UNIVERSITY OF ALBERTA

Climatic change and environmental implications in the Medicine Hat region using Billings, Montana as an analogue

BY

Wendy Ann Proudfoot ©

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Climatic change and environmental implications in the Medicine Hat region using Billings, Montana as an analogue" submitted by Wendy Ann Proudfoot in partial fulfilment of the requirements for the degree of Master of Science.

Dr. I.A. Campbell, Supervisor

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September 15, 1994
Date

ABSTRACT

There is concern that climatic change due to anthropogenic enhancement of the greenhouse effect may have considerable impacts on the natural and agricultural environments in Canada. The Palliser Triangle, encompassing southeastern Alberta, southern Saskatchewan, and southwestern Manitoba, is an area in which the impacts of climatic change could be significant; it is an important agricultural area, and is already sensitive due to its semiarid climate. This thesis examines possible effects of a change in the climate of the Medicine Hat area, in the Palliser Triangle, to a climate characteristic of a warmer, more southerly area, through the use of a regional analogue. The selected analogue region is the area around Billings, Montana. Aspects of the natural environment, including potential vegetation distribution, frost free period, and drought, as well as aspects of the agricultural environment, including agriculture practices and examination of wheat yields, are studied within each region. Comparisons are drawn between the two regions, to evaluate whether or not significant differences exist in the environmental aspects examined. It is shown that although a change in Medicine Hat's climate to one more like that of Billings may not have drastic impacts on the environment, such a change may require adjustments in current practices or adaptations to altered environmental conditions. Reviews of several policy areas will be necessary to ensure appropriate adjustments in agricultural or resource management practices. Regional analogy is shown to be an essential preliminary tool for determining possible effects of climatic change.

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1. CHAPTER ONE

INTRODUCTION, OBJECTIVES, AND BACKGROUND INFORMATION

1.1. Introduction

Over the last decade, there has been growing concern that climatic change in terms of global warming may have serious impacts on the environment and, in turn, the population which depends on it. The amount of literature in recent years on climate change and its potential biological, societal, and political implications (e.g. Glantz, 1988; Idso, 1989; Topping, 1989; Boer and De Groot, 1990; Houghton et al., 1990; Jager and Ferguson, 1990; Legget, 1990; Smith and Tirpak, 1990; Wall, 1990; Gates, 1993) clearly demonstrates the concern over climatic change and its possible repercussions. Levels of carbon dioxide and other gases in the atmosphere have been found to be increasing as a result of population growth, industrialization, and development of agriculture. The increased levels of these gases contribute to enhancement of the greenhouse effect, whereby atmospheric gases re-emit longwave, surface radiation back towards earth, warming the earth's surface and the lower atmosphere. Enhancement of the greenhouse effect is forecasted to cause temperatures to become higher than any in the last 150 000 years (IPCC Working Group I, 1990). Global mean temperature is expected to rise anywhere from 1.5-5.2°C (IPCC Working Group I, 1990; Mitchell, 1991). Central North America is projected to experience a warming greater than the global mean warming, and high latitude areas are expected to experience a winter warming much greater than the global mean warming (Houghton, 1990; Mitchell et al., 1990). Because Canada is a vast country which spans 41 degrees of latitude, it will experience the changes forecasted for both mid and high latitudes. This translates into a need for research into the potential impacts of climate change on the wide variety of Canadian landscapes, ecosystems, natural resources, and economic structures. Climate change studies in Canada have already covered a diverse range of topics, from implications for recreation activities such as downhill skiing (Lamothe and Periard Consultants, 1988), to agriculture (e.g. Arthur, 1988; Williams et al., 1988), forestry (e.g. Wheaton et al., 1989), water resources (e.g. Cohen, 1991) and sea-level rise (e.g. P. Lane and Associates, Ltd., 1988). In Alberta, adjustments in practice and policy may be required in natural resource management and agriculture, in order to ameliorate, or adapt to, the effects of future climatic change.

