation between the PNA index in October and Black soil zone yields the following year. Zonal flow over the PNA region in October is favorable and meridional flow unfavorable for yields harvested a year later. As speculated earlier, with strong El Niño (La Niña) conditions the PNA flow is likely to be zonal (meridional). The ocean has a great deal of memory and SSTs are slow in changing. The lag in PNA correlations is probably related to the persistence of SSTAs and their influence on 50-kPa flow. The SOI in April and Niño-3 and Niño-4 between May and July are correlated with yield. These correlations confirm that El Niño conditions favor spring wheat prospects in the Black soil zone while La Niña conditions are unfavorable.

In Table 3.10 a significant correlation is shown between Niño-4 in June, and July precipitation. A significant correlation is also evident between the PNA index in July, and July precipitation. This zonal flow over the PNA region in July is suggestive of wetter than normal conditions.

The ENSO signal appears to be the weakest in the Black soil zone. No significant correlations were found between teleconnection indices in the spring months and July precipitation as was found in the Brown and Dark Brown soil zones. Also the correlations between teleconnection indices and yield were not as strong as was found in the Brown and Dark Brown soil zones.

The correlations between ENSO and the different soil zones are fairly low. This might be explained by the fact that the study involves forty-eight years of data and focuses on relatively small regions of Saskatchewan. Many previous studies such as those by Garnett and Khandekar (1992), Garnett *et al.*(1998), Babb *et al.*(2001) and others have focused on larger areas of the Canadian prairies using teleconnection indices involving fewer years.

Table 3.9 Correlation coefficients between climatic indices and Black soil zone yields

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Precipitation									-0.13	0.15	0.34*
Temperature									0.15	-0.08	-0.19
SOI	-0.01	0.16	-0.11	-0.11	-0.13	-0.20	-0.14	-0.30*	-0.12	-0.11	-0.23
Niño-3	0.00	0.09	0.06	0.08	0.05	0.05	0.14	0.23	0.33*	0.25	0.28*
Niño-4	0.09	0.06	0.04	0.09	0.07	0.06	0.18	0.20	0.21	0.29*	0.30*
PNA	-0.13	0.30*	-0.12	0.02	0.14	0.06	0.30*	-0.04	-0.26	-0.26	-0.32*

*5% level of significance: 0.28

Table 3.10 Correlation coefficients between climatic indices and July precipitation in the Black soil zone

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SOI	-0.10	-0.16	-0.19	-0.21	0.08	-0.21	-0.03	-0.18	-0.07	0.04	-0.20
Niño-3	0.06	0.07	0.03	0.02	0.04	0.11	0.11	0.15	0.15	0.09	0.09
Niño-4	0.07	-0.08	-0.08	-0.14	0.17	0.09	0.16	0.16	0.21	0.29*	0.26
PNA	-0.03	0.07	0.13	0.15	-0.18	0.03	0.08	0.11	0.10	0.05	-0.32*

*5% level of significance: 0.28

3.1.3 Correlation coefficients revealing spatial coherence among soil zones

Table 3.11 reveals a high degree of coherence, between yield, temperature and precipitation of the three soil zones for the period 1950-1998. These correlations show that when yields in one soil zone is impacted by climate in any given year a similar effect will occur in the other two soil zones. The coherence is not as strong with temperature and precipitation.

Table 3.11 Correlation matrix showing coherence of spring wheat yield, June and July temperature and June and July precipitation among the three soil zones

Spring Wheat yield

	Brown	Dark Brown	Black
Brown	1.00	0.93	0.92
Dark Brown		1.00	0.93
Black			1.00

Mean June-July Temperature

	Brown	Dark Brown	Black
Brown	1.00	0.75	0.67
Dark Brown		1.00	0.93
Black			1.00

Total June-July Precipitation

	Brown	Dark Brown	Black
Brown	1.00	0.81	0.51
Dark Brown		1.00	0.70
Black			1.00

The overall strong coherence is probably related to Saskatchewan's gently undulating topography which allows weather systems to pass over the region relatively uninterrupted. This suggests that weather systems that affect the yields in one soil zone are likely to affect the other two soil zones over the course of a growing season. Greatest coherence exists with yield, followed by temperature and then precipitation. Precipitation is a discontinuous variable, with the nature of summer convection lowering its coherence. The least coherence is with precipitation between the Brown and Black soil zones. The greatest coherence exists with yield between the Brown and Dark Brown and Dark Brown and Black soil zones. With temperatures, highest coherence exists between Dark Brown and Black soil zones. These correlation coefficients indicate that whatever climatic factors affect yield in one soil zone in any given year are likely to have the same effect in the other two soil zones.

3.2 Results of composite analysis

3.2.1. El Niño, La Niña modulation of the PNA pattern

In order to assess the influence of El Niño and La Niña on the flow pattern over the PNA region, nine years were classified as either El Niño, La Niña or normal. Years in which SSTAs between the spring months (March, April and May) and summer months (June, July and August) deviated less than 0.1 C. were classified as normal years. Examples of such years were 1967, 1977 and 1978. Years in which the warming rate of change in Niño-3 SSTAs between the spring and summer months exceeded 0.6° C were classified as El Niño years. Years in which this warming trend occurred were 1972, 1976 and 1991. Years in which the cooling rate of change in Niño-3 SSTAs between the spring and summer months exceeded 0.6°C were classified as La Niña years. Examples were 1970, 1983 and 1988. Figure 3.1 reveals distinctly different profiles showing the typical response of the PNA index during El Niño, La Niña and normal years. The PNA response was essentially neutral during years classified as near normal.

PNA values were accumulated starting in September for each group of these years classified as El Niño, La Niña and near normal. Figure 3.1 suggests the PNA index is a reflection or derivative of El Niño/La Niña and that these events may be responsible for modulation of the PNA index. This composite shows that during La Niña events the flow over the PNA region is usually meridional (weak westerlies) while during El Niño events the flow over the PNA region is zonal (strong westerlies). During years described as normal the flow over the PNA region was neither meridional nor zonal. As proposed by Bjerknes (1966, 1969), El Niño appears to increase the strength of the westerlies while La Niña appears to reduce the strength of the westerlies.

The greatest heat waves over the Canadian prairies, such as in 1961 and 1988, have occurred with meridional flow (related to La Niña) for months on end prior to the critical June-July period, while the coolest June-July periods have followed periods of zonal flow (related to El Niño). Figure 3.1 shows the potential value in accumulating PNA values starting in the fall months.

3.2.2 Impact of growing season precipitation on yield

As shown by the correlation analysis (Table 3.1), the most significant climatic element affecting spring wheat yield is May to July precipitation. To further demonstrate the importance of summer precipitation in determining yield, Table 3.12 was constructed which shows the driest, intermediate and wettest summers in Saskatchewan. Summer is defined as the May-July period with the rainfall amounts in Table 3.12 representing total summer precipitation. The common experience that "rain makes grain" appears to be valid: dry summers produce low yields, and wet summers produce high yields within limits. Yields in the driest summers were 30% below the 1950-1998 mean of 1.63 t/ha; in the wettest summers yields were 20% above the mean, while in intermediate summers yields were 8% above the mean.

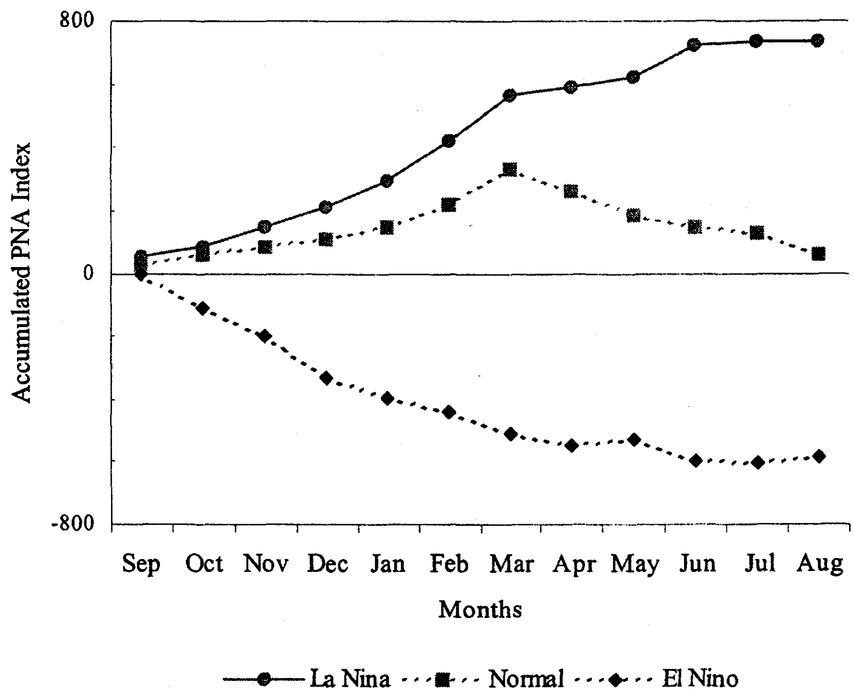


Figure 3.1 Accumulated PNA index in El Niño and La Niña and normal years, 1950-1998, Monthly PNA values multiplied by 100 (Data sources: University of Washington, 2000, Climate Prediction Centre, 2000)

Table 3.12 Driest, intermediate and wettest summers in Saskatchewan

Dry Summers			Intermediate Summers			Wet Summers		
Year	Precipitation (mm)	Yield (t/ha)	Year	Precipitation (mm)	Yield (t/ha)	Year	Precipitation (mm)	Yield (t/ha)
1967	88	1.17	1972	171	1.59	1991	264	2.12
1958	103	1.02	1995	174	1.92	1963	252	1.86
1961	110	0.58	1974	176	1.42	1953	240	1.57
1985	116	1.65	1981	178	1.86	1993	238	2.04
1957	122	1.10	1978	179	1.98	1986	236	2.13
1968	141	1.33	1983	181	1.81	1954	234	0.69
6 Yr. Mean	113	1.14		177	1.76		244	1.94
Mean yield 1950-1998		1.63			1.63			1.63
Deviation from mean		-30%			8%			20%

* 1954 not included in average because of low yields associated with rust problem

3.2.3 Impact of persistent sea surface temperature anomalies on precipitation

3.2.3.1 June-July precipitation over the Canadian Prairies

Garnett *et al.* (1998a) developed a distinct composite of Niño-3 SSTAs for the driest and wettest June-Julys over the Canadian prairies for the period 1964-1996. They found some predictive skill with a lead-time of 2-4 months. Their composite captured the effect of persistently warmer or colder than normal SSTs at Niño-3 between September and July on June and July precipitation. In this thesis an attempt is made to improve on this technique with reference to summer precipitation in Saskatchewan, by removing September to December months from the accumulation. Newman (personal communication) suggested that a three to six month period is more realistic in capturing the memory of the ocean. Also, the cold air over the North Pole contracts during the six-month period between February and August. As the circumpolar vortex collapses warm or cool SSTAS have a chance to dominate the annual cycle in the May through July period.

3.2.3.2 May-June-July precipitation in Saskatchewan

The precipitation totals for May-Julys, June-Julys and Julys for Saskatchewan were ranked from driest to wettest for the 1950-1998 periods. Monthly Niño-3 and Niño-4 SSTAs were then summed for the January-July periods for the wettest, intermediate and driest May-June-Julys, June-Julys and Julys for the stations shown in Figure 2.1. The six wettest May-June-July periods were: 1991, 1993, 1953, 1993, 1986 and 1954; the driest May-June-July periods were: 1967, 1958, 1961, 1985, 1957 and 1968 and the six nearest the median were: 1972, 1995, 1974, 1981, 1978 and 1983. Eighteen years represents about a third of the collected data allowing reliable composite analysis. Values of Niño-3 SSTAs were accumulated for each group starting from the month of January prior to the May-July period. Figure 3.2 shows an upward trend in SSTAs in the Niño-3 region between January and July during the wettest May-July periods in Saskatchewan. For the driest summers mild La Niña conditions prevailed from January through May with only slight SST warming during the months of June and July. For intermediate summers, El Niño conditions predominated between January and July i.e. SSTAs were predominantly positive in the Niño-3 region. This composite has clear utility in separating dry summers from intermediate and wet summers. During the wettest summers in Saskatchewan between 1950 and 1998 a SST warming trend was evident between January and July in the Niño-3 region.

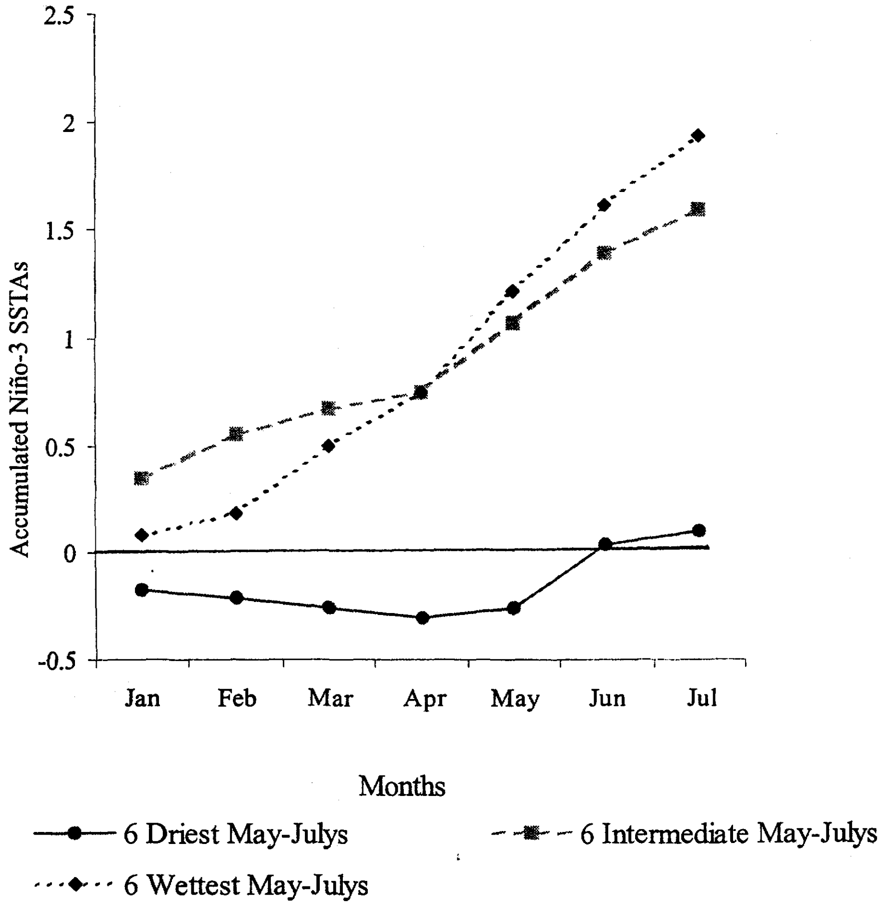


Figure 3.2 Niño-3 SSTA summations before and during the six wettest, intermediate and driest May-Julys
(Data sources: Climate Prediction Center 2000, Environment Canada, 2000)

3.2.3.3 July precipitation in Saskatchewan

As indicated in Table 3.1, July precipitation is the second most significant weather factor affecting spring wheat yield in Saskatchewan. Figure 3.3 shows the summation of Niño-4 SSTAs during the six driest, wettest and intermediate Julys for the 1950-1998 period. The six driest Julys were: 1961, 1985, 1959, 1967, 1960 and 1984 during which wheat yields averaged 25% below the 1950-1998 mean. During six intermediate Julys (1953, 1968, 1974, 1977, 1991 and 1995) yields were 5% above the mean. The wettest Julys were: 1993, 1990, 1982, 1987, 1986 and 1969 when yields averaged 23% higher than the mean. It is clearly evident from Figure 3.3 that a SST warming at Niño-4 between January and July is a good predictor of an extremely wet July in Saskatchewan. In years in which July rainfall was intermediate the warming at Niño-4 was far less pronounced. During extremely dry Julys, it is clear that La Niña conditions dominated and persisted between January and July.

