THE INFLUENCE OF SYNOPTIC-SCALE FORCING ON SOIL MOISTURE OVER THE EASTERN CANADIAN PRAIRIES

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THE INFLUENCE OF SYNOPTIC-SCALE FORCING
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ABSTRACT

The objective of this study was to examine the spatial and temporal patterns of measured autumn soil moisture on the eastern Canadian Prairies, and to relate the patterns to synoptic-scale forcings such as sea surface temperature anomalies.

Spatial and temporal patterns of soil moisture were determined using principal component analysis. The dominant pattern of the average soil moisture principal component was found to be one in which the entire region varied coherently, with the greatest amplitudinal change occurring in central Manitoba. The second pattern had the central area out of phase with the southeast and southwest. The third principal component spatial pattern was a dipole with centres over southern Manitoba and northeastern Saskatchewan.

Correlations were tested between the temporal principal component patterns and seven potential synoptic-scale forcings. The highest correlation was found with North Pacific sea surface temperature (SST) anomalies: late spring/early summer SST anomalies appear to influence autumn soil moisture the most. The other six synoptic-scale forcings were found to have very weak correlations with the soil moisture patterns.

The results of this study may assist in obtaining a better understanding and allow for predictions of the causes of the spatial and temporal soil moisture patterns in the eastern Canadian Prairies.

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LIST OF ACRONYMS

ENSO - El Niño-Southern Oscillation

GISS - Goddard Institute for Space Studies

GLAS - Goddard Laboratory for Atmospheric Sciences

ITCZ - Intertropical Convergence Zone

MNR - Manitoba Natural Resources

PC - Principal Component

PCA - Principal Component Analysis

PDSI - Palmer Drought Severity Index

PNA - Pacific/North America

SOI - Southern Oscillation Index

SPSS - Statistical Package for the Social Sciences

SST - Sea Surface Temperatures

1.0 INTRODUCTION AND OBJECTIVES

1.1 Introduction

Soil moisture is of critical importance to many segments of society on the Canadian Prairies. Exhibiting large variations from place to place and over time, soil moisture directly affects the growth of crops and natural vegetation as well as the amounts of erosion and runoff into rivers and lakes. The quantity of stored soil moisture available for plant growth is particularly important in years when growing-season precipitation is below normal. The spatial patterns of soil moisture are relevant to climate classification and in the assessment of impacts of moisture anomalies on forestry, agriculture and hydrology.

Soil moisture content depends on the soil's water-holding characteristics, its gains through precipitation, and its losses through evapotranspiration and drainage such as runoff. On a synoptic scale[1], soil moisture patterns reflect patterns of precipitation and evapotranspiration. Both precipitation and evapotranspiration are related to the atmospheric circulation patterns, which control the origin and movement of surface pressure systems that produce day-to-day weather, and that are controlled in turn by heat exchange on the surface.

1.2 Objectives and Hypothesis

Previous studies have examined teleconnections and precipitation on the Canadian Prairies (e.g. Chakravarti, 1972; 1990; Bonsal, 1991), but none have examined the relationship between Canadian Prairie soil

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[1]Synoptic-scale - large scale weather patterns

moisture and teleconnection[2] patterns. Soil moisture is related to atmospheric circulation patterns through precipitation. Soil moisture has a longer memory than precipitation events (Namias, 1983), therefore has importance when examining teleconnection patterns that are associated with the Canadian Prairie climate. The objectives of this study were:

1) To identify the spatial and temporal patterns of autumn soil moisture on the eastern Canadian Prairies using principal component analysis; and

2) To determine whether these patterns are related to synoptic-scale forcings such as North Pacific sea surface temperature anomalies that are known to influence global-scale atmospheric circulation.

Pursuit of these objectives has led to the following hypotheses:

1) Spatial and temporal patterns of soil moisture reflect the spatial and temporal patterns of rainfall and evapotranspiration; and

2) The soil moisture temporal patterns (as determined by principal component analysis) are significantly related to synoptic-scale forcing, such as North Pacific sea surface temperature anomalies.

This research is important as it seeks to find explanations to the spatial and temporal autumn soil moisture patterns in relation to macroscale atmospheric circulation patterns.

The results of this study may assist in obtaining a better understanding of the causes of the spatial and temporal soil moisture patterns in the eastern Canadian Prairies thus possibly increasing long-range prediction of the soil moisture patterns.

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[2]Teleconnection Patterns - correlations between weather at widely separated places on the Earth's surface (Chakravarti, 1984).

2.0 LITERATURE REVIEW

This chapter reviews the literature that pertains to this study. The areas include soil moisture patterns, principal component analysis, atmospheric circulation patterns, and teleconnections.

2.1 Soil Moisture Patterns

The amount of moisture in the soil is controlled by the balance between precipitation and evapotranspiration as influenced by such parameters as surface and underlying soil characteristics, topography and vegetation. Figure 2.1 illustrates the important role of soil moisture with regard to the exchanges of energy within the Earth-Atmosphere system. As an example, an increase in surface soil moisture lowers the albedo of the soil, which increases the absorption of solar radiation. Evaporative loss to the atmosphere is increased, cooling the surface and reducing sensible heat transfers to both the atmosphere and soil. Longer-term effects include increasing air humidity, soil water movement and soil and plant biological activity.

Ideally, a study of soil moisture should use measured soil moisture data. However, very few such data sets are available so usually this type of study cannot be done. Therefore, most soil moisture research is based on the use of calculated soil moisture (Thornthwaite and Mather, 1954; Baier and Robertson, 1966; Afshar and Marino, 1978; Calder, Harding and Rosier, 1983; Alley, 1984; 1985; Abbaspour, 1991; Bootsma, Dumanski and de Jong, 1992 and many others). The models used to calculate soil moisture usually include temperature

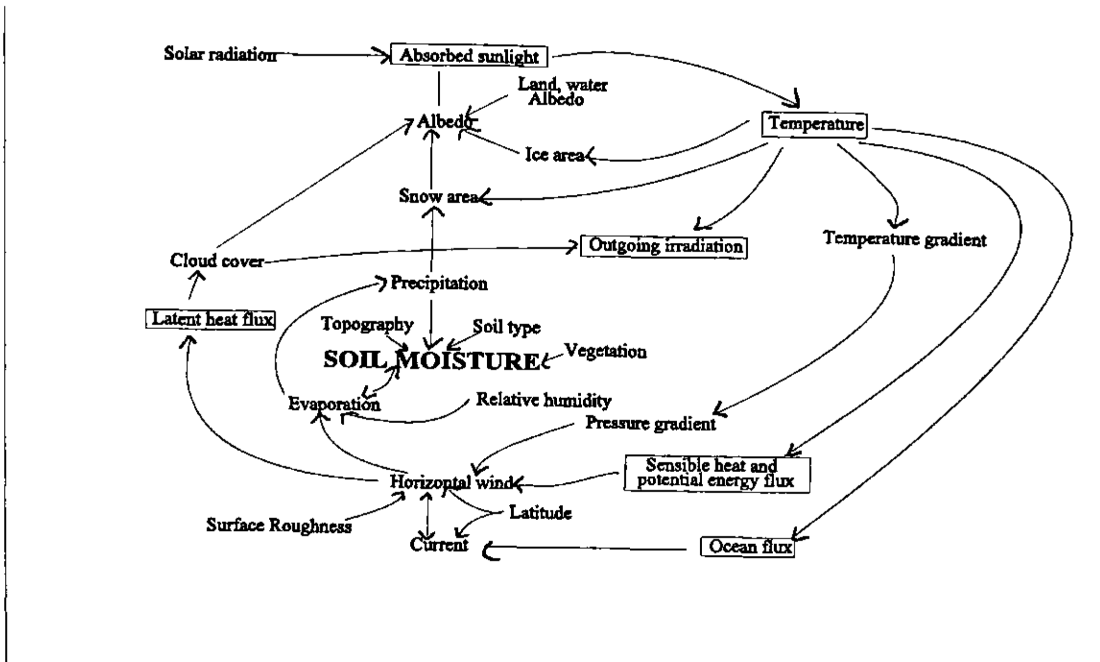

Figure 2.1 Processes affecting energy exchange within the Earth-Atmosphere System. Adapted from Kellogg and Schneider (1974).

and precipitation and may or may not consider evapotranspiration, runoff or soil type. These models have been generally used in drought determination.

Soil moisture patterns are related to weather patterns through precipitation (or lack of it) and are closely connected to regional pressure and wind systems. The vertical structure, or layering, of soil moisture provides a "memory" of atmospheric gains and losses extending back weeks or months before present (Namias, 1983). An understanding of these weather patterns and teleconnections is needed to explain soil moisture variations over the Canadian Prairies.

2.2 Principal Component Analysis

Principal component analysis (PCA) has been used to determine patterns of temperature and precipitation (Kutzbach, 1967; Richman and Lamb, 1985) and soil moisture (Daultrey, 1970; Ripley, 1992; Yin, 1994). The history of PCA use in meteorology has been reviewed by Christensen and Bryson (1966), Jolliffe (1986) and Preisendorfer (1988)amongst others. The main objective of PCA is to reduce a large number of variables to a set of principal components that retain most of the variation in the original variables (Jolliffe, 1986; 1990; 1993).

PCA is a linear statistical technique with input values on an x and y plane (Jolliffe, 1990). For example, this study will ascertain the principal components for soil moisture in relation to location and time. The method for calculating principal components is complex and was not widely used until the advent of the computer (Jolliffe, 1990).

PCA has a four step calculation process. First, the correlation (or covariance) matrix is calculated from the variables. The second step is the principal component extraction. The third step is determining the variance of each of the principal components. The fourth step, if it is used, is the rotation of the factors. The PCA equation is similar to a multiple regression equation. Each variable is a linear combination of principal components (Norušis, 1990).

Jolliffe (1993) developed criteria to determine how many principal components should be retained for the PCA to remain meaningful. Two of these criteria were based on previous work. The first (Anderson, 1963) was to use only those principal components that account for the greatest percentage of the total variation in the analysis. The second (Daultrey, 1976) was to keep those principal components whose variances are higher than the average variance of the original variables. The third criterion was to discard principal components which could not be physically interpreted. The third criterion is highly subjective to the individual researcher.

Principal component analysis produces results known as principal components (PC). The first PC is the linear function accounting for the highest variance. The second PC is a linear function with the next highest variance subject to being uncorrelated with the first PC. Subsequent PCs are all linear functions ranked in order of decreasing variance which are uncorrelated with the first and second PCs and each other (Jolliffe 1990). All the PCs are present but as the "layers" are removed the PC below becomes the dominant pattern. The spatial PCs are known as weights indicating the extent of variation around zero. The temporal PCs are known as the amplitudes also indicating the extent of variation around zero - the higher the number the greater the variation (Jolliffe 1990).

2.2.1 Principal Component Analysis of Soil Moisture

There is little past research dealing with soil moisture data and principal component analysis. This may be due to the limited amount of measured soil moisture data covering an extended period.

A preliminary analysis of the Manitoba Natural Resources (MNR) soil moisture data set (section 3.2) was carried out by Ripley (1992) using empirical orthogonal function analysis. This is essentially the same statistical procedure as principal component analysis. The Manitoba Natural Resources soil moisture data set was reduced in size by averaging the soil moisture sites in each drainage basin resulting in only five points being used in the analysis. The average soil moisture of the four depths was used. The spatial and temporal relationships of the first three principal components were examined. The first principal component explained 51% of the variance, the second 17% and the third 11% of the variance, for a total of 79% for the first three PCs. No other researcher has analysed the MNR data in this way therefore it is difficult to determine whether the variance that is explained is usual.

Principal component analysis was used to analyse the relationship between soil moisture, topography, and vegetation types in the Brazilian savanna (Daultrey, 1970). Three soil moisture levels, slope and topography were used in the analysis. The first three principal components were examined with a total variance explained at or above 79%. It was found that some of the measured environmental variables could explain the vegetation distribution.

Most recently, Yin (1994) used principal component analysis on modelled (Palmer Drought Severity Index) soil moisture conditions in the southeastern United States. Two months of data were used in the analysis - February and August. This was to associate winter climatic events to winter soil moisture and summer events to summer soil moisture. There were seven principal components used in the February period explaining 84% of the total variance; eight principal components for the August period explained 83% of the total variance. The principal components were used to determine regions of homogeneous moisture regimes and then the author related these regions to atmospheric circulation patterns such as the Southern Oscillation Index (SOI). The moisture conditions and teleconnection patterns were found to be statistically significant at the 0.10 level of probability. The autumn SOI had a significance level (r) of 0.4 for the first principal component. The spring SOI had a significance level of 0.47 for the second principal component.

2.3 Atmospheric Circulation

The major motions of the atmosphere are thermally-driven (Longley, 1970). Solar radiation reaching the Earth's surface is strongly latitude dependent and its partial reflection depends on the distribution of continents and oceans. It also depends on the surface cover of ice and snow and on the extent of vegetation and exposed soil. The resultant surface temperature pattern drives the atmospheric circulation as the air moves and transports heat from regions of excess (warm air) to regions of deficit (cool air). As expressed by Shukla (1985), the heating of the equatorial regions (by solar radiation absorbtion) and the cooling of the polar regions (by terrestrial radiation emission) provide the energy that moves the air in the atmosphere and the water in the ocean.

The distribution of continents and oceans also provides a pattern of heating which varies with the seasons. Desert areas warm and cool quickly, while wet surfaces tend to evaporate moisture instead of heating up as energy is absorbed. This moisture rises into the atmosphere and condenses, releasing latent heat of condensation that provides an energy source for atmospheric motions. The many-faceted mass and energy interactions between the oceans, land and atmosphere generate the Earth's weather (figure 2.2).

The series of troughs and ridges created by the undulating westerly streams of the mid-latitudes are called Rossby Waves (figure 2.3) and dominate the weather of the underlying surface. To the east of a trough position, warm air is being advected and surface low pressure areas are frequently generated (cyclogenesis); to the west there is cold-air advection and little likelihood of lows being generated. In general, ridges are associated with clear dry weather and troughs with cloudy skies and precipitation (Ahrens, 1991).

2.4 Teleconnections

Since the mean atmospheric motion is due largely to temperature differences related to latitude and surface characteristics, it is expected that surface-temperature anomalies will produce circulation

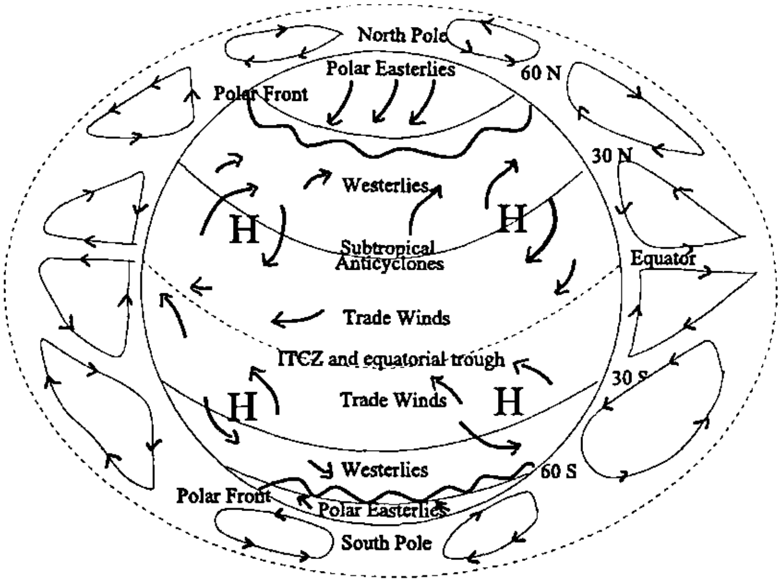

Figure 2.2 Schematic representation of the global-scale surface circulation of the atmosphere. Adapted from Moran and Morgan 1991; Anthes 1992. Note: ITCZ is the intertropical convergence zone.

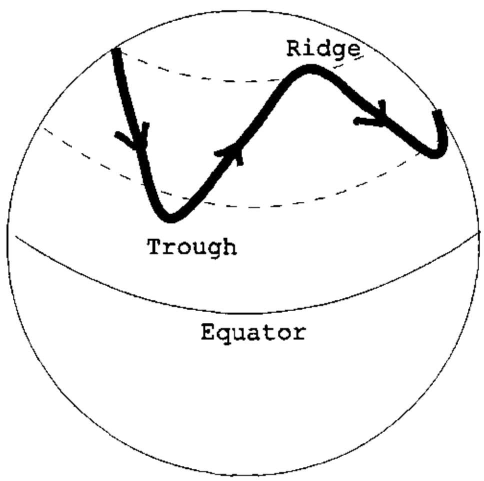

Figure 2.3 Schematic representation of Rossby Waves. Adapted from Whittow, 1984; Moran and Morgan, 1991.

anomalies. A good example of this is the strengthening of the mid-latitude westerlies as the latitudinal temperature gradient increases in winter (Ahrens, 1991). Even without surface anomalies, the circulation would vary because of the occurrence of unstable disturbances and the nonlinear dynamics of the atmosphere (Shukla, 1985). This natural variability makes the detection of surface-boundary-forced circulation anomalies difficult.

Teleconnections are linkages between atmospheric anomalies over extended distances, as the result of synoptic-scale atmospheric circulation processes (Yin, 1994). They were defined by Chakravarti (1984) as correlations between weather at widely separated places on the Earth's surface. Namias (1980) explained teleconnections as the tendency for meanders of the large scale atmospheric flow over one area of the Earth's surface to be associated with other atmospheric phenomena in other areas.

Perhaps the most widely investigated teleconnection phenomena are those associated with the El Niño-Southern Oscillation (ENSO), a reversal in the trade-wind circulation over the equatorial Pacific Ocean. ENSO has been found to have an influence on droughts in northeastern Brazil, Australia, Ethiopia and India; floods in Peru and Ecuador; warm winters in Russia and Canada; and cool summers in northeast China (Glantz et al., 1991).

Atlases of teleconnections of 70 kPa height anomalies, and associated North Pacific sea-surface temperature (SST) anomalies have been prepared by Namias (1979; 1981). The earlier of these (Namias, 1979) mapped the 70 kPa heights and height anomalies associated with North Pacific SST anomalies, for each season between 1947 and 1978. The latter (Namias, 1981) presented seasonal maps of correlations between 70 kPa height anomalies at 5° spaced latitude-longitude grid points for the period 1947-1972. An example is shown in figure 2.4 for the grid point closest to Saskatoon in the north central Canadian Prairie, in the winter season. The black dot is the "selected point", at which the correlation is 100%. Positive correlation extends over most of Canada and the Western United States while there is strong

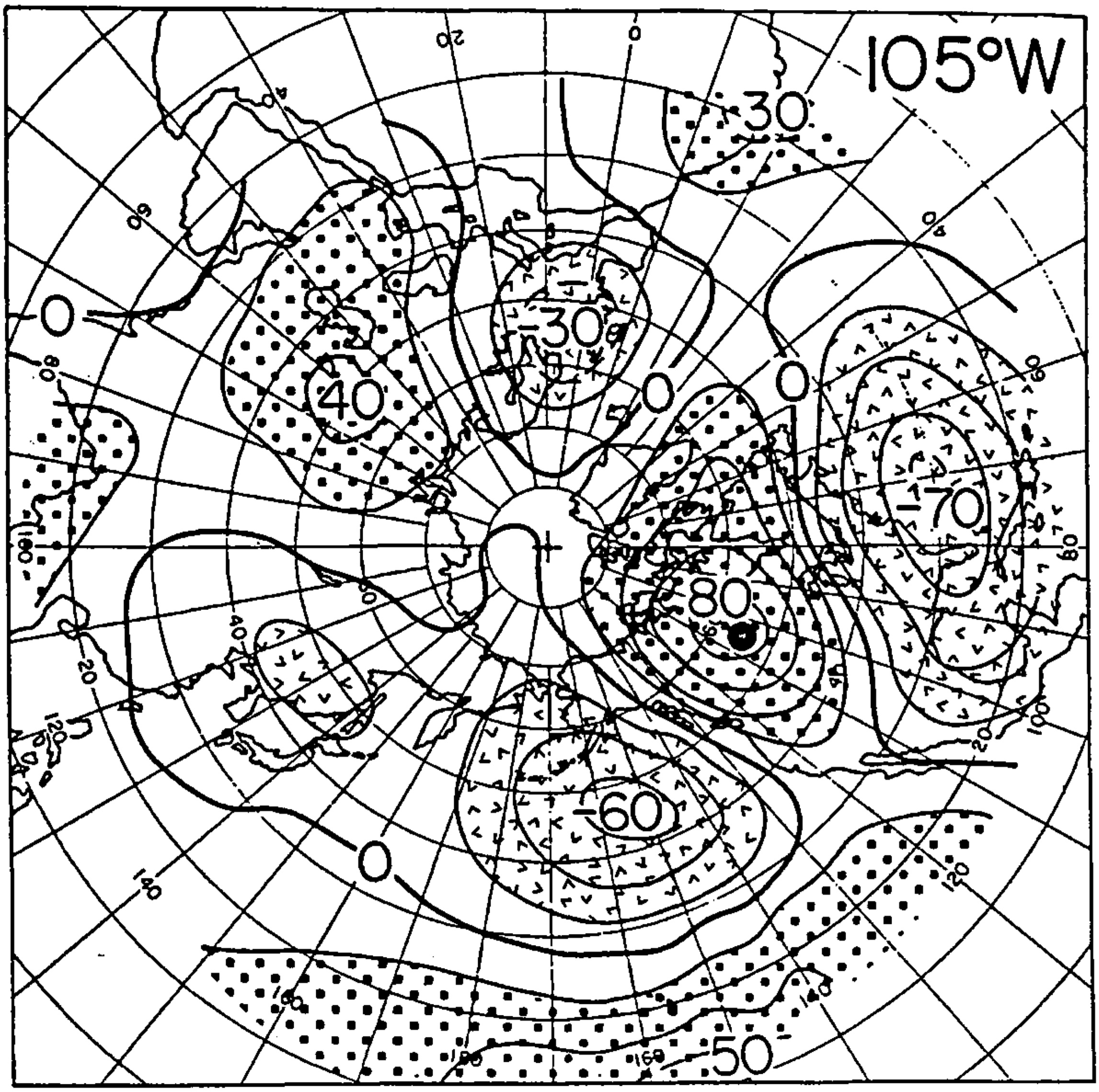

Figure 2.4 Winter 70 kPa height anomaly correlations.

The black dot is the location of 100% correlation.

Source: Namias, 1981.

negative correlation to the south of the Aleutian Islands and over the southeastern United States and the Caribbean. This is commonly called the Pacific/North American (PNA) pattern (Wallace and Gutzler, 1981). Somewhat weaker anomaly centres are found over Kazakhistan (positive) and western Europe (negative). Figure 2.4 implies that when pressure is high over the Canadian Prairies, it is low over the Gulf of Alaska and the southeastern United States, and vice-versa. It is reasonable to assume that the weather associated with high and low pressure systems would also be affected.

Jerome Namias has done extensive amounts of research on the teleconnections that cause weather patterns in the United States (Namias' Collected Works, 1934-1982). One study (Namias, 1960; 1962) found that the initiation of drought was associated with mid-tropospheric ridging and accompanying positive pressure anomalies. Warm dry weather over the US Great Plains in the spring provided a suitable environment for the lodgement of upper level anticyclones during the following summer. This is because a dry soil surface heats up more by insolation (due to the lack of evaporation), tending to form a pressure ridge and to perpetuate the drought. The ridge has the effect of suppressing frontal activity in the lee of the Rockies (Sweeney, 1985). A warm dry spring followed by a warmer than normal summer is more likely to occur than a warm dry spring followed by a cooler than normal summer (Namias, 1962). Goddard Institute for Space Studies (GISS) general circulation model simulation results show that when surface moisture is reduced over an area, the surface temperature rises because more energy is converted to sensible heat and precipitation diminishes. This effect may persist over an entire summer season (Rind, 1982).

Namias (1980) found that most cases of drought in the temperate latitudes were associated with persistent upper-level anticyclonic flow patterns and accompanying warm dry conditions in the lower atmosphere. He speculated that this was the result of boundary conditions, such as sea surface temperature anomalies and surface albedo changes, affecting the surface heat exchange.

The 1983/84 drought on the Canadian Prairies is a good example of how spring and summer drought conditions are related. The seasonal climatic anomalies tend to reflect the frequency of the air mass occurrences. Dry conditions in the spring, in this case 1984, often lead to summer droughts. The tendency for drought recurrence averages 20 to 24 years (Sweeney, 1985).

Atmospheric fluctuations may also be due, in a small and local degree, to changes in snow cover and soil moisture. These variables change relatively slowly compared to atmospheric circulation patterns. The role of snow cover and soil moisture on the atmosphere depends on region, and the season of the large scale circulation (Walsh, 1986).

Anthes and Kuo (1986) examined whether surface soil moisture availability affects mesoscale atmospheric circulation over an undulating topography. They used a medium resolution limited area (160 km grid) model to study the circulation perturbation by land and sea and the elevation differences. They ran the model for two 72 hour simulations over North America for the summer period. The model was initialized with a horizontally homogeneous atmosphere at rest. Results indicated the importance of evapotranspiration on the dynamics of the circulation at this scale. The first simulation had no available moisture and no evapotranspiration. The second simulation had uniform available moisture levels. The second simulation produced a monsoon circulation in the southern USA which was stronger than in the simulation without evapotranspiration. The maximum low-level pressure departure over land and upper-tropospheric height anomalies was double that without evapotranspiration. This is consistent with Namias's hypothesis that a persistent stronger-than-normal upper-level anticyclone over the US Great Plains during the summer is favoured by abnormally dry soil conditions during the spring.

Shukla and Fennessy (1987) examined how sea surface temperatures influenced continental precipitation; used the Goddard Laboratory for

Atmospheric Sciences (GLAS) climate model to simulate the effect of changing the sea surface temperature boundary conditions on atmospheric conditions and rainfall. They also studied the impact of the observed sea surface temperature anomalies on actual weather prediction. They concluded that sea surface temperatures did influence the amount of continental precipitation and that there would be significant improvements in forecasts, especially in the 30 to 60 day forecast period, if sea surface temperatures were included in the forecast models. Sea surface temperatures are now included in long-lead forecasts. For example, the 1995/96 Canadian winter temperature and precipitation forecasts include the use of large scale patterns of quasi-global sea surface temperature (e.g. Shabbar, 1995).

2.5 Canadian Prairie Teleconnections

Most studies that have examined teleconnection effects on the Canadian Prairies have focused on the influence of North Pacific sea surface temperatures on the precipitation patterns and upper atmospheric ridges (e.g. Chakravarti, 1972; 1976; Dey and Chakravarti, 1976; Bonsal, 1991). Many of these authors were specifically interested in finding a causal mechanism for droughts.

Precipitation also has long been used as an indicator (and a variable e.g. PDSI) for illustrating soil moisture patterns on the Canadian Prairies (Louie, 1986; Jones, 1988). One reason may be the ease of precipitation measurement and the numerous locations of precipitation measurement. Precipitation may not, however, be the best indicator of soil moisture patterns.

2.5.1 Canadian Prairie Precipitation Patterns

Drought patterns were determined for the 1921-1970 period on the Canadian Prairies (Chakravarti, 1976). It was found that when southern agricultural areas of the Canadian Prairies recorded below normal precipitation, the northern region received above normal precipitation and vice versa. Also, if there was below normal precipitation in southern Alberta, above normal amounts were recorded in Manitoba. Precipitation deficiencies seldom affected the same area with equal intensity in successive years (Chakravarti, 1976).

An examination of the seasonal distribution of precipitation showed that the precipitation maximum for the southern half of the Canadian Prairies was in June while that in the northern portion was in July (Chakravarti, 1972).

Daily patterns of precipitation events have been examined for May to September (Chakravarti, 1990; Chakravarti and Archibold, 1993). Large portions of the Canadian Prairies received more precipitation during night than day. July had the largest areas with nocturnal precipitation in both amounts and frequency (Chakravarti and Archibold, 1993). The nocturnal maxima during a normal-to-wet growing season was in south/central Saskatchewan and Manitoba and it changed to nocturnal minima during a dry year. This reduced the precipitation which reached the soil. Nocturnal precipitation is more available to plants and soil due to reduced evapotranspiration (Chakravarti, 1990).

2.5.2 Canadian Prairie Synoptic-Scale Patterns

Precipitation has also been related to synoptic-scale patterns over the Canadian Prairies (e.g. Chakravarti, 1972; Dey, 1973; Knox and Lawford, 1990; Bonsal, 1991). The monthly precipitation was speculated to be related to the North Pacific high pressure moving towards the northeast and a northward displacement of the jet stream, frontal zones and cyclonic tracks. The North Pacific high pressure cell moves northward in July corresponding to the July maximum precipitation in the northern portion of the prairies (Chakravarti, 1972; 1990).

Diurnal patterns may be related to recurrent surface or upper atmospheric flow patterns. The western Canadian Prairie regional topographic conditions allow west to east surface air drainage and upward movement of air and precipitation by night and divergence and subsidence by day. The eastern Canadian Prairie diurnal patterns are more likely to be quasi-stationary or to occur with a slow moving east-west front. At night, the eddy motion is weaker resulting in convergence along the front causing more precipitation than during the day (Chakravarti, 1990; Chakravarti and Archibold, 1993).

Dry conditions on the Canadian Prairies have been related to an extension of the subtropical high pressure cell in the northeastern Pacific Ocean and a quasi-stationary 50 kPa ridge presence with its northeast axis lying across the Canadian Prairies. These patterns generate an atmospheric block displacing the jet stream and cyclonic tracks (Dey, 1973; Dey and Chakravarti, 1976).

More recently, North Pacific sea surface temperature anomalies have been used to explain the synoptic-scale conditions that result in extended dry spells on the Canadian Prairies (Bonsal, 1991). When the east-central North Pacific is cooler than normal and the sea surface temperature along the west coast of North America is warmer than normal and the anomaly gradient of the ocean becomes positive, the dry spell over the Canadian Prairies becomes more severe. A dry spell is defined as a "period of at least 10 consecutive days during which 50% or more of the stations within the study area report no measurable precipitation and the entire period has a positive average 50 kPa anomalous height value within the study area."

2.6 Soil Moisture Patterns and Teleconnections

Synoptic-scale forcings and teleconnections have not been widely studied in conjunction with soil moisture patterns. This is somewhat surprising as Namias (1983) found that soil moisture has a long term memory for climatic events.

Yin (1994) used modelled soil moisture to determine teleconnection patterns. Yin (1994) examined the effects of Pacific/North American, reverse Pacific/North American, and North Atlantic Oscillations and ENSO on soil moisture patterns in the southeastern United States. He found the Southern Oscillation Index (part of ENSO) to be significantly correlated with the modelled soil moisture in the southeastern United States. The first principal component had an r value of 0.39 with the autumn SOI and February soil moisture. The spring SOI became statistically significant ($r = 0.47$) at the second principal component when correlated with the August modelled soil moisture.

2.7 Conclusion

This literature review indicates several key points:

1. Very little research involves measured soil moisture data, the main reason being the lack of data availability especially over a wide geographical area.

2. Principal component analysis is a tool that allows researchers to reduce a large data set down to one that is easier to handle without losing the natural variation of the actual values.

3. Principal component analysis of soil moisture is still a relatively new way of examining soil moisture patterns (e.g. Ripley. 1992; Yin, 1994).

4. Establishing the relationship between soil moisture patterns and synoptic-scale atmospheric circulation patterns is still very new.

The author of this study found only one other paper on this subject (Yin, 1994). Yin (1994) examined soil moisture in the southeastern United States where the Southern Oscillation Index was found to be influential.

All of these points indicate that this is an important study. It is the first study to deal with eastern Canadian Prairie soil moisture spatial and temporal patterns and to relate these patterns to synoptic-scale forcings.

3.0 STUDY AREA AND DATA SOURCES

3.1 Study Area

The study area of this project is the agricultural region of southeastern Saskatchewan and southern Manitoba (figure 3.1). This area was chosen because of the availability of long term measured soil moisture data.

The climate of the study area (figure 3.2) is prairie continental, with four distinct seasons (Hare and Thomas, 1979). The average annual precipitation is between 300 and 400 mm. The majority of the precipitation falls in the growing season. Most of the precipitation events are in the form of local convection and thunderstorms (Chakravarti, 1969). The potential evaporation rate during the summer months on the Canadian Prairies ranges from 600 to 700 mm (Environment Canada, 1982a). This high potential evaporation rate often leads to soil moisture deficits or droughts during the growing season.

In the Köppen system, the western portion of the study area (figure 3.1) is classified as Bsk or steppe (semiarid climate) and the eastern and the northeastern portions as Dcb (temperate continental) (Trewartha and Horn, 1980). These classifications indicate that the study area is susceptible to drought which for this study, is defined as insufficient precipitation during the growing season to meet the moisture requirement of the crops (Chakravarti, 1969).