The aim of this study is to provide some indications of the possible implications of climatic warming for one of Canada's most drought sensitive agricultural areas: the southern, semiarid prairie region known as the Palliser Triangle. An assessment is made of potential impacts of climatic change on selected aspects of the natural and agricultural environments within the portion of the Palliser

Triangle which lies in southern Alberta.

Objective and methodology

Smit (1990) indicates that climate change impact assessments rely almost exclusively on either a scenario approach or an analogue approach. A scenario approach uses modelling (e.g. statistical or bio-physical) to estimate changes to the environment and/or economy under an assumed future climate. An analogue approach involves the examination of some other place or time in which the current climate is similar to that forecasted for the study area. A scenario approach can be used independently of an analogue; however, choosing an appropriate analogue usually relies on a scenario developed by modelling. In estimating the effects of climatic change on agriculture in Saskatchewan, Williams et al. (1988) recommended that:

> ...in addition to employing models to estimate the impacts of the climatic changes implied by a 2 X CO2 scenario, analogue areas should be sought that have present climates comparable to the study area scenario climate. (Williams et al., 1988, p.64).

Several studies, particularly in agriculture, have used the scenario approach to try to determine the implications of climatic change in the Prairie provinces (see Chapter 4 for examples). Only a few studies have used a contemporary regional analogue approach. These have focused mainly on identifying the analogous regions themselves, rather than using the analogue region to assess the environmental impacts of a changed climate on the study area. Some previous regional analogue studies are discussed later in this chapter.

This thesis will assess some potential effects of climatic change on the Palliser Triangle region of southern Alberta through use of a regional analogue. The representative area in the Palliser Triangle, Medicine Hat, is an ideal central location within the Alberta portion of the Triangle; the analogue region which was selected is Billings, Montana (Figure 1.1). The primary reason for selecting Billings as analogue was that its mean annual temperature is approximately 3°C warmer than Medicine Hat's, and it receives approximately 10% more precipitation annually (1961-90 normals). The temperature and precipitation changes are in line with current forecasts of climate change for the Medicine Hat area; the forecasts are discussed in more detail in Section 1.3.

The objective will be met by examining key aspects of the natural and agricultural environments of the Medicine Hat area, and comparing them to those of the analogue region. The climates of the two areas will be analyzed in detail, in order to validate the analogue and discern possible

Figure 1.1. Locations of Billings and Medicine Hat. Adapted from Espenshade and Morrison (1982). Scale is 1 : 12 000 000.

changes in temperature, precipitation, drought, and growing season which will affect the environment. Plant phenology and vegetation distribution will be examined as indicators of potential effects of climatic change on the natural environment. Aspects of the agricultural environment which will be examined are the general character of agricultural land use, cropping practices and current problems of land degradation, and spring and winter wheat yields. Wheat is the primary crop in both the study and analogue areas and any significant changes in yield due to a warmer climate might be reflected in the differences in yields between the two areas. Other studies which have examined possible climate change-induced changes to wheat yields are Arthur (1988), Wilks (1988), Williams et al. (1988), Mooney and Arthur (1990), Okamoto et al. (1991), Wheaton and Wittrock (1992), and Brklacich and Stewart (1993). These studies are discussed in Chapter 4.

This thesis follows a broad, integrated approach. Its purpose is to synthesize the potential impacts of climatic change on various aspects of the environment, rather than using a narrow, analytical method which focuses on one sector of agriculture or natural resources.

The Palliser Triangle

In order to monitor the effects of climate change on geomorphic and geological processes, the Geological Survey of Canada (GSC) has established Integrated Research and Monitoring Areas (IRMAs) in three regions in Canada. Each of these regions are considered highly sensitive to climatically-induced changes in geomorphological processes, and therefore they represent ideal areas in which to study the geomorphic impacts associated with climate change. Two of the GSC IRMAs are in northern Canada; one in the lower Mackenzie river basin, and one on Ellesmere Island. In southern Canada, the Palliser Triangle was selected as the climate change IRMA. In addition to being an appropriate site for monitoring geomorphic responses to climate change, the Triangle region lends itself to the study of natural and agricultural impacts of climate change, due to its national agricultural importance, and its history of drought-related problems relative to the rest of Canada. The Triangle's history of human-environment interactions is characterized by a sort of boom-and-bust, in which climatic oscillations such as that of the dry 1930s can wreak havoc on the land, and the population which depends on it.