This is probably the most significant finding of this thesis as it relates directly to July precipitation, the most critical factor determining wheat yields in Saskatchewan. By the end of March a clear signal is evident regarding the amount of precipitation that can be expected the following July in Saskatchewan, representing a lead-time of four months. A probability estimate of temperature in July can also be made from this composite because a significant inverse correlation exists between July temperature and precipitation as shown in Table 3.1. Clearly, persistent El Niño conditions in the central Pacific are favourable and persistent La Niña conditions are unfavourable for the growth of wheat in Saskatchewan when they prevail through the January to July period. Figure 3.3 is the most revealing composite of all, substantiating that Niño-4 may be the

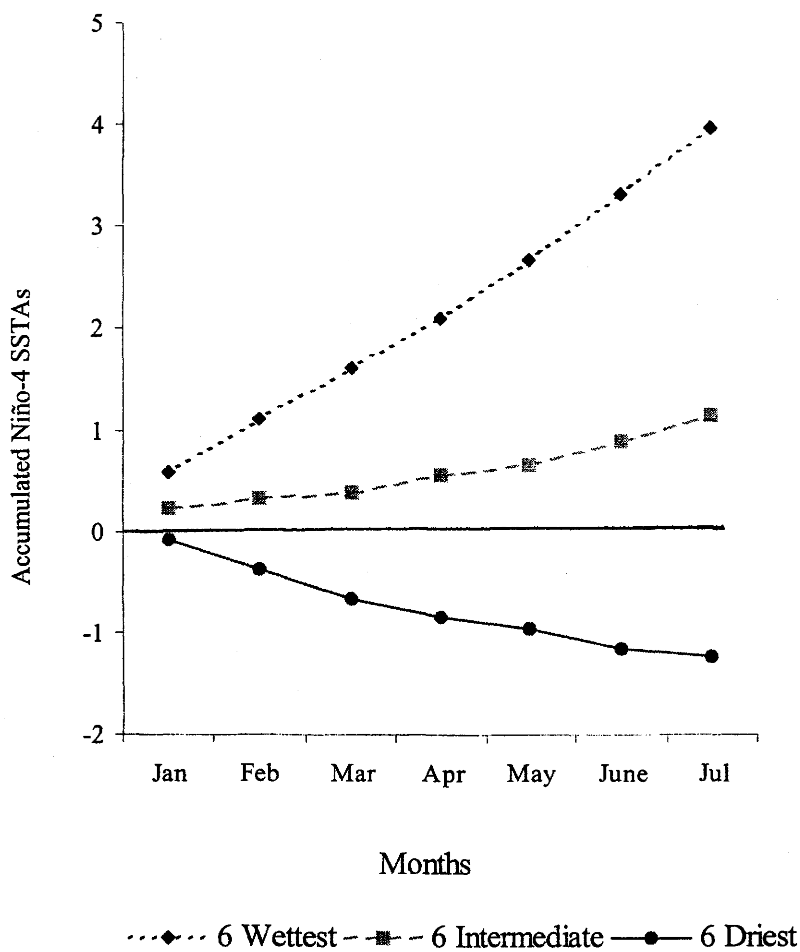


Figure 3.3 Niño-4 SSTA summations before and during the wettest, intermediate and driest Julys (Data sources: Climate Prediction Centre 2000, Environment Canada, 2000)

best predictor for the critical July precipitation factor.

Figure 3.3 shows the cumulative effect of months of warm vs. cold SSTAs in the central equatorial Pacific region. However, a large amount of variation occurs in the individual lines that make up the six-year average. This technique may not work in any given year, but is essentially an estimate of risk. A positive summation of Niño-4 SSTAs is associated with heavy July precipitation and a negative summation with light July precipitation. A probability might be assigned to each situation. This technique should not be used in isolation without scrutiny of many factors, such as the position and strength of the Pacific High, PNA accumulation, and other indices. Also a simple summation of anomalies is probably not the best representation of SST persistence.

3.2.3.4 June plus July precipitation in Saskatchewan

The six driest June-Julys were: 1961, 1967, 1985, 1958, 1977 and 1960. The six wettest were: 1993, 1963, 1991, 1970, 1990 and 1954 and six intermediate June-Julys were: 1951, 1973, 1980, 1983, 1994 and 1995. Figure 3.4 shows the summation of Niño-3 SSTAs for these three categories.

Of the three composite diagrams presented, Figure 3.4 is the most difficult to explain, although it does separate the dry June-Julys from the other categories. Years in which intermediate rainfall is likely to occur are clearly evident. As shown by Garnett *et al.* (1997) for the entire prairies, June precipitation was highly unpredictable. Perhaps this is why Figure 3.4 has the least orderly curves of the three composites. Only a subtle distinction was found between the wettest and driest June-Julys. During driest June-Julys,

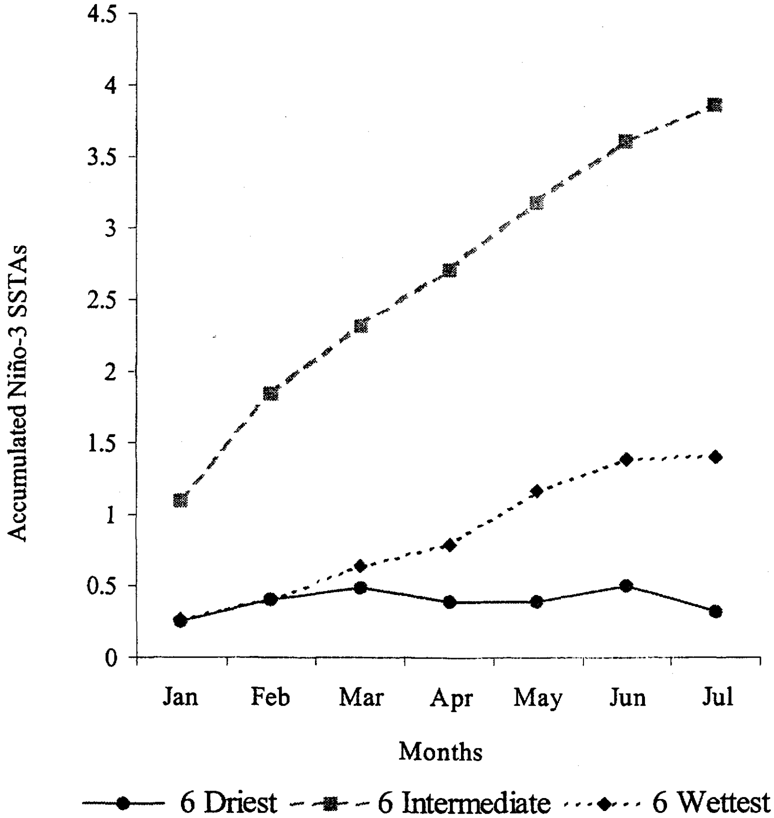


Figure 3.4 SSTA summation during wettest, intermediate and driest June-Julys (Data sources: Climate Prediction Centre 2000, Environment Canada 2000)

Nino-3 SSTs were slightly above the long-term mean between January and May. This kind of persistence suggests a risk of a very dry June and July.

Figures 3.2, 3.3 and 3.4 each indicate that El Niño is favourable and La Niña unfavourable for precipitation in Saskatchewan. This supports the findings of Garnett and Khandekar (1992) who contended that the transition of SSTAs in the east equatorial Pacific during the seasons before the summer months may be of early warning value for the Canadian and U.S. spring wheat crops. Figures 3.2, 3.3 and 3.4 also support the contentions of Khandekar and Jones (1995) regarding El Niño, La Niña and prairie moisture who concluded:

1) El Niño years are generally associated with higher than normal precipitation over the Canadian prairies during spring and early summer, and

2) La Niña years are generally associated with drier conditions during spring and early summer.

These results seem to disagree with the findings of Bonsal and Lawford (1999) that the number of extended dry spells on the prairies is associated with El Niño events and is significantly higher than for non-El Niño periods. It should be clarified however, that the study of Bonsal and Lawford focused on the summer following the onset of El Niño and La Niña events. They suggested that the North Pacific SSTAs are generated by the surface circulation associated with the Aleutian low which is stronger or weaker depending on the PNA pattern. Their reasoning is that El Niño is associated with an intense Aleutian low, which seems to be the main cause of the SST gradient in the North

Pacific. This gradient in the North Pacific induces a ridge on the west coast the following summer, which is associated with dryness over the Canadian prairies.

The opposite chain of events occurs during La Niña events. During La Niña events the Aleutian low is usually not be as intense meaning that there is less likelihood of forming the gradient in the North Pacific as defined by Bonsal (1991). With the absence of any such gradient in the North Pacific a ridge is unlikely to form on the west coast. Bonsal and Lawford (1999) confirm that ridging on the west coast is associated with dryness over the Canadian prairies.

3.2.4 50-kPa ridge determination, development and impacts

In the early 1990s, Khandekar (personal communication) suggested using a summation of PNA values for determining whether a 70-kPa ridge was developing over North America and for forecasting temperature during June and July over the Canadian prairies. Garnett and Khandekar (1995) noted that during the hottest summers between 1964 and 1995, namely: 1970, 1983, 1984 and 1988, the original four point PNA index was consistently positive several months prior to the summer period. The PNA index appears to be influenced primarily by El Niño/La Niña similar to what is demonstrated in the graph of summed values (Figure 3.1).

Extremely hot and cold summers are chosen to further test this technique. Ranking of June-July temperatures shows that 1961 and 1988 were the hottest June-Julys and 1951 and 1993 the two coldest June-Julys since 1950. Only two years were chosen to investigate extreme cases, especially the extreme drought years of 1961 and 1988. Figure 3.5 reveals that during June-July in 1961 and 1988, years of extreme June heat over the

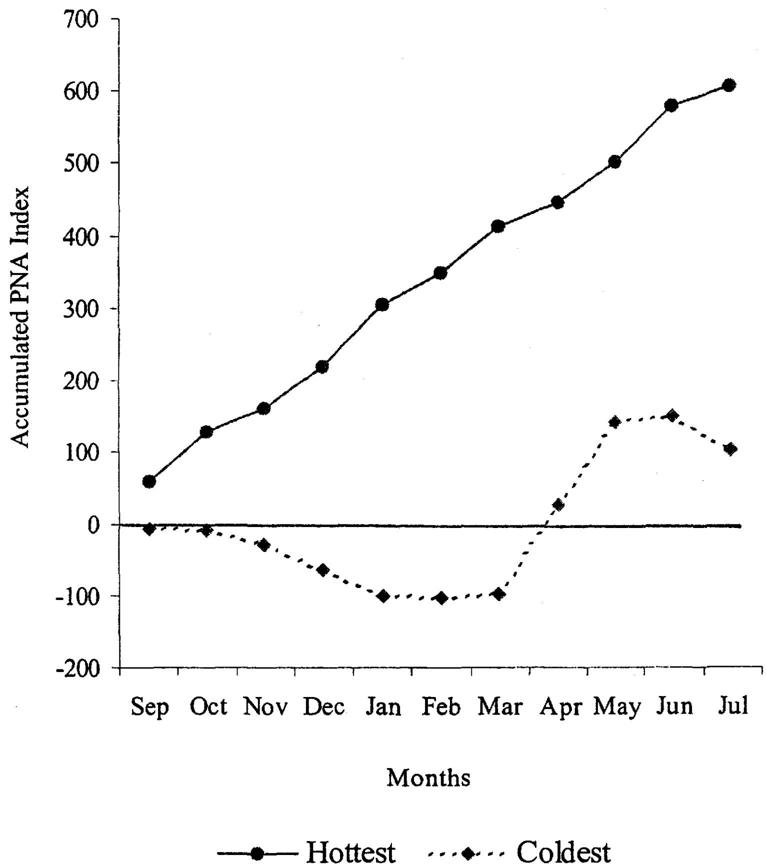


Figure 3.5 Accumulated PNA indexes during the two hottest (1961,1988) and two coldest June-Julys (1951, 1993). Monthly PNA values multiplied by 100. (Data sources: University of Washington, 2000, Environment Canada, 2000)

Canadian prairies, meridional flow was evident almost every month between September and July. During the two coolest June-Julys of 1951 and 1993, the flow over the PNA region was predominantly zonal between September and March, and then became meridional during March-April. This composite shows that during hot and cold Junes and Julys, the PNA index has behaved in a different fashion especially during the first seven months of the accumulation. June temperatures in 1961 and 1988 exceeded the mean for 1950-1998 by two standard deviations. Those were the two worst drought years in Saskatchewan since 1950. However, there have been years such as 1977 and 1981 when there was a great deal of meridional flow but no ensuing heat wave. PNA behaviour needs to be evaluated in relation to other factors such as El Niño/La Niña, the Pacific High and north Pacific SSTs. It is a technique useful for assessing the probability of an extremely hot or cold summer on the Canadian prairies.

Accumulated PNA index values for the six hottest and coldest Julys are shown in Figure 3.6. During the hottest Julys, the flow over the PNA region was meridional each month between September and July. During the coldest Julys, the flow over the PNA region was predominantly zonal between September and March, followed by predominant meridional flow between April and June. Constant meridional flow for months on end is termed "PNA blocking" and is usually a precursor to a heat wave where temperatures during July exceed 1 standard deviation above normal.

Bjerknes (1966) described how the westerlies strengthen following an increase in the equatorial heat source (El Niño), which influences the Hadley circulation, resulting in a northward flux of angular momentum. This is especially true when sea surface temperatures exceed air temperatures over the Niño-4 region which causes an increase in the upward vapour flux, heat of condensation and strong convection. La Niña has the reverse influence with reduced resultant vapour flux, less heat of condensation and weaker westerlies. Other factors that may modulate the PNA index are the Pacific High as described by Chakravarti (1972) and a SSTA gradient in the North Pacific as described by Bonsal (1991) and Bonsal and Lawford (1999). The composites in Figure 3.5 and 3.6 are probably the result of the same El Niño/La Niña influence described earlier. To reiterate, El Nino is conducive to zonal flow (strong westerlies) and La Niña meridional flow (weak westerlies) over the PNA region. During strong El Niño events it seems plausible that there is more water vapour in the atmosphere to be carried by stronger westerlies than is the case with La Niña.

3.2.5 Impact of temperature extremes during June and July

Assuming one can forecast temperature conditions during June and July using a simple PNA accumulation what are the effects on precipitation, yield and protein content? The PNA accumulation during the six hottest, six intermediate and six coldest Julys between 1950 and 1998 is shown in Figure 3.6. Table 3.13 shows various climatic statistics associated with the six hottest, six coldest and six intermediate Julys. During the six hottest Julys there were only two years in which the yield exceeded the average (Table 3.13). Hot Julys are usually drier than normal as the data reveals. Average yields during hot Julys were 5% lower than the long term mean of 1.63 t/ha. Hot Julys stress the wheat plant especially if it is also dry. In 1960 and 1975 high June precipitation was an offsetting factor. Extremely hot Julys resulted in precipitation that was 85% of the mean. During the coldest Julys spring wheat yield was 8% above the 1950-1998 mean.

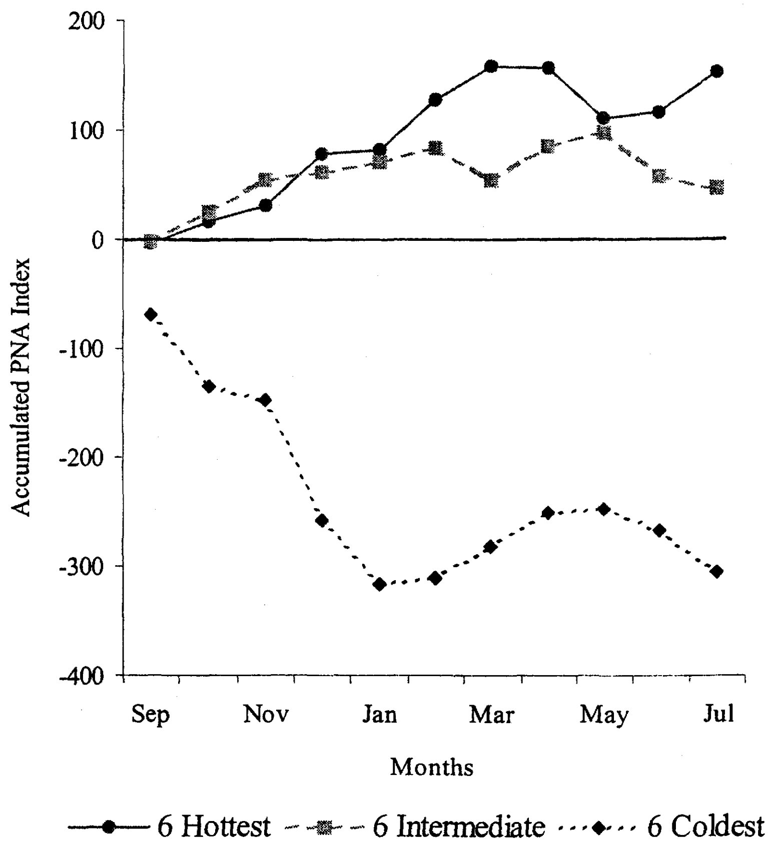


Figure 3.6 Accumulated PNA index during hottest, intermediate and coldest Julys, 1950-1998.(Data sources: University of Washington 2000, Environment Canada 2000) Monthly PNA values multiplied by 100

If 1954, the rust year is excluded from the six intermediately warm Julys, intermediate Julys produce the highest yields, followed by cold Julys and then hot Julys. Yields during intermediate Julys were 11% above the long term mean.