The topography is generally gently-to-moderately undulating. The soils range from dark brown to black Chernozems with a general loam texture (Moss and Clayton, 1967; Henry and Harder, 1991). Exceptions are the heavy clay soils of the Regina area and the alluvium near Kamsack (Department of Agriculture, Government of Canada, 1963; Moss

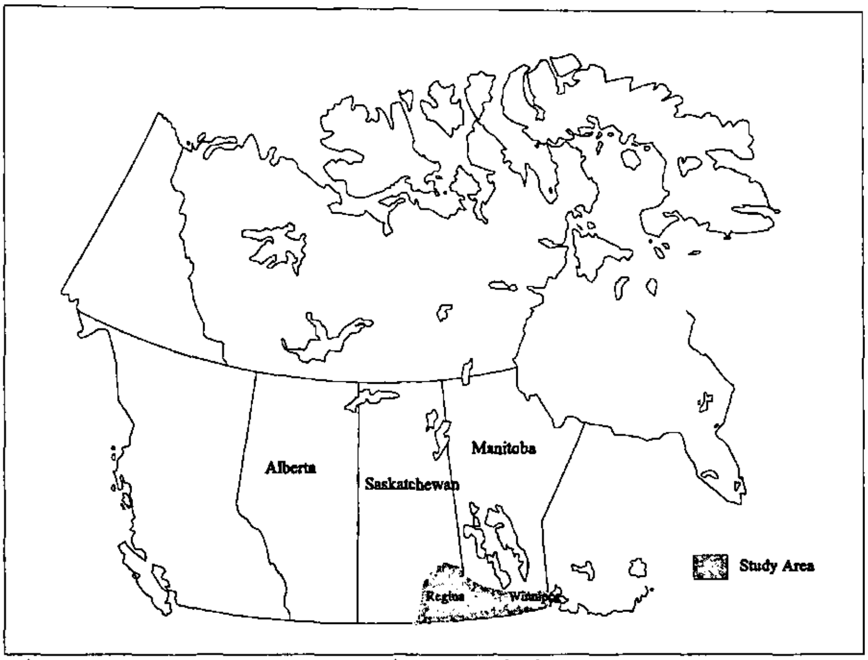

Figure 3.1 Eastern Canadian Prairie Study Area

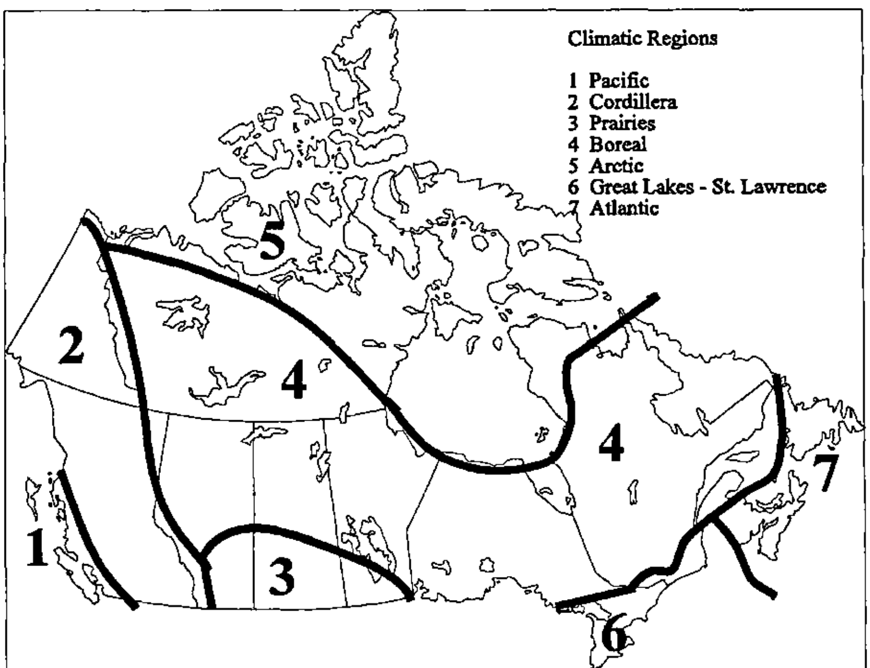

Figure 3.2 The seven climatic regions of Canada. The study area is in the Prairie (3) Climatic Region. Source: Hare and Thomas, 1979

and Clayton, 1967). The eastern portion of the study area is characterized by Organic mesisols intermixed with gravel deposits (Smith et al., 1964; Canada Soil Inventory, 1989) (figure 3.3).

3.2 Soil Moisture Sites and Sampling Methods

Soil moisture has been sampled discontinuously on the Canadian Prairies since the 1930s. The Saskatchewan Centre for Soil Research of the University of Saskatchewan produced an annual surface moisture content map of Saskatchewan soils between 1979 and 1989. The samples were taken the beginning of November with locations varying from year to year. The sampling sites were dependent on locations of precipitation prior to sampling. If there was precipitation in an area, samples would be taken; if there was no precipitation for the entire autumn period, the area would be assumed to be dry and no samples would be taken. The autumn period was defined as the period between harvest completion to about November first when the sampling was to take place (Henry, 1992).

Manitoba Agriculture records soil moisture amounts as well. The amounts have been measured from 1989 to present twice per year to a depth of 120 cm in Manitoba. The land use patterns of the sites have not been recorded. The soil moisture sampling locations vary from year to year, the spring of 1989 ranging with 33 sites from as far north as Swan River, Manitoba to 16 sites in the autumn of 1992 (Raddatz, personal communication, 1993). The sampling location variation makes site comparison to itself and other data sets, such as the Manitoba Natural Resources data set, difficult.

Alberta Agriculture, Food and Rural Development has been recording soil moisture amounts in the agricultural region of Alberta. The soil surface sampling of stubble fields was carried out in the spring (1988-1990) and fall (1982-1990). The soil moisture maps produced are based on a computer model supported by the soil surface sampling (Howard et al., 1992).

Many Agriculture Canada Research Stations, such as the one in Swift Current, do detailed soil moisture sampling but only at their stations. The soil moisture sampling at Swift Current is taken three

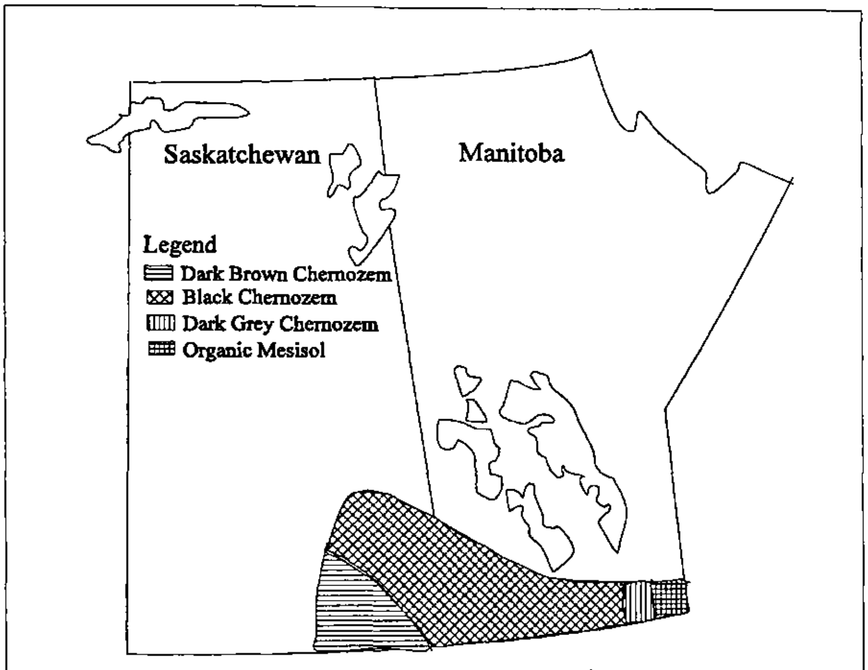

Figure 3.3 The four dominant soils in Eastern Canadian Prairie study area.
Sources: Smith et al., 1964; Moss and Clayton, 1967; Canada Soil Inventory, 1989; Henry and Harder, 1991.

times a year at five depths. This sampling began in 1967 (Zentner, personal communication with E. Ripley, 1990).

More recently, soil moisture data have been derived from satellite imagery (e.g. Curran, 1981; D'Iorio et al., 1991; Brown et al., 1992). This method of soil moisture measurement is new and refinements are required (Ragab, 1992).

The Manitoba Department of Natural Resources (MNR) began sampling soil moisture at four depths in 1955 with 27 sites, which were expanded to 35 in 1957 (figure 3.4). The samples were taken annually in late October or early November. The network was originally set up to assist MNR in predicting spring runoff. They believed the most relevant information for runoff prediction was autumn soil moisture before soil freeze up (Warkentin, 1992). The locations of the 35 sites have not changed during the 1957 to 1991 period. Each year the MNR technicians use a detailed road and site description map to locate the sampling sites thus maintaining sampling consistency even though there have been observer changes (Warkentin, personal communication, 1993).

The land use at the soil moisture sites is mainly agricultural, and therefore cultivated land dominates the sampling sites. The percentage of agricultural land has changed over the last 30 years but exact records of the changes were not kept (Warkentin, personal communication, 1993). Figures 3.5 and 3.6 illustrate typical soil moisture sites. Figure 3.5 is a summer fallow field located near Weyburn, Saskatchewan while figure 3.6 is the stubble field near Regina, Saskatchewan. Appendix B contains a list of the soil moisture latitudinal and longitudinal locations.

The soil samples were taken from one hole per site for four depths (15, 30, 46 and 76 cm) using an auger (figure 3.7). The samples were placed in air-tight containers. The samples were then transported to the laboratory in Winnipeg, Manitoba where they were weighed initially; placed in a 105°C oven for at least 12 hours; then weighed again. The volume fraction of soil moisture (θ) was then calculated as:

$$\theta = (W \cdot G) / (\rho \cdot D) \qquad (3.1)$$

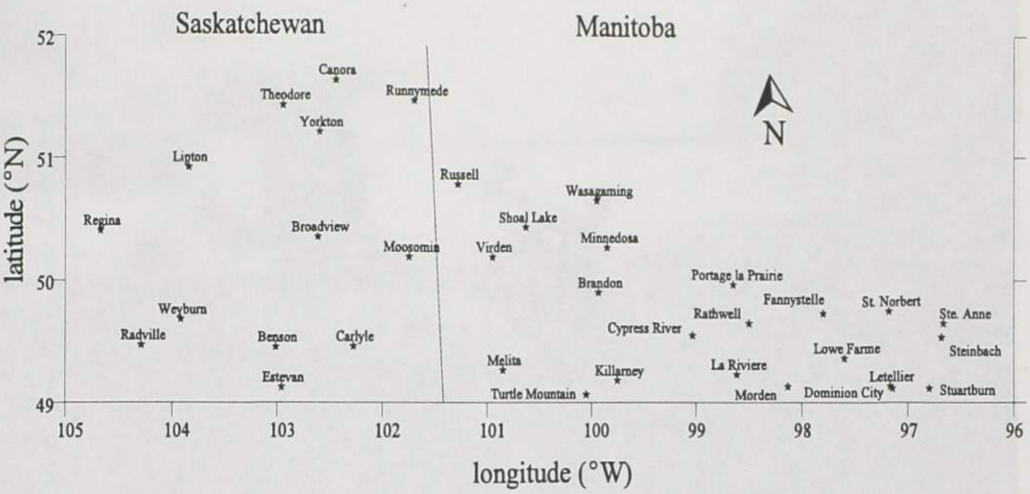

Figure 3.4 The 35 soil moisture sites in Southeastern Saskatchewan and Southern Manitoba as sampled by the Manitoba Natural Resources.

Figure 3.5 Summer fallow field near Weyburn, Saskatchewan. The technician is taking a soil moisture sample from one of the 35 soil moisture sampling sites in the network
Photo taken November, 1993, V. Wittrock.

Figure 3.6 Stubble field near Regina, Saskatchewan. The technician is taking a soil moisture sample from one of the 35 soil moisture sampling sites in the network.
Photo taken November 1993, V. Wittrock.

Figure 3.7 Soil moisture sampling method. Technician is emptying soil sample from the auger into a plastic cup which is sealed and taken to laboratory for analysis.
Photo taken November, 1993, V. Wittrock.

where W is the initial weight of the water in the soil sample, D is the dry sample weight, ρ is density of water and G is the bulk density of the sample (Wilson, 1971; Curtis and Trudgill, 1974; Warkentin, personal communication, 1993).

There were 12 sites with one to two missing soil moisture values. These gaps were filled in by averaging the other depths for the given year.

3.3 Precipitation Measurement Sites

Precipitation is the most important variable affecting soil moisture. There are, however, situations in which precipitation fails to recharge soil moisture, such as heavy showers producing runoff or very light rain which is evaporated from the vegetation canopy and never wets the soil.

Total monthly precipitation amounts for the period 1955 to 1987 were obtained from Jones (personal communication, 1993) of the Atmospheric Environment Service for 34 stations closest to the soil moisture sites. Only 19 of the 34 climate stations were used because their recording periods and locations corresponded most closely to the soil moisture sites (figure 3.8). Appendix C gives the exact locations and recording periods for each climate station used in the analysis.

This analysis does not distinguish the way the precipitation was measured nor precipitation type because this information was not readily available for all of the stations. It has been documented that in Canada depending on the gauge and precipitation type, precipitation values between gauges can vary up to 20% (Environment Canada, 1982b). The different types of precipitation also influence soil moisture recharge differently. Heavy rainfall tends to run off the land instead of infiltrating into the soil.

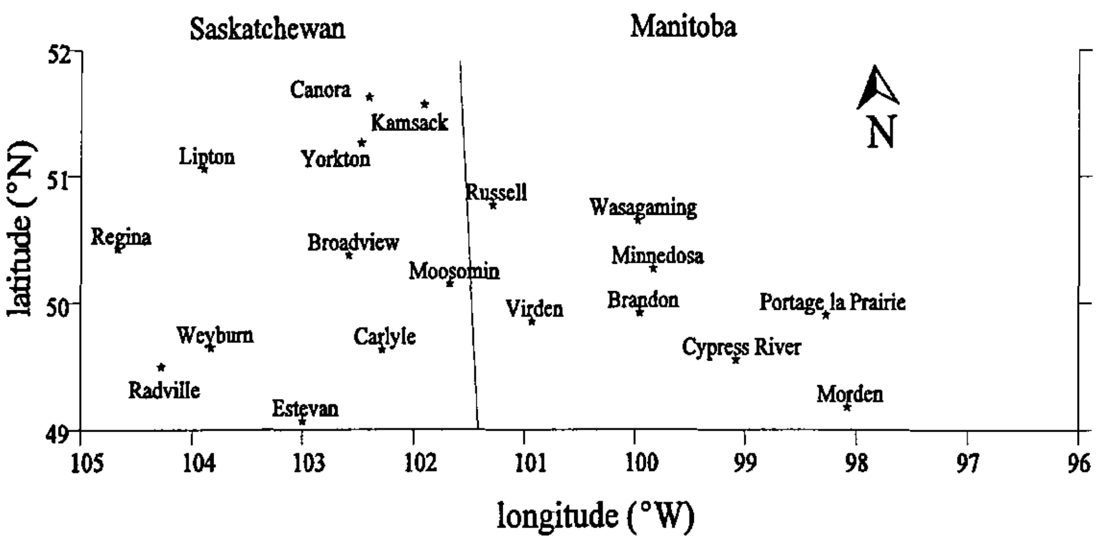

Figure 3.8 The 19 climate station sites in the Eastern Canadian Prairies as provided by Environment Canada.

3.4 Synoptic-Scale Forcings Data Bases

Synoptic-scale forcing data are used to determine temporal similarities between a possible synoptic-scale forcing and the soil moisture patterns. The data were obtained from various sources including the Carbon Dioxide Information Analysis Centre and journal articles.

The synoptic-scale forcing data sets came from two general regions of the Earth. Several data bases were selected from the Arctic. This is based on the premise that the Arctic's thermal characteristics are important in the large scale energy transfer of the northern hemisphere. Variations in these characteristics modify the surface-atmosphere exchanges of energy and moisture. These are believed to affect atmospheric circulation and the movement of the synoptic-scale systems (Ripley, 1991). The other data are from the Pacific Ocean region. This is based on the hypothesis of teleconnection patterns: what occurs in one part of the Earth influences the weather and soil moisture in another part (Gnomes, 1980). The Arctic and Pacific locations are the atmospheric boundaries for the Canadian Prairies because weather systems affecting this area tend to move west to east and northwest to southeast.

3.4.1 North Pacific Sea Surface Temperature Anomalies

This data set was obtained from B. Bonsal (personal communication, 1994). Bonsal obtained these data from the Scripps Institution of Oceanography in La Jolla, California. The data period is 1957 to 1990. A North Pacific sea surface temperature anomaly is defined as "the difference between the observed sea surface temperature value for a particular month and the 41 year average value at the same location for the same month" (Bonsal, 1991). The 41 year average was the period of record. This definition is comparable to the one used by Gnomes et al. (1988) who used 20 year averages because they were all that were available to them.

The sea surface temperature (SST) anomaly gradient is positive when the temperature anomaly along the west coast (50°N, 125°W) of

North America is warmer than the east-central North Pacific anomaly (30°N to 40°N latitude and 165°W to 135°W longitude - figure 3.9). This pattern resulted in the Canadian Prairies being in an extended dry spell situation 10 out of 11 times between 1948 and 1988. An extended dry spell is defined as "a period of at least 10 consecutive days during which 50% or more of the stations within the study area report no measurable precipitation and the entire period has a positive average 50 kPa anomalous height value within the study area." The SST gradient is negative when the temperature anomaly along the west coast is cooler than the temperature anomaly in the east-central North Pacific generally resulting in above normal precipitation on the Canadian Prairies (Bonsal, 1991; Bonsal et al., 1993).

3.4.2 Southern Oscillation Index

The Southern Oscillation Index covers the period of 1957 to 1986. The Southern Oscillation Index is the difference in normalized sea-level pressures between Tahiti and Darwin and is calculated on a monthly basis using the equation:

$$SOI=((P_T-\overline{P_T})/stddev_T)-((P_D-\overline{P_D})/stddev_D) \qquad (3.2)$$

where P_T is the actual pressure at Tahiti; $\overline{P_T}$ is the average pressure at Tahiti and $stddev_T$ is the standard deviation of the pressure at Tahiti. P_D is the actual pressure at Darwin; $\overline{P_D}$ is the average pressure at Darwin and $stddev_D$ is the standard deviation of the pressure at Darwin. SOI is the Southern Oscillation Index (Quinn et al., 1978; Wright, 1989; Clarke and Li, 1995).

The southern oscillation is a large-scale see-saw of atmospheric mass between the eastern and western tropical Pacific, resulting in an oscillation of surface pressure and of attendant wind, temperature and precipitation patterns that have teleconnections from the tropical Pacific to much of the rest of the world (Kidston, 1975; Yarnal, 1985; Philander, 1990).

The Southern Oscillation Index (SOI) gauges the net difference between two surface pressure centres of the southern oscillation. A high SOI denotes high pressure and dry conditions in the tropical

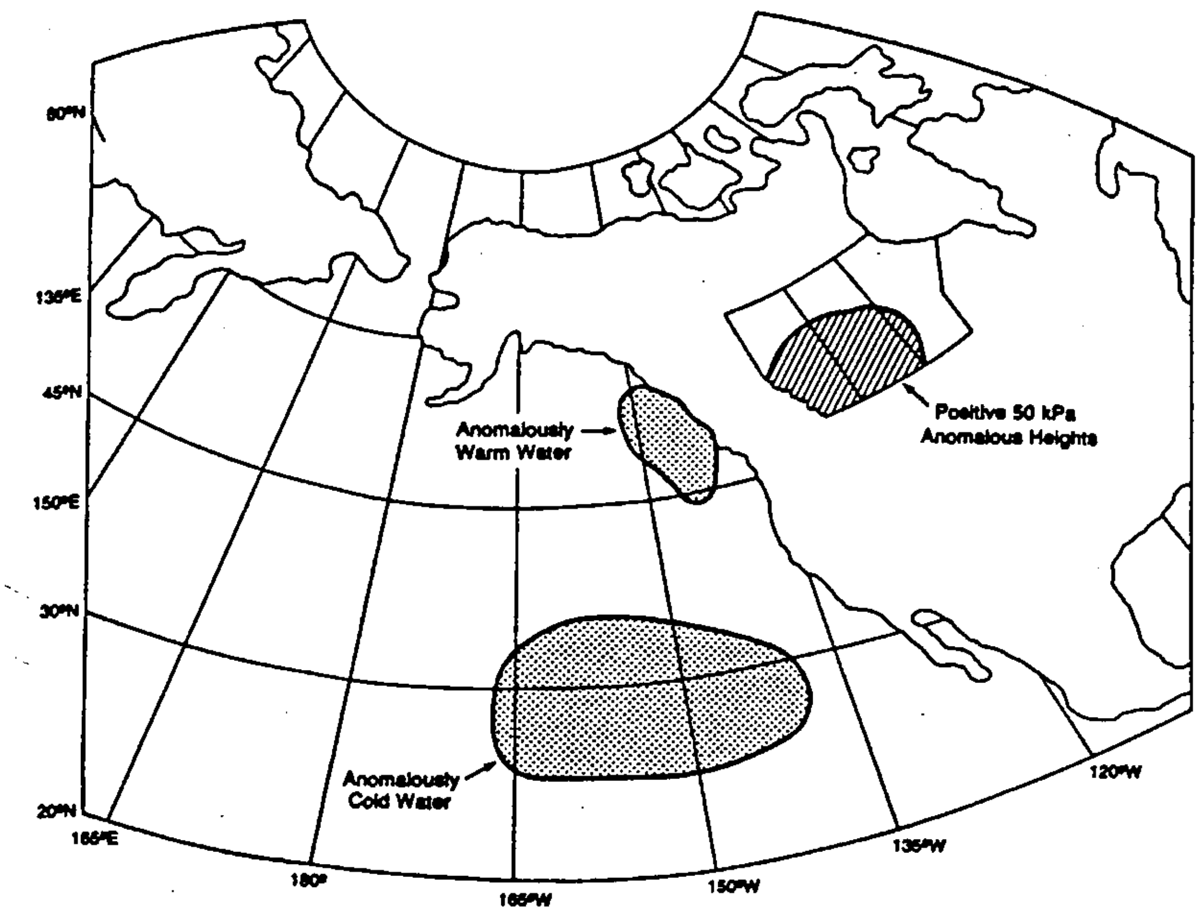

Figure 3.9 Schematic diagram of the Positive Sea Surface Temperature Anomaly Pattern. Source: Bonsal et al. 1993.

eastern Pacific (La Niña) while a low SOI is associated with low pressure and wet conditions (El Niño) (Yarnal, 1985; Shabbar, 1993). El Niño is associated with large scale warmings of the eastern Pacific that last for one to two years (Yarnal, 1985).

El Niño events have been found to influence the atmospheric circulation over the Canadian Prairies. During an El Niño event a stronger than normal high pressure ridge usually establishes itself near the west coast of the United States, while lows originating over the Aleutians follow a northerly track and travel southeastward along Rossby waves in the upper troposphere through the eastern Prairie Provinces. Such a flow pattern tends to produce a mild winter for western Canada (Trenberth et al. 1988). The higher than normal temperatures leads to higher evaporation rates which may lead to less soil moisture in the spring.

3.4.3 Pacific/North American Patterns

The El Niño/Southern Oscillation events influence the Pacific/North American (PNA) pattern, and account for approximately 20% of the variance in the pattern (Gnomes, 1969; Philander, 1990). The PNA is a pressure anomaly located in an area of the North Pacific south of the Aleutian Islands. When a strong negative pressure anomaly to the south of the Aleutians is associated with a positive anomaly over the northwestern US and southwestern Canada, there is a weaker negative anomaly over the southeastern US (Ripley, 1988). The PNA pattern is generated by tropical heating, mountains, land sea heating contrasts and barotropic instability. The PNA can be changed by altering the intensity and position of the forcing mechanism, and by altering the amplitude and polarity of the barotropic wave (Yarnal, 1985).

The PNA index (Bonsal, personal communication, 1994) is calculated from the 50 kPa heights (H) at the centres of action shown in figure 2.4. The following equation was used:

$$PNA = \tfrac{1}{3}\,[-H_{(45N,\ 160W)} + H_{(55N,\ 110W)} - H_{(35N,\ 80W)}]. \qquad (3.3)$$

This equation represents the average of the height reduction over the Aleutians and the southeastern US and the height gain over Western Canada. Each grid point value is the monthly anomaly which is defined as the difference from the 44-year mean (1948-1991).

3.4.4 Arctic Surface Temperature Anomalies.

This data set, prepared by Jones et al. (1985), was obtained by Ripley (1991) from the Carbon Dioxide Information Analysis Centre, Oak Ridge National Laboratory, Oak Ridge, TN. The period from 1957 to 1988 was used.

The temperature anomalies represent surface observations that have been gridded (5° latitude by 10° longitude) and are expressed as departures from the 1951-1970 averages. Ripley (1991) explains that the 1950s and 1960s were a cool period. This period influenced the average resulting in a large number of positive anomalies. There were extreme cool anomalies in the late 1960s early 1970s. The mid-1970s to end of period had pronounced warm anomalies.

3.4.5 Arctic 100-70 kPa Atmospheric Thickness Anomalies

This data set was obtained by Ripley (1991) from Dan Cayan at the Scripps Institution of Oceanography. The values have been expressed as departures from the mean and cover the period 1955 to 1983.

The 100-70 kPa thickness was obtained by calculating the difference in height between the two atmospheric pressure levels and is directly proportional to the mean temperature of the layer. The atmospheric pressure anomalies were calculated by subtracting the average atmospheric thickness values from the original data. The data was gathered in the region between 65° and 80°N latitude (Ripley 1991).

3.4.6 Arctic Sea Ice Coverage Anomalies

Arctic sea ice coverage was used in this analysis because of its influence on heat and mass exchange in the northern hemisphere. There are extreme seasonal and annual variations in the amount of ice cover (figure 3.10). The maximum extent of ice coverage is usually in February while the minimum is typically in August (Ripley, 1991).

These data were obtained by Ripley (1991) from Walsh (1978), and cover the period 1953 to 1986. Departures from the 1953-1986 averages were used. The years 1957 to 1986 were used to match the soil moisture data period of record.

These data show some significant variations; the late 1950s and late 1960s had extensive ice cover while the early 1970s had near average ice cover. The ice cover variation with latitude is extensive, with ice covering over 90% of the sea surface north of 79°N latitude in winter and north of 84°N in summer (Ripley 1991).

3.4.7 North Atlantic Icebergs

North Atlantic iceberg data were published by Barry (1994). The data consists of the annual number of icebergs that are counted by the International Ice Patrol as the icebergs go past the Grand Banks of Newfoundland. The period of record is 1957 to 1987.

It takes an iceberg, on average, three years to reach the extinction zones off Labrador and Newfoundland (Marko et al., 1986). The number of icebergs that reach the extinction zone depends on a complex interplay between climate (as it affects glacier dynamics), regional winds and currents, bathymetry, water properties and the extent of sea-ice in a season (Brown, 1993).

The number of North Atlantic icebergs was used in this analysis because it may be an indication of the surface-atmosphere exchanges (Brown, 1993) and it may be influenced by the atmospheric patterns associated with the North Atlantic Oscillation (Walsh et al., 1986).

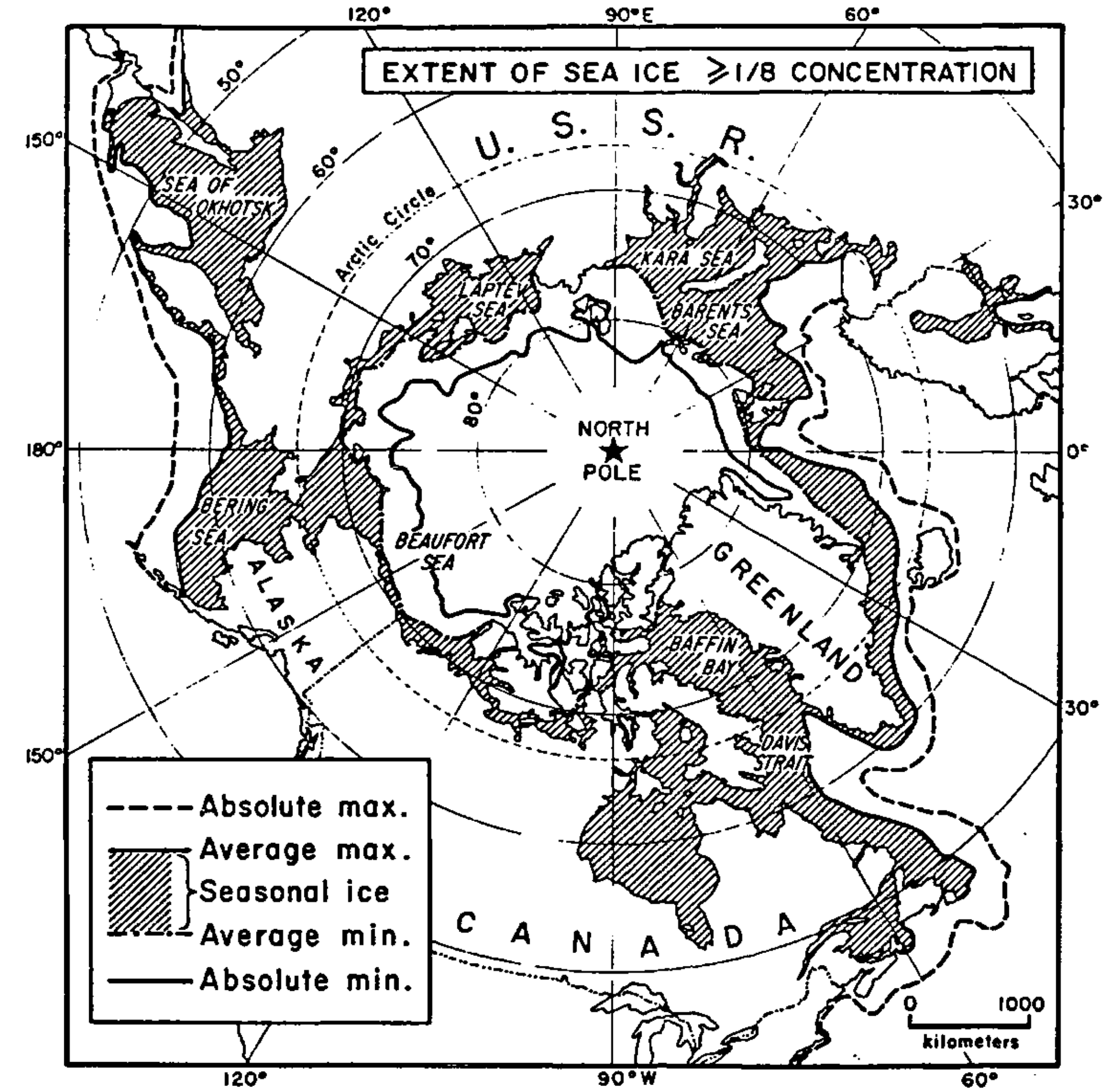

Figure 3.10 Schematic diagram of location of maximum and minimum arctic ice coverage (Source: Barry, 1983).

4.0 COMPARISON OF SOIL MOISTURE AND PRECIPITATION

4.1 Introduction

Although precipitation is the primary factor affecting soil moisture, there are some instances when precipitation has only a minor influence on soil moisture such as in heavy thundershowers and in very light rains. Winter and early-spring precipitation may have only a minor effect on soil moisture measured in late October or early November. Only a small amount of runoff from the previous winter's snowfall infiltrates into the soil.

Not all precipitation recharges root-zone soil moisture. Reasons for non-entry include runoff, soil drainage and interception losses. These are related to intensity of the rainfall, evapotranspiration, relief of the area, closeness of plant cover, degree of compaction of the organic horizons in the soil and the physical properties of the soil surface (including texture, aggregation, initial wetness and permeability) (Bunting, 1967). Figure 2.1 illustrates the complex role of soil moisture in the surface energy balance.

This chapter examines the relationship between precipitation and measured autumn soil moisture using scatter plots and correlation analysis. The study area is in southeastern Saskatchewan and southern Manitoba (figure 3.1)

4.2 Soil Moisture and Precipitation Comparisons

The soil moisture sites that were chosen for the comparisons had climate stations nearby (figure 4.1) usually within a few longitudinal and latitudinal minutes of each other (Appendix D). The shaded boxes in Appendix D lists the sites used in the comparison.

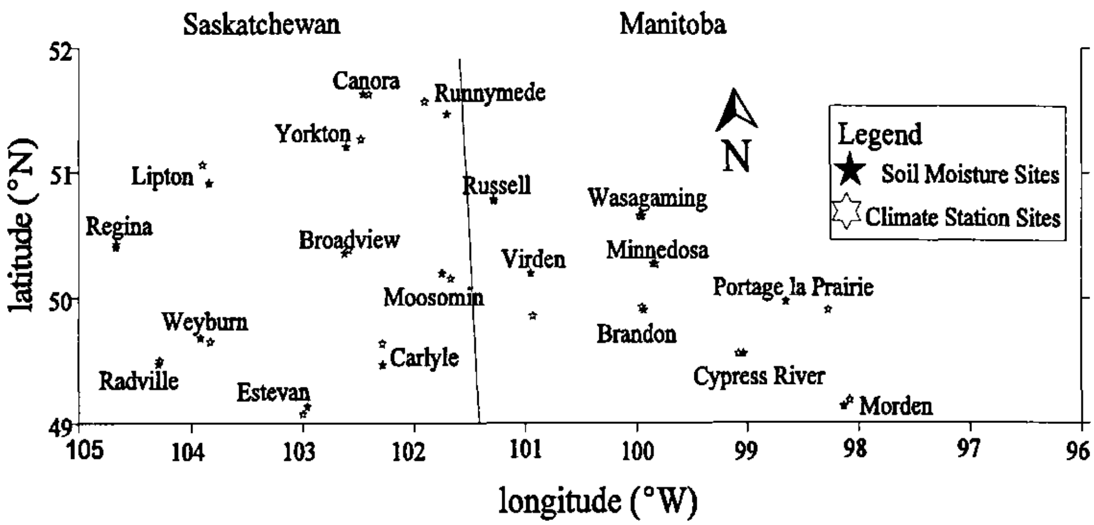

Figure 4.1 Locations of the 19 soil moisture sites and the nearest climate stations in the study area.

4.2.1 Scatter Plots

Scatter plots are used to identify the relationship between average autumn soil moisture and May to October precipitation (figures 4.2 to 4.15). The May to October precipitation period was chosen because of its relation to the growing season. Growing season is the portion of the year conducive to vegetation growth (Whittow, 1984).

Several of the locations show a positive relationship between soil moisture and precipitation. Cypress River (figure 4.6) is the best example of this. Other locations show this same trend but less clearly, e.g. Brandon, Broadview, Carlyle, Minnedosa, Moosomin, Portage la Prairie and Russell.

Regina's (figure 4.11) values are clustered around the top of the graph indicating that regardless of the amount of precipitation received the soil moisture remains relatively high and constant with 1957 and 1961 being the exceptions. These years had extremely low summer precipitation. This may be because of the heavy clay content of the soil and the location of the sampling point in a topographic depression or slough. Canora (figure 4.4) appears to have similar results as Regina but comparison between the two sites is difficult as Canora has fewer precipitation observations than Regina.

There are several stations that show no clear trend (Radville, Runnymede, Virden and Wasagaming) indicating that the May to October precipitation has very little influence on autumn soil moisture in these areas (figures 4.10, 4.12, 4.14 and 4.15). This lack of a clear trend may be due to location differences and resulting precipitation differences between the soil moisture sites and climate stations.

4.2.2 Correlations

Correlation analyses were carried out to determine the magnitude and size of the relationship between autumn soil moisture and precipitation at selected locations. The sites that were selected had 20 or more years of continual precipitation data collected close to the soil moisture sites.