The area now known as the Palliser Triangle (Figure 1.2) was identified in the report published on Captain John Palliser's expedition, which took place between 1857 and 1860. Palliser delineated the Triangle as a "central desert...forming a triangle, having for its base the 49th parallel from longitude 100° to 114°W., with its apex reaching

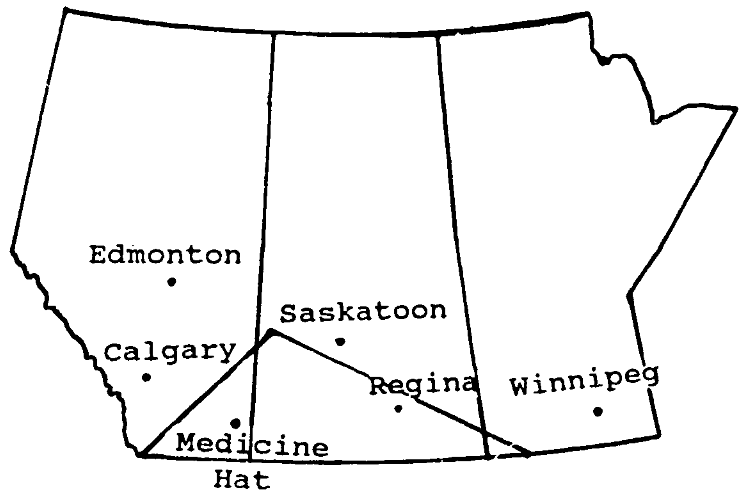


Figure 1.2. The Palliser Triangle, as delineated by Capt. John Palliser's expedition, 1857-1860. Drawn using description in Spry (1968) and map of Canada in De Blij et al. (1992). Scale is 1 : 19 600 000.

to the 52nd parallel of latitude" (Spry, 1968, p.9). The area of the Triangle, as defined by Palliser's limits, is approximately 175 000 km^2. In fact, the Triangle's boundary has never been precisely defined, although it has been delineated in various ways since the time of Palliser. Connor (1938) refers to the "Dry Belt" east of the Alberta foothills, whose "boundary...is hard to define and shifts considerably from decade to decade" (p. 362). Sanderson (1948) used the Thornthwaite moisture index when referring to "Canada's semi-arid climatic province (which) consists of a roughly triangular area in southern Saskatchewan and Alberta (where) average water deficiencies are large and impose serious limitations on agriculture" (p.511). For logistical convenience, the GSC has identified the core of the Triangle as being synonymous with the area of the Brown Chernozemic soils, which have an area of 100 230 km^2 (Clayton et al., 1977). According to Strong and Leggat's (1981) Alberta ecoregion classification, the area of Brown Chernozemic soils receives between 260 mm and 380 mm of precipitation annually, with an average of 330 mm. Isohyets within the Palliser Triangle (as delineated in Figure 1.2) show that annual precipitation ranges from about 300 mm to about 500 mm (Fisheries and Environment Canada, 1978). In summary, the Palliser Triangle's aridity and land use make it a good indicator of environmental impacts which might arise as a consequence of climate warming.