Table 3.13 Impact of hottest, intermediate and coldest Julys on precipitation and yield

Hottest				Intermediate				Coldest			
Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)	Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)	Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)
1960	18.5	31.2	1.40	1980	16.4	59.0	1.54	1972	14.3	52.1	1.59
1989	18.5	40.3	1.61	1994	16.4	48.0	1.90	1993	14.4	113.8	2.04
1975	18.1	41.4	1.72	1973	16.4	47.4	1.64	1992	14.4	75.4	1.92
1984	18.0	38.3	1.45	1954	16.4	70.6	0.69	1971	14.8	65.2	1.82
1964	17.9	58.0	1.22	1985	16.4	28.5	1.65	1952	15.1	70.0	1.82
1983	17.9	78.5	1.81	1996	16.5	73.1	2.29	1962	15.4	63.1	1.38
Means											
6 yrs		48.0	1.54			54.4	1.61			73.3	1.76
1950-1998		55.8	1.63			55.8	1.63			55.8	1.63

One can then indirectly forecast precipitation and yield in Saskatchewan using a simple PNA accumulation by considering: 1) the chances of an extremely hot or cold July given the PNA accumulation and 2), the amount of July precipitation that could be expected given the Julys temperature forecast.

This technique of summing PNA values for forecasting July temperatures in Saskatchewan was next applied to June temperature. The six hottest Junes were identified as: 1988, 1961, 1987, 1970, 1995, and 1962 while the six coolest Junes were: 1951, 1964, 1993, 1985, 1958, and 1969. Intermediate Junes or those closest to the median, were: 1980, 1982, 1976, 1963, 1971 and 1959. Garnett *et al.* 1998 show that accumulating PNA values starting in the September prior to the growing season is a useful technique for determining whether or not a 70-kPa ridge is developing over North America.

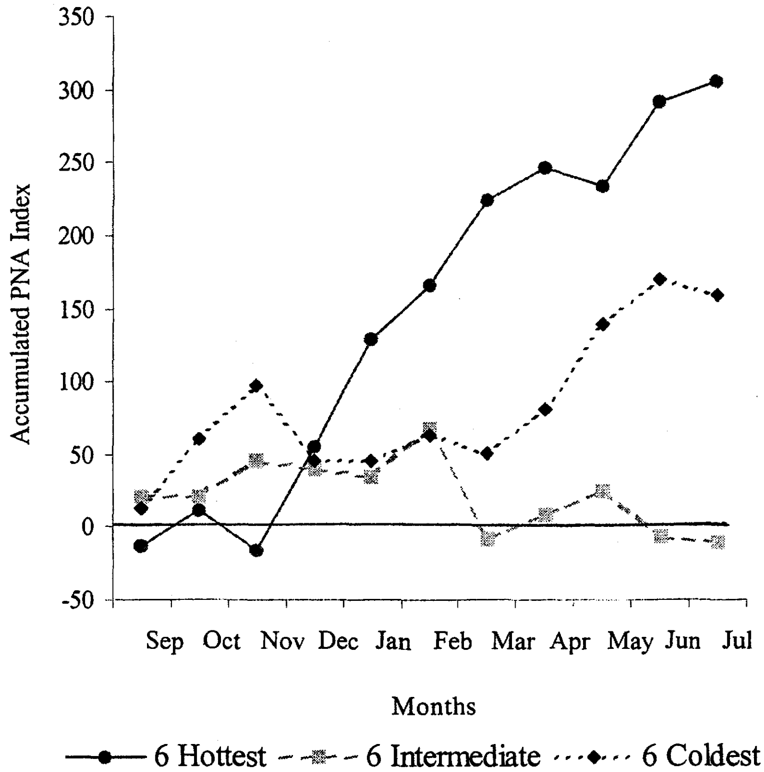


Figure 3.7 Accumulated PNA index during hottest, intermediate and coldest Junes Monthly PNA values multiplied by 100 (Data sources: University of Washington, 2000, Environment Canada, 2000)

Figure 3.7 suggests that forecasting cold Junes is not as straightforward as forecasting hot Junes. Distinct meridional flow over the PNA region beginning in November is especially evident during years with extremely hot Junes. This composite has utility for separating hot Junes from the cool and moderate Junes and appears ideally suited for anticipating extreme June heat waves similar to what occurred in 1961 and 1988. Wheat yields in those two years were .58 t./ha and .92 t./ha respectively of the mean yield of 1.63 t/ha.

Table 3.14 shows the impact of June temperature on June precipitation and subsequent wheat yields. During the hottest Junes, precipitation was 84% of normal with yields 86% of normal. Hot Junes are associated with dry Junes in five out of six occasions. Coldest Junes are also usually drier than normal with lower than usual yields. Only the intermediately warm Junes have produced above normal precipitation and yields.

Table 3.14 Impact of hottest, intermediate and coldest Junes on precipitation and yield

Hottest				**Intermediate**				**Coldest**			
Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)	Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)	Year	Temp. (°C)	Ppt. (mm)	Yield (t/ha)
1962	16.4	80.0	1.38	1980	15.0	76.1	1.54	1951	12.6	99.4	1.40
1995	16.4	74.7	1.92	1982	15.0	46.1	2.06	1954	12.9	104.0	0.69
1970	17.0	122.6	1.76	1976	15.0	118.3	2.10	1993	13.2	99.9	2.04
1987	18.0	55.7	1.87	1963	15.1	123.6	1.86	1985	13.3	43.1	1.65
1961	18.2	44.4	0.58	1971	15.2	93.9	1.82	1958	13.5	43.7	1.02
1988	19.2	63.3	0.92	1959	15.2	99.5	1.08	1969	13.5	49.8	1.83
Means											
6 yrs		73.5	1.41			92.9	1.74			73.3	1.44
1950-1998		87.1	1.63			87.1	1.63			87.1	1.63

The effect of temperature extremes on precipitation, yield and protein during consecutive hot and cold June and Julys was investigated next. Table 3.15 shows those years in which temperatures during June and July exceeded 1 standard deviation above normal. During those years there was a noticeable decline in precipitation and yield and an increase in protein content. During hot June-Julys (Table 3.15) yields were 18% above normal while during cold June-Julys yields were only 5% below normal. The most obvious impact of hot June and Julys was on yield and then protein content.

Table 3.15 Impact of temperature more than 1 SD above normal during June-July on precipitation, yield and protein content

Year	**Temperature** (°C)	**Precipitation** (mm)	(% of Norm)	**Yield** (t/ha)	**Protein** (%)
1988	18.4	112.7	82	0.92	14.8
1961	17.7	71.2	52	0.58	14.2
1989	17.2	113.5	83	1.61	14.5
1987	17.1	149.8	109	1.87	14.0
1970	16.9	192.4	140	1.34	13.2
5 Year Average	17.5	127.9	93	1.34	14.1
1950-1998	15.8	137.1		1.63	13.5

The impact of low June and July temperatures on precipitation, yield and protein content was then assessed (Table 3.16). June-July periods colder than normal by 1 SD usually experience normal rainfall. The yields are somewhat lower than average with below normal protein. The year 1954 is excluded from this analysis, as heavy rains that summer contributed to rusting and low yields. During cool June and Julys, precipitation was above average four out of eight years. Protein content during these cool June-Julys was noticeably below the 1950-1998 mean.

Table 3.16 Impact of temperature more than 1SD below normal during June-July on precipitation, yield and protein content

Year	Temperature	Precipitation		Yield	Protein Content
	(°C)	(mm)	(% of Normal)	(t/ha)	(%)
1993	13.8	213.7	155	2.04	12.4
1951	14.2	142.5	104	1.40	13.8
1992	14.6	117.7	86	86	12.6
1952	14.6	170.4	124	1.82	12.7
1954	14.7	174.6	127	0.69	12.6
1969	14.8	131.5	96	1.83	13.9
1958	14.8	86.3	63	1.02	13.8
1985	14.9	71.6	52	1.65	13.4
8 YearAverage	14.6	138.5	100	1.55	13.2
1950-1998	15.8	137.1		1.63	13.5

Similarly the regression scheme and composites developed by Garnett *et al.* (1998) are useful for anticipating June and July temperature, protein and to some extent yield. They were able to explain 65% of the temperature variation during June-July over the Canadian prairies using the PNA index during October, November and December prior to the growing season and Niño-3 SSTAs during April and May prior to the growing season. Their scheme underestimated the cool temperatures of 1992 and 1993, which was probably the result of the Pinatubo volcanic eruption in 1991. An accurate forecast of June and July temperature has implications for June and July precipitation as well as protein and yield.

Table 3.17 shows the ranking of June-July temperature, precipitation and yield in Saskatchewan for the 1950-1998 period. The ranking shows that the four highest yielding years 1996, 1990, 1986 and 1991 were years in which June and July precipitation was moderate to heavy with temperatures moderate to high. The four lowest yielding years of 1961, 1954, 1988

Table 3.17 Ranking of June-July temperature, precipitation and yield 1950-1998

Rank	Mean June-July Temperature (°C)		Total June-July Precipitation (mm)		Spring Wheat Yields (t/ha)	
1	1988	18.4	1993	213.7	1996	2.29
2	1961	17.7	1963	205.3	1990	2.14
3	1989	17.2	1991	199.9	1986	2.13
4	1987	17.1	1970	192.4	1991	2.12
5	1970	16.9	1990	180.2	1976	2.10
6	1984	16.7	1954	174.6	1982	2.06
7	1983	16.7	1950	173.1	1998	2.04
8	1991	16.6	1976	171.4	1993	2.04
9	1997	16.5	1953	171.3	1978	1.98
10	1974	16.4	1952	170.4	1977	1.98
11	1955	16.4	1986	163.4	1992	1.92
12	1979	16.4	1986	163.4	1995	1.92
13	1959	16.4	1971	159.1	1994	1.90
14	1963	16.4	1956	157.3	1997	1.88
15	1964	16.3	1987	149.8	1987	1.87
16	1995	16.3	1965	147.3	1966	1.86
17	1975	16.3	1975	146.6	1981	1.86
18	1960	16.2	1966	144.7	1963	1.86
19	1986	16.2	1981	144.6	1969	1.82
20	1996	16.1	1962	143.2	1952	1.82
21	1957	16.1	1982	143.0	1971	1.82
22	1990	16.0	1996	142.9	1983	1.81
23	1956	15.9	1994	142.6	1970	1.76
24	1962	15.9	1951	142.5	1975	1.72
25	1978	15.9	1980	135.0	1985	1.65
26	1973	15.8	1973	134.6	1956	1.64
27	1965	15.8	1983	133.2	1973	1.64
28	1976	15.8	1995	132.4	1989	1.61
29	1977	15.8	1969	131.5	1972	1.59
30	1981	15.8	1959	128.8	1953	1.57
31	1998	15.8	1997	126.8	1980	1.54
32	1980	15.7	1955	123.7	1955	1.52
33	1994	15.6	1978	120.2	1965	1.46
34	1982	15.6	1964	118.8	1979	1.46
35	1966	15.3	1992	117.7	1984	1.45
36	1967	15.3	1989	113.5	1974	1.42
37	1953	15.3	1972	113.1	1951	1.40
38	1950	15.2	1988	112.7	1960	1.40
39	1972	15.1	1984	111.0	1962	1.38
40	1968	15.0	1974	105.9	1968	1.33
41	1971	15.0	1979	104.1	1964	1.22
42	1985	14.9	1957	103.0	1967	1.17
43	1958	14.8	1968	101.5	1950	1.12
44	1969	14.8	1960	101.1	1957	1.10
36	1954	14.7	1977	97.8	1959	1.08
37	1952	14.6	1958	86.3	1958	1.02
38	1992	14.6	1985	71.6	1988	0.92
39	1951	14.2	1967	71.4	1954	0.69
40	1993	13.8	1961	71.2	1961	0.58

and 1958 were years in which June and July was very hot and dry, dry and cool or extremely wet and cold. The low yields in 1954 were largely the result of rust associated with cold wet conditions. The impact of climatic extremes during June and July on yield and hence protein is apparent. It is of considerable interest to those engaged in ago-business on the Canadian prairies.

3.2.6 Behaviour of the SOI in extremely dry, wet, hot, and cool Julys

The final portion of this chapter deals with behavior of the SOI in the months leading up to extremely hot/dry and cold/wet Julys. The behavior of the SOI was clearly different between extremely dry and wet Julys as revealed in Figure 3.8. The wettest Julys ranked in decreasing order were: 1993, 1990, 1982, 1987, 1986 and 1969. The six driest Julys were: 1961, 1985, 1959, 1967, 1960 and 1984. Intermediate Julys were: 1953, 1977, 1991, 1968, 1974 and 1995. During extremely wet Julys, the index was negative (El Niño) starting in October, becoming strongly negative in February and continuing to be negative from March through July. During extremely dry Julys, the SOI was mostly positive (La Niña) between September and July. The positive spikes in February and April leading up to dry Julys are noteworthy, and contrast with the SOI index during wet Julys when the index is consistently negative. Figure 3.8 agrees with the correlation analysis in Tables 3.2, 3.5, 3.6 and 3.9. Significant correlations were found with the SOI during April prior to the critical July period. This composite reinforces the notion that El Niño is the friend and La Niña the foe of the Canadian prairies during the February-April period. A strong Walker circulation (positive SOI) during April and May appears to be a precursor of a dry July. Conversely, a consistently weak Walker circulation (negative SOI) in the February to May period is a precursor of a moderate to wet July.

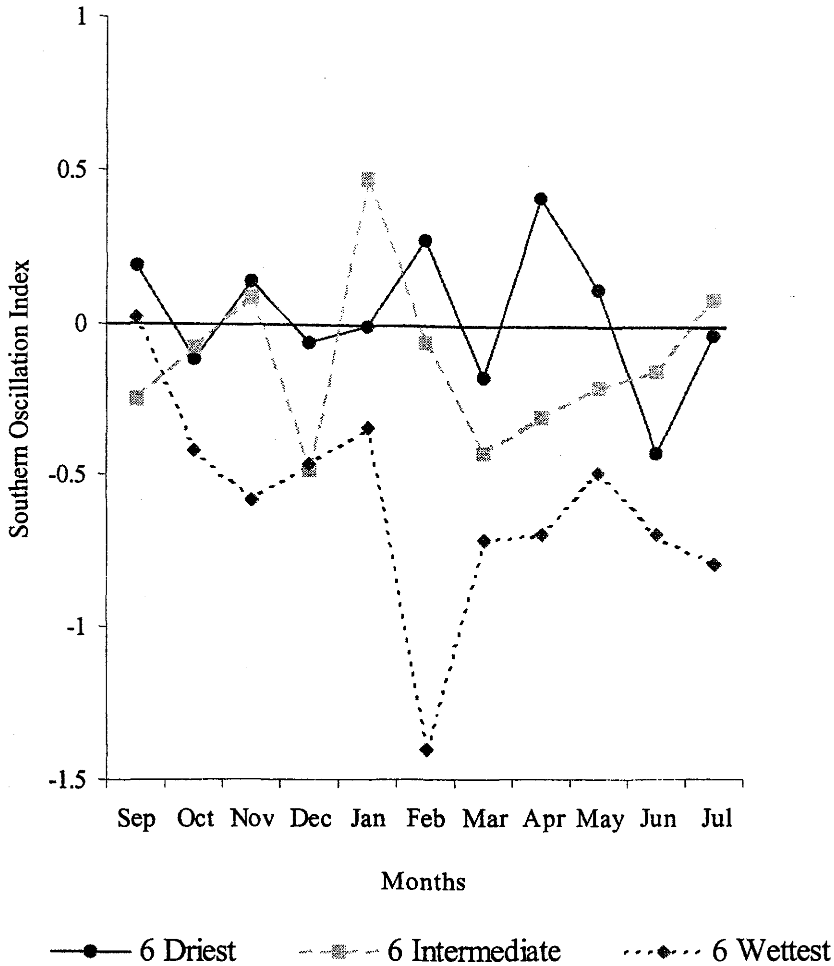


Figure 3.8 Southern Oscillation Index before and during the six driest, intermediate and wettest Julys (Data sources: Climate Prediction Center, 2000, Environment Canada, 2000)

Figure 3.9 shows the SOI during extremely hot, moderate and cold Julys. The six coolest Julys were: 1972, 1993, 1992, 1971, 1952, and 1962, the six hottest were: 1960, 1989, 1975, 1984, 1964, and 1983 and six moderately warm Julys were: 1954, 1966, 1973, 1985, 1994 and 1996. Most noteworthy was the behavior of the SOI during extremely hot Julys. The index was increasingly positive during the January to April period remaining positive during May. Behavior of the SOI in the April through July period appears to separate the hot from the moderate to cool Julys.