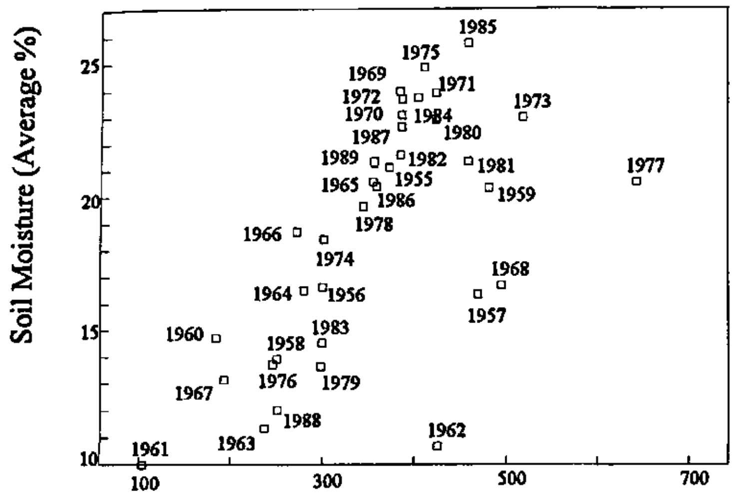

Figure 4.6 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Cypress River, Manitoba

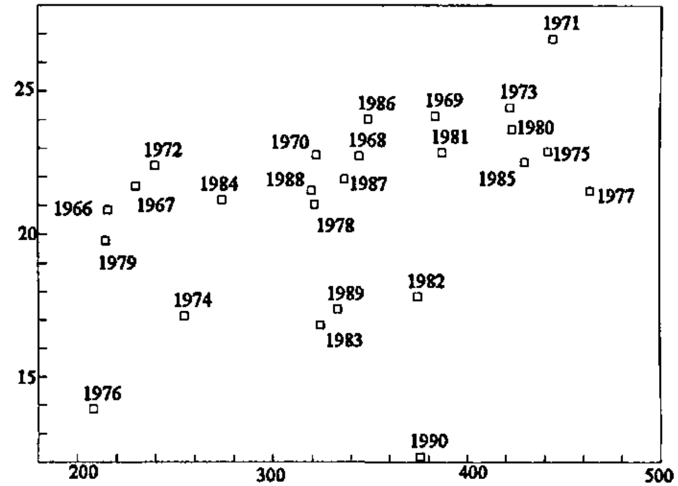

Figure 4.7 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Minnedosa, Manitoba

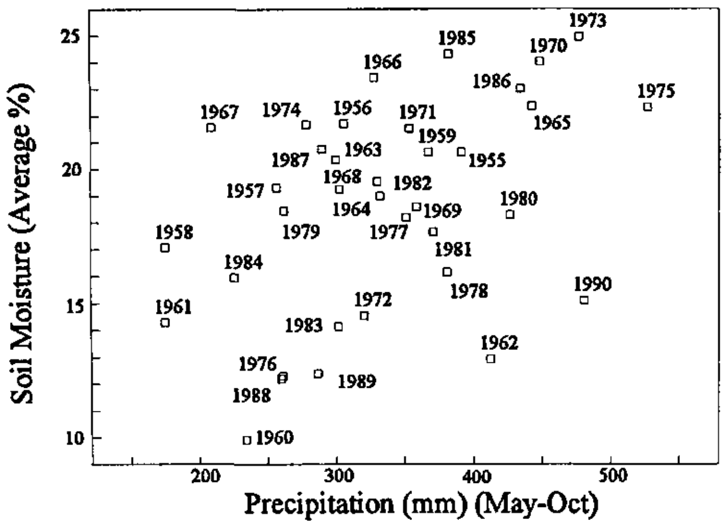

Figure 4.8 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Moosomin, Saskatchewan

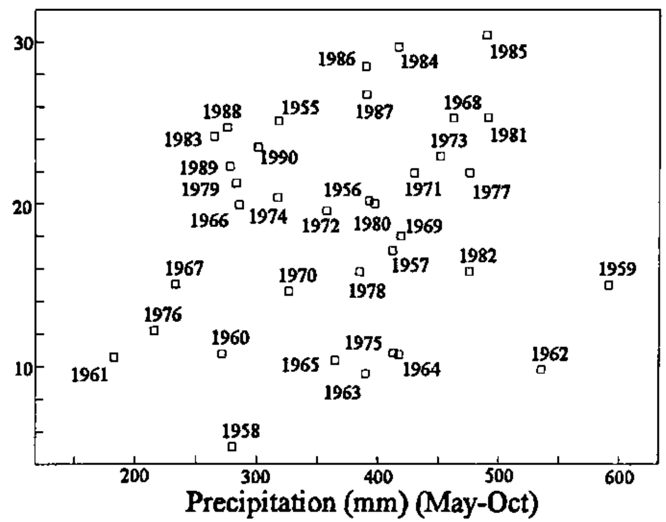

Figure 4.9 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Portage la Prairie, Manitoba

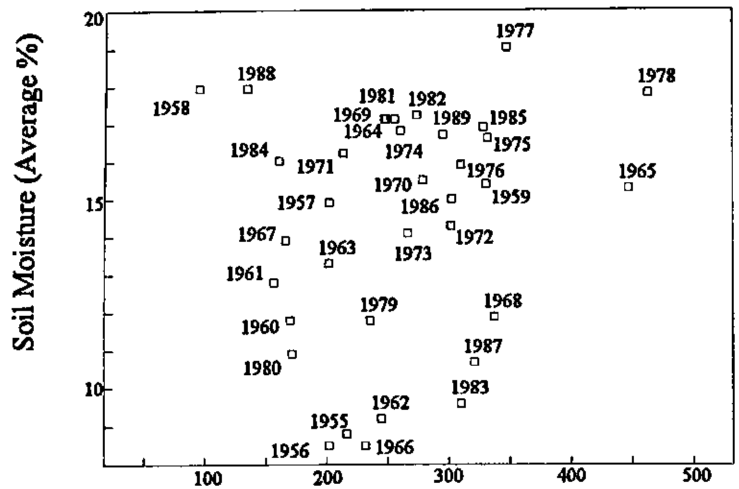

Figure 4.10 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Radville, Saskatchewan

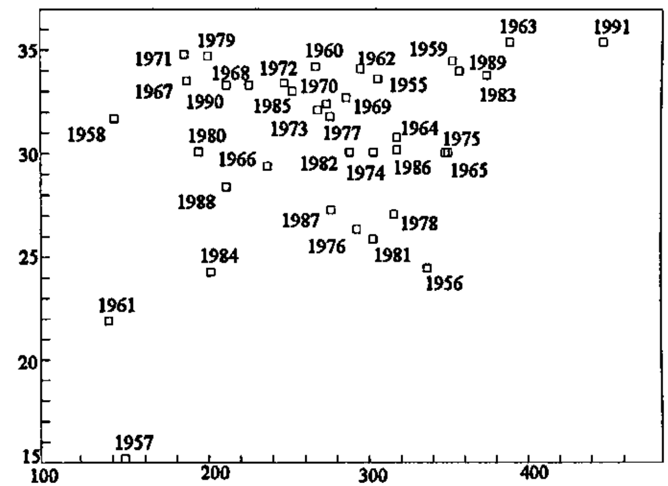

Figure 4.11 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Regina, Saskatchewan

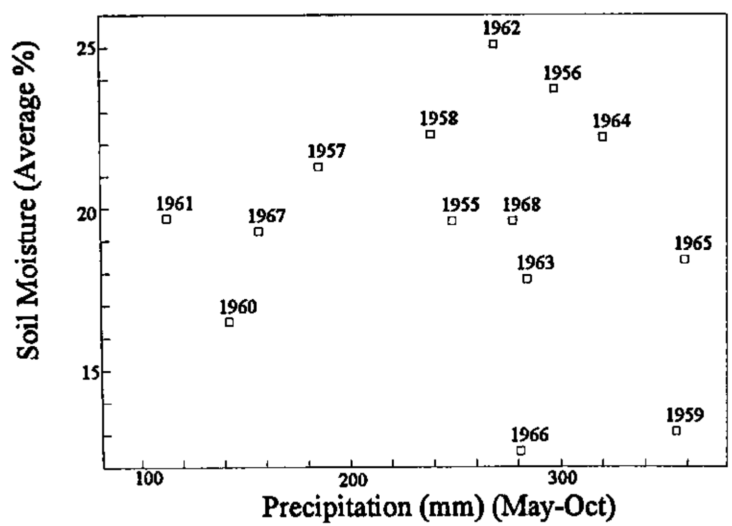

Figure 4.12 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Runnymede, Saskatchewan

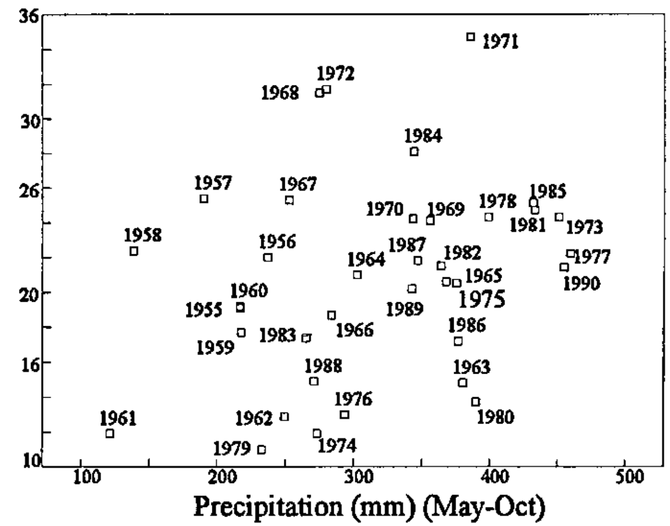

Figure 4.13 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Russell, Manitoba

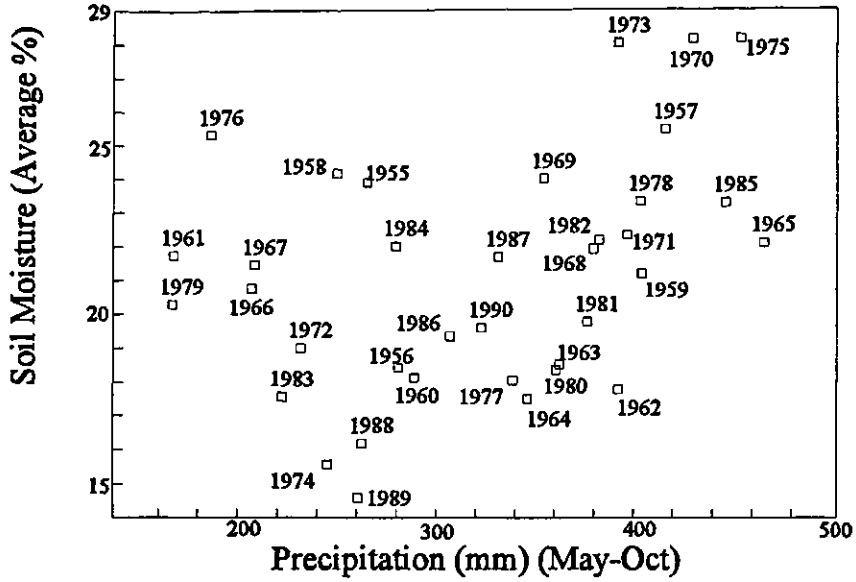

Figure 4.14 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Virden, Manitoba

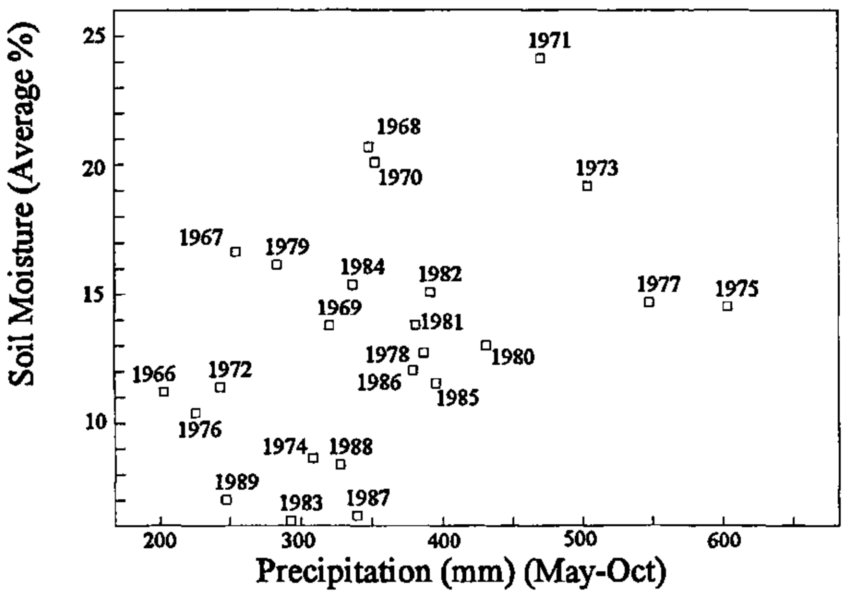

Figure 4.15 Scatter plot showing the relationship between May to October precipitation and autumn average soil moisture for Wasagaming, Manitoba.

It was uncertain which month's precipitation would have the greatest influence on autumn soil moisture. Therefore, cumulative seasonal precipitation amounts for the preceding August to October, May to October, February to October and November of the previous year to October (inclusive) were correlated against the soil moisture levels. The four soil moisture levels and the average soil moisture were then correlated with the cumulative seasonal precipitation (table 4.1).

The shaded cells in Table 4.1 indicate significant correlations between soil moisture and precipitation within the 10 percentile range. The highest correlations are found in the 15 and 30 cm range for August to October (table 4.1). For the May to October and February to October periods the majority of the higher correlations are in the moderate soil depths i.e. the 30 and 46 cm depths.

The graphs of cumulative seasonal precipitation (figures 4.16 to 4.20) illustrate that more climate stations show significant correlations between precipitation and soil moisture at the 30 and 46 cm depths than at the shallower or deeper levels.

The highest correlation coefficients are noted for Radville and Cypress River at almost all soil depths. About half of the sites show significant positive correlations, particularly for the later time periods such as February to October.

Several sites exhibit near zero or negative correlations coefficients (namely Broadview, Canora, Lipton, Morden and Portage la Prairie). Broadview and Canora are the only sites that show a consistent inverse relationship for the November to October, February to October and May to October precipitation periods, although it is not statistically significant. Portage la Prairie indicates a negative relationship at the deeper soil levels for the November to October and February to October time frames.

Possible explanations for the discrepancies are that other water balance terms (such as evapotranspiration, runoff or drainage) are stronger influences or that the soil moisture site did not receive the same precipitation as the climate station. Other explanations include:

Table 4.1 Correlation coefficients between precipitation amounts and autumn soil moisture for a number of preceding periods at 18 sites in the Eastern Canadian Prairies. Significant correlations for the 10 percentile are shaded.

Station	November to October					February to October					May to October					August to October				
	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average
Brandon	0.18	0.44	0.28	0.24	0.35	0.26	0.47	0.29	0.24	0.39	0.31	0.55	0.32	0.31	0.46	0.31	0.65	0.33	0.24	0.48
Broadview	-0.06	-0.07	0.01	-0.15	-0.05	-0.07	-0.05	0.03	-0.11	-0.03	0.02	-0.03	0.02	-0.12	-0.02	0.02	0.13	0.25	0.06	0.13
Canora	-0.23	-0.14	-0.07	-0.01	-0.17	-0.15	-0.14	-0.17	0.08	-0.13	-0.13	-0.15	-0.31	0.05	-0.17	0.30	0.16	0.13	0.27	-0.29
Carlyle	0.00	0.33	0.33	-0.07	0.29	0.00	0.33	0.32	-0.12	0.27	0.09	0.43	0.36	-0.09	0.36	0.37	0.51	0.41	-0.03	0.47
Cypress River	0.50	0.55	0.56	0.38	0.58	0.53	0.61	0.61	0.36	0.61	0.58	0.68	0.66	0.32	0.65	0.53	0.63	0.65	0.18	0.59
Estevan	0.16	0.26	0.31	0.47	0.30	0.17	0.32	0.31	0.45	0.33	0.40	0.39	0.10	0.36	0.39	0.40	0.39	0.10	0.36	0.39
Lipton	0.25	0.27	0.18	0.15	0.25	0.25	0.27	0.14	0.14	0.23	0.30	0.28	0.13	0.11	0.24	0.31	0.28	0.16	0.02	0.22
Minnedosa	0.11	0.22	0.38	0.12	0.27	0.20	0.26	0.44	0.14	0.34	0.28	0.40	0.41	0.19	0.41	0.48	0.44	0.37	0.32	0.51
Moosomin	0.37	0.33	0.44	0.30	0.42	0.40	0.31	0.46	0.28	0.42	0.41	0.32	0.48	0.25	0.43	0.34	0.42	0.42	0.35	0.44
Morden	0.14	0.23	0.09	0.17	0.20	0.13	0.20	0.03	0.13	0.15	0.16	0.19	0.00	0.06	0.13	0.28	0.25	0.08	0.00	0.21
Portage	0.11	0.06	-0.08	-0.09	-0.02	0.15	0.11	-0.02	-0.04	0.04	0.28	0.25	0.05	0.08	0.17	0.41	0.32	0.05	0.15	0.24
Radville	0.63	0.67	0.58	0.43	0.70	0.66	0.63	0.55	0.42	0.68	0.61	0.58	0.47	0.46	0.65	0.46	0.13	0.33	0.19	0.34
Regina	0.33	0.25	0.25	0.14	0.30	0.34	0.28	0.27	0.18	0.33	0.33	0.31	0.32	0.20	0.35	0.31	0.34	0.14	-0.23	0.21
Russell	-0.06	0.31	0.17	0.26	0.17	0.08	0.32	0.13	0.32	0.17	0.06	0.42	0.21	0.36	0.28	0.15	0.37	0.25	0.42	0.32
Virden	0.29	0.38	0.42	0.37	0.44	0.33	0.46	0.47	0.38	0.50	0.28	0.39	0.28	0.24	0.37	0.32	0.31	0.08	0.12	0.27
Wasagaming	0.35	0.56	0.45	0.13	0.48	0.35	0.57	0.43	0.11	0.47	0.23	0.54	0.41	0.15	0.42	0.19	0.36	0.14	0.29	0.29
Weyburn	0.47	0.54	0.43	0.44	0.53	0.46	0.54	0.44	0.45	0.53	0.38	0.49	0.38	0.40	0.46	0.31	0.32	0.31	0.29	0.34
Yorkton	0.25	0.34	0.46	0.40	0.42	0.30	0.41	0.55	0.46	0.50	0.19	0.35	0.44	0.40	0.40	0.09	0.09	0.13	0.19	0.15

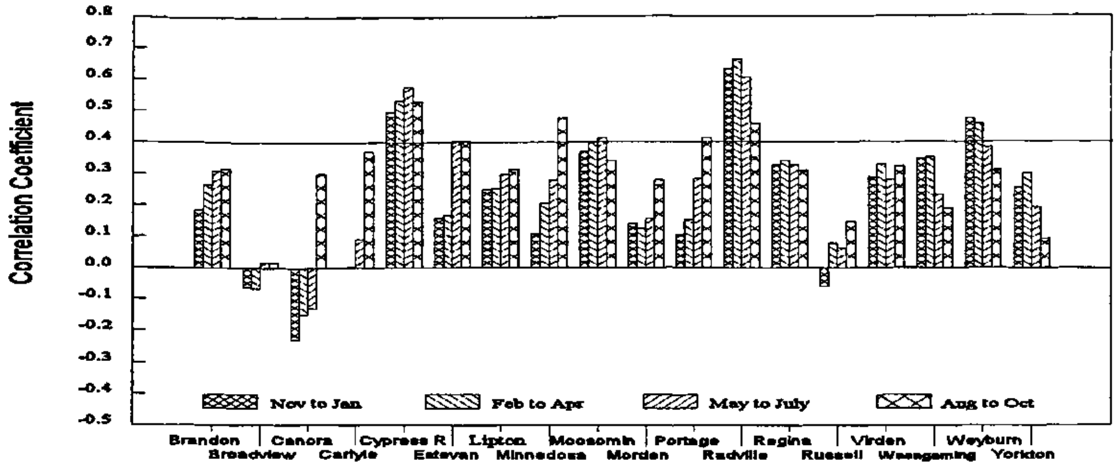

Figure 4.16 Correlation between cumulative seasonal precipitation and MNR 15 cm soil moisture. The solid line is the 0.10 significance line.

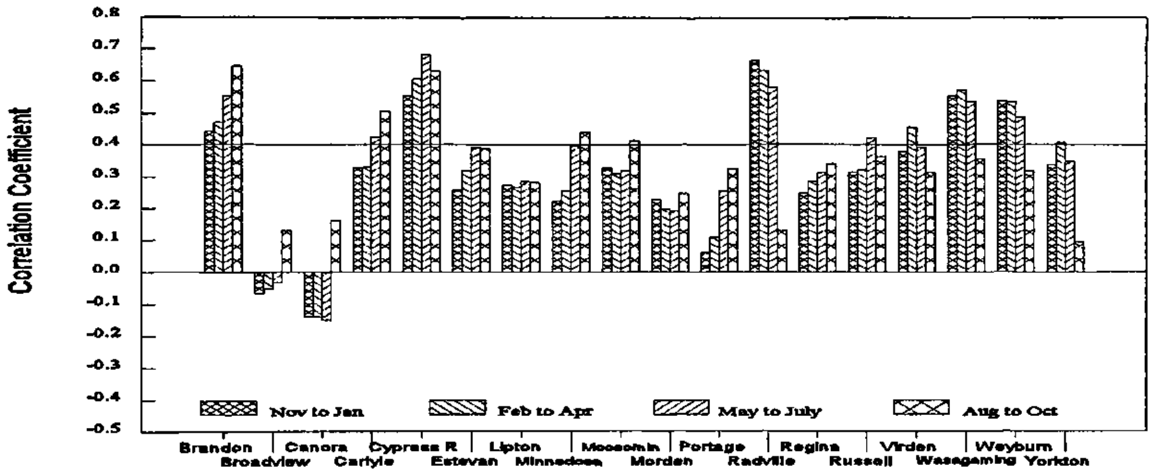

Figure 4.17 Correlations between cumulative seasonal precipitation and MNR 30 c
soil moisture. The solid line is the 0.10 significance line.

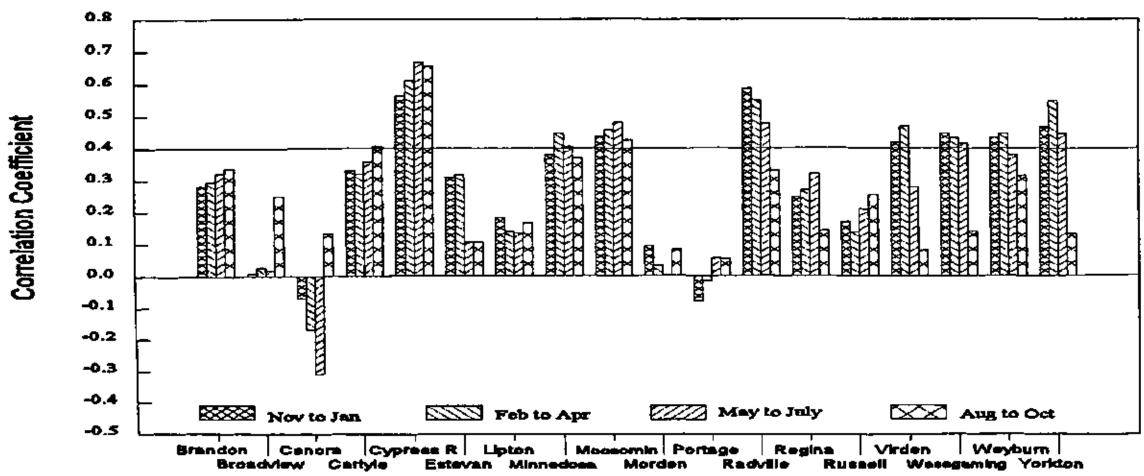

Figure 4.18 Correlations between cumulative seasonal precipitation and MNR 46 c
Soil moisture. The solid line is the 0.10 significance line.

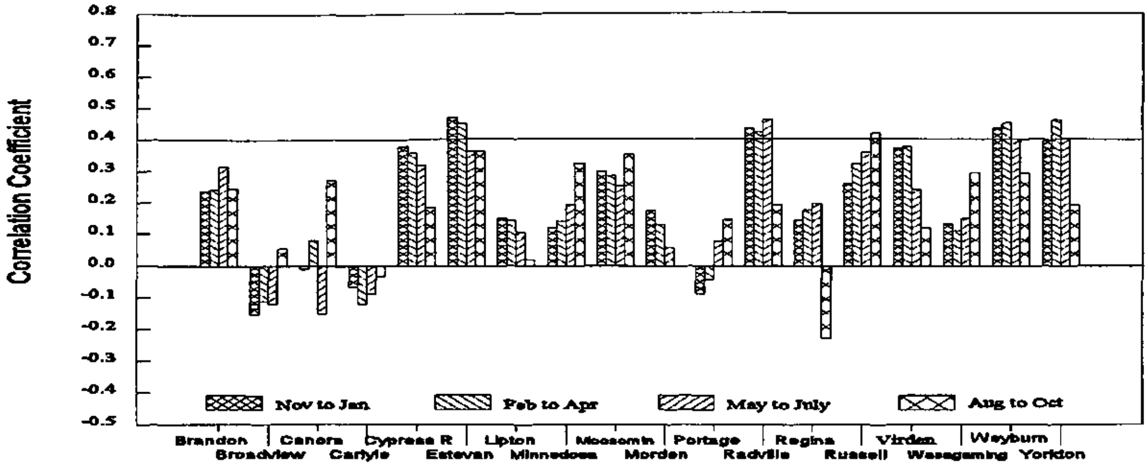

Figure 4.19 Correlations between cumulative seasonal precipitation and MNR 76 cm Soil moisture. The solid line is the 0.10 significance line.

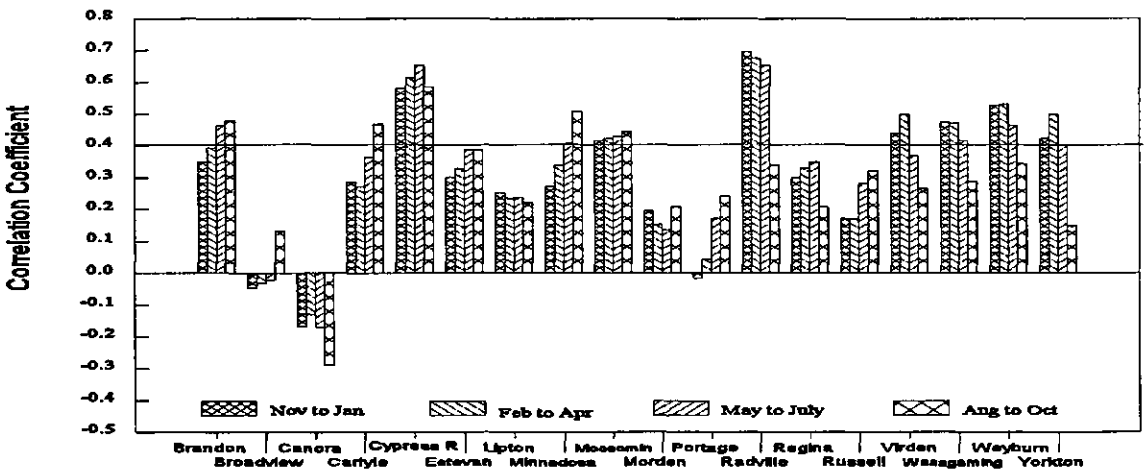

Figure 4.20 Correlations between cumulative seasonal precipitation and MNR average soil moisture. The solid line is the 0.10 significance line.

monthly precipitation could be too long a period to use especially for the shallower soil depths; soil moisture sampling sites may not be representative of the surrounding regions (i.e. the sampling site may be located in a slough); or the data, either the precipitation or the soil moisture, may be in error due to sampling or tabulating methods.

A seasonal precipitation versus soil moisture comparison was also carried out. This was to ascertain which preceding seasonal precipitation period had the greatest influence on the autumn soil moisture. The precipitation periods used were August to October, May to July, February to April and November to January (inclusive). These periods were chosen to correspond with the growing season and the seasonal changes.

Very few of the November to January and February to April correlations are statistically significant (table 4.2). The greatest number of significant relationships is found in the latest (August to October) period with a few in the May to July period. The shaded areas on the table are values considered to be significant at the 10 percentile range.

The seasonal precipitation graphs (figures 4.21 to 4.25) show that there is less significance when previous months are considered as in the cumulative seasonal graphs (figures 4.16 to 4.20). There are negative significance levels in the November to January period such as in the case of Brandon at the 15 cm soil moisture depth.

The cumulative seasonal and seasonal graphs (figures 4.16 to 4.25) have the significance line plotted on them. According to Brooks and Carruther (1953) values at or greater than 0.40 have at least a 10% confidence limit when there are at least 18 pairs. Canora has the lowest number of recording years (20 - see Appendix C). This is why the 0.40 level was chosen.

Table 4.2 Correlation coefficients between seasonal precipitation amounts and autumn soil moisture at 18 sites in the Eastern Canadian Prairies. Significant correlations at the 10 percentile are shaded.

	November to January					February to April					May to July					August to October				
Station	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average	15 cm	30 cm	46 cm	76 cm	average
Brandon	-0.41	-0.11	-0.04	0.00	-0.20	-0.06	-0.11	0.00	-0.14	-0.09	0.13	0.15	0.12	0.21	0.18	0.31	0.65	0.33	0.24	0.48
Broadview	0.02	-0.05	-0.09	-0.17	-0.07	0.25	0.07	0.03	0.00	-0.03	0.02	0.13	0.25	0.06	0.13	0.02	0.13	0.25	0.06	0.13
Canora	-0.21	0.00	0.26	-0.23	-0.09	-0.06	0.02	0.31	0.07	0.08	0.07	-0.07	-0.28	0.28	0.02	0.30	0.16	0.13	0.27	-0.29
Carlyle	-0.01	0.11	0.16	0.22	0.17	-0.19	-0.04	0.07	-0.12	-0.07	-0.17	0.13	0.12	-0.08	0.08	0.37	0.51	0.41	-0.03	0.47
Cypress River	0.00	-0.04	-0.02	0.20	0.04	-0.11	-0.20	-0.14	0.11	-0.10	0.44	0.52	0.47	0.33	0.51	0.53	0.63	0.65	0.18	0.59
Estevan	-0.04	-0.32	-0.03	0.10	-0.14	-0.06	-0.21	0.28	0.07	-0.02	0.00	0.27	0.25	0.36	0.21	0.40	0.39	0.10	0.36	0.39
Lipton	0.05	0.12	0.32	0.09	0.18	0.04	0.11	0.09	0.16	0.13	0.15	0.16	0.05	0.14	0.14	0.31	0.28	0.16	0.02	0.22
Minnedosa	-0.34	-0.09	-0.19	-0.06	-0.21	0.15	-0.29	0.10	-0.11	-0.13	-0.10	0.10	0.18	-0.06	0.04	0.48	0.44	0.37	0.32	0.51
Moosomin	-0.02	0.12	0.02	0.10	0.06	0.10	0.08	0.10	0.18	0.14	0.21	0.01	0.21	-0.02	0.12	0.34	0.42	0.42	0.35	0.44
Morden	0.09	0.17	0.24	0.21	0.21	-0.08	0.02	0.08	0.20	0.05	-0.02	0.05	-0.07	0.08	0.01	0.28	0.25	0.08	0.00	0.21
Portage la Prairie	-0.15	-0.15	-0.23	-0.17	-0.20	-0.37	-0.40	-0.17	-0.29	-0.33	-0.05	0.01	0.02	-0.05	-0.02	0.41	0.32	0.05	0.15	0.24
Radville	0.29	0.53	0.50	0.31	0.51	0.39	0.37	0.38	0.09	0.32	0.39	0.60	0.33	0.41	0.53	0.46	0.13	0.33	0.19	0.34
Regina	-0.01	0.11	0.06	-0.11	-0.08	0.12	-0.03	-0.10	-0.02	0.00	0.16	0.13	0.24	0.32	0.23	0.31	0.34	0.14	-0.23	0.21
Russell	0.03	0.12	0.18	-0.08	0.08	-0.39	-0.11	-0.12	0.06	-0.20	-0.04	0.30	0.08	0.15	0.12	0.15	0.37	0.25	0.42	0.32
Virden	-0.05	-0.14	-0.05	0.08	-0.06	0.14	0.19	0.45	0.32	0.33	0.06	0.23	0.29	0.21	0.24	0.32	0.31	0.08	0.12	0.27
Wasagaming	0.03	0.03	0.12	0.10	0.09	0.36	0.15	0.09	-0.10	0.20	0.15	0.42	0.46	-0.08	0.31	0.19	0.36	0.14	0.29	0.29
Weyburn	0.25	0.16	0.05	0.02	0.14	0.23	0.15	0.20	0.16	0.21	0.25	0.36	0.24	0.27	0.32	0.31	0.32	0.31	0.29	0.34
Yorkton	-0.19	-0.29	-0.35	-0.28	-0.32	0.38	0.21	0.38	0.22	0.36	0.20	0.42	0.52	0.41	0.45	0.09	0.09	0.13	0.19	0.15

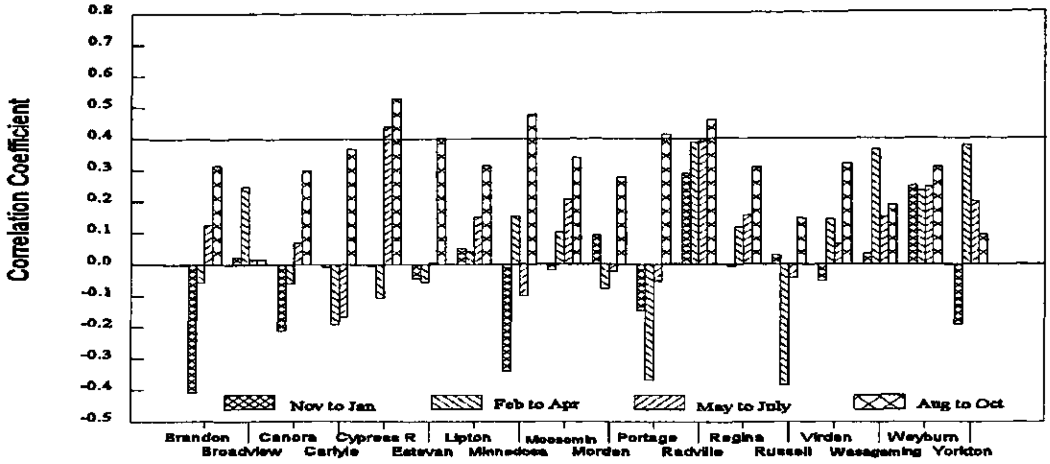

Figure 4.21 Correlations between seasonal precipitation and MNR 15 cm soil moisture. The solid line is the 0.10 significance line.

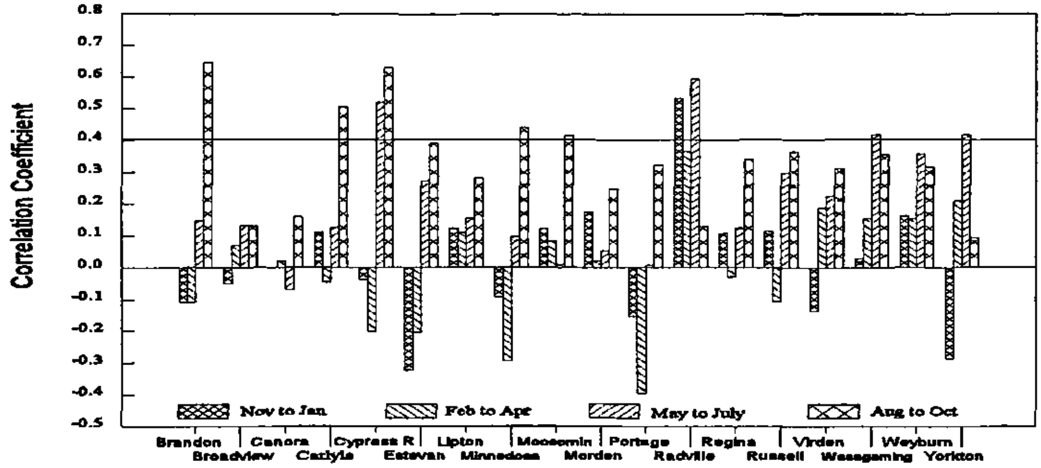

Figure 4.22 Correlations between seasonal precipitation and MNR 30 cm soil moisture. The solid line is the 0.10 significance line.