1.2. Background Information

Overview of climate change

The Earth's climate has fluctuated between temperatures both warmer and cooler than that at present over many thousands of years (see, for example, Nicholson and Flohn, 1980; Kutzbach and Street-Perrott, 1985; MacCracken and Kutzbach, 1991). Climatic change is partly due to changes in atmospheric circulation patterns; however, evidence resulting from analysis of Antarctic ice cores suggests that fluctuating concentrations of atmospheric CO_2 may have played a part in climatic change over the past 160 000 years (Barnola et al., 1987; Genthon, et al., 1987). While changes in atmospheric circulation patterns will continue to have an influence on the Earth's climate, it is widely believed that increased concentration in the atmosphere of the so-called greenhouse gases (carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and tropospheric ozone) resulting from human activities will intensify the effect of greenhouse warming. The result will be an increase in global mean annual temperature (IPCC Working Group I, 1990; Scheraga and Mintzer, 1990).

A factor which has the potential to alter the Earth's climate by disturbing the balance between solar energy absorbed by the Earth and radiation emitted by the Earth to space is called a "radiative forcing agent" (Shine et al., 1990, p.47). While all greenhouse gases contribute to radiative forcing, for simplicity total forcing is expressed in terms of the amount of CO_2 that would cause that forcing; this concept is known as the "equivalent carbon dioxide concentration" (IPCC Working Group I, 1990, p.xix). Although some greenhouse gases are increasing in concentration even more rapidly than CO_2 (Table 1.1), the Intergovernmental Panel on Climate Change (Houghton et al., 1990) have deemed CO_2 the most important greenhouse gas, as it was responsible for 61% of radiative forcing over the period 1765-1990 and 56% of forcing between 1980-1990 (Shine et al., 1990). CO_2 is the most abundant greenhouse gas and has a rapidly increasing concentration (Scheraga and Mintzer, 1990). During the decade between 1980 and 1990, the other greenhouse gases increased in an amount roughly equivalent to CO_2 (see IPCC Working Group I, 1990, p. xx). The scenario that is commonly used in climate models to predict the effects of global climatic change due to increased greenhouse gas concentration is that of doubling of the concentration of CO_2 by about the middle of the next century (the 2 X CO_2 scenario). Doubling of CO_2 concentration in the models estimates the contribution of all greenhouse gases to radiative forcing.

According to Scheraga and Mintzer (1990), predicted increases in temperature due to CO_2 doubling are of similar magnitude to the increase that has occurred since the last ice age, but within a much shorter time period; the increase that has occurred over the last 18 000 years could occur within a century. At the present rate of global climatic change, an increase in global mean annual temperature of somewhere between 1.9°C and 5.2°C may be expected by the middle of the next century (e.g. IPCC Working Group I, 1990; Mitchell, 1991). Temperature increases in southern Europe and central North America are expected to be greater than the global mean (Houghton, 1990). In general, high latitude areas are expected to experience greater warming than tropical areas (Mitchell et al., 1990; Mitchell, 1991). A large amount of warming is expected at high latitudes in winter, due to (a) reduction of albedo resulting from changes in sea-ice and snow cover; (b) changes in the radiation balance because of confinement of warming to the surface at high latitudes, and mixing of warming in the troposphere at lower latitudes; (c) increase in release of latent heat at higher latitudes as a result of an increased flux of moisture from the tropics (Mitchell et al., 1990). This greater potential for warming at higher latitudes reinforces the importance of assessing potential impacts of climatic change on vulnerable areas in Canada, such as the Palliser Triangle.

Models for projecting climate change

A widely used model for projecting future climate is the

	Carbon Dioxide	Methane	CFC-11	CFC-12	Nitrous Oxide
Atmospheric Concentration	ppmv	ppmv	pptv	pptv	ppbv
Pre-industrial (1750-1800)	280	0.8	0	0	288
Present day (1990)	353	1.72	280	484	310
Current rate of change per year	1.8 (0.5%)	0.015 (0.9%)	9.5 (4%)	17 (4%)	0.8 (0.25%)
Atmospheric Lifetime (years)	50-200	10	65	130	150

Symbols:
ppmv =parts per million by volume
ppbv =parts per billion (thousand million) by volume
pptv =parts per trillion (million million) by volume

Table 1.1. Changes in concentration of greenhouse gases. From IPCC Working Group I (1990).