Closer scrutiny of the SOI behavior prior to extremely dry, and hot Julys reveals a rapid rise in the SOI between March and April. This rapid rise in the SOI is comparable to the findings of Stone *et al.* (1996) with regard to the Australian growing season. The behavior of the SOI during hot, dry Julys is in sharp contrast to what happens during wet and cool Julys. The most useful time to observe the SOI for determining if July is likely to be hot or cold is the February-May period. A positive SOI during the April through July period is typically associated with hot Julys and appears distinguishable from normal and cool Julys. Again, La Niña (positive SOI) is associated with hot Julys and El Niño (negative SOI) is associated with intermediate to cool Julys confirming that El Nino is the friend and La Nina the foe to the Saskatchewan wheat farmer.

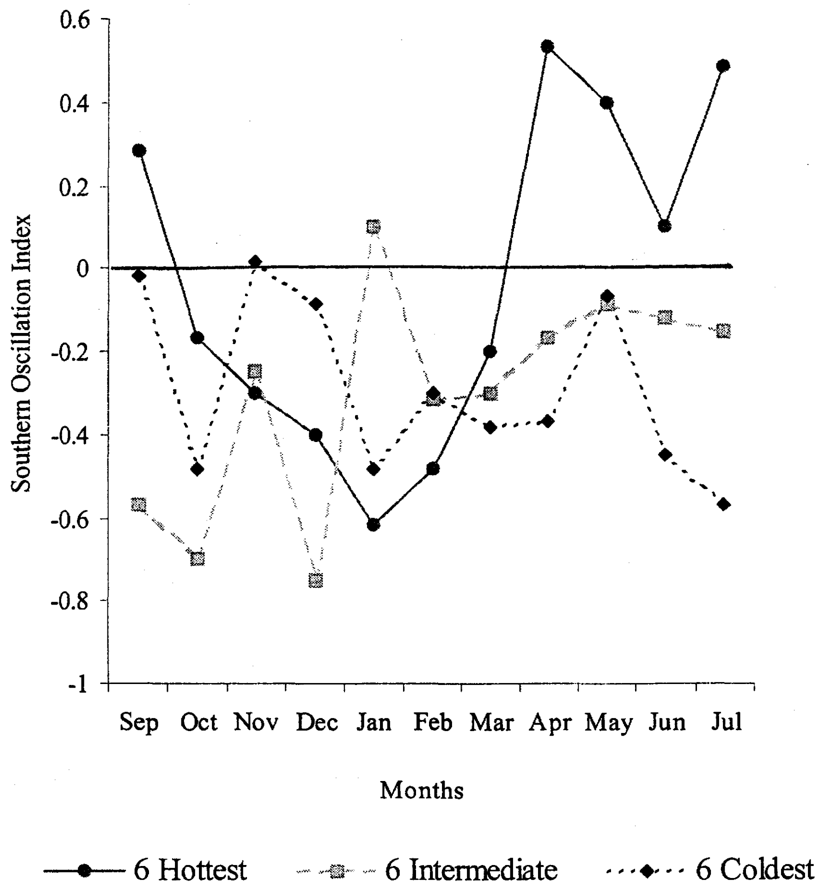


Figure 3.9 Southern Oscillation Index before and during six hottest, intermediate and coldest Julys (Data sources: Climate Prediction Center 2000, Environment Canada 2000)

3.3 Observational evidence

Historical spring wheat yields of western Canada for the 1961 to 1998 period were compared to those of Australia. Historical Australian wheat yields were obtained from the Canadian Wheat Board's Crop Database which dates back to 1961. It is apparent that El Niño favours spring wheat production over the Canadian prairies while diminishing wheat production in Australia (Figure 3.10). An inverse relationship is apparent between the wheat yields in Australia and Canada and suggests that ENSO events appear to have an opposite influence on these two wheat growing regions. The correlation between these two wheat yield series is $r = -0.45$ for the 1961 to 1998 period, significant at the 1% level. Garnett (1998) classifies well-known ENSO events based on SSTAs in the east equatorial Pacific and performance of the SOI. Years in which SSTs were at or above normal during spring and summer are classified as El Niño years. These years were: 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1991, 1994 and 1997. In 1963, 1976, 1982 and 1986 record yields were established over the Canadian prairies while in the remaining years yields were above average.

June precipitation in 1963 and 1976 was 123 and 118 mm respectively, well above the mean, while in July of 1982 and 1986 precipitation was 97 and 93 mm respectively, also well above the long term mean. The heavy rains in June and July of those years were a key factor in the record yields attained over the Canadian prairies. In contrast, extremely dry conditions were experienced in eastern Australia in the fall of 1972, 1982 and 1994 greatly reducing the wheat crops in those years. The difference in yield between Australia and Canada is particularly striking during the 1982/1983 event with the yield in Australia being the lowest in decades, while the yield in Canada was a record.

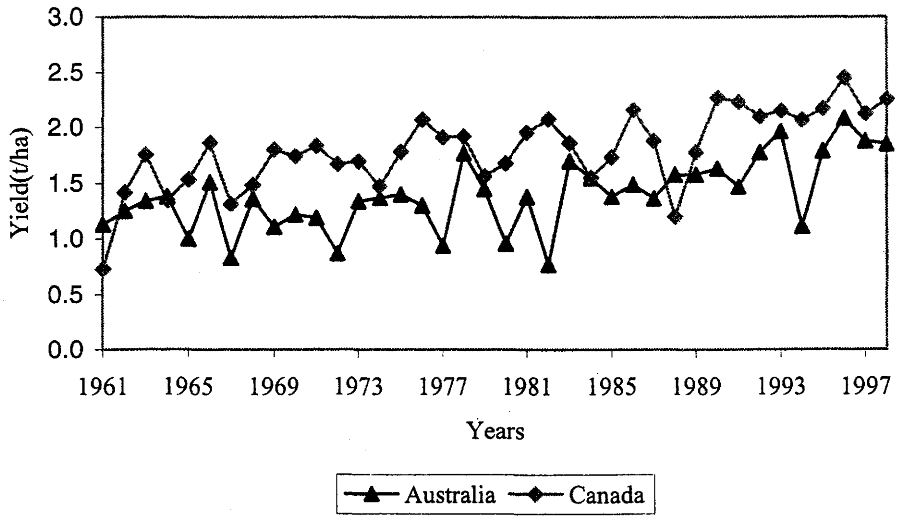


Figure 3.10 Canadian and Australian wheat yields during 1961-1998
(Data source:Weather and Crop Surveillance Dept. Database, CWB, 1998)

This observational evidence further confirms that El Niño (warmer than normal SSTs in the central and east equatorial Pacific in seasons leading up to the summer months) is a friend to western Canadian agriculture and a foe to Australian agriculture. Figure 3.10 shows 1961 and 1988 as the two biggest Canadian crop disasters of the 1950-1998 period. Khandekar and Neralla (1984), Garnett and Khandekar (1992) and Allan *et al.* (1996) show that in both years La Niña conditions existed and there were surplus monsoons in India. June temperatures in Saskatchewan in 1961 and 1988 were 2 standard deviations above normal.

3.4 Summary of analysis and results

The data and discussion presented in this chapter support the hypothesized influence of El Niño and La Niña during spring and summer months on Saskatchewan's wheat yield. The correlations between Saskatchewan wheat yield and April SOI and Niño-3 and Niño-4 during the months of May through July support the hypothesis that El Niño is friend and La Niña is foe to the Saskatchewan wheat farmer. Many of the correlations are shown to have predictive value with lead times of several months.

Significant correlations were found between Niño-3 SSTAs and July precipitation in Saskatchewan. For example, when SSTAs at Niño-3 during April and May are colder than normal, one can expect July precipitation in Saskatchewan to be drier than normal When SSTAs at Niño-4 during June and July are above normal one can expect July precipitation to be above normal. The strongest lead correlations for Saskatchewan July precipitation are with Niño-3 in April and May, as shown in Tables 3.4 and 3.6, which corroborate the findings of Garnett *et al.* (1997). One of the strongest leading lag correlations in this research was between the April SOI index and spring wheat yield in the different soil zones of Saskatchewan. In terms of soil zones, a six-month lag was found between Niño-4 and the SOI in February and July precipitation in the Brown soil zone. The ENSO response appears strongest in the Brown soil zone and weakest in the Black soil zone.

Significant correlations were found between Niño-4 SSTAs during May through July, and July temperature in Saskatchewan. When SSTs were below normal May through July, July was hotter than normal. Conversely, when SSTAs were above normal May through July, July was colder than normal, supporting the thesis hypothesis. No significant correlations were found between Niño-3 and Niño-4 SSTAs and June temperature and precipitation. The strongest ENSO signal was between the Niño-3 and Niño-4 SSTAs and July precipitation.

Table 3.3 indicates that a positive PNA index in July is associated with a warmer than normal July with an ensuing effect on precipitation, yield and protein content. This meridional flow is generally associated with La Niña conditions. Hot Julys are usually dry Julys, as demonstrated in Table 3.1. A significant inverse correlation of $r = -0.43$ exists between July temperature and precipitation. Also, July precipitation has a correlation of $r = 0.48$ with yield, one of the strongest in this research. Meridional flow over the Canadian prairies between September and July is conducive to hot, dry July conditions in Saskatchewan. Zonal flow during this period on the other hand is associated with cool wet conditions. This is consistent with what Romolo (1998) found for the Canadian prairies during April and May.

Figure 3.1 in this chapter reveals that the PNA index is modulated primarily by El Niño and La Niña. Summing the index starting in September prior to the growing season shows distinctly different profiles of the PNA index with meridional flow evident during La Niña and zonal flow evident with El Niño in keeping with what was found by Bjerknes in the late 1960s. Similarly when one examines accumulated values of the PNA index during extremely hot, cold and intermediate Julys, distinctly different behavior is noted (Figure 3.6). During hot Julys the PNA index flow is predominantly meridional while it is predominantly zonal during the coolest Julys. These two composites substantiate the correlation analysis. That is, El Niño conditions are conducive to cool conditions in Saskatchewan and La Niña is conducive to hot conditions in Saskatchewan.

Of special significance are El Niño or La Niña conditions in the central equatorial Pacific during the January to April period. El Niño conditions during January to March are favourable and La Niña conditions unfavourable for July precipitation in Saskatchewan. This is further established in composite analysis of the SOI in relation to July precipitation.

CHAPTER 4

CASE STUDIES OF EXTREME EL NINO AND LA NINA EVENTS

This chapter focuses on how the ENSO phenomenon influences atmospheric flow over the PNA region, which in turn influences temperature and precipitation during the May through July period in Saskatchewan. The first section describes aspects of the 50-kPa level flow during classical El Niño and La Niña situations. The second deals with case studies of monthly climatic extremes in Saskatchewan in relation to SSTA trends and 50-kPa flows.

4.1. Niño-4 the best predictor

Of the four regions of the equatorial Pacific shown in Figure1.1 why is the Niño-4 region the best predictor of Saskatchewan's precipitation and wheat yield? During La Niña a relatively fast Walker circulation cools the Niño-1 region near 100°W first, followed by Niño-2, Niño-3 and Niño-4 regions in that order. Rasmussen (1984) shows the upwelling that occurs near Niño-1 and Niño-2 during La Niña and how cold water is transported from east to west. The Niño-4 region will be the last region to be cooled with a fast or positive SO. During El Niño the reverse occurs. The Walker circulation slows down and there may even be a reversal in the direction of the SO with a weakening of the trade winds and the warming that occurs at the Niño-1 and Niño-2 regions. With a weakening of the trades warm water at the surface gradually migrates eastward cutting off the upwelling that occurs during La Niña at Niño-1 and Niño-2. These warmer than normal SSTs supply heat to the atmosphere. Niño-4 is more conservative than Niño-3 as is evident by the SD of SSTAs and less extreme values of SSTAs. The mean SD of Niño-4 SSTAs for the period 1950-1998 is 0.63 with mean minimum and maximum values of SSTAs of –1.24 and +1.20. This compares with Niño-3 with a mean SD of 0.87 SSTAs and with mean minimum and maximum SSTA values of -1.53 and +2.8. Hence, Niño-4 is the last region to cool off during La Niña and the first to warm up during El Niño making it the best predictor.

In other words the build-up of warm water in the Niño-4 region between January and April leads to increased condensation, increased precipitation in the atmosphere above Niño-4 and stronger westerlies (zonal flow) carrying moisture-laden air, which is conducive to heavy precipitation in Saskatchewan. A buildup of cold water at Niño-4 on the other hand, between January and July, is conducive to less condensation, less precipitation in the atmosphere above Niño-4, and weaker westerlies (meridional flow), with which to carry drier air and meaning less precipitation for Saskatchewan. Summing SSTAs in the Niño-4 region between January and early April captures SSTA persistence relative to condensation, precipitation potential above Niño-4, and the strength of the westerlies.

4.2 Case studies of 50-kPa flow during El Niño and La Niña years

Garnett (1998) classified 1951 as an El Niño year and 1988 as a La Niña year based on SSTAs in the Nino-3 region during the winter and spring months. The Junes of 1951 and 1988 were the coolest and the hottest respectively for the 1950-1998 period. During 1951 there was a distinct warming trend between January and June at Niño-4 (-0.7°C January to +0.7°C in June). During 1988, on the other hand, there was a distinct cooling trend at Niño-4 (+1.0 C in January to +0.4 C in June). On a seasonal basis, precipitation during May, June and July of 1951 was the 17th driest while May, June and July of 1988 was the 10th driest. The May through July period of 1951 was the 8th coolest summer, while the May through July period of 1988 was the hottest three-month period in Saskatchewan between 1950 and 1998. These observations support the notion that La Niña is more likely to be associated with warmer conditions and El Niño with cooler conditions during the summer months.

Figures 4.1 through 4.6 display the patterns of 50-kPa height anomalies from the central Pacific to Saskatchewan and provide some concept of how High and Low pressure systems move and how ridges and troughs form during El Niño and La Niña. They show the 50-kPa flow of May, June and July of 1951 and May, June July of 1988 as well as the movement of High pressures and Low pressures. The Lows and Highs have been clearly marked for ease of understanding. Systems migrate from west to east. The circulation around Lows is counter clockwise and around Highs clockwise, which provides some notion of the direction of the wind at the surface. Winds from the southwest desert area of the U.S.A are usually hot and dry. Winds from the southeast are more likely to be hot and moist, while winds from the north are likely to be cold and dry. Garnett (1986) indicated that the two main moisture sources for the Canadian prairies were the Gulf of Mexico for the eastern Canadian prairies and the Pacific Ocean for the western Canadian prairies. A trough on the west coast is favourable for the development of Colorado Lows and heavy precipitation on the prairies while a ridge on the west coast is a dry pattern for the Canadian prairies.