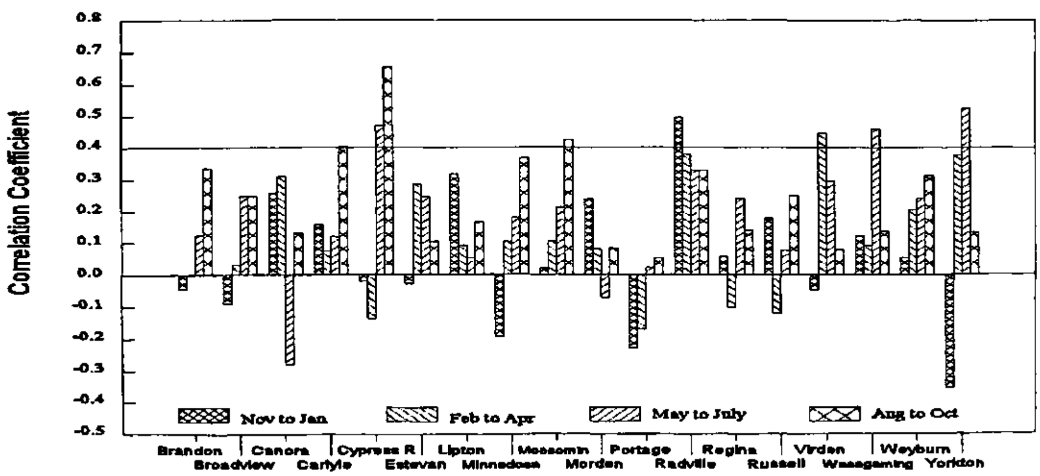

Figure 4.23 Correlations between seasonal precipitation and MNR 46 cm Soil moisture. The solid line is the 0.10 significance line.

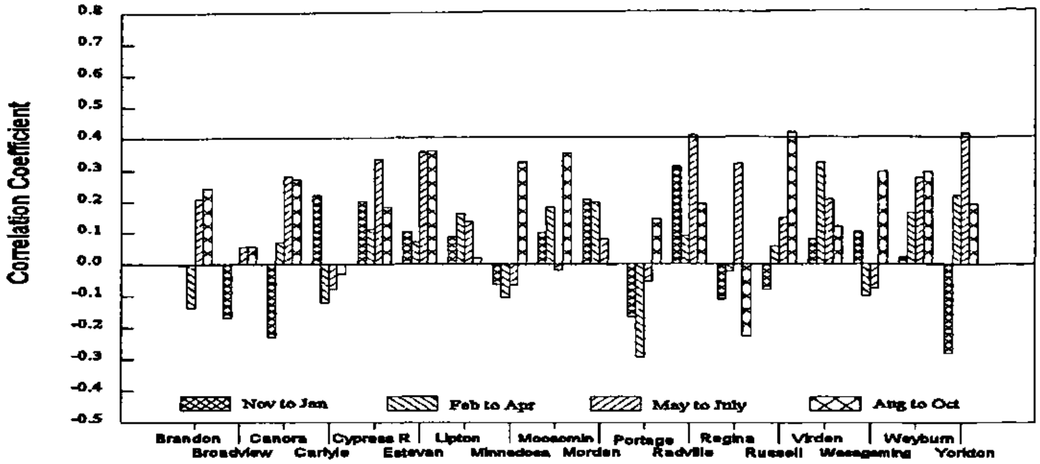

Figure 4.24 Correlations between seasonal precipitation and MNR 76 cm soil moisture. The solid line is the 0.10 significance line.

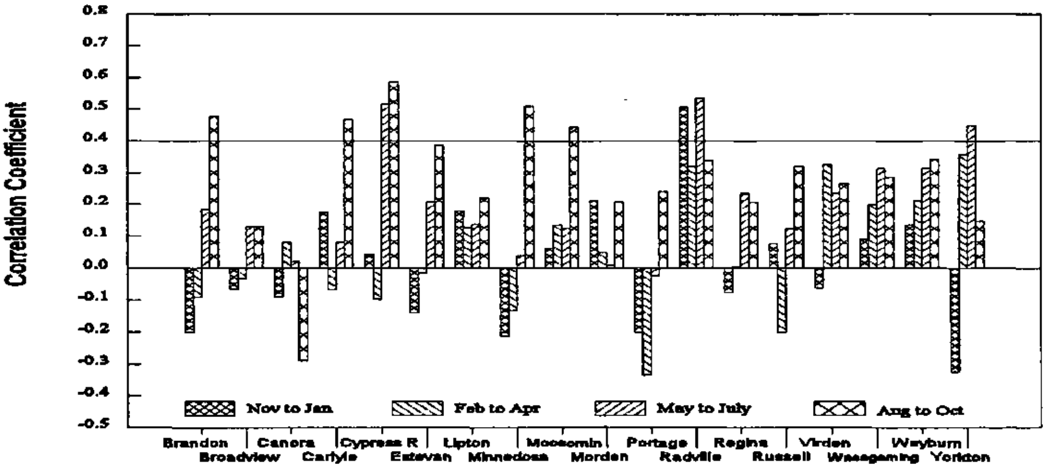

Figure 4.25 Correlations between seasonal precipitation and MNR average soil moisture. The solid line is the 0.10 significance line.

4.2.3 Discussion

The correlation graphs and scatter plots show that autumn soil moisture and the precipitation data preceding the soil moisture sampling period do not always have a positive linear relationship and are not always positively correlated. The reasons could include sampling methods for both precipitation and soil moisture. Precipitation is usually gathered by using a tipping bucket, an Atmospheric Environment Service Standard gauge, a Nipher gauge or a Belfort weighing gauge. These precipitation gauges can vary up to 20% of each other. The soil moisture samples may not have been handled properly before being analysed and may not have been analysed properly in the lab. The locations chosen for the soil moisture sampling sites may not be indicative of the surrounding area. The locations of the soil moisture and precipitation sampling sites in relation to each other could also be a reason for the low significance - intensive thunderstorm activity at one site may not have occurred at the other sampling site.

The low correlations may also be due to the relationship between precipitation, soil moisture and evapotranspiration. There is no soil moisture recharge during the winter as precipitation is usually in the form of snow which accumulates as a surface snowpack. During the spring, evapotranspiration is low and both snowmelt and precipitation recharge soil moisture. By June and July, potential evaporation may exceed the amount of moisture available, thus causing a soil moisture deficit situations. Therefore, even if precipitation is high, evapotranspiration may deplete the available soil moisture and result in uniformly low soil moisture in the autumn.

Soil moisture patterns (both temporally and spatially) on the Canadian Prairies are important. Chapter 5 examines these patterns by using principal component analysis to specify the temporal and spatial patterns of soil moisture.

5.0 PRINCIPAL COMPONENT ANALYSIS OF SOIL MOISTURE DATA

5.1 Introduction

The spatial and temporal patterns of soil moisture in the eastern Canadian Prairies are examined in this chapter. The spatial patterns indicate which areas are susceptible to drought and excess moisture. The temporal patterns indicate when the drought (and excess moisture) events occurred. This information will be used in the next chapter in the search for potential causes of these variations.

Principal component analysis (PCA) was the tool chosen to determine the spatial and temporal patterns. PCA has been widely used to explore the spatial and temporal relationships within large geophysical data sets (Horel, 1984). PCA has been used instead of other statistical tools such as averaging because PCA gives an indication of amplitudinal variation while averaging decreases that variation.

5.2 Methodology of the Principal Component Analysis

The main objective of principal component analysis is to reduce the number of variables in a data set to a set of principal components that retain most of the variation in the original data (Jolliffe, 1986; 1990; 1993). There were 35 soil moisture sites in the Manitoba Natural Resources data set with annual data for the 1957 to 1991 period (figure 3.4). Principal component analysis was applied to the data set initially using the SPSS (Statistical Package for the Social Sciences) program on the University of Saskatchewan mainframe computer.

The result was an "ill-conditioned matrix" error message and an extremely low Kaiser-Meyer-Olkin number. The "ill-conditioned matrix" message occurred because the data set was square (i.e. 35 years and 35 sites). A Kaiser-Meyer-Olkin number is an index for comparing magnitudes of observed correlation coefficients to the magnitudes of partial correlation coefficients. A low value is an indication that the data set has extremely low correlation and should not be used in further statistical analysis in its present state (Norušis, 1990).

In order to make the data suitable for further analysis the number of stations had to be reduced. The criteria for reducing the data set was subjective but logical. A correlation of all soil moisture sites with each other was undertaken. Then, two steps of reducing the data set were used. First, soil moisture sites that had six correlations or more below zero were deleted because of their zero to inverse relationships to the other sites. Negative correlations indicate inverse relationships resulting in one site being moist while the other sites were dry and vice versa. The assumption made was that there was too strong of an inverse correlation with six or more negative correlations i.e. the site with the strong inverse correlation did not correspond to surrounding sites. The lack of correspondence may be due to site specific parameters including different soil type, topographical location, or vegetation differences. The sites deleted were Carlyle, Estevan, Morden, Portage la Prairie, Radville and Regina.

The second step was to combine the sites that were within close spatial proximity of each other and that had correlation values greater than 0.5. The combining was done by averaging their yearly moisture content. This was done to eliminate any possible chance of duplicating or accentuating information by having sites with similar data too spatially close together. These sites were Brandon/Cypress River, Dominion/Lowe Farm, Fannystelle/Rathwell, Killarney/Turtle Mountain, Letellier/St. Norbert and Ste. Anne/Steinbach.

The resultant data set had 23 soil moisture stations (figure 5.1) and 35 years of data. As indicated in Chapter 4, many sites that were either deleted or combined had low non-cumulative positive

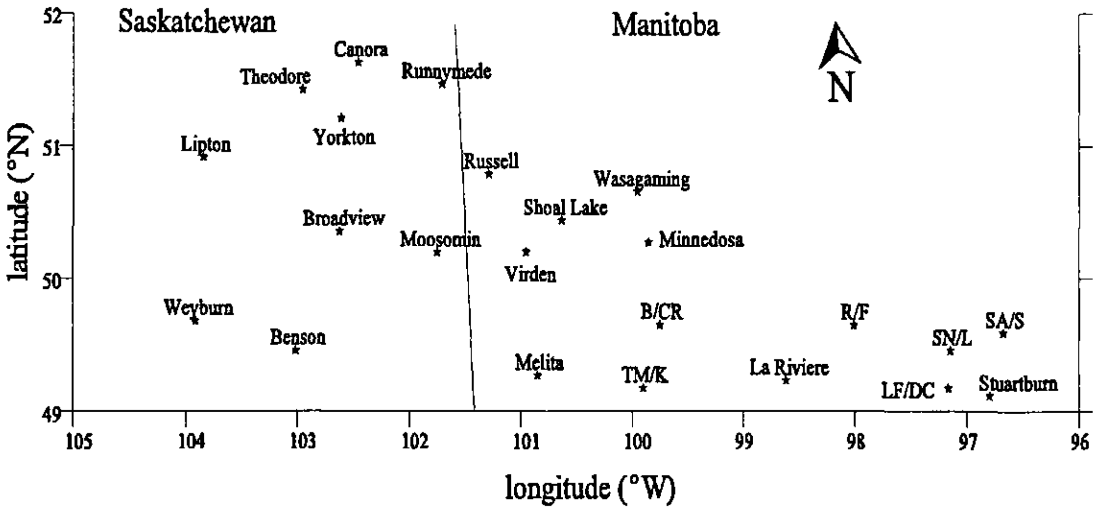

Figure 5.1 Optimum soil moisture network in study area.
B/CR = Brandon/Cypress River; LF/DC = Lowe Farme/Dominion City;
R/F = Rathwell/Fannystelle; TM/K = Turtle Mountain/Killarney;
SN/L = St. Norbert/Letellier; SA/S = Ste. Anne/Steinbach.

precipitation correlations in the months prior (particularly May to July and earlier) to the soil moisture.

The PCA program was run again and as the result of the data reduction the ill conditioned matrix error did not occur. Also the Kaiser-Meyer-Olkin measure of sampling adequacy increased from 0.16118 to 0.585. The disappearance of the errors allowed the analysis to continue.

The SPSS results were compared with the results from a program Ripley (1994) had written in FORTRAN Microsoft 5.0 (see Appendix A). The results were the same. The data presented are from Ripley's FORTRAN program. Ripley's program was chosen for the analysis because of ease of access and use.

The next step in the analysis was to determine whether to use a correlation or covariance matrix as the basis for computing the principal components. According to Eder, Davis and Bloomfield (1993)

> "Selection of a correlation matrix (as opposed to a covariance matrix) has two advantages. First, use of a correlation matrix is much more suitable for resolving spatial oscillations (Overland and Preisendorfer, 1982), which is a major goal of the analysis; secondly, use of a correlation matrix allows isopleths of component loading to be drawn, which can be regarded as the correlation coefficient between the component and the individual stations."

In essence, use of a covariance matrix would give more weight in the analysis to the highly variable sites, while a correlation matrix would put the emphasis on relative, rather than absolute, soil moisture variability. Therefore, the correlation matrix was chosen.

A further decision had to be made on the number of principal components that should be used in the analysis. Section 2.2 explained how previous researchers made their decisions. It was decided that only the first three principal components would be used as they explained the majority of the variance (over 40 percent) and the resulting patterns were the most likely to be explained (after Jolliffe 1993).

Rotation of the principal components was considered. Some authors think that rotation, especially varimax rotation, will make the data easier to interpret because the spatial weights will be less (e.g. Richman, 1986; 1993). Varimax rotation is orthogonal[1] in nature and attempts to simplify the PCA by achieving a simpler structure (Richman, 1986).

Rotation of the principal components using the varimax method in the SPSS program was carried out to determine if the principal components would become easier to interpret. It was not successful as it made interpretation more complicated. The principal components became more unstable (in terms of amplitude and weight) and the method did not make the spatial or temporal patterns easier to interpret. Daultrey (1976) agreed -

> "In principal component analysis there is little point in using an orthogonal rotation, because it eliminates the property of maximum variance....there is neither the need for rotation, nor the justification."

Walsh and Richman (1981) found rotation, in some instances, did not describe enough of the variance to be useful, especially if the majority of the explained variance is in the first few principal components. The amount of explained variance is dependent upon the data used and is subjective to the individual researcher. Therefore, unrotated principal components may be more useful for data reduction.

The exchange of articles between Legates (1991; 1993), Richman (1986; 1987; 1993) and Jolliffe (1987) indicates rotation is still controversial and not fully understood.

5.3 Principal Component Analysis of Soil Moisture Data

The principal component variances for each soil moisture depth and for the average soil moisture are given in table 5.1.

The first principal component (PC) explains 20.9 to 34.5% of the variance for the soil moisture depths (table 5.1). The second PC

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[1]An orthogonal line is defined as one drawn at right angles to or perpendicular to another line.

Table 5.1 Fractional Variances Explained by the First Three Principal Components by Soil Depth.

Soil Depth	First Principal Component	Second Principal Component	Third Principal Component	Total
Average	0.345	0.097	0.075	0.518
15 cm	0.305	0.094	0.084	0.483
30 cm	0.286	0.101	0.098	0.485
46 cm	0.286	0.108	0.077	0.471
76 cm	0.209	0.106	0.096	0.411

explains about 10% and the third a little less. The total variance for the three PCs explained ranges from 41% at the 76 cm depth to 52% for the average soil depth.

The following sections present maps and graphs summarizing the results of the principal component analysis. The corresponding data are tabulated in Appendix E. The maps were generated by the Surfer for Windows (Golden Software Inc., 1994) Contour Mapping program and were gridded using the linear Kriging geostatistical method. This was recommended by Golden Software (1994) for a data set with less than 250 observations. The data in this analysis has 23 principal components per soil moisture depth (Appendix E). Kriging attempts to express trends in the data such as putting high values along a ridge rather than creating a "bulls-eye."

Contouring levels were chosen to reduce the number of "bulls-eyes" that appear on the maps. "Bulls-eyes" tend to indicate a level of detail which may not be present therefore were removed before interpretation of maps occurred. Contours reflect the extremes associated in each of the principal component data sets. Therefore, different contour intervals were chosen for each principal component being investigated.

5.4 Average Soil Moisture Temporal and Spatial Variation

This section examines the spatial and temporal patterns of the average soil moisture principal components (PC). These patterns will be described in terms of temporal amplitudes and spatial weights. For example, the greater the absolute value of the number, the greater the amplitude (or weight) of the PC. The closer the value is to zero the less variation between moist and dry conditions will occur. Another characteristic to be aware of is that all principal components occur at the same time as the one that explains the majority of the variance the predominant pattern.

The average soil moisture spatial relationships vary with the PCs. The first PC has the dominant spatial pattern because it explains the majority of the total variance (34.5% - see table 5.1). The entire study area is negative for the first PC resulting in the region oscillating between moist and dry conditions i.e., the entire study area is either under moist or drier conditions (figure 5.2). However, there are differing weights. For example, the southeast corner of the study area around Stuartburn has a value of -0.113 while near Portage la Prairie, in south central Manitoba, the value is -0.254. This indicates that Stuartburn has lower weights of soil moisture than Portage la Prairie.

There is a general spatial pattern to the first PC of the average soil moisture (figure 5.2). The west side of the study area appears to have the lowest weighted variation (with Lipton as the exception). The centre of the study (west/central Manitoba) has increased variations while the area around Stuartburn (eastern Manitoba) has lower weights of the cycle. These differing weighted intensities are illustrated by the different sizes of the negative symbols (figure 5.2).

The spatial patterns of the second principal component of the average soil moisture is quite different from the first PC. The second explains 9.7% of the variance and is the second most likely pattern to occur. The second principal component oscillates between negative and positive values (figure 5.3) indicating that while one area may be experiencing a moist spell, another location may be experiencing a drier spell. For example, the western side of the study area around Weyburn is positive, the region to the east, around Broadview, is negative. This indicates that while the Weyburn region may be relatively dry, the Broadview region may be experiencing moister conditions or vice versa. The northern agricultural region of Saskatchewan has a stronger positive value (shown on the map by the extra large plus symbol). Therefore, the area may be more susceptible to droughts or floods because of the larger weight.

The third principal component is different again from the first and second PC. The third PC explains 7.5% of the total variance. It

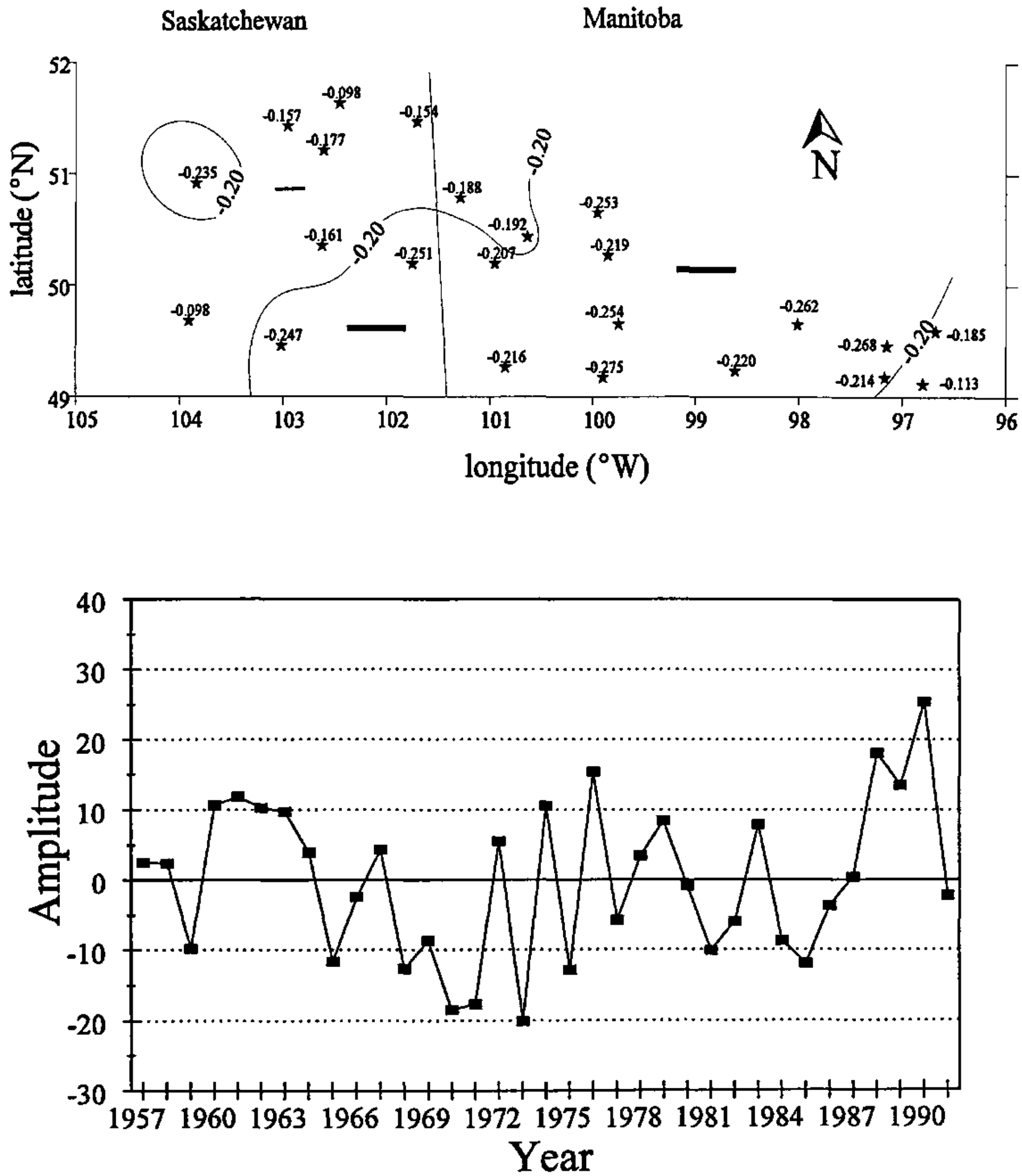
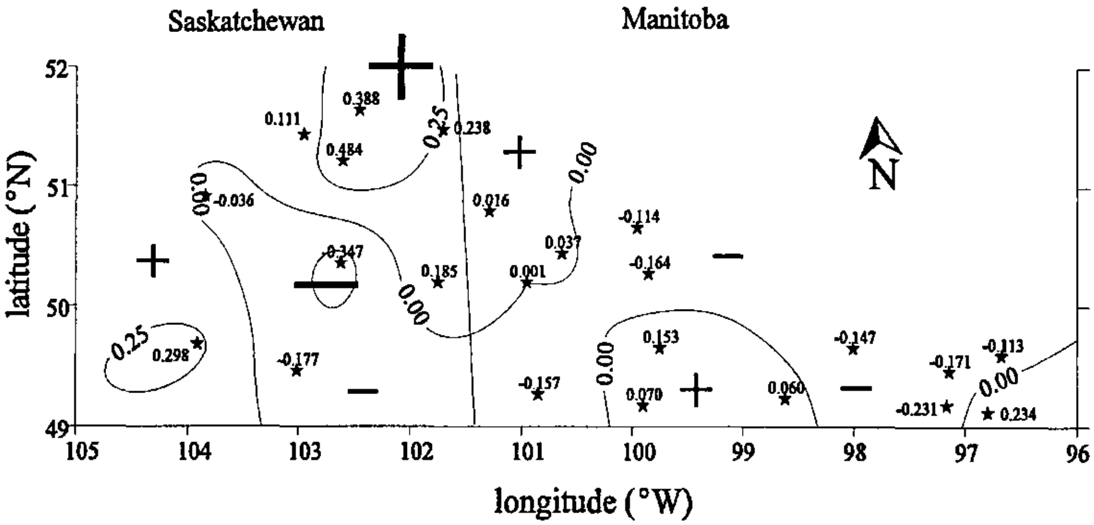


Figure 5.2 Spatial and temporal patterns of the first principal component for the average soil moisture. The map at the top of the page shows the spatial oscillating effect of the first principal component for the average soil moisture. The larger the +'s and -'s indicate larger weights occurring in those regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.



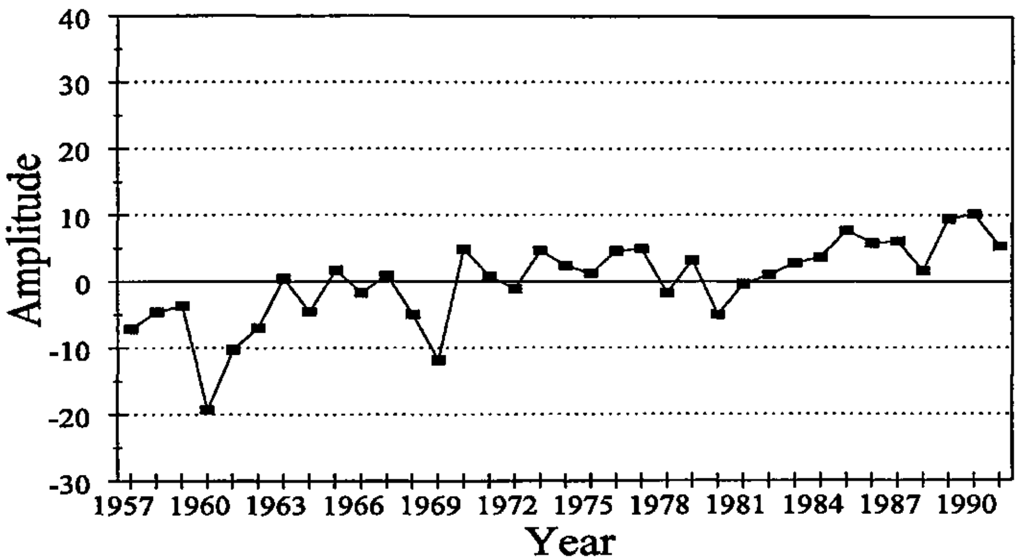


Figure 5.3 Spatial and temporal pattern of the second principal component for the average soil moisture. The map at the top of the page shows the spatial oscillating effect of the second principal component for the average soil moisture. The larger the +'s and -'s indicate large weights occurring in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

appears to have more of a north/south oscillation rather than east/west (figure 5.4). There is a relatively low value in the Russel region (indicated by the large negative symbol) while Melita's region in southwestern Manitoba is relatively high. This indicates while the south may be dry, the north in turn, may be wetter than normal.

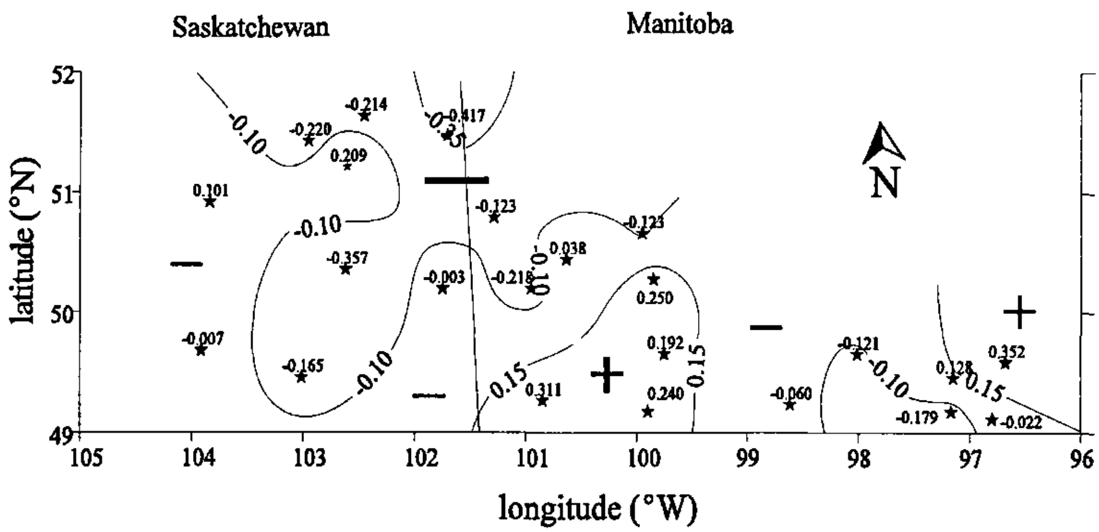
The three temporal graphs are important to examine in conjunction with three spatial patterns of the average soil moisture principal components. When the first spatial principal component occurs, the corresponding temporal variation is complex (figure 5.2). For example, the 1970s have a large amplitudinal variation from one year to the next. This suggests one year was moist while the next year is dry. The measured soil moisture for the stations show 1972 showed drier conditions than 1973. In turn, 1974 had again less soil moisture than 1973, while 1975 was again wet. This measured soil moisture variation is illustrated in the principal component temporal graph where the positive values indicate drier years and negative values wetter years (figure 5.2).

Principal components 2 and 3 temporal variations are even more complex. The second PC temporal variation appears to have a linear upward trend with decreasing amplitude of dry/wet fluctuation in the 1980s (figure 5.3). This trend indicates there has been less soil moisture in recent years, especially the 1980s, than when sampling first began.

The third temporal principal component has amplitudinal variation with a weak upward trend (figure 5.4). The third temporal PC has less amplitudinal variation than the second PC and much less than the first PC. This temporal pattern is the least dominant of the three as it explains 7.5% of the variance.

5.5 Soil Moisture Variation with Depth

Section 5.4 examined the average of the four soil moisture depths. This section looks at the variation the soil moisture principal components with depth in the soil over time and space.



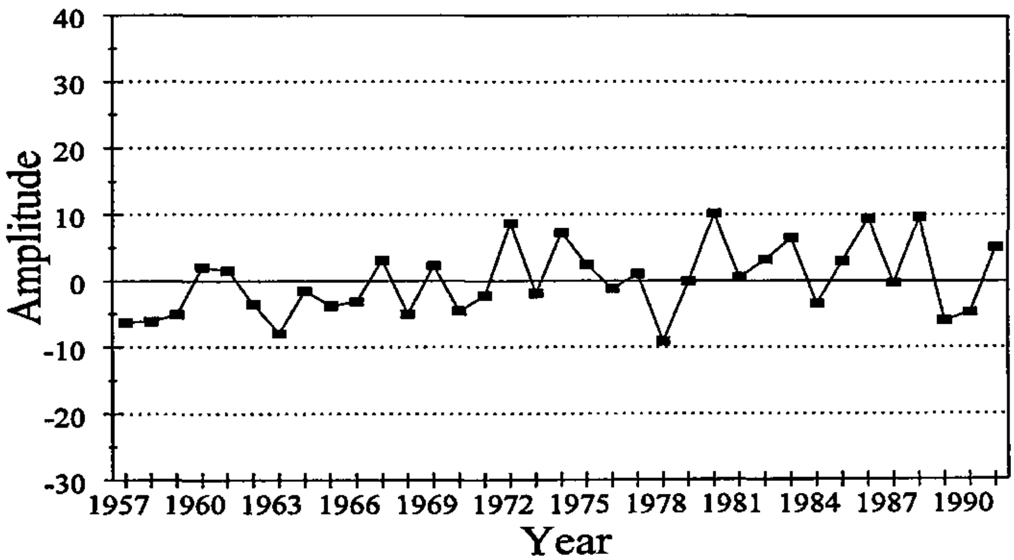


Figure 5.4 Spatial and temporal pattern of the third principal component for the average soil moisture. The map at the top of the page shows the spatial oscillating effect of the third principal component for the average soil moisture. The larger the +'s and -'s indicate larger weights occurring in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

The individual soil moisture depths have slightly different spatial and temporal patterns. The first PCs all have negative values for the spatial patterns and the dryness/wetness patterns of the, for example the 1970s are the same for all the soil moisture depths as it is with the average soil moisture principal component. The second and third PCs for the different depths have slightly different patterns (spatially and temporally) thus indicating different moist and dry patterns. These patterns are examined in greater detail in the next section.

5.5.1 Spatial Variation

The first three PCs explain at least 40 percent of the total variance at all soil depths (table 5.1). The top three levels explain the most (15 cm 48.3%, 30 cm 48.5% and 46 cm 47.1%) while the deepest depths explain 41.1% of the total variance.

As with the average soil moisture, the first spatial PC for all soil moisture depths is negative (figure 5.5 to 5.8). The entire study area is, therefore, either moist or dry for all depths. The spatial patterns of the first PC are dominant because the greatest amount of variance is explained (at least 20.9%).

The principal components of each soil depth have different spatial patterns. For example, the first PC 15 cm soil moisture depth has a northwest southeast pattern (figure 5.5). The area of strongest oscillation is in southeastern Saskatchewan and south central Manitoba. The edge of the study area (with the exception of Lipton) is less extreme.

The first PC at 30 cm also has a northwest to southeast pattern (figure 5.6). The 30 cm spatial pattern differs from the 15 cm pattern by having a larger spatial oscillation extreme in the northwest section of the study area.