General Circulation Model, or GCM. Several GCMs have been created by different organizations, such as the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), Oregon State University (OSU), the United Kingdom Meteorological Office (UKMO), the National Center for Atmospheric Research (NCAR), and the Canadian Climate Centre (CCC). GCMs solve simultaneous equations for the conservation of energy, mass, and momentum, and the thermodynamic equations of state for water and air, for grid points covering the earth's surface. The solutions to the equations are used to run a simulation of the daily development of weather systems. The results of the daily runs are averaged over simulated years to yield useable output data. The resulting climatic scenarios are usually developed for an atmosphere which has reached equilibrium at doubled concentration of CO_2. Because the gridpoints are relatively widely spaced (typically 300-1000 km according to Cubasch and Cess, 1990), GCMs are best suited to use on a continental rather than on a regional scale. Nevertheless, GCM results have been applied on a regional scale, as assessments of regional impacts of climate change are in demand, and as GCMs remain the most sophisticated method available to forecast CO_2-induced climatic change. For example, Williams et al. (1988) applied GISS results to Saskatchewan; Mooney and Arthur (1990) applied GISS results to Manitoba; and Cohen (1991) applied GISS, GFDL, and OSU results to the Saskatchewan River sub-basin.

Different GCMs include different values for their components; for example, grid spacing, number of atmospheric layers, seasonal and diurnal cycles, hydrology, and radiation vary between GCMs. Different GCMs also deal differently with ocean circulation, if they include an ocean component at all. These differences in model construction result in varied projections of future climate (Table 1.2).

<u>Analogue models for examining the impacts of climate change</u>

Four types of analogue model have been used to assess impacts of climatic change either on the environment or on society and the economy. They are: 1. paleoanalogues, 2. historical analogues, 3. situational analogues, and 4. regional analogues.

Paleoanalogues

Paleoanalogue models use proxy data derived from sources such as ice cores, pollen, and tree rings to determine paleoclimates and reconstruct paleoenvironments. Paleoclimates are often used to forecast 2 X CO_2 climate or to validate GCMs. Reconstruction of paleoenvironments, for example mapping vegetation patterns from pollen data (e.g. COHMAP members, 1988), can help show how paleoenvironments changed along with changing climate. Evidence from

GROUP	YEAR	RESOLUTION: N° of waves or lat. X long.	RESOLUTION: N° of vertical layers	Diurnal Cycle	Convection	Ocean Heat transport	Cloud	Cloud Properties	Temperature Change (°C)	Precipitation Change (%)
OSU	1989	4X5	2	N	PC	N	RH	F	4.4	11
NCAR	1989	R15	9	N	MCA	N	RH	F	4.0	8
GISS	1984	8X10	9	Y	PC	Y	RH	F	4.8	13
CCC	1989	T32	10	Y	MCA	Y	RH	V	3.5	4
GFDL	1989	R30	9	N	MCA	Y	RH	F	4.0	8
UKMO	1989	2.5 X 3.75	11	Y	PC	Y	CW	F	3.5	9

T =Rhomboidal/Triangular truncation in spectral space
N =Not included
Y =Included
PC =Penetrative convection
MCA =Moist convective adjustment
RH =Condensation or relative humidity based cloud
CW =Cloud water
F =Fixed cloud radiative properties
V =Variable cloud radiative properties

Table 1.2. Selected General Circulation Models indicating differences in construction and forecasts. Adapted from Cubasch and Cess (1990).