During May 1951, a deep Low existed at 50-kPa at 170°W and 45°N accompanied by a High over the Hudson's Bay and a Low over Newfoundland (Figure 4.1). This pattern, which depicts meridional flow (PNA 1.28), brought cooler and drier than normal dry conditions to Saskatchewan that May consistent with the findings of Romolo (1998). Meridional flow over the PNA region that year was strongest during May. SSTs at Niño-4 that year during May were slightly below normal but warmed between May and August. Similarly the SOI became more strongly negative between May and August consistent with the SST warming at Niño-4 and Niño-3. The High Pressure in the vicinity of the Hudson's Bay may have impeded the flow at the 50-kPa level.

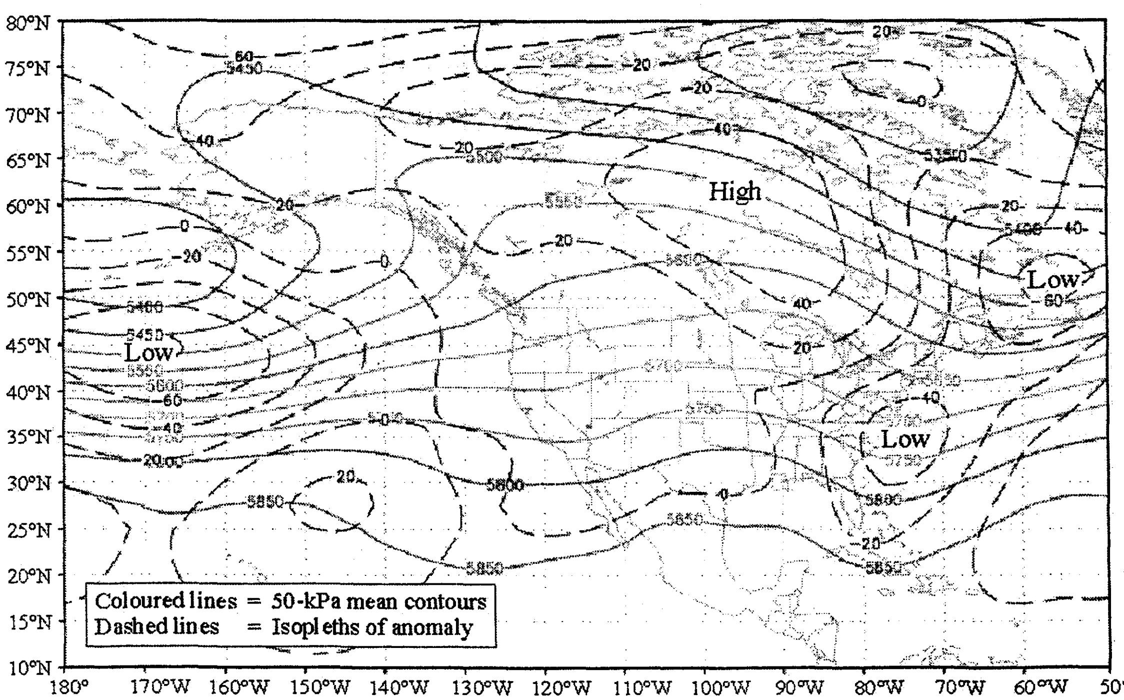


Figure 4.1 50-kPa heights and height anomalies during May 1951
(Data source: National Centre for Atmospheric Research, 2000)

During June 1951, the Low at 170°W and 45°N deepened, helping to induce a very pronounced High-pressure ridge at 140°W and 50°N as shown in Figure 4.2. A Low is evident near the border at 105°W and 50°N. The extremely cold June experienced in Saskatchewan that year was largely the result of northwesterly flow that came over the ridge at 140°W and 50°N. A trough is evident in the southwestern region of North America. Temperatures during June of 1951 were 12.6°C compared to the 1950-1998 mean of 15.6°C. The Low over Montana was probably a factor in the heavier than normal precipitation in Saskatchewan during June of 1951. The cool, wet weather may have been prohibitive for yield establishment stunting vegetative growth, delaying crop development, and increasing the risk of frost damage late in the growing season.

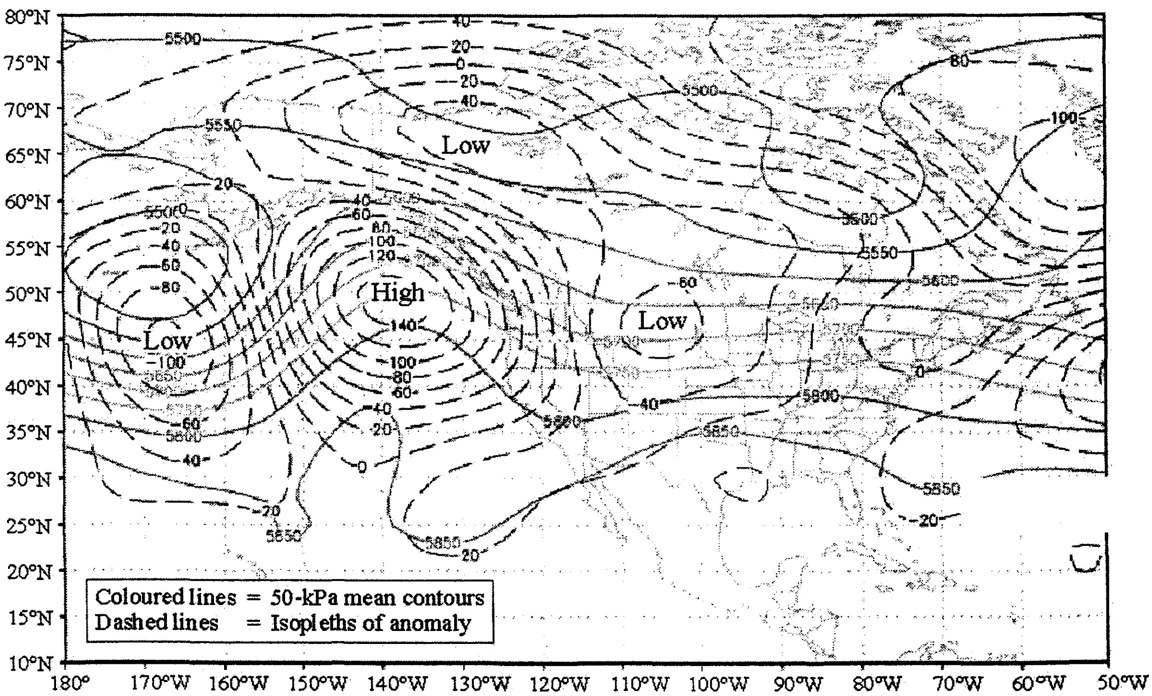


Figure 4.2 50-kPa heights and height anomalies during June 1951
(Data source: National Centre for Atmospheric Research, 2000)

During July the High-pressure ridge that existed at 140°W during June retrograded to 160°W and was less pronounced (Figure 4.3). The trough over the Manitoba-Saskatchewan border moved eastward to sit over the Hudson's Bay.

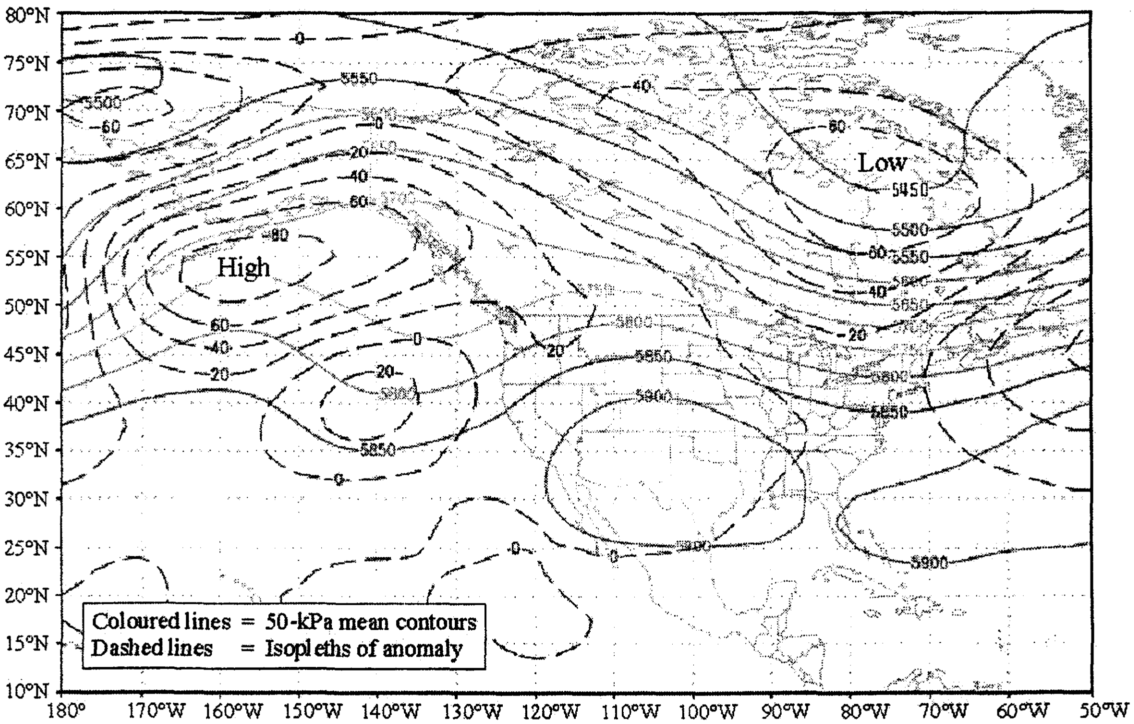


Figure 4.3 50-kPa heights and height anomalies during July 1951
(Data source: National Centre for Atmospheric Research, 2000)

Clockwise rotation around the High in the Gulf of Alaska brought cool, dry air to Saskatchewan during July. The cool northerly flow during July probably contributed to the dry July of 1951 and below average yields of that year, 1.40 t/ha versus the long term mean of 1.63 t/ha.

The La Niña of 1987/88 was associated with one of the worst droughts in North America in 50 years. Niño-4 SSTAs plunged from 1.3°C in September 1987 to -0.6°C in

July of 1988. Niño-4 SSTAs first fell below normal in April of 1988. May of 1988 brought warmer and drier than normal weather to Saskatchewan as a result of southwesterly flow caused by a Low centered at 140°W off the west coast of North America (Figure 4.4). One of the early signs of drought may well be southwesterly flow during the month of May, as occurred in 1988.

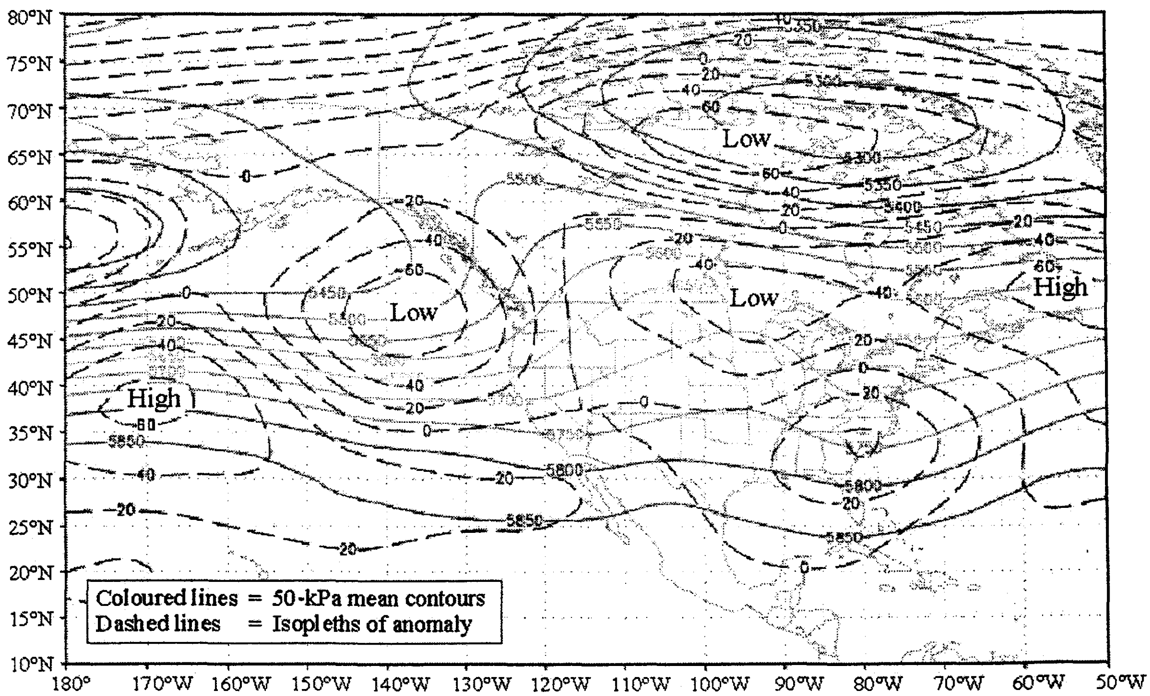


Figure 4.4 50-kPa heights and height anomalies during May 1988
(Data source: National Centre for Atmospheric Research, 2000)

Figure 4.5 shows that during June of 1988, a Low remains at 140°W with a pronounced High pressure at 100°W and 50°N. This intense High-pressure cell brought southerlyflow into the Canadian prairies and was a primary factor behind the tremendous heat and dryness that occurred over the Canadian prairies and U.S.A. Corn Belt in the summer of 1988. An accompanying Low was situated over the Gulf of the St. Lawrence. This wave train of a High at 180°W, Low at 140°W and High at 100°W has the potential for causing the greatest drought damage to North America if it sets up in June.

During June of 1988, a Low remained at 140°W with a pronounced High pressure at 100°W and 50°N (Figure 4.5). This intense High-pressure cell brought southerly flow into the Canadian prairies and was a primary factor behind the tremendous heat and dryness that occurred over the Canadian prairies and U.S.A. Corn Belt in the summer of 1988. An accompanying Low was situated over the Gulf of the St. Lawrence. This wave train of a High at 180°W, Low at 140°W and High at 100°W has the potential for causing the greatest drought damage to North America if it sets up in June as suggested by Namias (1981) in his description of teleconnections at 70-kPa in the Northern Hemisphere. Figure 4.6 shows the trough retrograding to 150°W 50°N during July as the pronounced ridge that had existed over Manitoba collapsed, moderating the conditions over the Canadian prairies. The trough originally located over the St Lawrence migrated eastward.

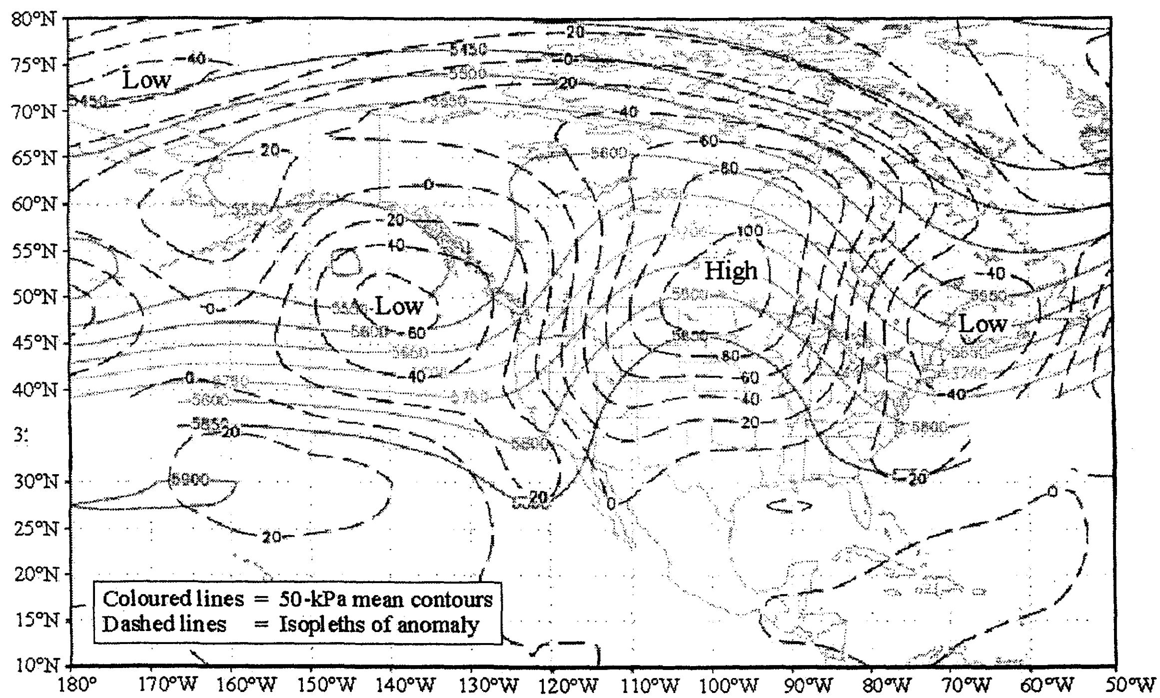


Figure 4.5 50-kPa heights and height anomalies during June 1988
(Data source: National Centre for Atmospheric Research, 2000)

In June 1951 (Figure 4.2) the pressure systems were arranged with a Low at 170°W, a High at 140°W and a Low at 110°W while in June 1988 (Figure 4.5) the alignment was a High at 180°W, Low at 140°W, High at 100°W and Low at 70°W. Thus, the wave train or alignment of Highs and Lows from the central Pacific to North America was distinctly opposite in these classic examples of El Niño (1951) and La Niña (1988).