The first PC at 46 cm soil moisture depth also has a northwest to southeast pattern (figure 5.7). This pattern differs from the

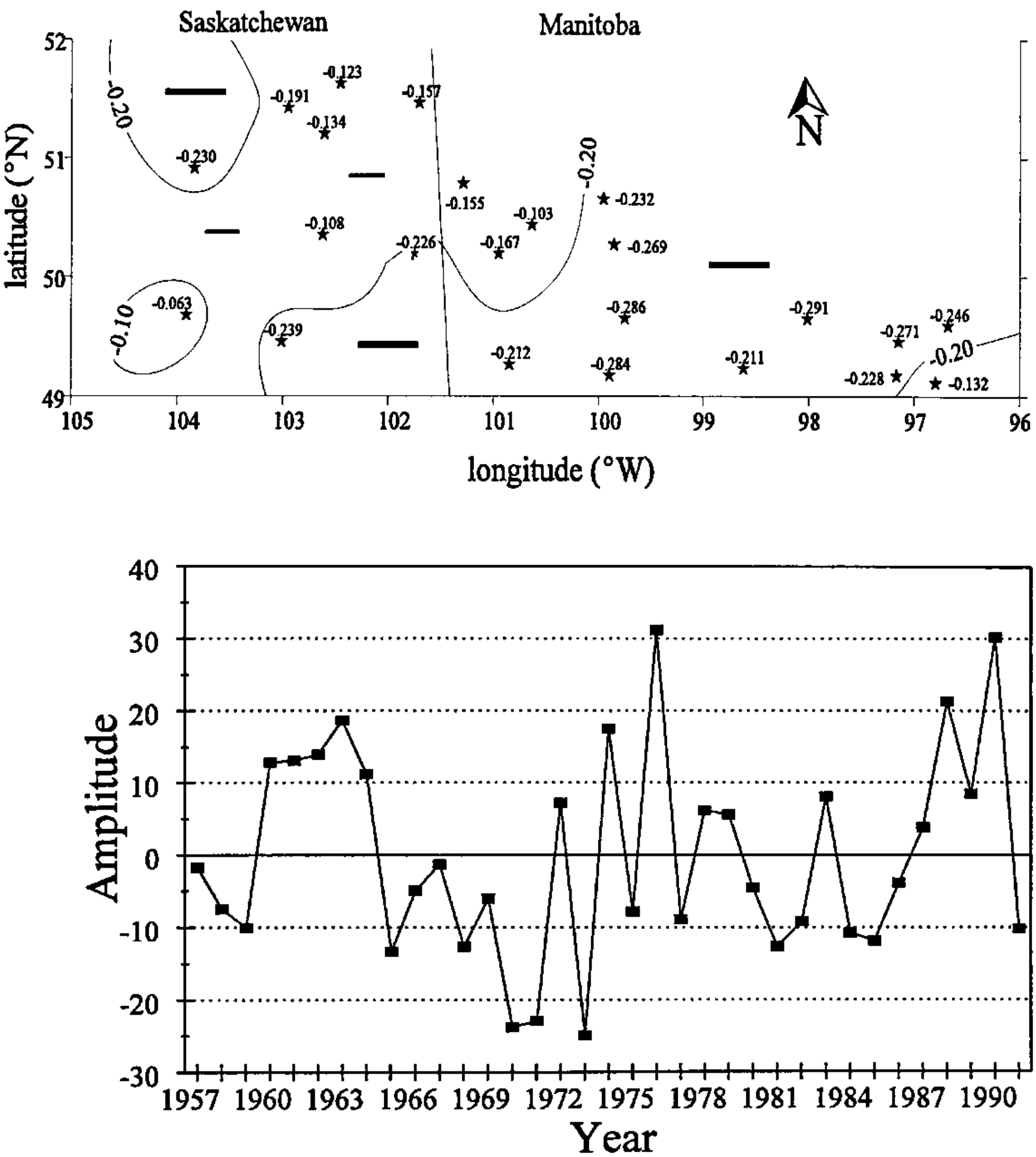


Figure 5.5 Spatial and temporal pattern of the first principal component for the 15 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the first principal component for the 15 cm soil moisture. The larger the +'s and -'s indicates the larger the weights will be in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

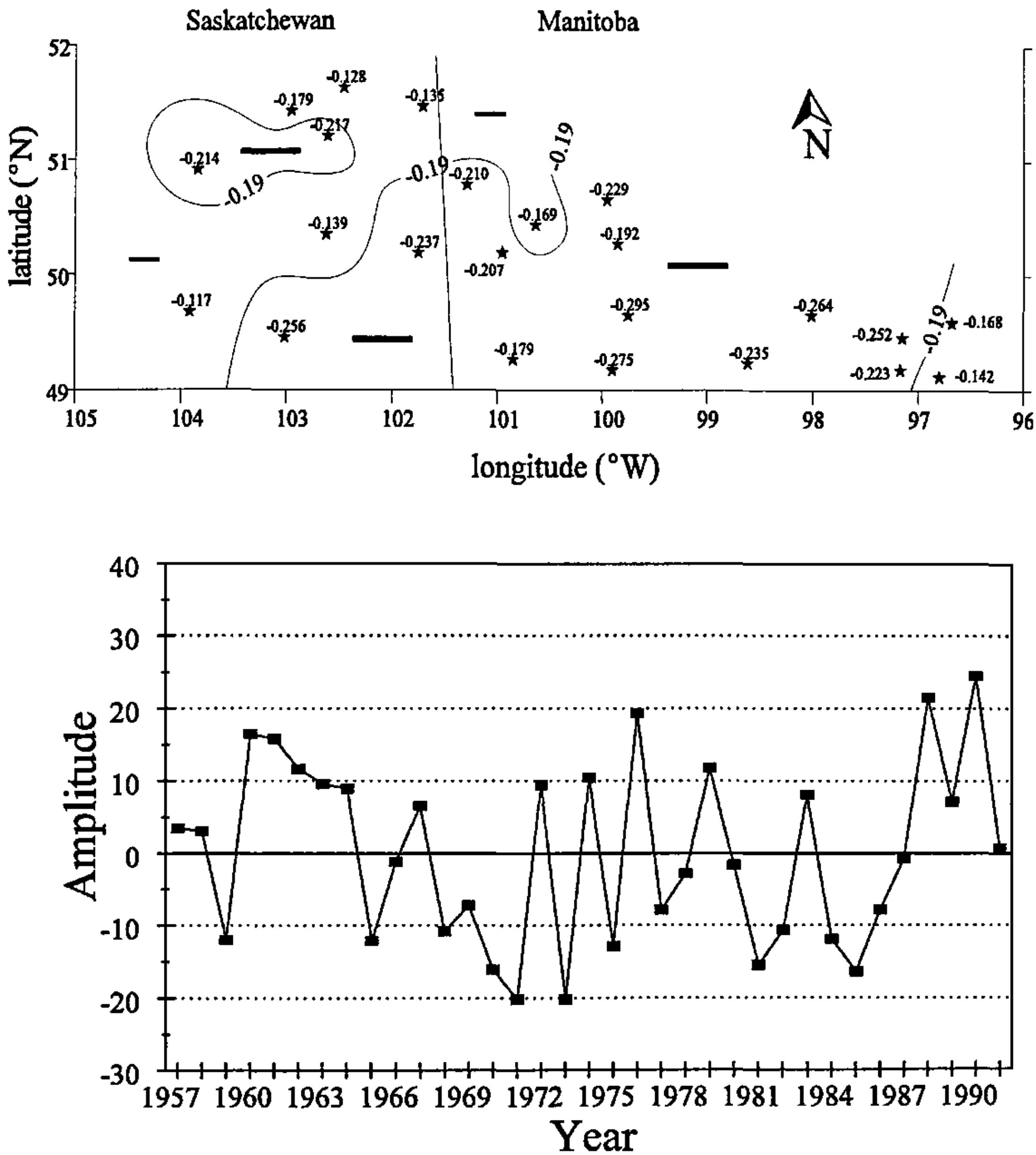
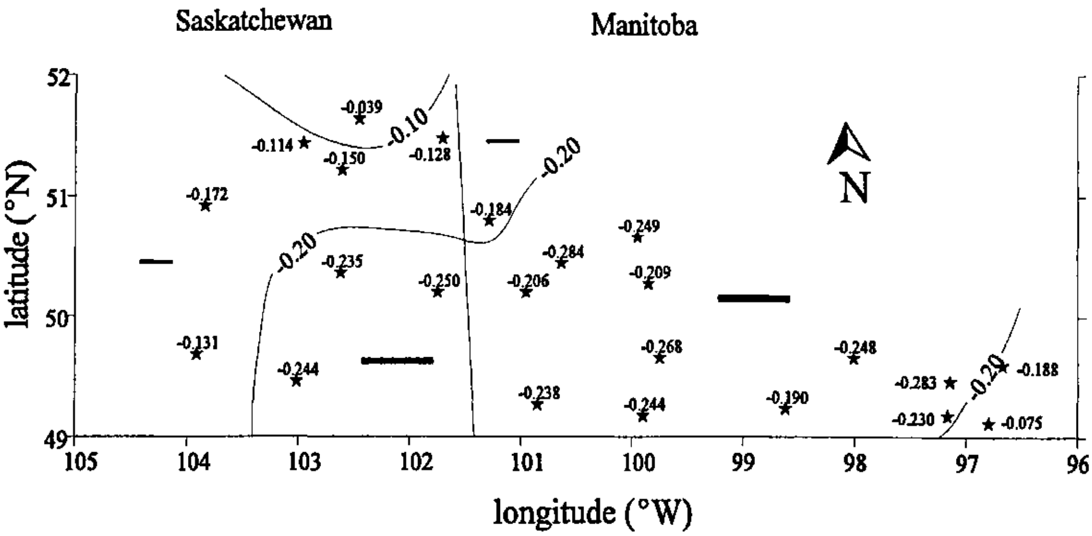


Figure 5.6 Spatial and temporal patterns of the first principal component for the 30 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the first principal component for the 30 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.



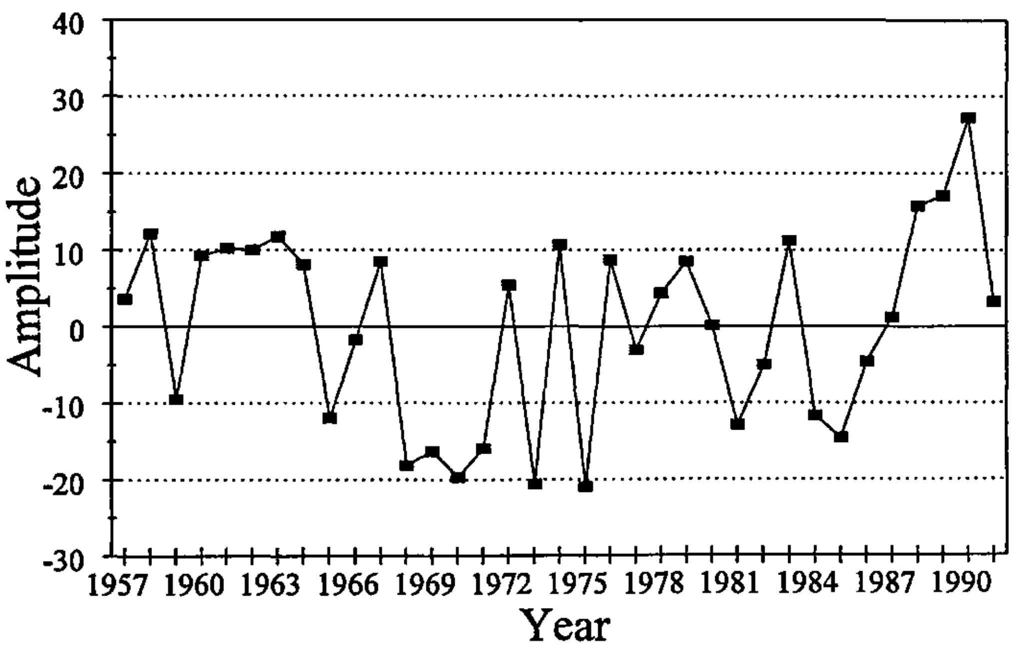


Figure 5.7 Spatial and temporal pattern of the first principal component for the 46 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the first principal component for the 46 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

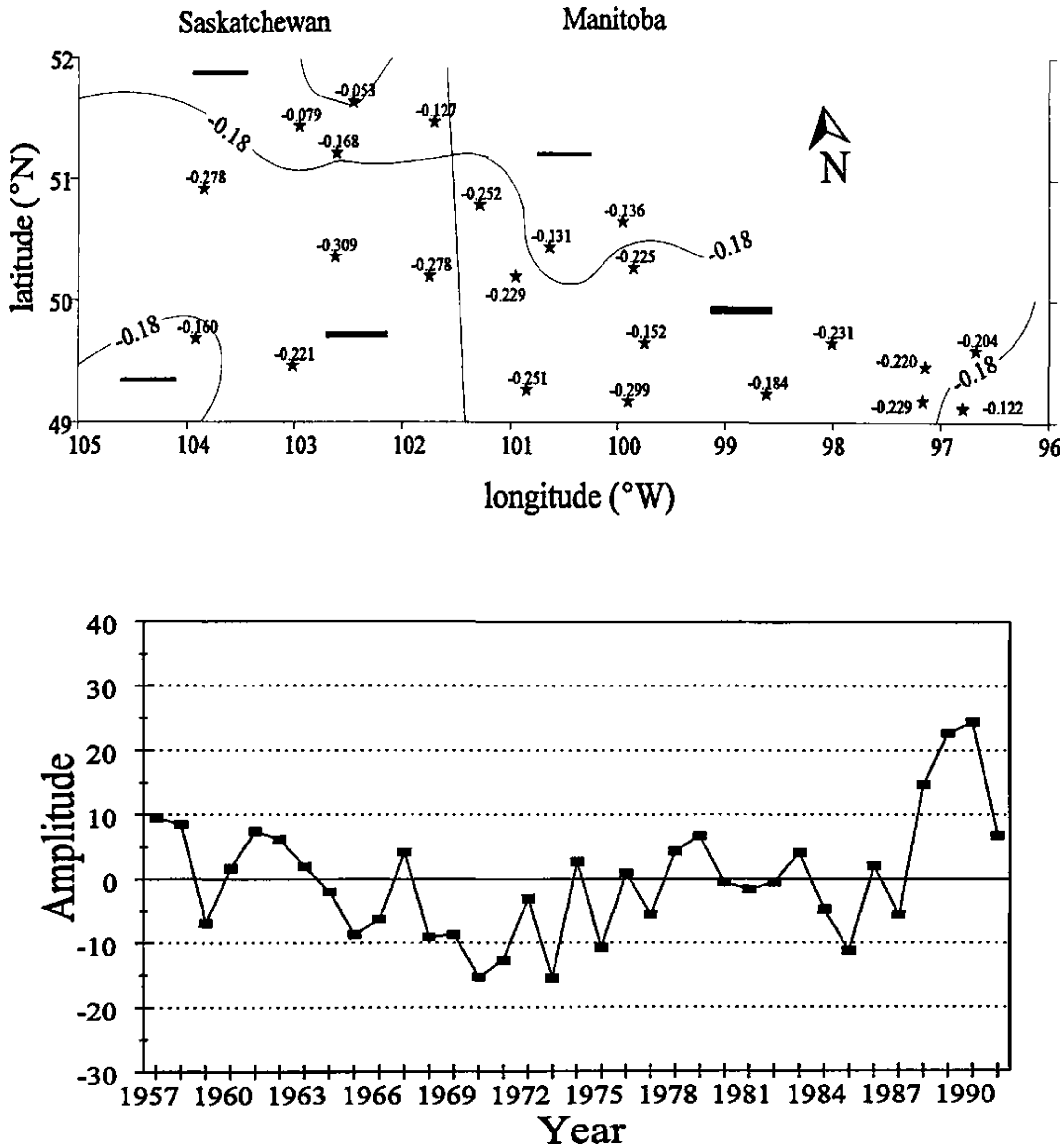


Figure 5.8 Spatial and temporal pattern of the first principal component for the 76 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the first principal component for the 76 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

other two by the lack of the north west relatively strong negative pattern.

The 76 cm soil depth (figure 5.8) spatial pattern is different from the other three. This principal component has a north/south pattern. The strongest oscillations occur in the south/central portion of the study area. This area is more susceptible to dryer or moister conditions than the rest of the study area because the weights are greater.

The second principal component oscillates between positive and negative for all the soil depths just like the average (figures 5.9 to 5.12 and figure 5.3). This spatial pattern is the second most dominant pattern because it explains about 10% of the variance for each soil depth.

The second PC at 15 cm has a northwest to southeast pattern (figure 5.9). The strongest positive weight is in the northern section of the study area while the strongest negative is in the east. This indicates that while the north (in the Canora/Yorkton region) may be dry, the east will be experiencing moister conditions and vice versa.

The second PC at 30 cm depth has a north/south pattern (figure 5.10). The northern region has a strong positive oscillation as it did in the 15 cm PC 2 pattern. The strongest negative is in southeastern Saskatchewan.

The second PC at 46 cm has a strong positive value in the Yorkton region with negative values occurring west of Lake Winnipeg (figure 5.11). The 76 cm second PC oscillates from negative weights in the centre of the study area to positive values at the edges with the exception of the southwest edge (figure 5.12).

The third principal component has different spatial patterns again (figures 5.13 to 5.16). This spatial pattern is the least dominant of the three because it explains the least variance (less than 10 percent).

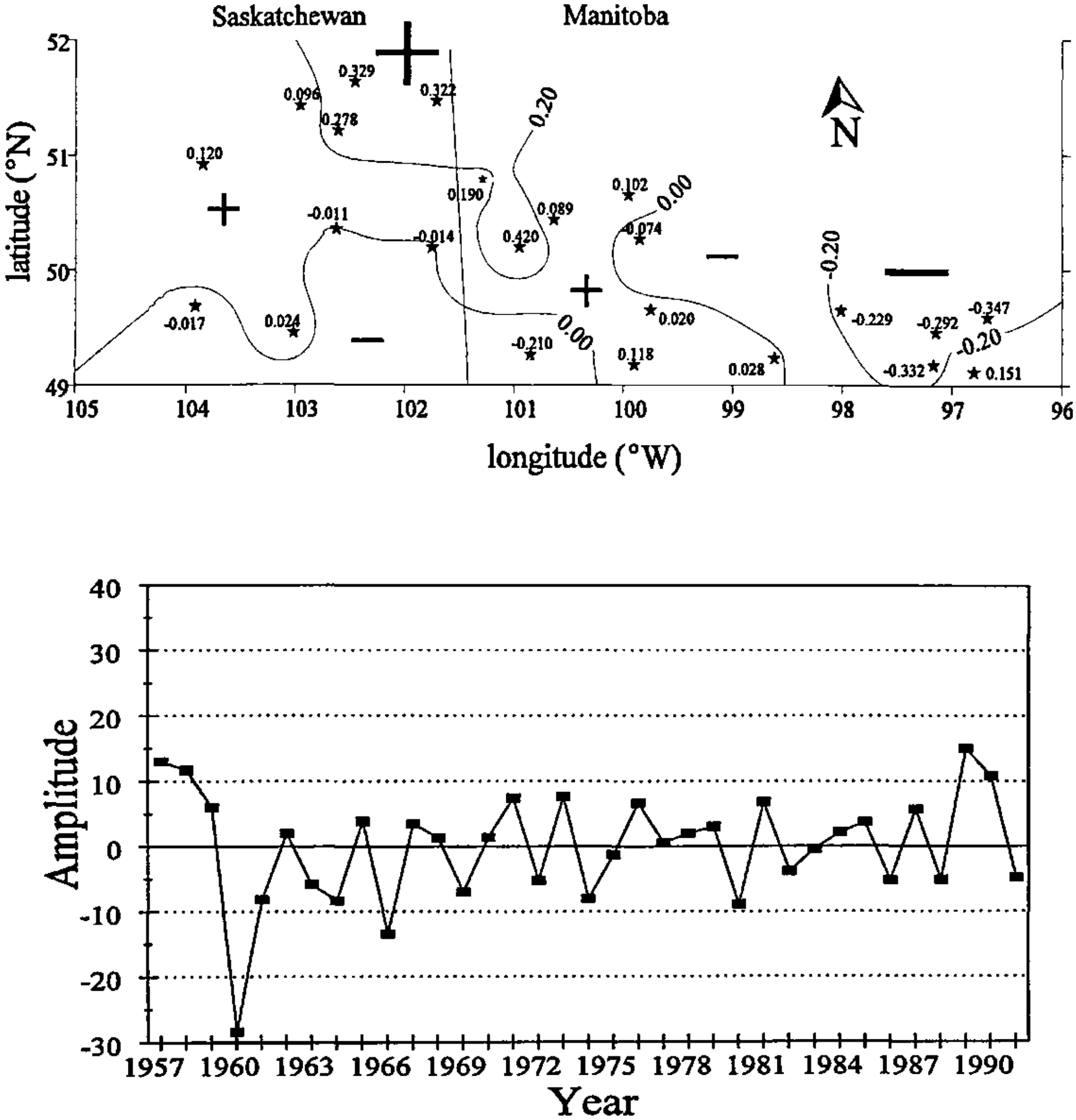
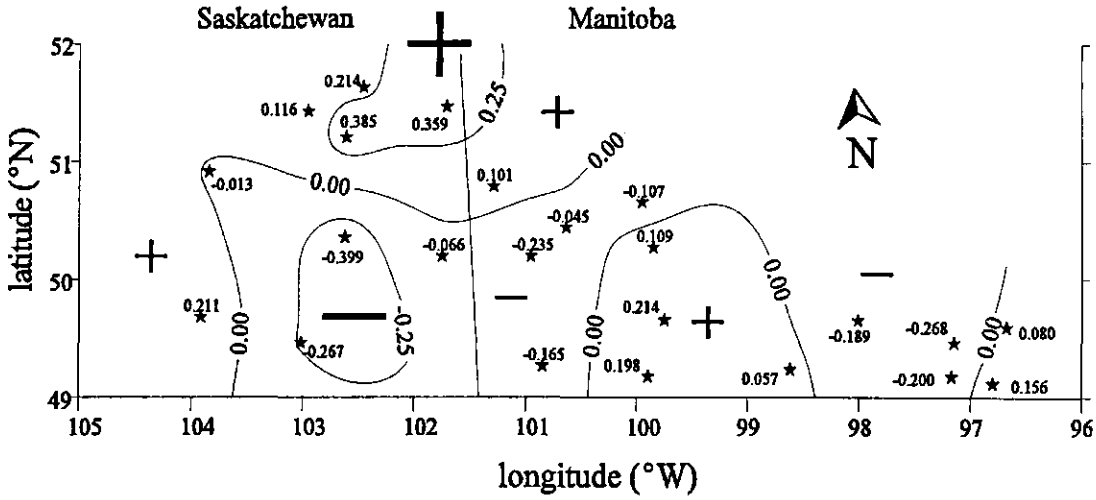


Figure 5.9 Spatial and temporal pattern of the second principal component for the 15 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the second principal component for the 15 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.



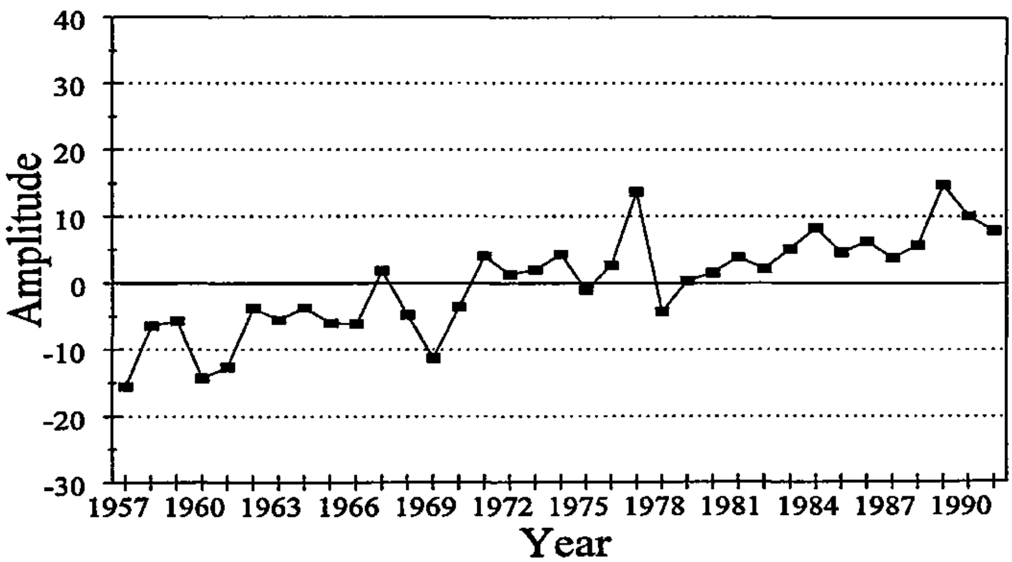


Figure 5.10 Spatial and temporal pattern of the second principal component for the 30 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the second principal component for the 30 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

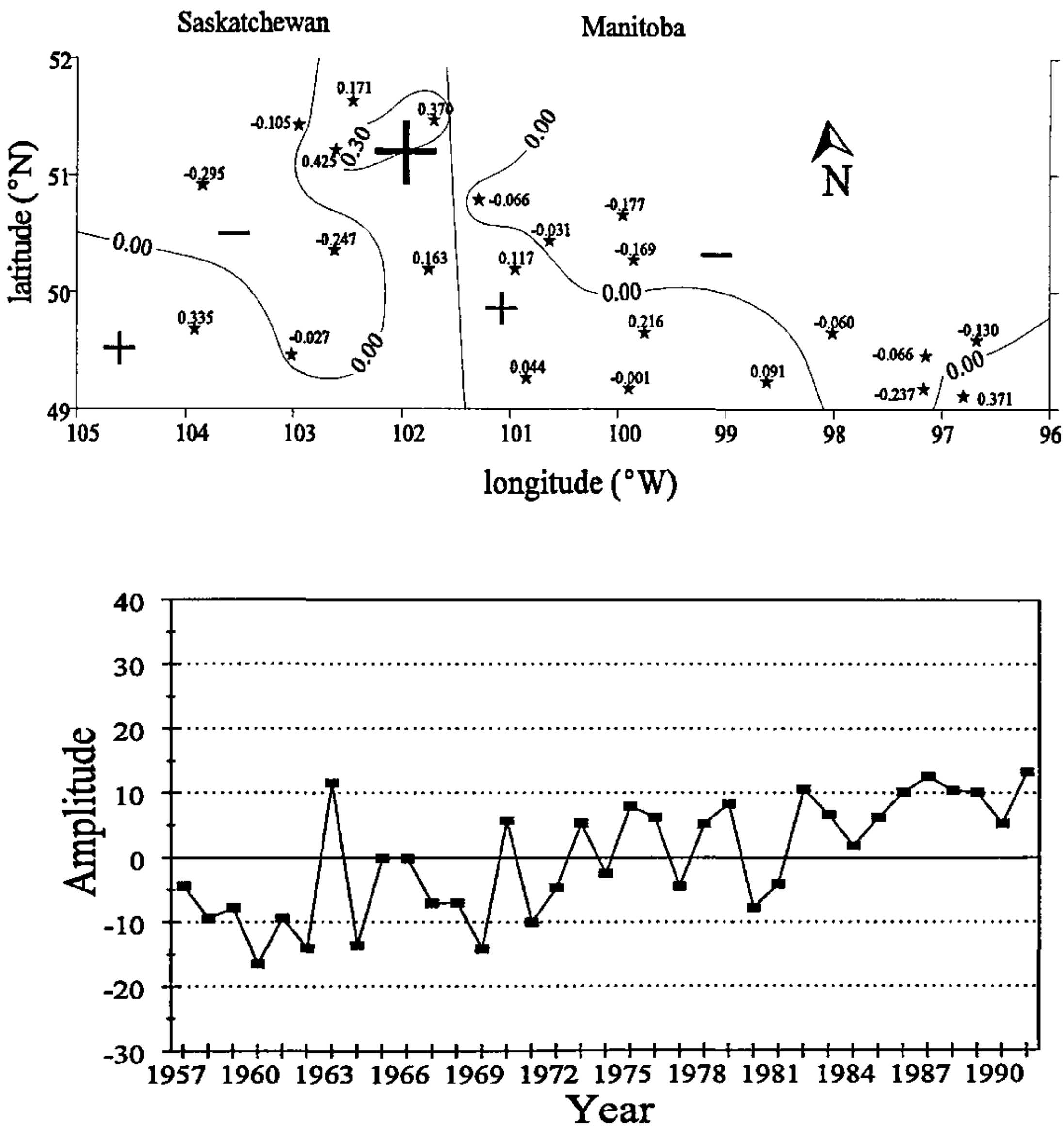


Figure 5.11 Spatial and temporal pattern of the second principal component for the 46 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the second principal component for the 46 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

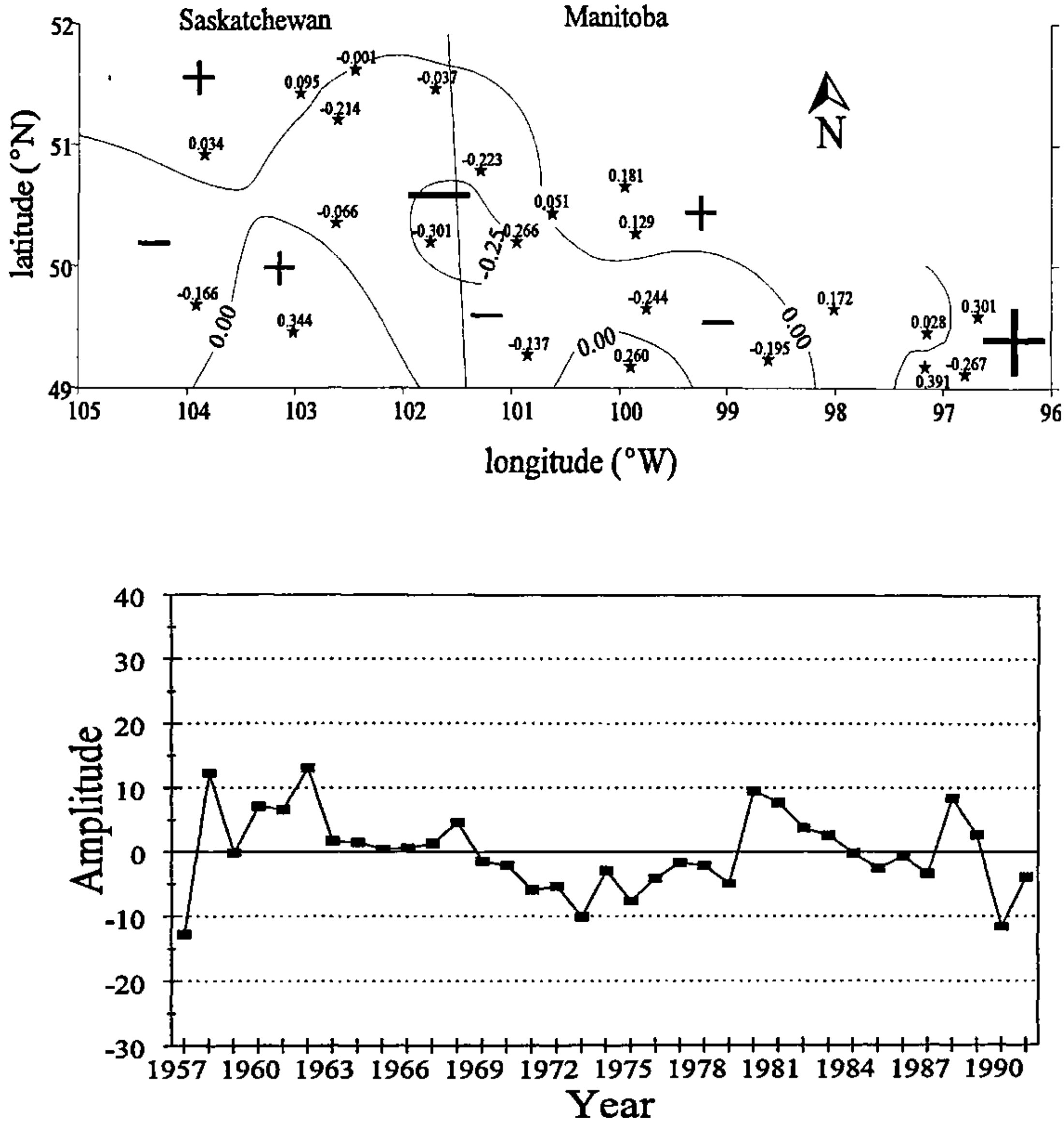


Figure 5.12 Spatial and temporal pattern of the second principal component for the 76 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the second principal component for the 76 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

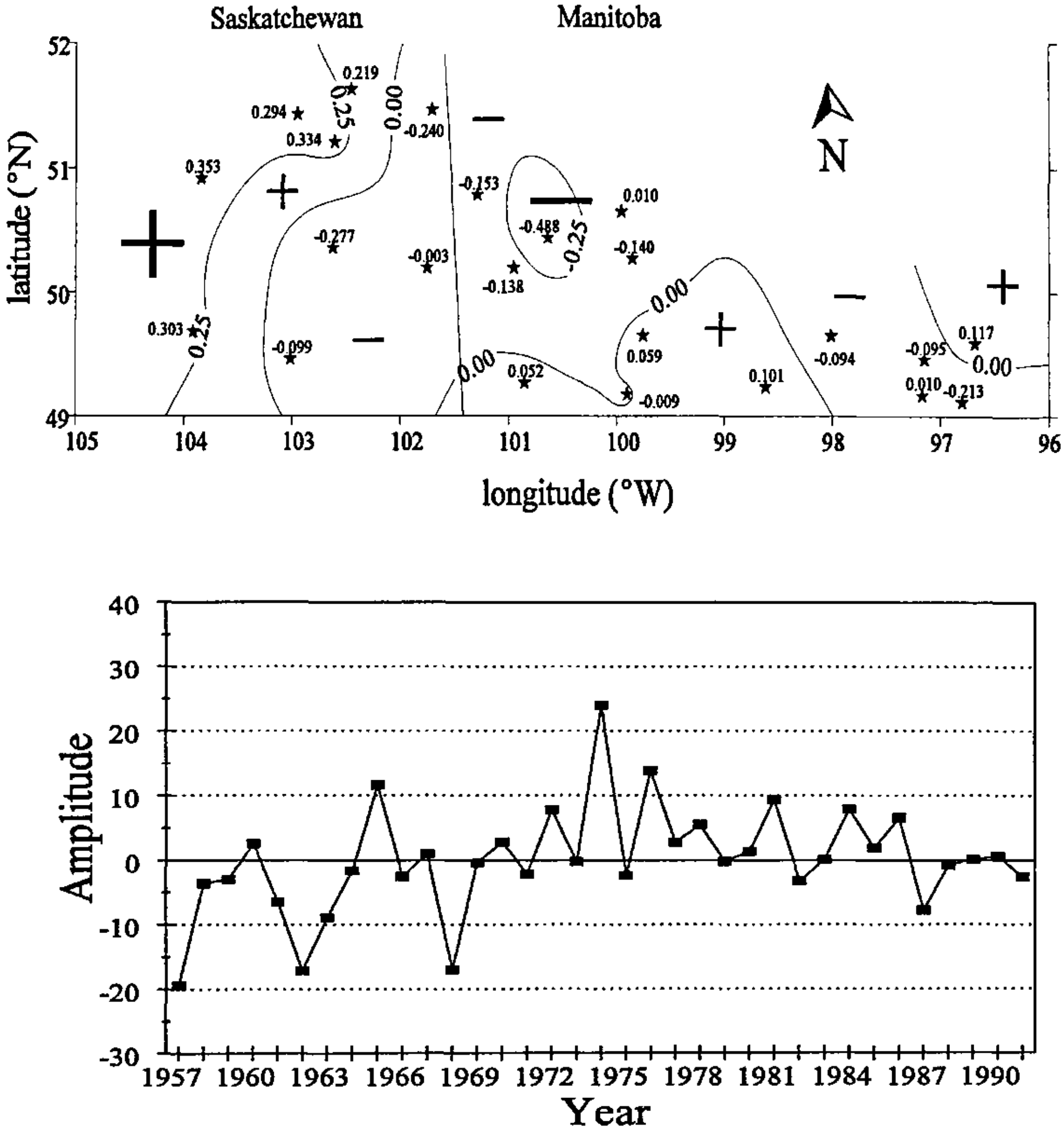
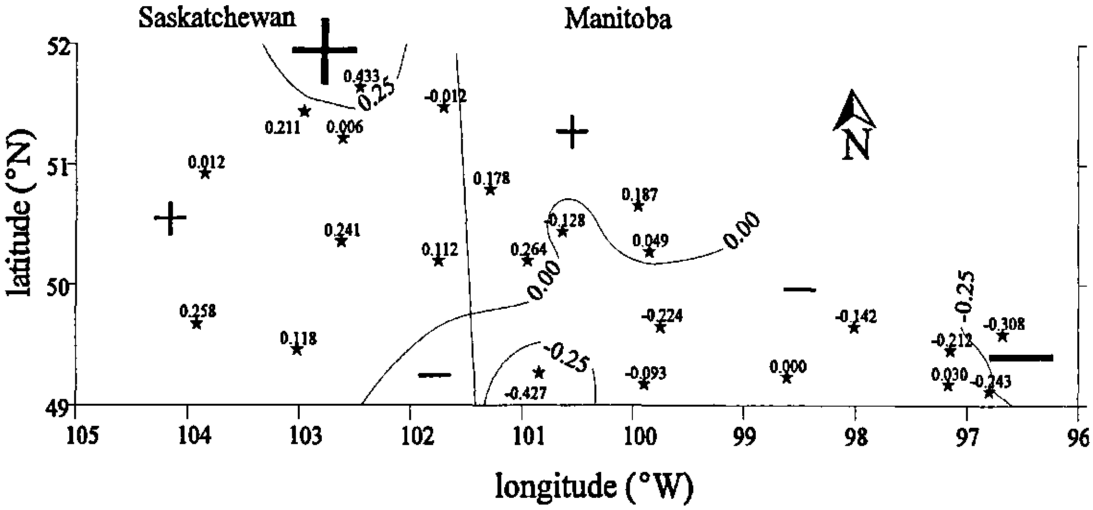


Figure 5.13 Spatial and temporal pattern of the third principal component for the 15 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the third principal component for the 15 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.



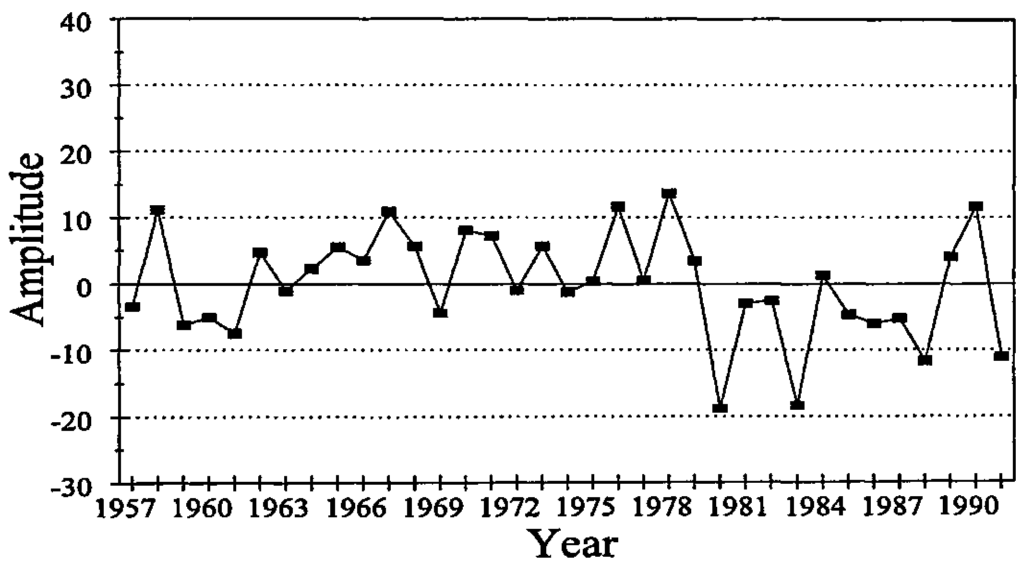


Figure 5.14 Spatial and temporal pattern of the third principal component for the 30 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the third principal component for the 30 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

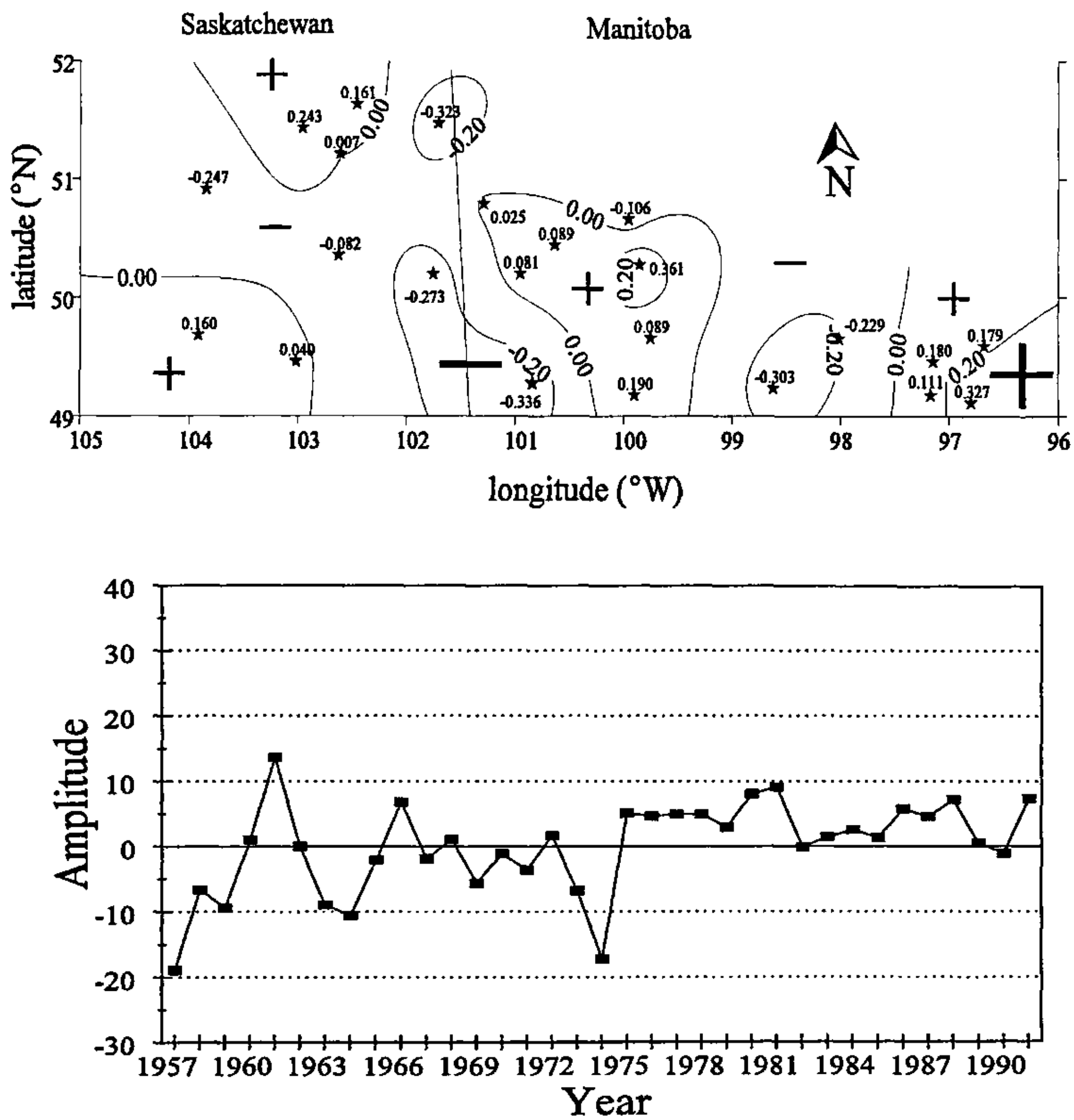


Figure 5.15 Spatial and temporal pattern of the third principal component for the 46 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the third principal component for the 46 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

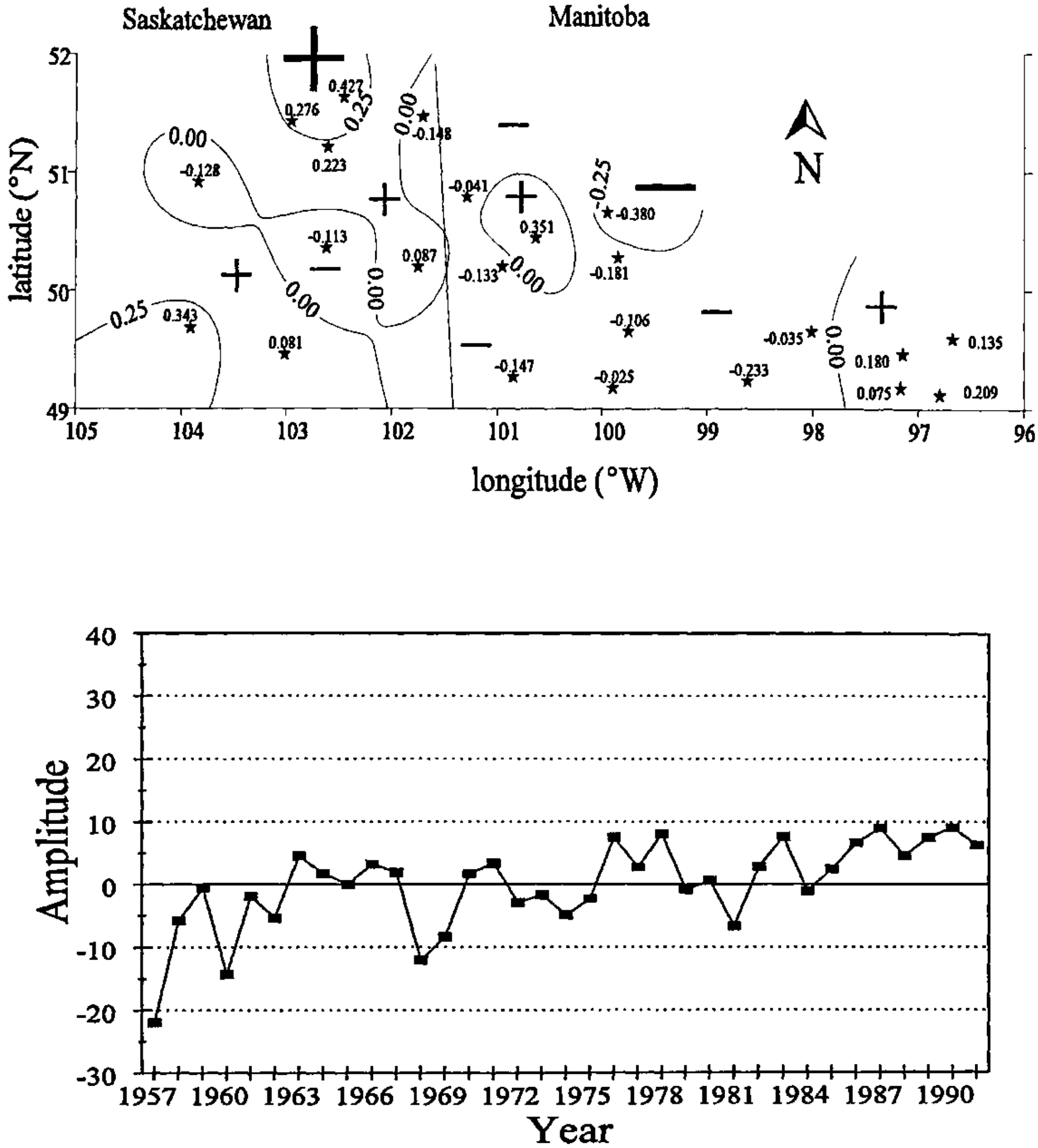


Figure 5.16 Spatial and temporal pattern of the third principal component for the 76 cm soil moisture. The map at the top of the page shows the spatial oscillating effect of the third principal component for the 76 cm soil moisture. The larger the +'s and -'s indicate larger weights occur in these regions. The line graph indicates the years when the spatial pattern was positive and negative and also the amplitudes (or strength) of each drier/wetter episode.

The third PC at 15 cm depth has a west/east spatial pattern with the strongest weight occurring in the western edge of the study area (figure 5.13). The third PC at 30 cm depth (figure 5.14) appears to have a southeast (negative) to northwest (positive) pattern with the north having the strongest positive weight. The third PC at 46 cm (figure 5.15) fluctuates between positive and negative. The strongest negative pattern occurs in the south central portion of the study area. The third PC at 76 cm (figure 5.16) has a complex positive/negative spatial pattern. The strongest positive is in the north (Canora/Theodore region) while the strongest negative area is around Wasagaming in the northeast portion of the study area.

5.5.2 Temporal Variation

The first PC temporal variations at 15, 30, 46 and 76 cm (figures 5.5 to 5.18) are similar to the average soil moisture patterns. There is a strong oscillation in the mid-seventies for the top three soil levels while the deepest soil level has more stable moisture levels, i.e., fluctuations of lower magnitude.

The second PC temporal variation (figures 5.9 to 5.12) is similar to the average at the 30 cm and 46 cm depths with the continuation of the linear upward trend over the 1957 to 1991 period. The 15 cm soil moisture depth seems to oscillate around zero with no apparent upwards or downwards trend. The 76 cm depth appears to have a multi-year oscillation, similar to the lower amplitude fluctuations that occurred in the first PC.

The temporal variation for the third PC is different for all levels (figures 5.13 to 5.16). The first two depths oscillate on a year to year basis. The 76 cm depth has a linear upward trend. The 46 cm depth has greater amplitudes during the first portion of the period with smaller amplitudes during the later years.

5.5.3 Spatial and Temporal Variation

It is important to examine the spatial and temporal PCs together. The temporal graphs give an indication of when the wet and dry cycles occurred as well as the temporal amplitudinal variation. The spatial maps give an indication of the areal pattern of the temporal variation.

For example, the first PC for all depths, 1972 was dryer than 1973. The spatial pattern for these two years were different for each depth as was the temporal amplitudinal variation. The 15 cm temporal amplitude was the strongest of the four depths. Therefore, the spatial pattern at the 15 cm depth would have the most pronounced variation. The 30 cm and 46 cm temporal amplitudes have progressively fewer extremes while the 76 cm has the least amplitudinal variation for the first principal component.

5.6 Discussion and Conclusion

The average soil moisture spatial and temporal variations can be generally compared with the results of Ripley (1992). The first principal component patterns are very similar. The spatial patterns in both Ripley (1992) and this study are negative, with the greatest weighted variation in the Rathwell/Fannystelle area (south central Manitoba). The temporal pattern is the same. The main difference is the amount of variance explained. This study explains 34.5% of the total variance for the first principal component. Ripley's explains 51% of the variance.

The difference may be because Ripley analysed a simplified data set having only five averaged points for the 1955-1980 period. This study examined 23 points for the 1957 to 1991 period therefore uses a more detailed data set.

The second and third spatial and temporal principal component patterns of the two studies are different. The amount of variance explained in Ripley's study is also higher than this study for these two principal components. Ripley's explained 17% for the second principal component and 11% for the third. This study explained 9.7% and 7.5% for the second and third PC. These differences are probably due to the reasons discussed in the above paragraph.

The spatial pattern of the first PC is similar to the results of Richman and Lamb (1987). The precipitation pattern they examined using PCA was determined for the growing season (May-August) 1949-1980 period using three-day and seven-day precipitation totals. The eastern Canadian Prairies, for the first principal component, had 19% of the variance explained with the entire region oscillating together. The oscillation pattern is similar to the one obtained in this study.

The spatial patterns could be a function of the study area, and may be influenced by the location of Lake Winnipeg and Lake Manitoba. They are also likely to be influenced by soil type. The eastern edge of the study area, around Ste. Anne/Steinbach and Stuartburn, has the steepest spatial gradients (e.g. figure 5.2). This eastern zone is also the area where the soil types change from being largely Chernozemic to Organic (figure 3.3) indicating influence on soil moisture.

6.0 SYNOPTIC-SCALE FORCING OF SOIL MOISTURE

6.1 Introduction

The previous chapter examined the temporal, spatial and vertical patterns of soil moisture as determined by principal component analysis. This chapter examines possible causes of these principal component patterns, that is possible synoptic-scale forcings of the soil moisture patterns. This is done by examining the correlation of potential synoptic-scale forcings with the temporal amplitudes of the three principal components at the various soil moisture depths in the study area (figure 5.1).

As stated in the Chapter 3, several synoptic-scale forcings are examined. These are: North Pacific sea surface temperature anomalies; Southern Oscillation Index; Pacific/North American patterns; Arctic surface temperature anomalies; Arctic 100-70 kPa atmospheric thickness anomalies; Arctic sea ice coverage anomalies and North Atlantic iceberg numbers.

6.2 Methodology

This chapter examines the temporal pattern correlations between the seven synoptic-scale forcings and the first three soil moisture principal components.

The correlation data are arranged in three sections (tables 6.1 to 6.6): the first shows the r values for the first principal component and the synoptic-scale forcing, for the four soil depths and average, over each of the 22 months preceding the month of soil moisture measurement; the second section deals with the second principal component and the third with the third principal component.

The synoptic-scale forcings are examined during the 22 months prior to the soil moisture sampling is because there may be an atmospheric lag involved. For example, SST anomalies may not influence the Canadian Prairie weather until many months after the anomaly was initiated (Bonsal et al., 1993). It is therefore necessary to examine a time of at least 22 months before the soil moisture sampling. The lag time chosen can be different for each synoptic-scale forcing (Namias et al., 1988; Garcíaortiz and Ruizdeelvira, 1995). Therefore, for consistency, the same lag of 22 months was used for all synoptic-scale forcings.

6.3 Synoptic-Scale Forcing

The first three synoptic-scale forcings examined in this chapter relate to the North and Central Pacific regions. They undoubtedly are interrelated therefore have a very complex influence on macroscale atmospheric patterns. The Southern Oscillation transfers warm ocean water northwards thus influencing the Pacific/North American patterns. These patterns in turn influence the North Pacific sea surface temperatures.

Sections 6.3.4 to 6.3.7 examine the influence of Arctic synoptic-scale forcings on Canadian Prairie soil moisture. Arctic synoptic-scale forcings such as Arctic surface temperatures and Arctic sea ice coverage are interrelated. For example, when land and water surfaces are snow and ice covered, the albedo of the surface increases up to 0.6. This results in lower surface air temperatures (Agnew, 1988).

The atmospheric fluctuations associated with the polar region can influence atmospheric circulation patterns and weather in other parts of the world, especially the northern hemisphere (Walsh and Johnson, 1979). Therefore, the reason for choosing these Arctic forcing factors is to assess their influence on the Canadian Prairie soil moisture.

6.3.1 North Pacific Sea Surface Temperature Anomalies

North Pacific sea surface temperature anomalies have been chosen as a possible synoptic-scale forcing for soil moisture in the study area because of their involvement in macroscale atmospheric circulations (Walsh et al., 1985). Sea surface temperature anomalies may have a strong atmospheric circulation influence because they strongly influence the transfer of heat between the ocean and atmosphere. SST anomalies can last for more than five months and have lag correlations up to twelve months (Namias et al., 1988). The 22 preceding months to the soil moisture measurement is a long enough period to take into account the five and twelve month correlations. North Pacific sea surface temperature anomalies have been found to be associated with extended dry spells on the Canadian Prairies (Bonsal et al., 1993).

The soil moisture amplitudes for the first three principal components were correlated against the monthly sea surface temperature anomalies (table 6.1). There are more than thirty pairs correlated, therefore if values are 0.31 or greater the significance level is 0.10 (Brooks and Carruthers, 1953 - Appendix F).

This correlation set of the first principal component shows some statistical significance for a direct relationship between the autumn soil moisture using North Pacific sea surface temperature (table 6.1). Referring back to Chapter 5, the first principal component is the dominant principal component pattern of the soil moisture because it explains the highest variance. Therefore, the first principal component spatial and temporal patterns are the most probable patterns to occur.

The June North Pacific sea surface temperature anomalies influence the first principal component of autumn soil moisture at 15 cm and 30 cm indicated by the statistical significance (table 6.1). The sea surface temperature anomalies that occur in May, June, July and August affect the 46 cm and 76 cm autumn soil moisture. October SST anomalies, just before the soil sample was taken, also appears to

Table 6.1 Correlation coefficients between monthly values of North Pacific sea surface temperature anomalies and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.31 are significant at the 0.10 level and are shaded.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct
First Principal Component																						
15 cm	0.03	0.13	0.06	0.03	0.04	-0.10	0.07	-0.24	-0.16	0.05	-0.27	-0.12	-0.05	-0.09	-0.08	0.12	0.23	0.34	0.21	0.22	0.12	0.32
30 cm	0.02	0.10	0.01	0.11	0.10	-0.01	0.14	-0.19	-0.07	0.15	-0.32	-0.06	0.00	-0.08	-0.07	0.11	0.26	0.39	0.22	0.30	0.20	0.37
46 cm	0.05	0.15	0.03	0.11	0.16	0.08	0.17	-0.07	-0.09	0.18	-0.31	-0.03	0.09	0.01	0.00	0.19	0.38	0.46	0.31	0.39	0.29	0.38
76 cm	0.17	0.20	0.11	0.19	0.33	0.23	0.36	-0.05	-0.07	0.21	-0.26	-0.09	0.01	-0.04	0.00	0.17	0.48	0.49	0.44	0.37	0.15	0.21
Average	0.07	0.16	0.07	0.10	0.14	0.01	0.17	-0.17	-0.13	0.14	-0.31	-0.08	0.01	-0.05	-0.04	0.16	0.34	0.42	0.30	0.33	0.20	0.35
Second Principal Component																						
15 cm	0.00	-0.05	-0.02	-0.05	0.13	0.39	-0.04	0.06	-0.13	-0.05	-0.07	-0.30	-0.29	-0.24	-0.21	-0.25	0.05	-0.13	0.17	0.19	0.15	-0.10
30 cm	-0.15	-0.07	-0.04	0.05	0.08	0.03	0.03	0.02	-0.06	0.03	-0.25	-0.27	-0.12	-0.06	0.00	-0.13	-0.03	-0.21	-0.05	0.01	-0.02	-0.21
46 cm	-0.20	-0.13	-0.08	0.03	0.08	0.12	-0.07	-0.18	-0.15	-0.24	-0.17	-0.33	-0.13	0.04	0.11	0.09	0.06	-0.03	0.14	0.02	0.01	0.15
76 cm	0.41	0.34	0.26	0.29	0.27	0.18	0.35	0.29	0.29	0.52	0.34	0.45	0.56	0.51	0.46	0.42	0.30	0.20	0.24	0.03	-0.19	0.17
Average	-0.27	-0.21	-0.19	-0.10	0.04	0.13	-0.16	-0.09	-0.15	-0.15	-0.21	-0.40	-0.25	-0.14	-0.11	-0.18	-0.13	-0.28	-0.05	0.02	0.07	-0.15
Third Principal Component																						
15 cm	-0.24	-0.16	-0.17	-0.22	-0.22	-0.21	-0.19	-0.29	-0.20	-0.08	-0.19	-0.22	-0.03	-0.07	-0.02	-0.10	-0.07	-0.10	-0.33	-0.07	-0.12	-0.13
30 cm	-0.02	-0.08	-0.19	-0.25	-0.09	0.11	-0.27	-0.10	-0.20	-0.13	-0.08	-0.25	-0.30	-0.31	-0.36	-0.41	-0.40	-0.35	-0.37	0.15	0.11	-0.12
46 cm	0.13	0.11	0.12	0.11	0.09	-0.05	0.02	-0.08	0.00	0.19	0.03	0.06	0.32	0.38	0.40	0.30	0.08	0.04	0.17	0.01	-0.26	0.04
76 cm	-0.12	0.01	-0.04	0.00	-0.01	0.04	-0.12	-0.06	-0.19	-0.12	-0.13	-0.09	0.13	0.21	0.17	0.24	0.03	-0.06	0.05	-0.02	0.05	0.12
Average	-0.15	-0.10	-0.05	0.01	-0.16	-0.33	0.06	-0.08	0.19	-0.04	-0.25	-0.09	0.00	-0.05	0.06	0.12	-0.03	0.12	-0.01	-0.22	-0.13	-0.06

influence soil moisture except for the deepest level. October's precipitation may not have infiltrated to the deepest level resulting in the poor correlation. These correlations are positive meaning that when the sea surface temperature anomaly is positive the soil is drier.

Positive sea surface temperature anomalies are associated with extended dry spells on the Canadian Prairies (Section 3.4.1). The gradient becomes significant when there is anomalously cooler water in the east/central North Pacific and anomalously warmer waters at the central west coast of North America. These higher positive correlations indicate that a positive sea surface anomaly results in a dry spell while a negative sea surface anomaly would result in moister weather conditions (Bonsal et al., 1993).

The second principal component correlation data have statistical significance for the 76 cm level. The correlation with the sea surface temperatures for the previous October to April of the soil moisture sampling year are all significantly positively correlated at the 0.10 level.

The third principal component is also somewhat related to the sea surface temperatures, especially at the 30 cm depth. For the months of February to July there is a significant negative correlation of the soil moisture principal component with the North Pacific sea surface temperature. Another interesting pattern to note is that the first depth's (15 cm) correlations are all negative while the second depth has only three months that are positive out of the total 22 month period prior to the time of soil sampling. The negative values may indicate that another synoptic-scale forcing have a positive influence on the soil moisture pattern thus offsetting any positive influence of the sea surface temperature in this third principal component. This principal component pattern is less likely to occur as it explains less than 10 percent of the total variance for all soil levels.

Other individual months also show some significance between the soil moisture principal components and the North Pacific sea surface temperature anomalies but no apparent pattern. The most important pattern is the one that occurs with the first principal component and that affects all the soil moisture depths.

The temporal variations for the first principal component of the months with significant correlations are presented in figures 6.1 to 6.5. The two lines do not always follow each other but there are sequences of years when they do. For example, the first principal component was considered significant at all levels for June (figure 6.2). In this series of graphs there is some correspondence in the late 1950s, late 1960s and early 1970s. This means that during that period the spatial pattern (figure 5.2) for this first principal component would probably have occurred during those years. The most significant months for soil depth analysis, May, July and August, also show some similar years.

These results correspond to Bonsal et al.'s (1993) findings. Although 24 out of the 27 sea surface temperature anomalies were associated with Canadian Prairie dry spells, the growing seasons of 1963, 1978 and 1983 were the exceptions. However, a positive 500 hPa occurred near the Canadian Prairies but not close enough to produce an extended dry spell.

October's sea surface temperature anomalies were significantly correlated with the top three soil moisture depths for the first principal components (figure 6.5). The graphs for this period show similarities. The strongest period was again in the mid 1970s and in the late 1950s.

The results of these correlation and trend analyses indicate that North Pacific sea surface temperature anomalies of the late spring and summer months have the strongest influence on the autumn soil moisture levels on the eastern Canadian Prairies. The influence is greatest in the deeper soil levels. October's sea surface temperature mainly influences the top levels of soil moisture.

As noted in Chapter 2, Shukla and Fennessy (1987) believe that 30 to 60 day forecasts could be improved by examining sea surface temperatures. This research indicates that if sea surface temperatures are used, the soil moisture forecast period may be extended up to six months.

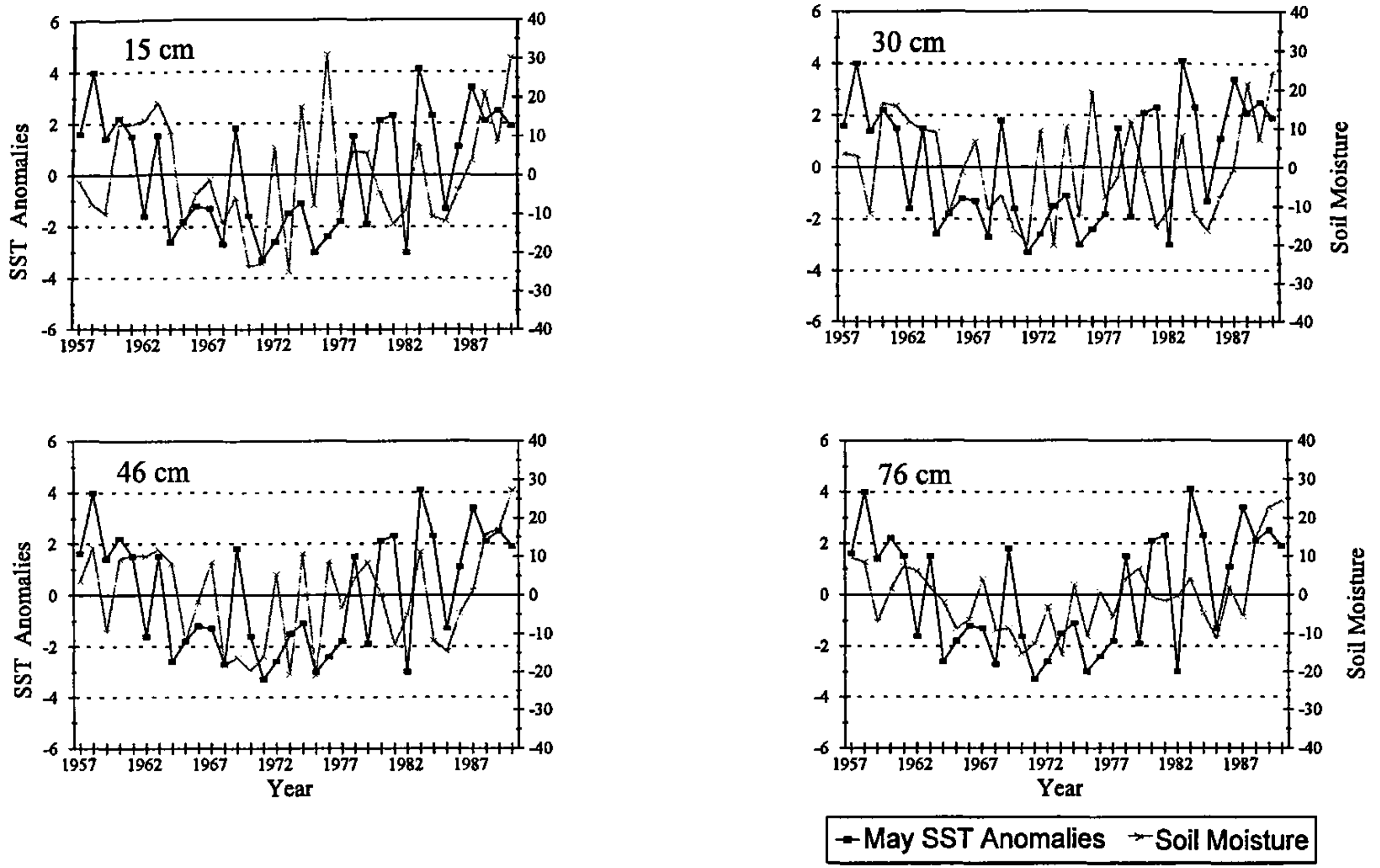


Figure 6.1 Time series of May sea surface temperature anomaly indices and the first principal component soil moisture amplitudes for each of the four soil depths. The darker line with solid squares represents the SST anomalies for 1957 to 1991, while the lighter line represents the first soil moisture principal component.

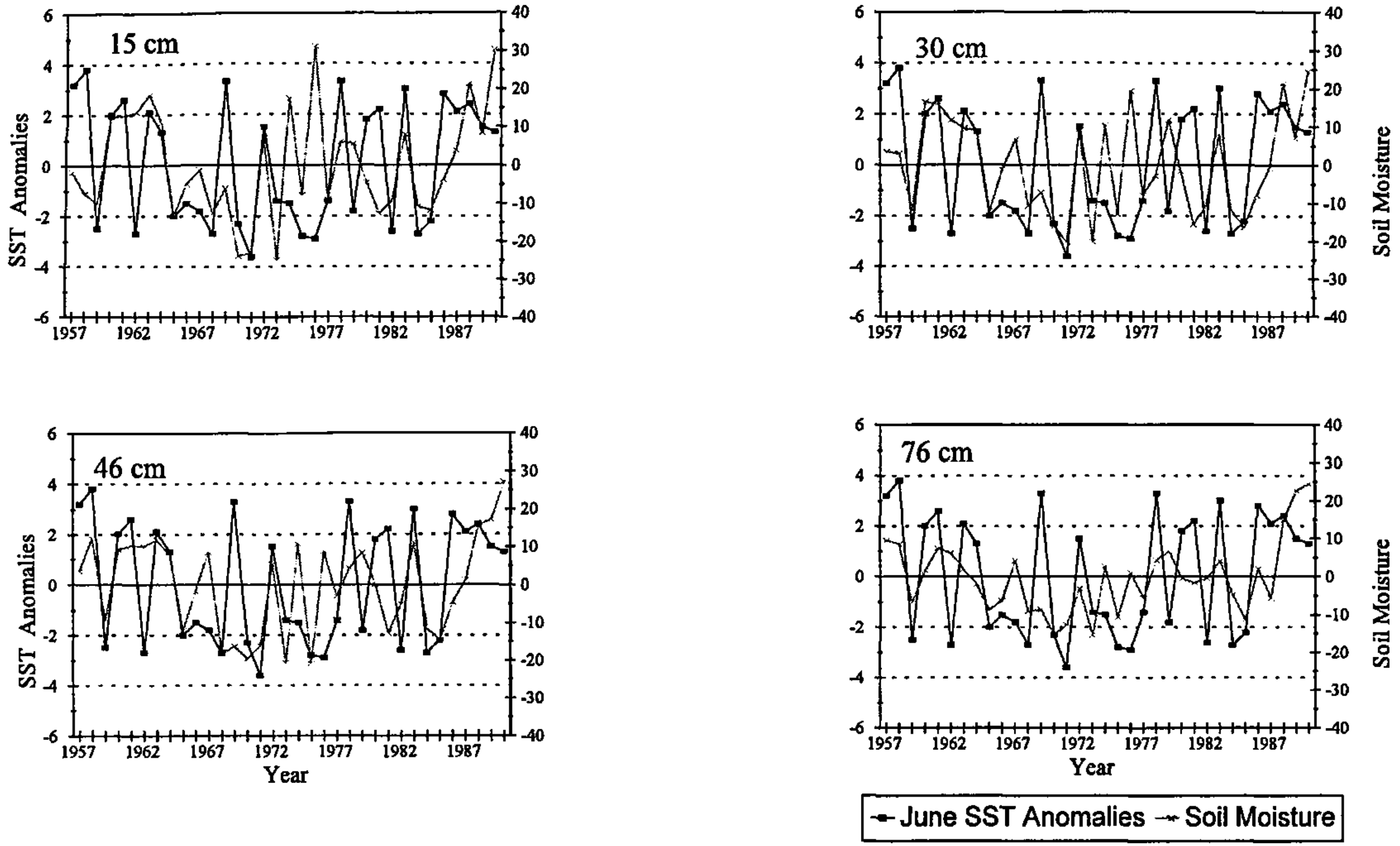


Figure 6.2 Time series of June sea surface temperature anomaly indices and the first principal component soil moisture amplitudes for each of the four soil depths. The darker line with solid squares represents the SST anomalies for 1957 to 1991, while the lighter line represents the first soil moisture principal component.