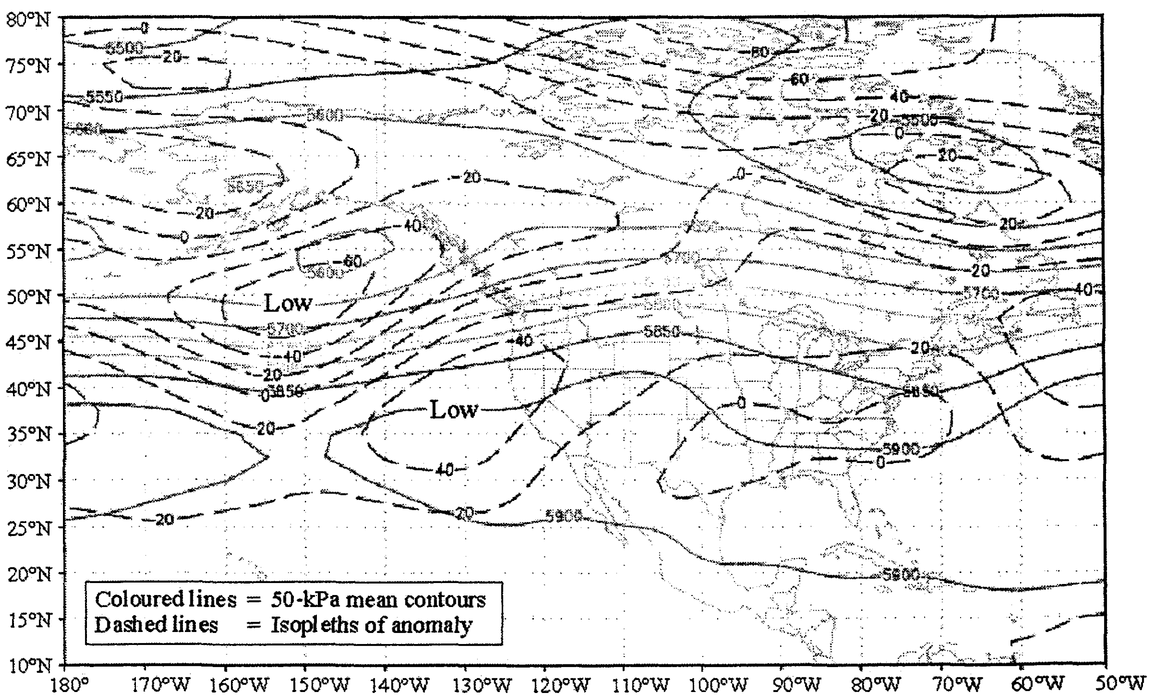


Figure 4.6 50-kPa heights and height anomalies during July 1988
(Data source: National Centre for Atmospheric Research, 2000)

The flow over the PNA region in June of 1988 was strongly meridional, probably forced by falling SSTs at Niño-4 between January and April. This contrasted with what occurred in 1951 when there was a SST warming at Niño-4 between January and April. This supports the concept that a build-up of warmer than normal SSTs between January and July at Niño-4 in the earlier part of the year is favourable for cool, wet conditions in Saskatchewan in the summer months, while a build-up of cooler than normal SSTs at

Niño-4 between January and July is favourable for a hot, dry summer in Saskatchewan. This is consistent with the conceptual model described in the text and the composites presented in Figures 3.2, 3.3 and 3.4.

The above case studies add support to the notion that El Niño is associated with cooler, wetter than normal conditions and La Niña with hotter, drier than normal conditions based on an examination of the 50-kPa flows during El Niño and La Niña years of 1951 and 1988.

4.3 Other case studies

Climatic extremes were investigated for other years besides 1951 and 1988. A ranking procedure of the data revealed that monthly temperature extremes were experienced as follows: coldest June 1951, the hottest June 1988, the coldest July 1972 and the hottest July 1960. Extreme precipitation was experienced as follows: wettest June 1991, driest June 1967, wettest July 1993 and driest July 1961. These special cases are described in relation to the trend in east equatorial Pacific SSTs, 50-kPa flow and the impact on precipitation, temperature and yield.

The coldest July in Saskatchewan during the period 1950-1998 was July 1972. A trough existed over the center of the continent much like June of 1951. Between January and June there was a marked upward trend or warming at Niño-4 or transition from La Niña to El Niño. Northerly flow from Alaska brought cool weather to the Canadian prairies with a mean of 14.3°C; 72 mm of precipitation was received that July, versus the mean of 91 mm. Garnett (1998), classified 1972 as an El Niño year with SSTAs at Niño-3 warming between February and July from -0.24°C. to +1.03°C. Flow over the PNA region between February and July was zonal with negative values of the PNA index in nine of the twelve months. The yield that year was 1.59 t/ha versus the long-term average of 1.63 t/ha.

One of the hottest Julys during the 1950-1998 period was 1960. The mean temperature that July was 18.5°C compared to the mean of 16.6°C. Agricultural Saskatchewan July rainfall was 31.2 mm vs. the long-term mean of 60 mm. Examination of the flow over North America that July, revealed a ridging pattern on the west coast. This ridging pattern occurred despite a slight warming at Niño-4 between January and June of -0.35°C to –0.21°C. The flow over the PNA region was predominantly meridional between September and July.

The wettest June during the 1950-1998 period was June 1991, when 144 mm of precipitation was received in the grain-growing region of Saskatchewan. The most notable 50-kPa feature that year was troughing along the west coast of North America during the month of June. A dramatic warming from 0.26 to 1.27° C occurred at Niño-3 between February and June of 1991. The flow over the PNA region for the February to July period was predominantly zonal bringing cool moist air. Saskatchewan yields that year matched the record yields of 1986 with an average yield of 2.12 t/ha.

The driest June in Saskatchewan during the 1950-1998 period was 1967. The High-pressure ridge on the west coast of North America during that June was accompanied by a slight ridging at 180°W. Ridging at 180°W is associated with ridging over the west coast of North America (Namias, 1981). Under such a pattern it is very difficult to get moisture from the Gulf of Mexico or over the Rocky Mountains into the Canadian prairie region. In 1967 La Niña conditions prevailed in February at Niño-4 with a slight warming of 0.5° C occurring between February and April. The flow over the PNA region in all months in the February to July period was zonal, except for the month of June when the flow was meridional. The blocking pattern in June was the major reason for the greatly reduced rainfall and yield, which was somewhat unusual with a warming trend at Niño-3. Saskatchewan's spring wheat yield in 1967 was 1.17 t/ha., well below the long-term average of 1.63 t/ha.

The wettest July during the 1950-1998 period was 1993 when 114 mm of precipitation was received in Saskatchewan's grain growing region. The yield was the seventh highest for the period. In 1993 a dramatic warming occurred at Niño-3 between January and May. At Niño-4 moderate El Niño conditions prevailed between January and June with a slight warming apparent. 1993 also brought the most extreme flooding to the U.S. Corn Belt, the worst in fifty years (Garnett *et al.* 1995).

The driest July between 1950-1998 was July 1961 with 26.8 mm of precipitation. July 1961 was the 14th warmest for the period. The wheat yield was 0.58 t/ha, the lowest for the 1950-1998 period. Between February and July, there was a slight cooling at Niño-4 and a ridge on the west coast in July, which was unfavourable for drawing in moisture over the Rocky Mountains from the Gulf of Mexico.

The above descriptions of the climate of these extreme months support the composite analysis in the previous chapter where cool, wet (hot, dry) conditions occurred during June and July on the Canadian prairies with a warming (cooling) trend in the central equatorial Pacific between January and July. To reiterate El Niño is more conducive to cool, wet conditions and La Niña is more conducive to hot, dry conditions during June and July.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary of correlation analyses

May-June-July and July precipitation totals correlate significantly with wheat yield. Correlation analysis was done between independent variables of SOI, Niño-4, Niño-3, and PNA index and monthly values of July precipitation and temperature, June precipitation and temperature, and May precipitation and temperature. This analysis was done first on a provincial basis, and then by soil zone, with the following findings:

1) A significant correlation was found between the PNA index in October and wheat yield close to a year prior to harvest, which takes place from mid-August to mid-October.

2) A significant correlation was found between the SOI in April and spring wheat yield about six months prior to harvest. Similarly SSTAs in the Niño-3 and Niño-4 region during the April through July period give an indication of yield several months before harvest.

3) A significant correlation was found between Niño-3 SSTAs during April and May and July precipitation and between Niño-4 SSTAs during June and July and July precipitation. A significant concurrent correlation was also found between the PNA index and precipitation in July.

4) A number of significant correlations were found between the independent variables and July temperature. For example, colder than normal SSTAs at Niño-4 in the May through July period are associated with warmer than normal temperatures in July. A

correlation of -0.39 was found between the Niño-4 region in June and July temperature in Saskatchewan. July temperature is a significant factor affecting Saskatchewan spring wheat yield. Hot Julys are usually dry Julys and cold Julys are usually wet Julys.

5) May precipitation and temperature did not correlate significantly with yield even though May is an important month in which seeding and tillering take place. A significant correlation exists however between the PNA index in May with May precipitation, substantiating the findings of Romolo (1998). Zonal flow is favourable and meridional flow unfavourable for May precipitation. Correlations were found between Niño-3 in September and May temperature and between the PNA index in January and May temperature, and the PNA index in April and May temperature. The physical mechanism behind these correlations is not known.

To investigate the ENSO association at a finer spatial resolution and to find out where the association is strongest in Saskatchewan, correlation analysis was then done between the independent variables and yield and July precipitation, in the three main soil zones in Saskatchewan, namely the Brown, Dark Brown, and Black soil zones. These are presented in Tables 3.6, 3.8 and 3.10. For the Brown soil zone significant correlations were found between yield and the SOI in April and Niño-4 SSTAs during April, May, June, and July. Significant positive correlations were found between Niño-3 during May, June, and July, and yield and Niño-4 during April, May, June, and July, and yield. Some signal was evident with the SOI in February and Niño-4 in February with July precipitation in the Brown soil zone. The correlations shown in Table 3.6 represent a lag of six months. The physical mechanism is unknown. Positive correlations between Niño-3 SSTAs during the months of April and May and July precipitation are noted. A contemporaneous correlation was found between the PNA index in July with July precipitation in the Brown soil zone.

In the Dark Brown soil zone, significant negative correlation was found between the PNA index in October and spring wheat yield. Zonal flow over the PNA region in October was found to be favourable to yield. July precipitation was found to be positively correlated with yield in all three-soil groups especially the Dark Brown soil zone.

A similar negative correlation of equal strength was evident between the SOI in April and yield. Yield correlated positively with Niño-3 in May, and with Niño-4 during June and July. Significant positive correlations were found with Niño-3 in April and May, and Niño-4 in June, with July precipitation in the Dark Brown soil zone. Positive concurrent correlations were found between Niño-4 in July, and July precipitation, and the PNA index in July and July precipitation.

In the Black soil zone, the longest lead correlation was between the PNA index in October and yield followed by the PNA index in March and yield. Again the SOI in April correlated negatively with yield. Niño-3 SSTAs correlated positively with yield during the months of May and July. Similarly Niño-4 SSTAs in June and July correlated with yield. As for July precipitation in the Black soil zone, a significant positive correlation was found with Niño-4 SSTAs in June. As in the other two soil zones, a significant concurrent negative correlation was found between the PNA index in July and July precipitation.

The ENSO association with Saskatchewan's climate appears to be strongest in the Brown soil zone, and weakest in the Black soil zone with the Niño-4 region providing the longest lead indication. The correlations between Niño-4 and Brown soil yields are some of the strongest found in this research. These correlations suggest that below normal SSTs in the April through July period at Niño-4 means a lower than normal yield in the Brown soil zone.

Correlation analysis was also carried out for coherence of yield, June-July precipitation, and June-July temperature between the three soil groups. The coherence was greatest for yield, then temperature and lowest for June-July rainfall. The correlation matrices of Table 3.11 demonstrate that when yield, for example, is heavily impacted in one soil zone the entire wheat-growing region is likely to be affected. The same applies to temperature and precipitation, except that precipitation has the least degree of coherence.

5.2 Summary of composite analyses

Composite analysis revealed that the PNA index appears to be primarily forced by El Niño and La Niña, the stronger the El Niño or La Niña event, the greater the impact on the PNA flow pattern. In other words the PNA index seems to be a derivative or reflection of El Niño/La Niña.

It should be reiterated that May to July total precipitation correlated best with wheat yield. In relating Niño-3 SSTAs to May, June and July precipitation in Saskatchewan for the period 1950-1998, it was found that during the six driest May-Julys, La Niña conditions prevailed during the spring months of February, March, April and May, followed by a SST warming occurred during the months of June and July. During the wettest summers a SST warming occurred at Niño-3 during each of the months between January and July. In summers in which there were moderate amounts of precipitation in Saskatchewan, there was a gradual warming between January and July at

Niño-3 each month between January and July. Distinctly different profiles existed for the driest versus the wettest and intermediate summers, suggesting some predictive skill with a lead-time of several months. This technique allows one to distinguish whether it is likely to be a dry summer versus a moderate to wet summer in Saskatchewan at the end of March.

Composite analysis reveals that driest Julys are associated with intensifying La Niña conditions between the months of January and July especially at the Niño-4 region. During the wettest Julys El Niño conditions intensified between the months of January and July. In the case of moderately wet Julys, there was moderate intensification of El Niño conditions between the months of January and July. Distinctly different composites were constructed for the driest, wettest and intermediate Julys, suggesting some predictive skill with a lead-time of 3-4 months.

In the composite analysis relating Niño-3 SSTAs to June and July rainfall, it was apparent that SSTAs were normal or slightly below normal between the months of January through May during the driest June and Julys. This pattern is separate and distinct from June and Julys in which there was moderate to heavy rainfall. In these years, there was a warming at Niño-3 between January and July. The wet, and intermediate June and Julys, can thus be separated from the dry June and Julys with a lead-time of about two months using this composite analysis.

For the six hottest, six coldest Julys and six intermediate Julys, monthly values of the PNA index were accumulated starting from September of the preceding year. The composite for the six hottest Julys showed meridional flow between the months of September and February with the flow being mostly zonal between the months of March and June and meridional during July and August. During the coldest Julys, the flow over the PNA region was strongly zonal between September and December and meridional during January, February, March and April, and predominantly zonal during the summer months of June, July and August. During moderately warm Julys, the flow over the PNA region was predominantly neutral to slightly zonal. These distinctly different profiles of accumulated PNA values for the hottest and coldest Julys suggest a predictive skill of two to four months.

During the six hottest Julys, rainfall was 78% of normal with yield 12% below normal. The six coldest Julys brought 125% of normal precipitation and yields that were 8% above normal. This confirmed that when Julys are extremely hot they are usually dry, and when extremely cold they are usually wet. In years having moderately warm Julys, yields were 16% above the mean for 1950-1998. The accumulated PNA index technique provides a means of forecasting July temperature and indirectly precipitation, wheat yields, and protein content.