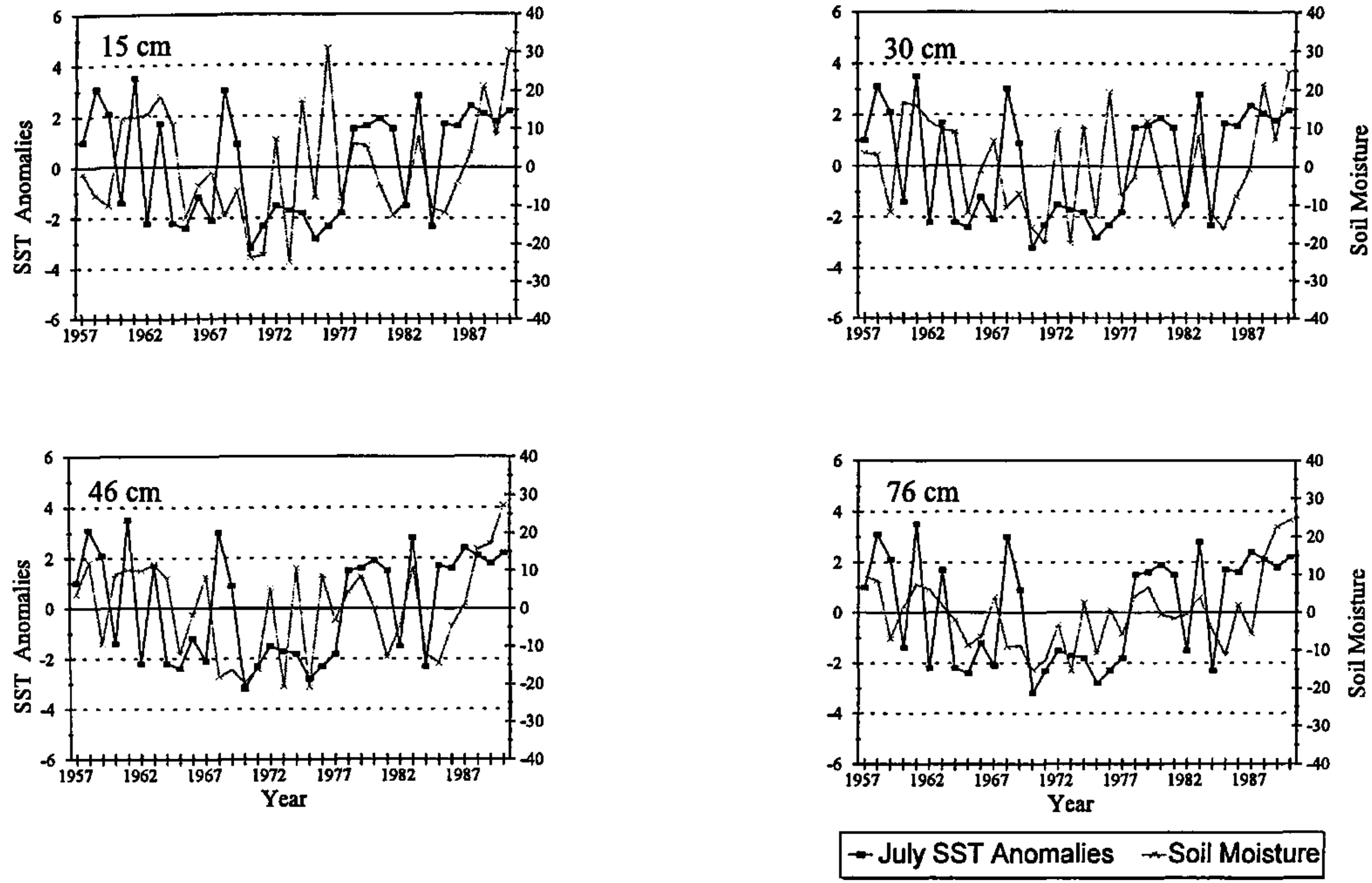


Figure 6.3 Time series of July sea surface temperature anomaly indices and the first principal component soil moisture amplitudes for each of the four soil depths. The darker line with solid squares represents the SST anomalies for 1957 to 1991, while the lighter line represents the first soil moisture principal component..

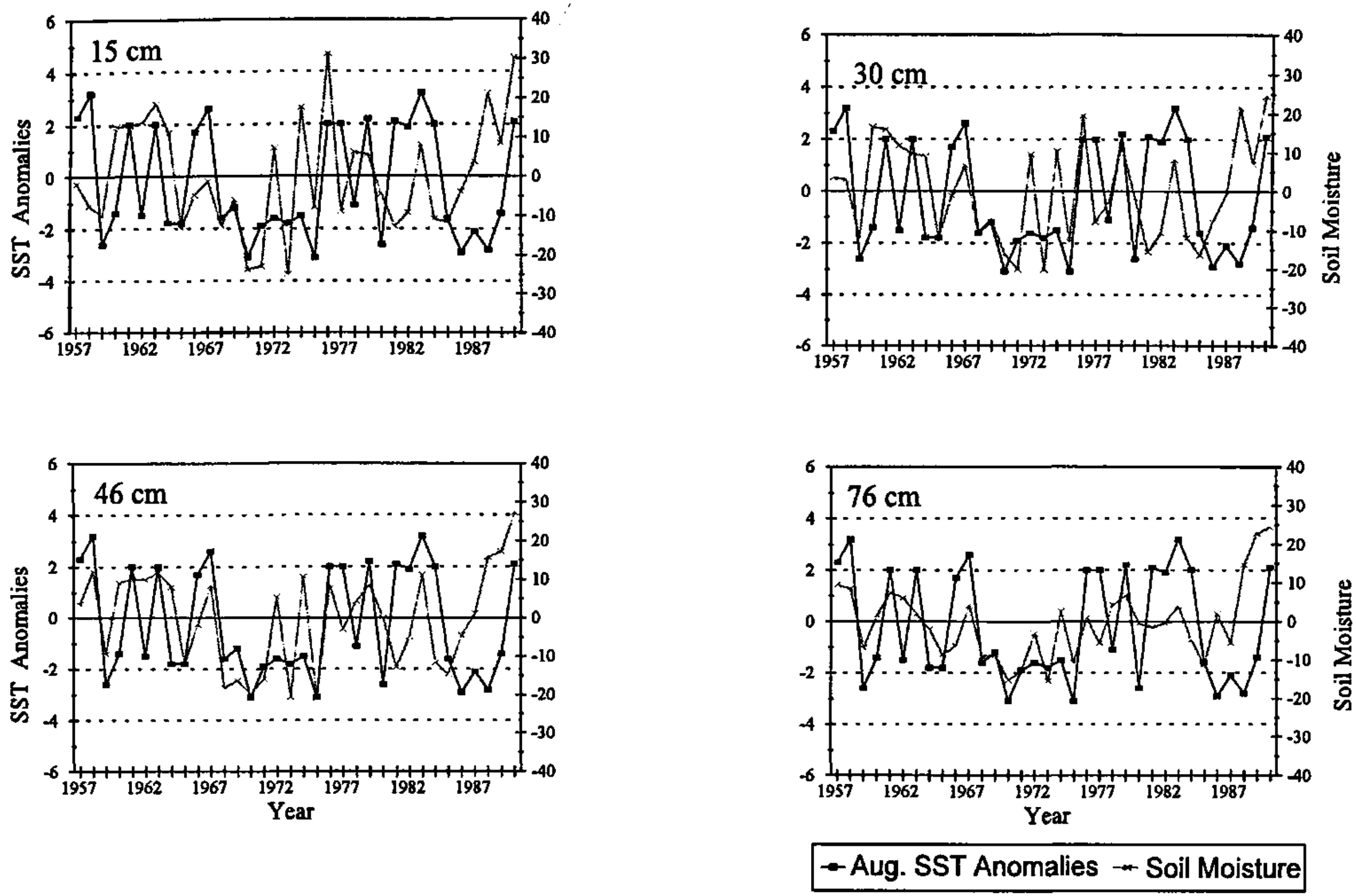


Figure 6.4 Time series of August sea surface temperature anomaly indices and the first principal component soil moisture amplitudes for each of the four soil depths. The darker line with solid squares represents the SST anomalies for 1957 to 1991, while the lighter line represents the first soil moisture principal component.

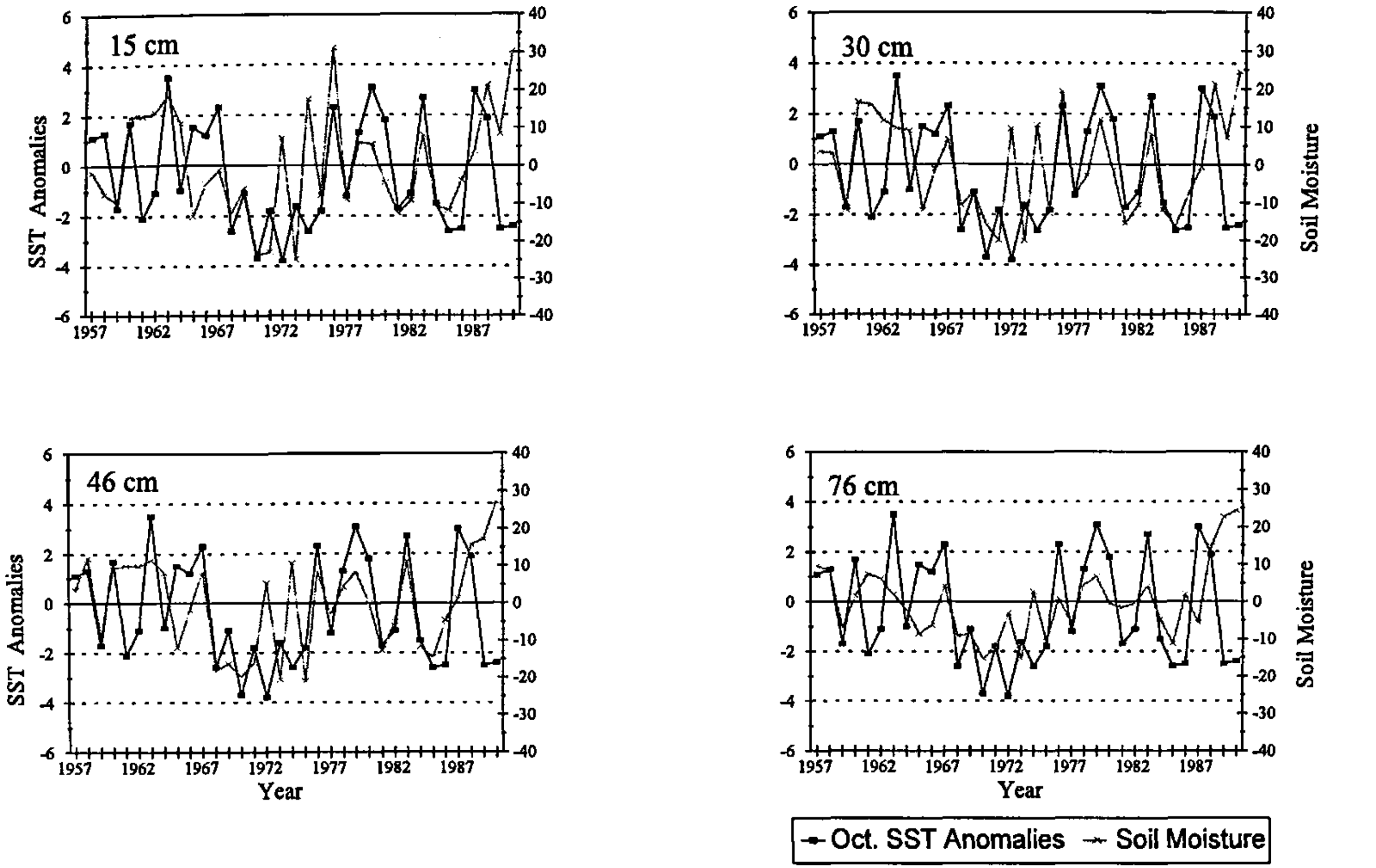


Figure 6.5 Time series of October sea surface temperature anomaly indices and the first principal component soil moisture amplitude for each of the four soil depths. The darker line with solid squares represents the SST anomalies for 1957 to 1991, while the lighter line represents the first soil moisture principal component.

6.3.2 Southern Oscillation Index

Section 3.4.2 describes the Southern Oscillation Index data used in the correlation analysis. The Southern Oscillation Index was chosen as a possible synoptic-scale forcing because of its potential influence over the Canadian Prairie climate. El Niño events are thought to induce warm winters and may influence summer drought conditions on the Canadian Prairies.

Correlations between the Southern Oscillation Index and the soil moisture principal components were calculated (table 6.2). There are very few significant values based on a data set of 25 pairs. However, there are some trends. The correlations of the first principal component for all of the soil moisture depths are negative closest to the time of the soil moisture sampling, and increase with time prior to sampling.

The 15 cm depth correlation is negative for the months of June to October. Prior to the June preceding the soil sampling, the values are positive. The strongest positive values are from July of the previous year to January of the current year. This indicates a time delay between the onset of El Niño and its effect on the Canadian Prairies. The low significance values suggests that the Southern Oscillation Index probably has only minor influence over the autumn soil moisture levels in the eastern prairies. This corresponds with the comments made by Cayan (1987 in Ripley, 1988) and Jones and Peterson (1993, draft). They suggested that the El Niño influence declines from west to east on the Canadian Prairies.

At the 30 cm depth, the negative values for the correlations extend towards March of the same year of the soil sampling. At 46 cm the negative values for the correlations extend into February of the same year of the soil sampling. The 76 cm depth tends to alternate between positive and negative values more than the upper soil moisture levels. These positive/negative oscillations may indicate the Southern Oscillation Index has a stronger influence over autumn soil moisture at

Table 6.2 Correlation coefficients between monthly values of the Southern Oscillation Index and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.34 are significant at the 0.10 level and are shaded.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct
First Principal Component																						
15 cm	0.14	-0.03	0.10	0.40	0.22	0.09	0.25	0.18	0.27	0.22	0.17	0.26	0.31	0.09	0.04	0.07	0.05	-0.11	-0.09	-0.17	-0.15	-0.07
30 cm	0.08	-0.12	0.11	0.36	0.19	0.04	0.18	0.08	0.15	0.14	0.12	0.22	0.21	0.11	-0.06	-0.02	-0.12	-0.10	-0.13	-0.15	-0.13	-0.06
46 cm	0.05	-0.17	-0.05	0.23	-0.02	-0.07	0.00	-0.09	-0.02	0.02	0.02	0.09	0.18	-0.01	-0.12	-0.06	-0.17	-0.21	-0.15	-0.18	-0.17	-0.13
76 cm	0.00	-0.16	-0.26	0.11	0.04	-0.09	0.10	-0.05	0.00	-0.07	-0.04	0.10	0.22	-0.07	-0.26	-0.13	-0.19	-0.08	-0.03	-0.27	-0.23	-0.19
Average	0.06	-0.11	0.00	0.31	0.15	0.02	0.15	0.05	0.14	0.12	0.10	0.20	0.26	0.06	-0.10	-0.04	-0.10	-0.16	-0.13	-0.21	-0.19	-0.14
Second Principal Component																						
15 cm	-0.04	0.01	-0.23	-0.14	-0.37	0.10	0.15	0.06	-0.03	0.04	-0.14	-0.17	-0.04	-0.01	0.04	-0.06	-0.01	0.14	-0.07	-0.05	-0.03	0.12
30 cm	-0.04	-0.05	-0.12	-0.14	-0.03	0.03	-0.11	-0.06	0.00	0.06	0.09	-0.10	0.14	0.18	0.02	-0.09	0.05	-0.10	-0.11	-0.04	0.09	0.05
46 cm	0.17	-0.01	-0.03	-0.09	-0.06	-0.00	-0.05	0.00	-0.00	-0.04	-0.22	-0.21	-0.04	-0.24	-0.03	-0.14	0.08	-0.05	-0.07	-0.26	-0.10	-0.14
76 cm	-0.01	-0.01	-0.35	-0.06	-0.13	-0.10	-0.03	-0.21	-0.16	-0.19	-0.15	0.03	-0.01	-0.06	-0.37	-0.16	-0.01	-0.06	-0.08	0.00	-0.09	-0.19
Average	0.00	-0.04	-0.05	-0.10	-0.15	0.03	-0.06	0.06	0.00	0.02	-0.04	-0.15	0.04	0.05	0.11	-0.07	0.06	-0.02	-0.13	-0.08	0.05	0.07
Third Principal Component																						
15 cm	-0.35	-0.19	0.12	0.05	0.19	0.07	0.15	0.30	0.27	0.29	0.36	0.22	0.10	0.11	0.23	-0.06	0.16	-0.08	-0.04	-0.03	0.03	-0.02
30 cm	-0.15	-0.03	-0.06	-0.07	-0.18	0.08	0.11	0.20	0.12	0.14	0.19	0.28	0.22	0.24	0.41	0.14	0.14	0.28	0.03	0.16	0.07	0.13
46 cm	0.02	0.20	0.07	0.02	0.20	-0.18	-0.04	-0.13	-0.01	-0.05	-0.25	-0.06	-0.13	0.02	-0.53	-0.27	0.03	0.05	-0.11	-0.07	-0.08	-0.19
76 cm	-0.03	0.02	-0.05	0.00	-0.19	-0.13	-0.21	-0.16	-0.13	-0.15	-0.28	-0.23	-0.13	-0.20	-0.03	-0.09	0.14	-0.14	-0.25	-0.08	0.02	0.01
Average	0.07	0.15	0.21	0.30	0.40	0.08	0.17	0.13	0.16	0.07	0.17	0.04	0.12	0.17	-0.05	-0.10	-0.22	-0.09	-0.06	-0.07	-0.02	0.01

the shallower depths than the deeper soil moisture depths. Further research is required to determine if this is true.

The second and third principal components do not appear to have any major trends in their correlation values. This suggests that the Southern Oscillation Index has little influence on the study area, and that it has the most significance for the first principal component pattern.

6.3.3 Pacific/North American Pattern

The Pacific/North American (PNA) pattern was chosen as a synoptic-scale forcing in this correlation analysis because of its documented influence over the Canadian Prairie climate (e.g. Ropelewski and Halpert, 1986).

The PNA pattern is correlated against soil moisture's principal components (table 6.3). The correlations are based on thirty pairs for 1957 to 1991 with the significant values being shaded. The PNA data are described in section 3.4.3. In general, few correlations were statistically significant at the 10% level.

The October correlation values have a statistically significant positive value with the first principal components at the 15 and 30 cm levels. The previous two months are also positive but not statistically significant. Prior to August (July in the 15 cm depth) there is an overall negative correlation until the previous September. This suggests the PNA pattern has the strongest influence just before the soil moisture samples are taken. The lower values for the deeper soil moisture depths indicate that PNA pattern has less influence on the deeper depths. The PNA pattern has the greatest influence on the shallower depths. The June correlation coefficients, a year prior to the soil sampling, are negatively significant. However, these values are not thought to signify the PNA influencing the autumn soil moisture because the values on either side are too low to be considered

Table 6.3 Correlation coefficients between monthly values of the Pacific/North American pattern and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.31 are significant at the 0.10 level and are shaded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
First Principal Component																						
15 cm	0.05	-0.21	-0.20	0.01	-0.16	-0.39	0.25	-0.29	0.05	-0.23	-0.17	0.00	-0.25	-0.18	-0.24	-0.02	-0.26	-0.17	0.01	0.06	0.22	0.33
30 cm	-0.09	-0.30	-0.12	-0.06	-0.13	-0.34	0.28	-0.26	0.14	-0.17	-0.22	-0.02	-0.26	-0.19	-0.23	-0.09	-0.19	-0.08	-0.06	0.11	0.20	0.35
46 cm	-0.01	-0.38	-0.15	-0.06	-0.05	-0.31	0.18	-0.18	0.11	-0.15	-0.21	-0.04	-0.18	-0.15	-0.23	-0.04	-0.28	-0.17	-0.21	0.15	0.16	0.28
76 cm	0.01	-0.36	-0.15	-0.08	0.02	-0.26	0.04	-0.25	0.09	-0.19	-0.15	-0.15	-0.24	-0.26	-0.09	-0.04	-0.10	-0.23	-0.24	0.17	0.21	0.17
Average	0.02	-0.31	-0.14	-0.03	-0.08	-0.35	0.23	-0.28	0.07	-0.21	-0.20	-0.07	-0.24	-0.20	-0.20	-0.04	-0.21	-0.18	-0.12	0.12	0.21	0.30
Second Principal Component																						
15 cm	-0.01	0.05	-0.02	-0.04	0.28	0.13	-0.34	0.13	-0.02	-0.01	0.05	-0.33	-0.03	-0.17	0.06	0.03	0.09	-0.19	-0.03	0.15	0.10	-0.28
30 cm	0.05	-0.17	-0.00	0.06	0.25	-0.14	-0.15	0.01	0.07	-0.30	-0.03	-0.18	0.04	-0.02	-0.11	0.11	-0.03	-0.23	-0.35	0.08	-0.02	-0.30
46 cm	0.03	-0.13	0.05	0.06	-0.03	-0.11	-0.08	-0.05	-0.14	-0.09	-0.10	-0.03	0.07	-0.11	-0.04	-0.23	0.03	-0.19	-0.07	0.00	0.14	-0.22
76 cm	0.22	-0.11	-0.06	-0.19	0.04	0.10	0.12	-0.10	0.05	0.29	0.04	0.20	0.41	0.15	-0.05	0.05	-0.12	0.06	-0.17	-0.12	-0.19	0.09
Average	-0.02	-0.14	0.01	0.11	0.09	-0.08	-0.21	0.02	-0.02	-0.19	-0.09	-0.17	0.04	-0.12	-0.09	-0.10	-0.11	-0.15	-0.21	0.14	0.07	-0.35
Third Principal Component																						
15 cm	-0.07	0.11	-0.09	0.32	0.10	-0.21	0.18	-0.45	-0.10	-0.20	-0.15	0.04	0.15	-0.04	0.09	0.19	0.03	-0.04	-0.03	0.21	-0.04	-0.02
30 cm	-0.07	-0.04	-0.06	-0.03	-0.03	0.24	-0.23	0.15	0.03	-0.00	0.08	-0.27	-0.17	-0.02	-0.15	-0.08	-0.14	-0.15	0.15	0.32	0.43	-0.13
46 cm	0.06	-0.13	0.07	0.11	-0.07	-0.19	0.13	-0.18	-0.10	0.10	0.02	-0.03	0.45	0.10	0.20	-0.06	0.29	-0.07	-0.01	0.13	-0.13	-0.29
76 cm	0.09	-0.18	-0.07	-0.04	-0.08	-0.11	-0.06	0.04	-0.10	-0.15	-0.12	0.02	0.20	0.03	-0.17	-0.01	-0.27	-0.13	-0.26	-0.00	-0.02	-0.21
Average	0.00	-0.06	0.16	0.06	0.16	-0.29	0.29	-0.15	0.10	-0.35	-0.29	0.12	0.09	-0.04	-0.07	-0.07	0.25	0.19	-0.25	-0.05	-0.29	0.13

Table 6.4 Correlation coefficients between monthly values of the Arctic surface temperature anomalies and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.34 are significant at the 0.10 level and are shaded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
First Principal Component																						
15 cm	0.28	0.43	0.09	0.21	0.44	0.11	0.21	-0.06	0.19	-0.15	-0.14	-0.00	0.04	0.01	-0.16	-0.03	0.00	0.06	0.23	0.01	0.06	0.04
30 cm	0.21	0.33	-0.05	0.02	0.25	0.05	0.20	-0.04	0.20	-0.16	-0.16	0.03	0.02	0.11	-0.16	-0.05	0.02	0.13	0.28	0.08	0.02	0.09
46 cm	0.30	0.35	-0.12	0.01	0.36	0.20	0.31	0.06	0.20	-0.14	-0.09	0.07	0.09	0.17	-0.16	-0.06	0.07	0.04	0.30	0.06	0.00	0.26
76 cm	0.21	0.36	-0.04	-0.00	0.42	0.34	0.39	0.19	0.29	-0.02	-0.17	0.20	0.26	0.22	-0.01	-0.04	0.14	0.07	0.26	0.11	0.11	0.38
Average	0.29	0.39	0.01	0.09	0.40	0.17	0.27	0.01	0.21	-0.16	-0.16	0.07	0.08	0.10	-0.14	-0.03	0.06	0.09	0.29	0.08	0.05	0.18
Second Principal Component																						
15 cm	0.08	0.01	0.03	0.18	0.04	0.12	0.16	0.02	0.04	0.17	0.11	-0.00	0.13	0.23	0.11	-0.10	0.13	-0.34	-0.16	0.09	-0.07	-0.07
30 cm	0.21	-0.02	0.07	0.25	0.33	0.14	0.34	0.23	0.18	0.02	-0.07	0.14	0.07	0.00	0.35	0.33	0.52	0.13	0.22	0.12	0.01	0.03
46 cm	0.10	-0.13	0.20	0.17	0.06	0.03	0.22	-0.03	0.18	0.22	0.09	0.08	0.13	0.10	0.11	0.14	0.34	0.09	0.32	0.15	0.36	0.10
76 cm	-0.01	0.23	-0.19	-0.19	0.20	0.22	0.16	0.25	0.31	0.21	-0.08	0.26	0.28	0.13	-0.07	0.05	0.11	0.07	0.05	-0.03	-0.05	0.04
Average	0.13	-0.18	0.05	0.16	0.09	0.04	0.23	0.01	0.12	0.13	0.02	0.02	0.04	-0.00	0.28	0.17	0.35	-0.02	0.17	0.12	0.12	0.09
Third Principal Component																						
15 cm	-0.02	0.02	-0.02	0.12	0.14	0.13	0.01	-0.05	-0.05	-0.39	-0.21	0.19	0.07	-0.33	0.26	0.05	-0.18	0.19	-0.02	-0.12	-0.10	0.26
30 cm	0.00	-0.02	0.17	0.16	-0.20	0.14	0.06	-0.08	-0.08	-0.10	0.13	-0.27	-0.11	-0.05	-0.02	-0.27	-0.19	-0.55	-0.52	-0.38	-0.42	0.38
46 cm	-0.03	-0.41	0.07	-0.09	-0.02	0.09	-0.06	-0.17	0.32	-0.08	-0.07	0.29	0.19	-0.02	0.22	0.25	0.28	0.29	0.05	0.02	-0.04	0.18
76 cm	0.15	-0.15	-0.06	0.03	0.15	0.12	0.22	-0.05	0.28	-0.04	0.11	0.02	0.12	-0.15	0.15	0.18	0.28	-0.05	0.20	-0.16	-0.04	0.03
Average	-0.15	-0.10	-0.12	-0.20	0.08	-0.12	-0.11	0.20	0.12	-0.09	-0.29	0.19	-0.07	-0.18	0.24	0.49	0.10	0.44	0.40	0.28	0.16	0.21

6.3.5 Arctic 100-70 kPa Atmospheric Thickness Anomalies

Table 6.5 provides the correlation values between the atmospheric thickness over the Arctic (as explained in section 3.4.5) and the principal components of the eastern Canadian Prairies soil moisture values.

The first principal component has statistically significant positive values for April of the previous year with the soil moisture at all depths. The 76 cm level has strong positive correlations for the April to August period of the previous year to the soil sample measurement. These positive correlations are nearly the same periods and same depths as with the Arctic surface temperature. This is the result of the atmospheric thickness being directly related to density and therefore surface temperature.

The second and third principal components appear to have no strong trends or high correlation values.

6.3.6 Arctic Sea Ice Coverage Anomalies

Arctic sea ice functions as an interface between the ocean and the atmosphere. The ice reduces the heat flux in the cold atmosphere and thus affects the radiation budget (Johnson, 1980).

The monthly Arctic sea ice coverage is correlated with the soil moisture principal components (table 6.6). The level of statistical significance is based on 25 pairs. The sea ice coverage data set is described in section 3.4.6.

The correlation table appears to have one major area of strong correlations (table 6.6). The first principal component has the strongest negative correlation values during the June to September period of the year before the soil moisture sampling time. The 15 cm depth has the highest correlation values and the deepest depth (76 cm) also has significantly high correlations. Although the middle depths

Table 6.5 Correlation coefficients between monthly values of the Arctic 100-70 kPa atmospheric thickness and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.34 are significant at the 0.10 level and are shaded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
First Principal Component																						
15 cm	-0.03	0.16	-0.01	0.48	0.19	0.19	0.14	0.16	-0.29	-0.12	0.15	-0.10	0.03	-0.03	-0.00	0.20	0.05	-0.26	-0.06	-0.04	-0.08	0.02
30 cm	-0.18	0.05	-0.08	0.45	0.17	0.15	0.13	0.20	-0.29	-0.19	0.13	-0.10	-0.03	-0.16	-0.01	0.11	0.08	-0.16	0.05	0.02	-0.07	0.03
46 cm	-0.04	0.18	-0.07	0.42	0.26	0.23	0.18	0.16	-0.26	-0.18	0.21	-0.07	-0.00	-0.12	0.01	0.07	0.06	-0.19	0.05	0.05	-0.18	0.03
76 cm	0.17	0.24	0.08	0.45	0.50	0.35	0.39	0.36	-0.04	0.04	0.18	0.04	0.13	0.07	0.16	0.24	0.20	-0.06	0.14	0.13	-0.07	0.16
Average	-0.04	0.16	-0.01	0.48	0.27	0.24	0.22	0.22	-0.23	-0.14	0.19	-0.07	0.05	-0.08	0.04	0.17	0.11	-0.18	0.05	0.03	-0.08	0.06
Second Principal Component																						
15 cm	0.01	0.40	0.10	-0.11	0.16	0.09	0.30	-0.04	0.12	0.12	-0.41	-0.02	0.11	-0.03	0.35	0.18	-0.07	0.08	0.01	-0.03	0.26	0.13
30 cm	0.13	0.32	0.34	-0.06	0.15	0.05	0.16	-0.25	0.42	0.08	0.04	0.25	0.31	0.20	0.31	-0.04	0.17	0.09	0.15	-0.12	0.23	0.11
46 cm	0.31	0.38	0.29	0.17	0.10	0.04	0.22	0.14	0.08	0.21	0.34	0.30	0.13	0.14	0.17	0.07	0.08	-0.15	0.06	-0.35	0.14	-0.05
76 cm	0.04	-0.11	-0.11	0.27	0.25	0.25	0.03	0.22	0.02	0.34	0.09	-0.08	0.11	0.21	0.04	-0.11	-0.03	-0.06	-0.16	-0.05	-0.26	0.05
Average	0.09	0.39	0.17	-0.10	0.02	-0.03	0.14	-0.14	0.24	0.09	0.04	0.30	0.16	0.07	0.25	-0.08	-0.01	-0.07	0.04	-0.33	0.24	-0.01
Third Principal Component																						
15 cm	-0.05	0.15	-0.06	-0.14	-0.07	0.01	-0.09	0.16	0.09	-0.10	-0.11	0.04	0.28	0.04	0.19	-0.14	0.07	-0.13	0.06	-0.05	0.31	0.10
30 cm	-0.09	0.15	-0.25	0.10	0.07	-0.02	-0.02	0.02	-0.06	-0.18	-0.11	-0.23	-0.33	-0.39	-0.04	-0.15	-0.41	-0.33	-0.14	-0.19	-0.10	-0.36
46 cm	0.22	0.10	0.19	0.05	0.27	0.09	0.23	0.09	0.28	0.14	0.23	0.17	0.17	0.13	-0.01	-0.02	0.16	0.04	0.01	-0.36	0.03	-0.02
76 cm	0.22	0.33	-0.04	-0.09	-0.00	-0.00	0.13	-0.19	-0.12	-0.15	0.24	0.31	-0.11	0.13	-0.01	-0.27	-0.11	-0.27	-0.17	-0.47	-0.03	-0.18
Average	-0.08	-0.26	0.09	-0.13	-0.05	0.09	0.02	0.03	0.25	0.05	0.07	0.24	0.24	0.32	0.26	0.05	0.36	0.25	0.27	0.09	0.22	0.28

Table 6.6 Correlation coefficients between monthly values of the Arctic sea ice coverage and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.34 are significant at the 0.10 level and are shaded.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct.
First Principal Component																						
15 cm	-0.26	-0.33	-0.12	-0.07	-0.08	-0.52	-0.44	-0.38	-0.35	-0.04	-0.37	-0.25	-0.44	-0.30	-0.17	-0.15	-0.07	-0.07	-0.03	0.12	0.12	0.01
30 cm	-0.14	-0.24	0.05	0.04	0.04	-0.33	-0.22	-0.24	-0.27	0.12	-0.21	-0.12	-0.32	-0.21	-0.11	-0.25	-0.10	-0.08	0.01	0.19	0.17	0.09
46 cm	-0.19	-0.27	0.08	-0.06	-0.08	-0.37	-0.22	-0.33	-0.31	0.04	-0.28	-0.24	-0.25	-0.21	-0.19	-0.32	-0.22	-0.10	0.02	0.16	0.15	0.09
76 cm	-0.23	-0.40	0.06	-0.06	-0.24	-0.44	-0.31	-0.46	-0.35	-0.04	-0.27	-0.20	-0.17	-0.29	-0.28	-0.44	-0.30	-0.21	-0.06	0.05	0.03	0.07
Average	-0.20	-0.32	0.00	-0.04	-0.09	-0.46	-0.34	-0.37	-0.36	0.02	-0.30	-0.21	-0.35	-0.27	-0.18	-0.27	-0.15	-0.12	-0.02	0.12	0.11	0.04
Second Principal Component																						
15 cm	0.12	0.06	-0.01	-0.20	-0.26	-0.09	-0.04	0.10	0.12	0.08	0.22	0.07	0.24	0.20	-0.01	0.00	-0.09	-0.15	-0.13	-0.16	-0.07	0.18
30 cm	-0.11	0.12	-0.11	-0.10	-0.29	-0.15	-0.13	-0.20	-0.12	-0.20	-0.03	-0.14	-0.02	0.05	-0.16	0.01	-0.24	-0.26	-0.36	-0.31	-0.27	-0.37
46 cm	-0.28	-0.23	-0.31	-0.19	-0.08	-0.11	-0.16	-0.13	-0.20	-0.33	-0.30	-0.23	-0.11	0.11	0.01	-0.08	-0.33	-0.07	-0.04	-0.19	-0.04	-0.05
76 cm	-0.08	-0.24	0.01	-0.27	-0.21	-0.13	0.03	-0.01	0.02	-0.10	-0.12	-0.11	-0.03	-0.26	-0.47	-0.32	-0.01	-0.01	-0.04	0.03	0.06	-0.06
Average	-0.20	0.02	-0.21	-0.18	-0.16	-0.02	-0.00	0.02	-0.03	-0.22	-0.11	-0.18	-0.08	0.13	-0.06	0.04	-0.27	-0.05	-0.11	-0.14	-0.04	-0.15
Third Principal Component																						
15 cm	0.04	0.31	0.17	0.10	-0.10	-0.21	-0.23	-0.29	-0.18	-0.10	-0.24	0.10	-0.20	-0.11	-0.31	-0.09	-0.28	-0.06	-0.07	0.04	0.07	-0.15
30 cm	0.01	-0.03	0.35	0.26	0.09	0.16	0.15	0.36	0.46	0.28	0.28	0.24	0.04	0.05	-0.20	-0.01	0.05	-0.07	-0.07	0.12	0.06	0.46
46 cm	-0.11	-0.26	-0.17	-0.06	-0.15	-0.03	-0.12	-0.07	-0.11	-0.22	-0.02	0.00	0.06	-0.12	-0.10	-0.08	-0.16	-0.22	-0.24	-0.26	-0.23	-0.17
76 cm	-0.27	-0.13	-0.19	-0.23	-0.09	-0.09	-0.17	-0.17	-0.23	-0.27	-0.31	-0.37	-0.01	0.10	-0.12	0.03	-0.17	0.11	0.12	0.13	0.10	-0.02
Average	-0.07	0.10	-0.10	0.14	-0.01	-0.08	-0.15	-0.45	-0.50	-0.33	-0.30	-0.09	-0.08	-0.03	-0.05	-0.10	-0.10	-0.06	-0.06	-0.02	-0.07	-0.39

have few significant values, some of them are relatively high. These negative correlations suggest that a large areal extent of ice coverage precedes drier soil moisture conditions on the Canadian Prairies. The correlations also tend to be grouped because sea ice anomalies have high monthly persistence (Johnson, 1980). There are also lags between sea ice extent and atmospheric changes. The lag in atmospheric response to the sea ice buildup or depletion can be as much as two months (Walsh and Johnson, 1979).