In attempting to forecast June temperature using the accumulating PNA technique, it was found that extremely hot Junes could be separated from the moderate and cool Junes with a lead-time of about four to five months. Table 3.14 reveals that during the six hottest Junes, precipitation was 84% of normal and yields 86% of the long-term mean. Coldest Junes brought precipitation that was 84% of normal and yields that were 88% of normal. Intermediate Junes had precipitation that was 107% of normal and a yield 107% of normal. Hence, the accumulated PNA index has some potential for forecasting June temperature, especially hot Junes, and consequently June precipitation yield, and protein.

Finally, values of the SOI were plotted for the six driest, six intermediate and six wettest Julys. During the wettest Julys, the SOI was negative each month beginning in September becoming sharply negative during the month of February. During moderate and wet Julys, the SOI was decidedly more positive. The SOI was usually negative during El Niño conditions and positive during La Niña conditions, confirming that El Niño is usually the friend and La Niña usually the foe to the Saskatchewan wheat farmer.

In plotting the SOI during years in which July was either extremely hot or cold or intermediate it is apparent that the index was consistently negative during cold Julys and consistently positive during the months of April through July for hottest Julys. In cool intermediately warm and wet Julys the SOI was negative in all months. The SOI plot provides guidance in distinguishing dry Julys from intermediate and wet Julys, and hot Julys from a moderately warm and cold Julys. The behaviour of the index between March and April is especially noteworthy during dry and hot Julys.

5.3 Conclusions

This study focused on the relationship between indices of ENSO and May to July temperature, precipitation, which are factors that bear directly on spring wheat yield in Saskatchewan. Best results for forecasting July precipitation in Saskatchewan were obtained from the Niño-4 region. The results indicate that persisting El Niño conditions at Niño-4 January through July favour precipitation during July, while persisting La Niña conditions January through July at Niño-4 were unfavourable for precipitation during July. Similar findings were evident for precipitation during the months of May through July using an accumulation of Niño-3 SSTAs.

It is also worth knowing when a summer is likely to be extremely wet or dry. Under dry conditions protein content will be high and yields low. Figure 3.2 could assist the CWB in establishing a crop quality early in the growing season. The grain they sell is priced depending on the grade and protein content. In a situation when drought is anticipated a marketing agency such as the CWB would need to withdraw from the market place and limit forward selling. During intermediate and wet summers the CWB could be aggressive in the international market place and seek to gain market share. Organizations like the Saskatchewan Wheat Pool, farm credit and insurance adjusters could use such composite analysis for planning revenues for each growing season. Producers could take measures to increase yield potential or limit their losses depending on which scenario exists. To reiterate, wheat yields during the intermediate summers have been 8% above the 1.63 t/ha mean; during the wettest summers yields were 20% above the mean, and during the driest summers 30% below the mean.

Correlation analysis of SOI, Niño-3, Niño-4 and PNA indices with wheat yield indicated that El Niño (La Niña) conditions in the April through July period favoured (disfavoured) the Saskatchewan wheat crop through heavier (lighter) precipitation during the month of July. The PNA index appeared to provide a predictive signal for the spring wheat crop in the fall months prior to the growing season. Temperatures during the month of July were usually warmer than normal with La Niña conditions, and cooler than normal with El Niño conditions. No correlations were found between ENSO indices and June precipitation and temperature. Zonal flow over the PNA region in May, June, and July usually favoured precipitation during these months. ENSO indices provided some indication of May temperature.

In terms of the three different soil groups, the ENSO link was strongest with the Brown soil zone and weakest in the Black soil zone. Correlations were significant at the 5% level in many instances in all three soil zones. The ENSO signal was strongest in the Brown soil zone; with a six-month lead correlation found between Niño-4 in February and July precipitation, and the SOI in February and July precipitation. The PNA index in the fall months provided a predictive signal for yield in the Dark Brown and Black soil zones. Zonal (meridional) flow over the PNA region in July was favourable (unfavourable) for July precipitation in all three soil zones.

An accumulation of PNA index values, beginning in September of the preceding year, had utility in foreshadowing July temperature in Saskatchewan with a lead-time of 3-5 months. Similarly, an accumulation of PNA values was useful in foreshadowing extremely hot Junes. Extremely hot June and Julys were usually dry June and Julys with an impact on yield and protein. Cold Julys were associated with wet Julys with a favourable impact on yield and unfavourable impact on protein.

Plotting the SOI beginning in the month of September, prior to the growing season, provided some guidance as to whether or not July will be hot, cold, dry or wet. These composites reinforce the notion that El Niño is the friend and La Niña the foe to the wheat crop. The key timeframe to observe the SOI is February through July.

In terms of climatic coherence among the three soil zones, greatest spatial coherence was found with yield, then temperature and then June-July rainfall. This analysis indicates that whatever climatic regime affects one soil zone will also have a similar effect on the other two. This is likely the result of Saskatchewan's relatively flat and uniform topography whereby the weather systems that pass over the region affect all three soil zones in a similar fashion. Case studies of various years revealed that, during extremely hot Junes and Julys, a ridge usually existed on the west coast, which prohibited moisture from being drawn into North America through the Gulf of Mexico or over the Rocky Mountains. This ridging tendency was more likely to occur with cooling SSTs between January and July at Niño-4 and La Niña conditions as occurred in 1988. Also when there was a ridge (trough) at 180°W there was usually a ridge (trough) on the North American west coast at 125°W. During extremely cool wet June and Julys there is a tendency for troughing at 180°W as well as on the west coast. This troughing tendency was more likely to occur with a warming at Niño-4 between the January and July period and El Niño conditions. A close examination of 1951 (an El Niño year), and 1988 (a La Niña year), also years with extremely cold and hot Junes respectively, revealed a contrasting alignment of Lows and Highs from the central Pacific to central North America.

Flow over the PNA region was usually meridional during La Niña and zonal during El Niño. Zonal flow over the PNA region was associated with cool wet conditions especially during the months of May, June and July. Conversely meridional flow over the PNA region especially during the months of May, June and July was associated with hot, dry conditions.

The strongest correlation with yield was May, June and July precipitation, followed by July precipitation and June-July precipitation. A significant inverse correlation existed between July temperature and precipitation. Also the Niño-4 region correlates better with yield than does Niño-3.

Finally questions were addressed as to the management strategies wheat producers in Saskatchewan might adopt if they were confident that there would be a hot, dry July versus a cool wet July. First, it should be noted that an accurate seasonal forecast or long-range forecast is highly unlikely for an individual farm. Application of these findings is aimed at very large regions (at least the size of a soil zone) of the Canadian prairies, using large-scale teleconnection indices. Based on this research, best success might be attained using a simple PNA accumulation for assessing the likelihood of a hot or cool July and accompanying effects on precipitation, yield and protein during that month. Similarly a summation of Niño-4 SSTAs beginning in January provided guidance as to precipitation amounts in July. Moreover, the SOI or Walker circulation during the spring months and summer had predictive value as to heat/dryness during July.

What strategy might producers adopt to maximize yields? If a farmer is confident of a hot, dry July he or she might:

- consider how much he/she is going to spend on tillage
- with zero tillage he/she would save on fuel, summer fallow and crop insurance
- consider applying less nitrogen fertilizer
- consider lentils which are more drought resistant
- consider planting wheat, barley, oats in that order because wheat is the most drought resistant and oats the least drought resistant of these cereal crops.
- consider planting canola last as it is less drought resistant than the cereal crops.

If a farmer were confident of a cool wet July he or she might do as follows:

- consider applying more nitrogen fertilizer
- consider planting canola first since its yield response is greatest with wet Julys

- consider planting oats, barley, and wheat in that order with the yield response being optimal in that sequence
- consider planting lentils last, as this crop is better suited to drought situations.

These actions are aimed at increasing yield only, without any economic consideration of prices and cost of inputs (Metternach and Baldwin, personal communication). As set out in chapter one, each spring the producer like any businessman needs to consider his net worth and potential cash flow as well as the cost of his operation. Climate poses the biggest risk of all.

In conclusion, the purpose of this research is that of improving the climatic early warning system for Saskatchewan, the leading wheat producing province in Canada. The correlation and composite analyses presented provide operational techniques for foreshadowing summer weather over Saskatchewan using monthly values of well-known teleconnection indices. These analyses are reinforced by an empirical procedure which yields distinctly different profiles of accumulated values of monthly teleconnection indices for hottest and coldest or driest and wettest Julys over Saskatchewan with lead times of several months.

The thesis tests the hypothesis: Is El Niño usually the friend and La Niña the foe to Saskatchewan's wheat crop? The answer is yes, confirming earlier studies and showing the nature and strength by soil zone. This thesis has met the objectives of:

1) Increasing the understanding of the strength and nature of the relationship between the El Niño/Southern Oscillation and June and July temperatures, precipitation and wheat yield in Saskatchewan.

2) Investigating the effect of antecedent zonal versus meridional flow over

the Pacific North American region on Saskatchewan summer temperature, precipitation and yield in Saskatchewan.

3) Proposing a conceptual model, which explains how El Niño/La Niña modulates upper level flow, which in turn influences May through July temperature and precipitation.

5.4 Recommendations

1) Garnett *et al. (1998a)* make optimal use of two teleconnection indices for forecasting June and July temperature and precipitation over the Canadian prairies. There are at least another half dozen teleconnection indices that can be investigated. I have often stated, "this is what was done with two teleconnection indices, think what could be done with six or seven." Quiring and Blair have also pursued similar investigations and their work is to be encouraged. A concerted effort should be made to develop a statistical teleconnection based model for the prediction of June-July precipitation, temperature and yield over the Canadian prairies. Such a model should be able to provide lead-time indications of 3-6 months.

2) The work of Groissmayer (1929) needs to be cross validated and applied to other seasons over the Canadian prairies.

3) There may be better ways of depicting the persistence of SSTAs at Niño-4 and Niño-3 than presented in this thesis. An example is the Box Jenkins approach.

4) Weather typing might well strengthen some of the techniques outlined in this thesis.

5) The annual cycle of the contraction and expansion of the circumpolar vortex in relation to the Canadian prairie climate needs to be studied and understood in greater depth.

Canadian prairie climatology could be better understood through investigating weekly normals for at least 50 years. The working of the general circulation is contained in the climatic history. Factors worthy of study in such an analysis are as follows:

a) Weekly precipitation, temperature and wind speed normals.

b) Daily maximum temperature reversals and variation normals for assessing storm frequency

c) Weekly dew point temperatures

d) Weekly cloud cover normals

e) Grouping Canadian and U.S. spring wheat belts together should be considered. Early anomalies in dew point temperatures or windiness in the U.S. spring wheat area could serve as an alert for future developments on the Canadian prairies.

5.5 Contributions of this thesis

1. This thesis reveals that the best predictor of precipitation and yield in Saskatchewan is the Niño-4 region. A simple summation of Niño-4 SSTAs between January and July indicates whether the July precipitation in Saskatchewan is likely to be light, intermediate or heavy. This technique captures the persistence of the El Niño or La Niña effect and has direct usefulness to Saskatchewan farmers and grain industry planners.

2. A summation of PNA values beginning in September, prior to the growing season, has utility in forecasting temperature during the July period with a lead-time of six months. With June-July temperature the lead is four months.

3. The ENSO signal to Saskatchewan is the strongest in the Brown soil zone of the southwest and weakest in the Black soil zone of the northeast. Six month lead

correlations are found between the SOI and Niño-4 in February and July Brown soil precipitation.

4. The composite and correlation analyses presented have clear, easy operational utility as well as huge practical economic value.

Additional note

The Canadian prairie drought of 2001 was very well forecast. The PNA summation was essentially meridional (weak westerlies) between September 2000 and May of 2001 and less able to carry what little water vapour was convected at 180° W with the La Niña conditions that existed in that region during the first quarter of 2001. Extremely low soil moisture at the beginning of the 2001 growing season was also a contributing factor and helped set up a positive feedback between the surface and the atmosphere above which sustained the dry conditions. By July 20, 2001 Ken Rosaasen in the Agricultural Economics Department of the University of Saskatchewan was estimating the low rainfall to be comparable to the 1988 drought when yields were 57% of the 1950-1998 mean of 1.63 t/ha. The Niño-3 and Niño-4 composites and SOI composites used to forecast the 2001 drought in Saskatchewan are presented in Figures 3.3, 3.4 and 3.8.

REFERENCES

Agriculture Canada. 1979. Canadian Red Spring Wheat. Canadian Grain Commission, Ministry of Supply and Services, Ottawa, Ontario.

Alaka, M.A. and Elvander, R.C. 1971. Optimum Interpolation from Observations of Mixed Quality. *Mon. Weather Rev.* 100: 612-624.

Allan, R., Lindsay, J. and Parker, D. 1996. *El Niño/Southern Oscillation and Climatic Variability.* CSIRO Publishing, Collingwood, Victoria, Australia, 405 pp.

Anderson, J.A. and Eva, W.1939. Protein Content of the 1939 Crop of Western Canadian Wheat. Department of Trade and Commerce, Canada Board of Grain Commissioners, Grain Research Laboratory, Winnipeg, Manitoba, p.1.

Babb, J.C., Khandekar, M.L. and Garnett, E.R. 2001. Long Range Forecasting of Canadian Red Spring Wheat Yield: Can Climatic Teleconnections Help? (Unpublished) Department of Mathematics and Statistics, University of Winnipeg, Winnipeg, Manitoba.

Baier, W. 1977. Climatic Variability in Relation to Agricultural Productivity and Practices. Theme papers prepared for the Canadian Committee on Agrometeorology (CCA) Meeting, Winnipeg, Manitoba, January 11-12, 1977. Research Branch, Canada Department of Agriculture, Ottawa, Ontario, 1977.

Berlage, H.P. 1966. The Southern Oscillation and World Weather. *Mededeelingen en Verhandelingen, No. 88,* 152 pp, *Meteorologisch Institut, Koninklijk Nederlands,*

Bjerknes, J. 1966. A Possible Response of the Atmospheric Hadley Circulation to Equatorial Anomalies of Ocean Temperature. *Tellus* 18: 820-829.

Bjerknes, J. 1969. Atmospheric Teleconnections from the Equatorial Pacific. *Monthly Weather Review* 97:1 63-172.

Bonsal, B.R. 1991. Possible Teleconnections between North Pacific Sea Surface Temperatures and Extended Dry Spells and Droughts on the Canadian Prairies. M.Sc. Thesis, Geography Department, University of Saskatchewan, Saskatoon, Saskatchewan.

Bonsal, B.R. 1999. Canadian Prairie Growing Season Precipitation Variability and Associated Atmospheric Circulation. *Climate Research* 11:191-208.

Bonsal, B.R. and Lawford, R.G. 1999. Teleconnections between El Niño and La Niña Events and Summer Extended Dry Spells On The Canadian Prairies. *International Journal of Climatology* 19: 1445-1458.

Canadian International Grains Institute.1993. *Grains and Oilseeds.* Canadian International Grains Institute, Winnipeg, Manitoba.

Canadian Wheat Board. 1998. Crop Database. Weather and Crop Surveillance Dept., Canadian Wheat Board, Winnipeg, Manitoba.

Chakravarti, A.K. 1972. The June-July Precipitation Patterns in the Prairie Provinces. *Geography* 71:155-160.

Chipanshi, A.C., Ripley, E.A., and Lawford R.G. 1999. Large-scale Simulation of Wheat Yields in a Semi-arid Environment Using a Crop-growth Model. *Agricultural Systems* 59 (1): 57-66.

Climate Prediction Center. 2000. Climate Diagnostics Bulletin, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 5200 Auth Road, Camp Springs, MD

Cole, J.S. and Matthews, O.R. 1923. Use of Water by Spring Wheat on the Great Plains.United States Department of Agriculture Bulletin 1004. United States Department of Agriculture, Washington, D.C.

Dey, B. 1973. Synoptic Climatological Aspects of Summer Dry Spells in the Canadian Prairies. PhD. Thesis, Geography Dept., University of Saskatchewan, Saskatoon, Saskatchewan,180 pp.

Dey, B. 1977. Nature and Possible Causes of Heavy Summer Precipitation in the Canadian Prairies. *Geographical Perspectives* 40: 26-33.

Dey, B. 1982. Nature and Possible Causes of Droughts on the Canadian Prairies - Case Studies. *Journal of Climatology* 2: 233-249.