The second and third principal components have no significant correlation values indicating that sea ice coverage has little influence on these soil moisture principal components.

6.3.7 North Atlantic Iceberg Numbers

The icebergs that appear off the Grand Banks of Newfoundland originate from various locations. These include the tidewater glaciers of Greenland and the glaciers and ice shelves of Ellesmere, Devon and Bylot Islands (Marko et al., 1986).

The number of icebergs reaching the Grand Banks depends on several environmental and atmospheric factors (Brown, 1993). These environmental and atmospheric properties may have some influence on the soil moisture on the Canadian Prairies due to teleconnection processes. This section investigates this possibility.

The annual North Atlantic iceberg numbers observed off Newfoundland's Grand Banks are correlated with the soil moisture principal component values (table 6.7). The significance values are based on 25 pairs (see section 3.4.7 for explanation of data set).

The correlations indicate North Atlantic iceberg numbers have little influence on the Canadian Prairie soil moisture. There does appear to be greater correlation in the second and third components rather than the first.

Table 6.7 Correlation coefficients between yearly values of the North Atlantic iceberg numbers and the amplitudes of the three soil moisture principal components. Values greater than the absolute value of 0.34 are significant at the 0.10 level and are shaded.

	Previous Year	Current Year
First Principal Component		
15 cm	-0.02	-0.06
30 cm	-0.02	-0.08
46 cm	0.14	-0.04
76 cm	0.16	0.04
Average	0.06	-0.04
Second Principal Component		
15 cm	0.00	0.18
30 cm	0.28	0.21
46 cm	0.34	0.13
76 cm	0.19	-0.13
Average	0.20	0.18
Third Principal Component		
15 cm	0.00	-0.01
30 cm	-0.36	-0.28
46 cm	0.07	-0.11
76 cm	0.31	-0.03
Average	0.16	-0.00

These correlations do have some correspondence with the Arctic sea ice coverage levels and the iceberg numbers in the third principal component during the year before the soil sampling time. The 30 cm depth for the third principal component for both data sets has strong significance levels. The sea ice values are mainly positive while the iceberg correlation value is negative. This could be an indication that while there is heavy ice buildup there is little iceberg calving.

6.4 Discussion and Conclusion

Seven synoptic-scale forcings are investigated in this chapter to determine if they are significantly correlated with Canadian Prairie soil moisture. Some interesting relationships are found (table 6.8).

The synoptic-scale forcing that appears to have the strongest relationship to Canadian Prairie soil moisture is the North Pacific sea surface temperature anomalies. They have statistically significant values for all soil depths about five months prior to the soil sampling. This lag is similar to Bonsal's (1991; 1993) results. He indicated that the longer the SST anomaly existed the longer the dry spell lasted. However, he did not state the lag time between SST occurrence and it's observed influence on the Canadian Prairie climate. This study found a three to six month lag between anomaly onset and the resultant influence on soil moisture.

Even though the Southern Oscillation Index, does not have very many significant correlations, it does have some interesting trends, especially with the first principal component. Negative correlations occurred in the fall and summer months then progressed to positive correlations in the spring and winter months prior to the soil sampling. This trend may indicate a slight influence but it is not statistically significant.

Table 6.8 Summary of synoptic-scale forcings and their significance levels

Synoptic-Scale Forcing	Principal Component	Soil Depth	Time of Significant Correlation	Positive /Negative Correlation
Sea surface temperature	1	All levels	May to August prior to sampling	positive
Sea surface temperature	1	15, 30, 46 cm	October prior to sampling	positive
Sea surface temperature	1	30, 46 cm	November of year prior to sampling	negative
Sea surface temperature	2	76 cm	October to April prior to sampling	positive
Sea surface temperature	3	30 cm	February to July prior to sampling	negative
PNA	1	15, 30, 46 cm	June of year previous to sampling	negative
Arctic temperature	1	15, 46, 76 cm	May of year previous to sampling	positive
Arctic temperature	1	76 cm	May to July prior to sampling	positive
Arctic atmospheric thickness	1	All levels	April of year previous to sampling	positive
Arctic atmospheric thickness	1	76 cm	April to August of year previous to sampling	positive
Arctic sea ice coverage	1	15, 46, 76	June to September of year previous to sampling	negative

While the Southern Oscillation Index and Pacific/North American patterns may not have had high correlations with the eastern Canadian Prairie soil moisture, they do have an influence on the North Pacific sea surface temperatures (Deser and Blackmon, 1995). Others (e.g. Jones and Peterson Draft, 1993) have stated that El Niño has very little influence over the eastern Canadian Prairies so these low correlations were anticipated.

Yin (1994) found that the Southern Oscillation Index most influenced the south eastern United States in his first principal component analysis (with an r value of 0.395). The difference between his analysis and this one may arise from the difference in study location (southeastern U.S. versus eastern Prairies) and timing of soil moisture data (February versus November). Yin's correlation value was for February soil moisture. The difference may also be due to Yin using the Palmer Drought Severity Index as apposed to measured soil moisture.

The Arctic anomalies also had some interesting trends and interrelationships. The first principal component had significant correlations in the spring and summer 15 to 17 months prior to the soil moisture sampling. The 100-70 atmospheric thickness and the temperature had positive r values while the sea ice coverage had negative values. The positive relationship is the result of the atmospheric thickness being directly related to density and therefore surface temperature while the negative correlation is the result of an inverse relationship between sea ice coverage and temperature. The fact that all three Arctic monthly anomalies have significant values at about the same time indicates that these anomalies do have some influence on the Canadian Prairie soil moisture.

7.0 CONCLUSION AND RECOMMENDATIONS

7.1 Summary

There were two main objectives of this thesis: first, to identify the spatial and temporal patterns of soil moisture on the Canadian Prairies by using principal component analysis; and second, to determine whether these patterns are related to synoptic-scale forcings. They were both achieved, making it possible for the hypothesis to be determined as true. The hypothesis found to be true is:

The soil moisture patterns (as determined by principal component analysis) are significantly related to North Pacific sea surface temperature anomalies.

This research was undertaken because of the opportunities to explain the spatial and temporal autumn soil moisture patterns in relation to synoptic-scale forcing. Understanding which synoptic-scale forcing most influences Canadian Prairie soil moisture may assist in improving extended forecasts for the Canadian Prairies.

This study has resulted in some interesting findings. Monthly and seasonal precipitation were not found to be significantly correlated with autumn soil moisture. These correlations may be low because vegetation tends to deplete all available soil moisture, resulting in uniformly low autumn soil moisture levels. The strongest correlations were in August to October period. This indicates that precipitation closest to the time of soil moisture sampling has the greatest influence.

The soil moisture principal component spatial patterns indicate weighted variations on the eastern Canadian Prairies. For example, the first principal component of the average soil moisture results in the entire study area having a negative weighted variation. However, there are differing weights. For example, Stuartburn has lower variation than Portage la Prairie indicating that Stuartburn has lower extremes than Portage la Prairie (Chapter 5).

The temporal soil moisture patterns show when drought or excess moisture events occurred. The early 1970s first principal component has large amplitudinal variation. The comparison between measured soil moisture and the principal component amplitudes did indicate, for example, that 1972 was a drier year than 1973 (Chapter 5).

The methodology for determining the spatial and temporal patterns of soil moisture was principal component analysis (Chapter 5). This analysis was used because of its ability to reduce the number of variables examined and to maintain the original variable variation. The first principal component for all soil depths was found to explain more than 40% of the variance. Therefore, the first principal component is the most dominant pattern both spatially and temporally.

It was thought that soil type patterns influence the soil moisture patterns. The soil order at the eastern edge of the study area changes from Chernozemic to Organic. This region is also the location where principal component weighted patterns tend to become more extreme (Chapter 5).

The quantity of soil moisture is related to the precipitation an area receives. The long memory of the deeper soil layers can indicate the teleconnections and the synoptic-scale forcings involved. The methodology for determining synoptic-scale forcings of the soil moisture was correlation analysis (Chapter 6). North Pacific sea surface temperature anomalies were found to have the strongest influence on the eastern Canadian Prairie autumn soil moisture for the first principal component. North Pacific sea surface temperature anomalies of late spring/early summer were found to be positively correlated with the autumn soil moisture. This means that when there is a positive sea surface temperature anomaly there is less soil moisture. The opposite is also true - when there is a negative sea surface anomaly the soil is moister.

The synoptic-scale forcings from the Arctic had little individual significance on the eastern Canadian Prairie autumn soil moisture. When the Arctic surface temperature anomalies and the Arctic atmospheric thicknesses are examined together, however, they become important. The period 17 to 19 months before the soil moisture sampling has relatively strong correlations for both forcings in the first principal component. This suggests that there is some interaction occurring with these synoptic-scale forcings and both influence the soil moisture a year and a half later.

The Arctic anomalies also had some interesting trends and interrelationships. The first principal component had significant correlations in the spring and summer 15 to 17 months prior to the soil moisture sampling. The 100-70 atmospheric thickness and the temperature had positive r values while the sea ice coverage had negative values. The positive relationship is the result of the atmospheric thickness being directly related to density and therefore surface temperature while the negative correlation is the result of an inverse relationship between sea ice coverage and temperature. The fact that all three Arctic monthly anomalies have statistically significant values at about the same time indicates that these anomalies do have some influence on the Canadian Prairie soil moisture.

The North Atlantic iceberg numbers appear to have a minor relationship with the autumn soil moisture in the third principal component. Iceberg numbers are also related to the Arctic ice cover. Therefore, these synoptic-scale forcings are again interrelated.

7.2 Conclusion

This study focused on the spatial and temporal characteristics of soil moisture on the eastern Canadian Prairies and the influence of synoptic-scale forcing on those characteristics.

The spatial and temporal patterns changed from principal component to principal component and with each depth. The first principal component corresponded most closely to the measured soil moisture - especially the temporal patterns.

The correlation between the synoptic-scale forcings and the principal components resulted in the discovery of one primary synoptic-scale forcing influencing the eastern Canadian Prairie soil moisture. This synoptic-scale forcing was the North Pacific sea surface temperature anomalies.

This study has expanded the knowledge of synoptic-scale factors and teleconnections for the study area the Canadian Prairies. The knowledge that the spring North Pacific sea surface temperature anomalies influence autumn soil moisture will aid in expanding the long term forecasting capabilities.

The Earth is but a small planet and everything is interconnected. The oceans influence the atmosphere; the land influences the atmosphere; the atmosphere influences the ocean and land. The influence of oceans, land and atmosphere on the global momentum budget is ongoing (Salstein and Rosen, 1984). This thesis tried to unravel a small portion of the global macroscale circulation and to find out which portion had the strongest influence on the Canadian Prairies.

7.3 Recommendations for Further Research

This study examined many synoptic-scale forcings influencing soil moisture on the Canadian Prairies. Other issues that need to be examined, but were out of the scope of this research, include the following:

a) determine land use patterns for each year with available data. This will help explain the differences in infiltration and evaporation processes that may influence the autumn soil moisture and help to explain the soil moisture patterns.

b) determine the spatial and temporal characteristics of precipitation using principal component analysis and determine whether these have the same patterns as the soil moisture maps and graphs. Also, determine if the same synoptic-scale forcings for precipitation have the significance correlation patterns as soil moisture. This will show whether synoptic-scale factors that influence precipitation are also the primary factors that influence autumn soil moisture.

c) determine how local weather affects the autumn soil moisture. Local weather patterns, e.g. convective storms, may have a strong influence on soil moisture and are only marginally influenced by broader weather patterns.

d) determine if other synoptic-scale forcings, e.g. hurricanes in the Caribbean, have an influence on autumn soil moisture.

e) further examine the interrelations among the synoptic-scale forcings. The interrelations between the synoptic-scale forcings themselves may have a large impact on autumn soil moisture. The interrelations for the Arctic region specifically are not well understood.

f) the information acquired by this study may be able to assist in further development of a drought forecast model for the Canadian Prairies.

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APPENDIX A

FORTRAN PCA Data Analysis Program (Microsoft 5.0).
Revised by E.A. Ripley June 30, 1994.

```
      Program EOFs
C  Calculates the covariance & correlation matrices and the EOFs
C  and time-series amplitudes for a data set, where:
C      b is the eigenvalue matrix
C      c is the eigenvector matrix,
C      nop is the order of the matrix,
C      nom the number of modes desired, and
C      noy the number of points in each series.
C--Arrays must be dimensioned as follows:
C      dat and amp -- nop, noy
C      cov and cor -- nop, nop
C      avg and b -- nop
C      a -- noc (number of non-zero elements in covariance matrix;
            i.e.nop*(p+1/2)
C      c -- nop, nom
      dimension dat(23,35), cov(23,23), cor(23,23), avg(23)
      dimension a(276), b(23), c(23,3), amp(23,35)
      data nop /23/, nom /3/, noy /35/
C--Open input data file
      open (unit=1,file='avgsoil.dat', status='old')
C--Open output data files
      open (unit=3,file='output.dat')
      open (unit=4,file='outbin.dat',form='unformatted')
      noc=nop*(nop+1)/2
C--Read data into an array
      do k=1,noy
            read(1,150) (dat(i,k),i=1,nop)
      enddo
C--Choose covariance or correlation matrix
      10 write (*,120)
      read (*,130) ino
      if (ino.eq.1) then
            write (3,140)
            goto 15
      elseif (ino.eq.2) then
            write (3,160)
            goto 15
      else
            goto 10
      endif
C--Zero accumulators
     15 summ=0.0
      do i=1,nop
            do j=1,nop
                  cov(i,j)=0.0
                  cor(i,j)=0.0
            endo
            avg(i)=0.0
      enddo
C--Calculate averages
      do i=1,nop
            do k=1, noy
                  avg(i)=avg(i)+dat(i,k)
            enddo
            avg(i)=avg(i)/noy
      enddo
C--Write inpute data and averages to file
      write (3,110)
      do i=1,nop
            write(3,250) i,(dat(i,k),k=1,noy), avg(i)
```

```
      enddo
C--calculate covariances
      do i=1,nop
            do j=i, nop
                  do k=1, noy
                        cov(i,j)=cov(i,j)+(dat(i,k)-avg(i))*(dat(j,k)-
avg(j))
                  enddo
                  cov(i,j)=cov(i,j)/noy
                  if(i.eq.j) then
                        summ=summ+cov(i,j)
                  endif
            enddo
      enddo
      write(3,200) summ
      write(3,140)
      do i=1,nop
            write(3,170) (cov(i,j),j=1,nop)
      enddo
      if (ino.eq.2) then
C--Calculate correlation coefficients
      do i=1,nop
            do j=1,nop
                  cor(i,j)=cov(i,j)/sqrt(cov(i,i)*cov(j,j)
            enddo
      enddo
      write (3,160)
      do i=1,nop
            write(3,170) (cor(i,j),j=1,nop)
      enddo
       endif
C--Convert from 2-dimension to 1 dimension array
      k=0
      do i=1,nop
            do j=i,nop
                  k=k+1
                  if (ino.eq.1) a(k)=cov(i,j)/summ
                  if (ino.eq.2) a(k)=cor(i,j)/nop
            enddo
      enddo
C--Call FHOUSE to calculate EOFs and write output data
      call fhouse (nop,nom,nop,b,nom,a,c)
      write (3,101) (l,l=1,nom)
      write (3,102) (b(l),l=1,nom)
      write (3,103)
      do i=1,nop
            write (3,104) i,(c(i,l),l=1,nom)
      enddo
C--Calculate time-series amplitudes from original data and
eigenvectors
C--and produce output
      do j=1,nop
            do k=1,noy
                  amp(j,k)=0.0
                  do i=1,nop
                        amp(j,k)=amp(j,k)+(dat(i,k)-avg(i))*c(i,j)
                  enddo
            enddo
      enddo
      do l=1,nom
            write(4) l,b(l),(c(i,l),i=1,nop),(amp(l,k),k=1,noy)
      enddo
      write (3,101) (l,l=1,nom)
      write (3,105)
      do k=1,noy
```

```
            write (3,104) k,(amp(l,k),l=1,nom)
      enddo
100 format (1x,/)
101 format (/' Modes--          ',8i8)
102 format (' Eigenvalues--     '8f8.3)
103 format (' Eigenvectors--')
104 format ('                   ',i2,2x,8f8.3)
105 format (' Amplitudes--')
110 format (' Location Input data----',56x, 'Averages')
120 format (' Enter 1 for covariance, 2 for correlation matrix ')
130 format (i2)
140 format (/,' Covariance Matrix')
150 format (23(F5.0))
160 format (/,' Correlation Matrix')
170 format (35(F5.1))
200 format (/ ' Total variance is ',f10.5)
250 format (1x,i8,36f5.1)
300 format (/ '      Mode Eigenvalues Eigenvectors----')
  20 end
```

APPENDIX B

SOIL MOISTURE STATIONS (Manitoba Natural Resources, 1991)

Station	Identifier	Latitude	Longitude
Russell	A-I-1	50°47'	101°17'
Runnymede	A-I-2	51°28'	101°42'
Yorkton	A-I-3	51°12'38"	102°36'13"
Canora	A-I-4	51°38'	102°27'
Theodore	A-I-5	51°26'	102°57'
Broadview	A-II-1	50°21'15"	102°37'11"
Lipton	A-II-2	50°55'19"	103°50'43"
Regina	A-II-3	50°24'19"	104°40'21"
Melita	A-III-1	49°16'	100°51'
Carlyle	A-III-2	49°38'46"	102°16'41"
Benson	A-III-3	49°27'32"	103°00'54"
Estevan	A-III-4	49°07'43"	102°57'37"
Weyburn	A-III-5	49°40'59"	103°55'05"
Radville	A-III-6	49°28'22"	104°17'28"
Brandon	A-IV-1	49°54'	99°56'
Shoal Lake	A-IV-2	50°26'	100°38'
Virden	A-IV-3	45°47'	100°57'
Moosomin	A-IV-4	50°11'32"	10°44'50"
Minnedosa	A-V-1	50°16'	99°51'
Wasagaming	A-V-2	50°39'	99°57'
Portage la Prairie	A-VI-1	49°58'	98°21'
Cypress River	A-VI-2	49°33'	99°02'
St. Norbert	R-I-1	49°45'	97°11'
Fannystelle	R-I-2	49°44'	97°48'
Rathwell	R-I-3	49°39'	98°30'
Killarney	R-I-4	49°11'	99°45'
Turtle Mountain	R-I-5	49°04'	100° 03'
Morden	R-I-6	49°08'	98°08'
Lowe Farme	R-I-7	49°22'	97°36'
Letellier	R-I-8	49°08'	97°17'
La Riviere	R-I-9	49°14'	98°37'
Ste. Anne	R-II-1	49°39'	96°40'
Steinbach	R-II-2	49°32'	96°41'
Dominion City	R-II-3	49°07'	97°09'
Stuartburn	R-II-4	49°07'	96°48'

APPENDIX C

LIST OF PRECIPITATION STATIONS

Station	Continuous Period of Record	Years		Latitude	Longitude
Altona, Man.	1965-1990			49° 06'	97° 33'
Arborg, Man.	1955-1990		(1955-1967)	50° 54'	97° 13'
			(1967-1978)	50° 55'	97° 03'
			(1978-1990)	50° 59'	97° 06'
Birtle, Man.	1955-1990			50° 25'	100° 50'
Brandon, Man.	1955-1990	34		49° 55'	99° 57'
Broadview, Sask.	1965-1991	24		50° 23'	102° 35'
Canora, Sask.	1965-1984	20		51° 38'	102° 24'
Carlyle, Sask.	1954-1990	34		49° 38'	102° 17'
Carman, Man.	1965-1990			49° 31'	98° 01'
Cypress River, Man.	1955-1989	34		49° 33'	99° 05'
Deloraine, Man.	1966-1990		(1966-1990)	49° 11'	100° 30'
Elm Creek, Man.	1964-1990			49° 43'	98° 00'
Emerson, Man.	1955-1990		(1955-1977)	49° 00'	97° 12'
			(1977-1980)	49° 01'	97° 13'
			(1980-1990)	49° 01'	97° 12'
Estevan, Sask.	1954-1991	34		49° 04'	103° 00'
Foam Lake, Sask	1956-1974			51° 38'	103° 32'
	1975-1989			51° 42'	103° 33'
Gretna, Man.	1955-1966		(1955-1966)	49° 00'	97° 34'
	1972-1973		(1972-1973)	49° 02'	97° 34'
Hamiota, Man.	1955-1977			50° 11'	100° 37'
Kamsack, Sask.	1955-1969			51° 34'	101° 54'
Killarney, Man.	1970-1976		(1970-1976)	49° 11'	99° 40'
	1980-1990		(1979-1990)	49° 10'	99° 40'
Kisbey, Sask.	1960-1976		(1960-1975)	49° 33'	102° 43'
			(1976-1977)	49° 33'	102° 38'
Lipton, Sask.	1961-1990	28	(1961-1979)	50° 52'	103° 47'
			(1979-1990)	51° 05'	103° 54'
Manitou, Man.	1970-1981		(1970-1972)	49° 13'	98° 30'
			(1972-1981)	49° 16'	98° 29'
Marchand, Man.	1972-1974; 1976-1981; 1984			49° 25'	96° 24'
Midale, Sask.	1954-1983			49° 24'	103° 25'
Minnedosa, Man.	1966-1990	23	1966-1990	50° 16'	99° 50'
Moosomin, Sask.	1955-1990	34		50° 09'	101° 40'
Morden, Man.	1955-1990	34		49° 11'	98° 05'
Morris, Man.	1956-1978			49° 21'	97° 22'
Peace Gardens, Man.	1967-1978 & 1984-1990			49° 00'	100° 03'
Pilot Mound, Man.	1958-1986			49° 12'	98° 54'
Portage la Prairie, Man.	1955-1990	34		49° 54'	98° 16'
Radville, Sask.	1955-1990	33		49° 30'	104° 17'
Regina, Sask.	1954-1991	34		50° 26'	104° 40'
Russell, Man.	1962-1990	27	(1962-1971)	50° 47'	101° 16'
			(1971-1990)	50° 46'	101° 17'
Selkirk, Man.	1964-1978			50° 09'	96° 53'
St. Alphonse, Man.	1963-1989			49° 27'	99° 01'
Virden, Man.	1965-1990	24		49° 51'	100° 56'
Wasagaming, Man.	1966-1989	23		50° 39'	99° 58'
Weyburn, Sask.	1954-1988	34	(1954-1972)	49° 40'	103° 51'
			(1972-1988)	49° 39'	103° 50'
Winnipeg, Man.	1955-1990			49° 54'	97° 14'
Yorkton, Sask.	1954-1991	34		51° 16'	102° 28'

APPENDIX D

Locations of Soil Moisture and Corresponding Climate Station Sites

Soil Moisture			Precipitation (mm)			
Station	Latitude	Longitude	Station	Period of Record	Latitude	Longitude
Lowe Farme	49° 22'	97° 36'	Altona, Man.	1955-1990 (1965-1990)	49° 06'	97° 33'
Brandon	49° 54'	99° 56'	Brandon	1955-1990	49° 55'	99° 57'
Broadview	50° 22'	102° 37'	Broadview	1965-1991	50° 23'	102° 35'
Canora	51° 38'	102° 27'	Canora	1965-1984	51° 38'	102° 24'
Carlyle	49° 38'	98° 30'	Carlyle	1954-1990	49° 38'	102° 17'
Rathwell	49° 39'	98° 30'	Carman	1964-1990 (1965-1990)	49° 31'	98° 01'
Cypress River	49° 33'	99° 02'	Cypress River	1955-1990 (1955-1989)	49° 33'	99° 05'
Fannystelle	49° 44'	97° 48'	Elm Creek	1964-1990	49° 43'	98° 00'
Dominion City	49° 07'	97° 09'	Emerson	1955-1990	(1955-1977) 49° 00' (1977-1980) 49° 01' (1980-1990) 49° 01'	97° 12' 97° 13' 97° 12'
Estevan	49° 07'	102° 57'	Estevan	1954-1991	49° 04'	103° 00'
Theodore	51° 26'	102° 57'	Foam Lake	1956-1974 1975-1989	51° 38' 51° 42'	103° 32' 103° 33'
Letellier	49° 08'	97° 17'	Gretna	1955-1966 1972-1973	(1955-1966) 49° 00' (1972-1973) 49° 02'	97° 34' 97° 34'
Shoal Lake	50° 26'	100° 38'	Hamiota	1955-1990 (1955-1977)	50° 11'	100° 37'
Runnymede	51° 28'	101° 42'	Kamsack	1955-1969	51° 34'	101° 54'
Killarney	49° 11'	99° 45'	Killarney	1969-1990 (1970-1976) (1980-1990)	(1969-1976) 49° 11' (1979-1990) 49° 10'	99° 40' 99° 40'
Benson	49° 27'	103° 02'	Kisbey	1959-1977 (1960-1976)	(1959-1975) 49° 33' (1976-1977) 49° 33'	102° 43' 102° 38'
Lipton	50° 56'	103° 51'	Lipton	1961-1990	(1961-1979) 50° 52' (1979-1990) 51° 05'	103° 47' 103° 54'
Minnedosa	50° 16'	99° 51'	Minnedosa	1957- 1990 (1966-1990)	(1957-1964) 50° 15' (1964-1965) 50° 15' (1966-1990) 50° 16'	99° 50' 99° 51' 99° 50'
Moosomin	50° 11'	101° 45'	Moosomin	1955-1990	50° 09'	101° 40'
Morden	49° 08'	98° 08'	Morden	1955-1990	49° 11'	98° 05'
Lowe Farme	49° 22'	97° 36'	Morris	1955-1987 (1956-1978)	49° 21'	97° 22'
Turtle Mountain	49° 04'	100° 03'	Peace Gardens	1961-1990 (1967-1978 & 1984-1990)	49° 00'	100° 03'
La Riviere	49° 14'	98° 37'	Pilot Mound	1958-1986	49° 12'	98° 54'
Portage la Prairie	49° 54'	98° 21'	Portage la Prairie	1955-1990	49° 54'	98° 16'
Radville	49° 28'	104° 18'	Radville	1955-1990	49° 30'	104 17'

Regina	50° 24'	104° 38'	Regina	1954-1991	50° 26'	104° 40'
Russell	50° 47'	101° 17'	Russell	1955-1990 (1962-1990)	(1955-1971) 50° 47' (1971-1990) 50° 46'	101° 16' 101° 17'
Shoal Lake	50° 26'	100° 38'	St. Alphonse	1962-1990 (1963-1989)	49° 27'	99° 01'
Virden	45° 47'	100° 57'	Virden	1955-1990 (1965-1990)	49° 51'	100° 56'
Wasagaming	50° 39'	99° 57'	Wasagaming	1966-1989	50° 39'	99° 58'
Weyburn	49° 41'	103° 54'	Weyburn	1954-1988	(1954-1972) 49° 40' (1972-1988) 49° 39'	103° 51' 103° 50'
St. Norbert	49° 45'	97° 11'	Winnipeg	1955-1990	49° 54'	97° 14'
Steinbach	49° 32'	96° 41'				
Yorkton	51° 12'	102° 37'	Yorkton	1954-1991	51° 16'	102° 28'
Stuartburn	49° 07'	96° 48'				
Ste. Anne	49° 39'	96° 40'				
Melita	49° 16'	100° 51'				

Note: the shading indicates the sites that were used in the analysis.

APPENDIX E
Spatial Principal Components (PC) of Soil Moisture

	15 cm Soil Moisture			30 cm Soil Moisture			46 cm Soil Moisture			76 cm Soil Moisture		
Station	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3
Benson	-0.239	0.024	-0.099	-0.256	-0.267	0.118	-0.244	-0.027	0.040	-0.221	0.344	0.081
B/CR [1]	-0.286	0.020	0.059	-0.295	0.214	-0.224	-0.268	0.216	0.089	-0.152	-0.244	-0.106
Broadview	-0.108	-0.011	-0.277	-0.139	-0.399	0.241	-0.235	-0.247	-0.082	-0.309	-0.066	-0.113
Canora	-0.123	0.329	0.219	-0.128	0.214	0.433	-0.039	0.171	0.161	-0.053	-0.001	0.427
LF/DC	-0.228	-0.332	0.010	-0.223	-0.200	0.030	-0.230	-0.237	0.111	-0.229	0.391	0.075
R/F	-0.291	-0.229	-0.094	-0.264	-0.189	-0.142	-0.248	-0.060	-0.229	-0.231	0.172	-0.035
TM/K	-0.284	0.118	-0.009	-0.275	0.198	-0.093	-0.244	-0.001	0.190	-0.299	0.260	-0.025
La Riviere	-0.211	0.028	0.101	-0.235	0.057	0.000	-0.190	0.091	-0.303	-0.184	-0.195	-0.233
SN/L	-0.271	-0.292	-0.095	-0.252	-0.268	-0.212	-0.283	-0.066	0.180	-0.220	0.028	0.180
Lipton	-0.230	0.120	0.353	-0.214	-0.013	0.012	-0.172	-0.295	-0.247	-0.278	0.034	-0.128
Melita	-0.212	-0.210	0.052	-0.179	-0.165	-0.427	-0.238	0.044	-0.336	-0.251	-0.137	-0.147
Minnedosa	-0.269	-0.074	-0.140	-0.192	0.109	0.049	-0.209	-0.169	0.361	-0.225	0.129	-0.181
Moosomin	-0.226	-0.014	-0.003	-0.237	-0.066	0.112	-0.250	0.163	-0.273	-0.278	-0.301	0.087
Runnymede	-0.157	0.322	-0.240	-0.135	0.359	-0.012	-0.128	0.370	-0.323	-0.127	-0.037	-0.148
Russell	-0.155	0.190	-0.153	-0.210	0.101	0.178	-0.184	-0.066	0.025	-0.252	-0.223	-0.041
Shoal Lake	-0.103	0.089	-0.488	-0.169	-0.045	-0.128	-0.284	-0.031	0.089	-0.131	0.051	0.351
SA/S	-0.246	-0.347	0.117	-0.168	0.080	-0.308	-0.188	-0.130	0.179	-0.204	0.301	0.135
Stuartburn	-0.132	0.151	-0.213	-0.142	0.156	-0.243	-0.075	0.371	0.327	-0.122	-0.267	0.209
Theodore	-0.191	0.096	0.294	-0.179	0.116	0.211	-0.114	-0.105	0.243	-0.079	0.095	0.276
Virden	-0.167	0.420	-0.138	-0.207	-0.235	0.264	-0.206	0.117	0.081	-0.229	-0.266	-0.133
Wasagaming	-0.232	0.102	0.010	-0.229	-0.107	0.187	-0.249	-0.177	-0.106	-0.136	0.181	-0.380
Weyburn	-0.063	-0.017	0.303	-0.117	0.211	0.258	-0.131	0.335	0.160	-0.160	-0.166	0.343
Yorkton	-0.134	0.278	0.334	-0.217	0.385	0.006	-0.150	0.425	0.007	-0.168	-0.214	0.223

[1] B/CR = Brandon/Cypress River; LF/DC = Lowe Farme/Dominion City; R/F = Rathwell/Fannystelle; TM/K = Turtle Mountain/Killarney; SN/L = St. Norbert/Letellier; SA/S = Ste. Anne/Steinbach

Spatial Principal Components of Soil Moisture (continued)

Station	Average Soil Moisture PC 1	PC 2	PC 3
Benson	-0.247	-0.177	-0.165
B/Cr	-0.254	0.153	0.192
Broadview	-0.161	-0.347	-0.357
Canora	-0.098	0.388	-0.214
LF/DC	-0.214	-0.231	-0.179
R/F	-0.262	-0.147	-0.121
TM/K	-0.275	0.070	0.240
La Riviere	-0.220	0.060	-0.060
SN/L	-0.268	-0.171	0.128
Lipton	-0.235	-0.036	0.101
Melita	-0.216	-0.157	0.311
Minnedosa	-0.219	-0.164	0.250
Moosomin	-0.251	0.185	-0.003
Runnymede	-0.154	0.238	-0.417
Russell	-0.188	0.016	-0.123
Shoal Lake	-0.192	0.037	0.038
SA/S	-0.185	-0.113	0.352
Stuartburn	-0.113	0.234	-0.022
Theodore	-0.157	0.111	-0.220
Virden	-0.207	0.001	-0.218
Wasagaming	-0.253	-0.114	-0.123
Weyburn	-0.098	0.298	-0.007
Yorkton	-0.177	0.484	0.209

APPENDIX F

Values of r from a Non-Correlated Population at four levels of significance

# of Pairs	Significance Level 0.100	0.050	0.010	0.001
14	0.457	0.532	0.661	0.780
16	0.426	0.497	0.623	0.742
18	0.400	0.468	0.590	0.708
20	0.378	0.444	0.561	0.679
25	0.337	0.396	0.505	0.618
30	0.306	0.361	0.463	0.570
35	0.283	0.334	0.429	0.532
40	0.264	0.312	0.403	0.501

Source: Brooks and Carruthers, 1953