Diaz, H., and Markgraf, V. 1992. *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation.* Cambridge University Press, New York, N.Y. 476 pp.

Duvenaud, J. 1995. How Long Range Weather and Forecasting Matters – A Users Perspective. Garnett, E.R and Khandekar, M.L. (Eds.). Proceedings of the Long-Range Weather and Crop Forecasting Working Group Meeting II, Canadian Wheat Board, Winnipeg, March 21-23, 1995 Winnipeg, Manitoba.

Environment Canada. 2000. Canadian Monthly Climate Data and 1961-1990 Normals on CD-Rom. 1993 Release, plus supplementation for 1993-1998 period.Environment Canada, Saskatoon, Saskatchewan.

Garnett, E.R. 1986. A Back-to-Basics Approach to Longer-Range Weather and Crop Forecasting. An Internal Canadian Wheat Board (CWB) Report. Winnipeg, Manitoba.

Garnett, E.R. 1998. La Niña from a Canadian Perspective, Proceedings of the La Niña Summit. M.H.Glantz (Ed). National Center for Atmospheric Research, Boulder, Colorado, USA. July 15-17.

Garnett, E.R. 2000. Causes of the Billion-Dollar Drought in North America in 1999 -A Verification Study. *Prairie Perspectives* October 2000:17-21.

Garnett, E.R. and Khandekar, M.L. 1992. The Impact of Large-scale Atmospheric Circulations and Anomalies and Indian Monsoon Droughts and Floods and on World Grain Yields-a Statistical Analysis. *Agricultural and Forest Meteorology* 61: 113-128.

Garnett, E.R., Babb, J.C, and Khandekar, M.L. 1993. Teleconnective Linkages Associated with Major Swings in Spring Wheat Yields on the Canadian Prairies. R. Garnett and R. Lawford (Eds.). Proceedings of the Long-Range Weather and Crop Forecasting Working Group Meeting I, Canadian Wheat Board, Winnipeg, Manitoba, held at National Hydrology Research Center, Saskatoon, Saskatchewan April 22-23, 1993.

Garnett, E.R., Babb, J.C. and Khandekar, M.L. 1995. Current Global ENSO Impacts and Some Preliminary Findings Regarding Teleconnections from the Pacific Ocean to The North American Great Plains. E.R.Garnett and M.L. Khandekar (Eds.). Proceedings of the Long-Range Weather and Crop Forecasting Working Group Meeting II, Canadian Wheat Board, Winnipeg, Manitoba, March 21-23, 1995.

Garnett, E.R., Babb, J.C. and Khandekar, M.L. 1997. Forecasting of Weather and Crop Yield over the Canadian Prairies in 1997: Verification Study. L.Lefaivre, M.L. Khandekar and E.R. Garnett (Eds.). Proceedings of the Long-Range Weather and Crop Forecasting Working Group Meeting III, Canadian Meteorological Centre, Dorval, Quebec, October 20-21.

Garnett, E.R., Khandekar, M.L. and Babb, J.C. 1998a. On the Utility of ENSO and PNA Indices for Long-Lead Forecasting of Summer Weather over the Crop-Growing Region of the Canadian Prairies. *Theoretical and Applied Climatolology* 60: 37-45.

Garnett, E.R. Khandekar, M.L. and Babb, J.C. 1998b. Teleconnections from Asia to the Canadian Prairies: Implications for Long-Range Weather and Crop Forecasting. R.Wilson and V.L.Tharp (Eds.) Proceedings of the Fourteenth Annual Pacific Climate (Paclim) Workshop, Asilomar, California, April 6-9,1997.

Glantz, M.L. 1996. *Currents of Change: El Niño's Impact on Climate and Society.* Cambridge University Press, New York, N.Y. 194 pp.

Gray, W.M., Sheaffer, J.D and Knaff J.A. 1992. Influence of the Stratospheric QBO on ENSO Variability. *Journal of the Meteorological Society of Japan* 70(5): 975-994.

Groissmayr, F.B.1929. Relations Between Summers in India and Winters in Canada. *Monthly Weather Review* 57: 453-455.

Handler, P.1983. Corn Yields in the United States and Sea-surface Temperature Anomalies in the Equatorial Pacific Ocean during the Period 1868-1892. *Agricultural and Forest Meteorology* 31: 25-32.

Haun, J.R. 1974. Prediction of Spring Wheat Yields from Temperature and Precipitation Data. *Agronomy Journal* 66: 405-409.

Hogg, W.D., Louie P.Y.T., Nitro, Milewski, E., Routledge, B. 1997. Gridded Water Balance Climatology for the Canadian McKenzie Basin. GWEX study area. *In*: Proc. Workshop on the Implementation of the Arctic Precipitation Data Archive at the Global Precipitation Climatology Centre.10-12 July 1996, Offenbach, Germany. WMO/TD No. 804, pp.47-50.

Hopkins, J.W. 1935. Weather and Wheat Yield in Western Canada. *Canadian Journal of Research* 12:306.

Hsieh, W.W., Tang, W. and Garnett, E.R. 1999. Teleconnections between Pacific Sea Surface Temperatures and Canadian Prairie Wheat Yield. *Agricultural and Forest Meteorology* 96: 209-217.

Huang, J. M. van den Dool, H. M. and Barnston, A.G. 1996. Long-Lead Seasonal Temperature Prediction Using Optimal Climate Normals. *Journal of Climate* 9 (4): 809-817.

Khandekar, M.L. 1991. Eurasian Snow Cover, Indian Monsoon and El Niño/Southern Oscillation- A Synthesis. *Atmosphere-Ocean* 29 (4):636-647.

Khandekar, M.L. and Neralla, V.R. 1984. On the Relationship between the Sea Surface Temperatures in the Equatorial Pacific and Indian Monsoon Rainfall. *Geophysical Research Letters* 11: 1137-1140.

Khandekar, M.L. and Jones, K. 1995. El Niño, La Niña and Prairie Moisture. E.R. Garnett and M.L.Khandekar (Eds.) Proceedings of The Long-Range Weather and Crop Forecasting Working Group II, March 21-23, Canadian Wheat Board,Winnipeg, Manitoba.

Kiladis, G.N. and Diaz, H.F. 1989. Global Climate Anomalies Associated with Extremes in the Southern Oscillation. *Journal of Climate* 2: 1069-1090.

King, W.J. 1987. Irrigation of Cereal Crops. Saskatchewan Water Corporation, Outlook, Saskatchewan.

Kulshrehtra, S.N. and Story, G.G.1999. Agricultural Land Use. *Atlas of Saskatchewan.* Second Edition, K. Fung (Ed).University of Saskatchewan, Saskatoon, Saskatchewan p.221.

Lau, K.M., and Sheu, P.J. 1988. Annual Cycle, Quasi-Biennial Oscillation, and Southern Oscillation in Global Precipitation. *Journal of Geophysical Research* 93:10975-10988.

Lehane, J.J. and Staple,W.J. 1965. Influence of Soil Texture, Depth of Soil Moisture Storage, and Rainfall Distribution on Wheat Yields in Southwestern Saskatchewan. *Canadian Journal of Soil Science 45*: 207-219.

Martins, V. and Hylnka, I. 1969. Protein Content of Canadian Wheat 1927-1968. Board of Grain Commissioners, Department of Agriculture, Winnipeg, Mb.

Milewski, M.A. and Lavender, R.C. 1971. Gandin Optimal Interpolation Technique-Optimum Interpolation from Observations of Mixed Quality. *Monthly Weather Review* 100: 612-172.

Namias, J. 1950. The Index Cycle and Its Role in the General Circulation. *Journal of Meteorology* 7(2): 130-139.

Namias, J. 1978. Long-Range Weather and Climate Predictions. Geophysical Predictions. National Academy of Sciences, Washington, D.C. pp 103-114.

Namias, J. 1981. Teleconnections of 700 mb Height Anomalies for the Northern Hemisphere. Scripps Institution of Oceanography, La Jolla, California, U.S.A. Fleminger, A.(Ed.). CALCOFI Atlas No. 29, August 1981, 265 pp. Marine Life Research Program.

National Center for Atmospheric Research. 2000. 500 mb. Charts. Boulder, Colorado, U.S.A.(http://dss.ucar.edu/pub/reanalysis/rean other.html).

Nkemdirim, L. and Weber, L. 1999. Comparison between the Droughts of the 1930s and the 1980s in the Southern Prairies of Canada. *Journal of Climate* 12: 2434-2450.

Pan, J. and van den Dool, H. 1998. Extended-Range Probability Forecasts Based on Dynamical Model Output. *Weather and Forecasting* 13(4):983-996.

Peterlin, A, Scheeringa, K.L., Newman, J.E and McIntyre, J. 1988. Variable Length Seasons: The Circumpolar Index Classification System. January. Agronomy Department, Purdue University, West LaFayette, Indiana.

Peterson, R.F. 1965. *Wheat.* Interscience Publishers Inc., New York, NewYork.

Quiring, S.M. and Blair, D. 2001.The Utility of Global Teleconnection Indices for Long-Range Crop Forecasting on the Canadian Prairies. *Prairie Perspectives,* October 2000: 23-61.

Raddatz, R.L., 1989. An Operational Agro-meteorological Information System for the Canadian Prairies. *Climatological Bulletin* 23(3): 83-97.

Rasmussen, E.M. 1984. The El Niño: the Ocean/atmospheric Connection. *Oceanus* 27(2): 5-15.

Robertson, G.W. 1974. Wheat Yields for 50 Years at Swift Current, Saskatchewan, in Relation to Weather. *Canadian Journal of Plant Science* 54:625-650.

Romolo, L. 1998. The Relationship Between The Pacific/North American Teleconnection Pattern and Spring Precipitation. Masters Thesis, Geography Department, University of Saskatchewan, Saskatoon, Saskatchewan.

Ropelewski, C.F. and Halpert, M.S. 1987. Global and Regional Scale Precipitation Patterns Associated with El Niño/Southern Oscillation. *Monthly Weather Review* 115: 1606-1626.

Ropelewski, C.F., and Halpert, M.S. 1989a. Precipitation Patterns Associated with the High Phase of the Southern Oscillation. *Journal of Climate* 2: 268-284.

Ropelewski, C.F. and Halpert, M.S. 1989b. North American Precipitation and Temperature Pattern Associated with El Niño/Southern Oscillation (ENSO). *Monthly Weather Review* 114: 2352-2362.

Saskatchewan Agriculture and Food, Agricultural Statistics. 1998. Saskatchewan Agriculture and Food, Statistics Branch, 3085 Albert Street, Regina, Saskatchewan, Canada.

Saskatchewan Water Corporation (SWC). 1987. Irrigation of Cereal Crops, Crop Development vs.Water Use. SWC, Outlook, Saskatchewan.

Shabbar, A., and Barnston, A. 1996. Skill of Seasonal Climate Forecast in Canada Using Canonical Correlation Analysis. *Monthly Weather Review* 124: 2370-2385.

Shabbar, A., Bonsal, B. and Khandekar, M.L. 1997. Canadian Precipitation Patterns Associated with the Southern Oscillation. *Journal of Climate* 10: 3016-3027.

Shabbar, A. and Khandekar, M.L. 1996. The Impact of El Niño-Southern Oscillation on the Temperature Field over Canada. *Atmosphere-Ocean* 34 (2):401-416.

Statistics Canada.1998. Field Crop Reporting Series. Statistics Canada catalogue number 22-002-xpb. Statistics Canada, Ottawa, Ontario.

Statistics Canada.1999. Field Crop Reporting Series. Statistics Canada catalogue 22-000-xpb. Statistics Canada, Ottawa, Ontario.

Stewart, D.W. and Dwyer, L.M. 1990. A Model for Spring Wheat (Triticum aestivum) for Large-area Yields Estimations on the Canadian Prairies. *Canadian Journal of Plant Science* 70: 19-132.

Stone, R.C., Hammer, G.L. and Marcussen, T. 1996. Prediction of Global Rainfall Probabilities Using Phases of the Southern Oscillation Index. *Nature* 384: 252-255.

Stowe, L.L, Carey, R.M.and Pellegrino, P.P. 1992. Monitoring the Mt. Pinatubo Aerosol Layer with NOAA-11 AVHRR Data. *Geophysical Research Letters* 19(2):159-162.

Tannehill, I.R. 1947. *Droughts, Its Causes and Effects*. University Press, Princeton, N.J.

Tipples, K.H. 1996. Red Spring Wheat Crop Characteristics. From notes taken while Director of the Canadian Grain Commission Research Laboratory,Winnipeg, Manitoba.

Trenberth, K.E. 1976. Spatial and Temporal Variations of the Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society* 102: 639-653.

University of Washington. 2000. Pacific North American (PNA) Teleconnection index data. Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington, Seattle, Washington, U.S.A. http://www.cpc.ncep.noaa.gov/products/precip/Cwlink/pna/norm.mon.pna wg.jan1950-jan2002)

Van Loon, H. and Labitzke, K. 1988. Association between the 11-Year Solar Cycle, the QBO, and the Atmosphere. Part II: Surface and 700mb in the Northern Hemisphere inWinter. *Journal of Climate* 1: 905-920.

Walker, G.K., 1989. Model for Operational Forecasting of Western Canada Wheat Yield. *Agricultural and Forest Meteorology* 44: 339-351.

Walker, G.T. 1923. Correlations in Seasonal Variation of Weather, VIII, A Preliminary Study of World Weather. *Memoirs, India Meteorological Department.* 24: 75-131.

Walker, G.T.1924. Correlation in Seasonal Variation of Weather, IX, A Further Study of World Weather. *Memoirs, India Metorological Department,* 24: 275-332.

Walker, G.T. and Bliss, E.W. 1932. World Weather V. *Memoirs, Royal Meteorological Society* 4(36): 53-84.

Wallace, J.M., and Gutzler, D.S. 1981. Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter. *Monthly Weather Review* 109: 784-812.

Webster, P. 1995. The Annual Cycle and Predictability of the Tropical Coupled Ocean-atmosphere System. *Meteorology and Atmospheric Physics* 56:33-55.

Wheaton, E.E., 1993. Agricultural and Climatic Variations in the Canadian Prairies. Garnett, R. and Lawford, R. (Eds.) Proceedings of the Long-Range Weather and Crop Forecasting Working Group Meeting I, Canadian Wheat Board, Winnipeg, Manitoba April 22-23, 49 pp.

Wheaton, E.E., Arthur, L.M., Chorney, B., Shewchuk, S., Thorpe, J., Whiting, J, and Wittrock, V. 1992. The Prairie Drought of 1988. *Climatological Bulletin* 26: 188-205.

Williams, G.D.V., Fautley, R.A., Jones, K.N. Stewart, R.B. and Wheaton, E.E. 1988. Estimating Effects of Climate on Agriculture in Saskatchewan, Canada. In: M.L. Parry, T.R. Carter, N.T. Konini (Eds.) The Impact of Climatic Variations on Agriculture, Kluwer Academic Publishers, Dordrecht, pp. 223-379 223-379.

APPENDIX A

Location of Climate Stations

Station	Crop District	Soil Zone
1) Leader	4B	Brown
2) Shackleton	4B	Brown
3) Swift Current	3BN	Brown
4) Klintonel	4A	Brown
5) Shaunavon	4A	Brown
6) Kincaid	3BS	Brown
7) Assinaboia	3AS	Brown
8) Scott	7B	Dark Brown
9) Biggar	7B	Dark Brown
10) Saskatoon	6B	Dark Brown
11) Davidson	6A	Dark Brown
12) High Point	3BN	Dark Brown
13) Beechy	3BN	Dark Brown
14) Moose Jaw	2B	Dark Brown
15) Regina	2B	Dark Brown
16) Yellow Grass	2A	Dark Brown
17) Weyburn	2A	Dark Brown
18) Midale	3AS	Dark Brown
19) Estevan	1A	Dark Brown
20) Waseca	9B	Black
21) North Battleford	9A	Black
22) Pilger	8B	Black
23) Prince Albert	9A	Black
24) Codette	9A	Black
25) Wynard	5B	Black
26) Kelliher	5A	Black
27) Yorkton	5A	Black
28) Kipling	1B	Black
29) Willmar	1A	Black
30) Oxbow	1A	Black