paleoclimatic and paleoenvironmental research indicates that during the mid-Holocene (approximately 5000-6000 BP) the climate in the continental interiors of North America and Eurasia, and in the high latitudes, was warmer than present (COHMAP Members, 1988; MacCracken and Kutzbach, 1991). Reconstructing past, warmer environments may provide useful indications of the changes in environmental aspects such as hydrology, vegetation distribution and landscape that might occur if the climate became more like it was at a previous time. Vance et al. (1992) used the mineralogical and paleobotanical data from two lake cores taken at Chappice Lake, approximately 27 km northeast of Medicine Hat, to assess approximately 7000 years of Holocene climatic characteristics in the area. The cores revealed alternation between sections dominated by laminae of carbonaceous sediment, containing fossils of plants associated with hypersaline conditions, and sections dominated by massive sediment, containing high amounts of silica and few hypersaline indicator fossils. The alternation signified low- and high-water periods; the low-water periods were associated with drought, and the high-water periods were associated with moist conditions. The results of the study suggest that over at least the last 7300 years there has been alternation between periods of repeated drought and periods of near absence of drought, and that the droughts in southeastern Alberta during earlier Holocene time (ca. 7000 BP to 6000 BP) were of greater magnitude than those in the area in the late 1800s, 1930s, and 1980s.

Historical Analogues

Historical climatic oscillations, such as the drought years in the 1930s, can also serve as analogues for the effects of future warming. Historical analogues can be used to study impacts of climate change on natural and agricultural systems, as well as studying past climatic patterns. This allows projections to be made as to what the societal and economic effects might be if the climate changed to one resembling climates of the recent past. For example, Williams et al.(1988) used scenarios representing the 1930s and the anomalous year 1961, in addition to using two scenarios given by the GISS GCM, (one including temperature and precipitation changes, and one including temperature only), to assess impacts of climate change on food production in Saskatchewan. The results from the historical scenarios indicate the potential for: an increase of 3-18% in growing degree-days; a decrease in precipitation effectiveness of 18-53%; a reduction in biomass potential of 26-100%; an increase of 123% in wind erosion potential; a reduction of 20-76% in spring wheat production; a reduction of $599-$1810 in expenditures by agriculture, and a reduction in employment in agriculture of 2647-8000 person-years.

Situational Analogues

Situational analogies can also be used to try to forecast responses to climate change. Glantz and Ausubel (1988) used the situation of the depletion of the Ogallala Aquifer in the American Great Plains as a contemporary analogue to global warming. They drew several parallels between the problem of global warming and the problem of depletion of the aquifer. Firstly, both situations are expected to become progressively worse over time, with the possibility of serious consequences by the next century. Secondly, the effects of both situations will be difficult and costly to reverse. Thirdly, delay in implementing policies to reduce contribution to both depletion of the aquifer and climate warming may result in the necessity to adapt to altered environments. Fourthly, both issues have resulted from near disregard for long-term consequences in favour of short-term gains. Finally, each of the situations represents a "Tragedy of the Commons" in which a resource is abused and depleted because everyone enjoys its accessibility, but no one takes responsibility for its management.

Regional Analogues

Regional, or spatial analogy is another method by which the potential impacts of climate change can be examined. Parry and Carter (1988) suggest that regional analogues can be useful in interpreting scenario climates (in their case, the GISS 2 X CO_2 scenario) "as effective illustrations of climatic change...", "as indicators of likely agricultural adaptations..." and "as indicators of potential productivity..." (Parry and Carter, 1988, pp.38-39.). The advantages of spatial analogy are that it is relatively simple, it is cost effective as it needs no elaborate equipment, and requires little fieldwork, as data on climate, crop yields, and the natural environment are usually readily available.

Early and numerous attempts to select regional analogues for climatic regions were made by Nuttonson (1947a-g, 1949, 1950a-d, 1951, 1952). He sought contemporary agroclimatic analogues in order to determine if plant cultivars could be exchanged between the analogous regions. Nuttonson's (1947a) study is most similar to this thesis because it deals with finding agroclimatic analogues for stations in Ukraine, an area which is similar to the Canadian Prairies. He selected analogous areas using mean monthly and yearly temperatures; average monthly, seasonal, and yearly precipitation; Thornthwaite precipitation effectivity indexes and ratios; length of frostless period; and latitudes. Nuttonson (1947a) also considered crop phenology and geography, vegetative cover-belts, and soil and physiographic characteristics in assigning analogous regions. Agroclimatic analogues for stations in Ukraine were found in Nebraska, Michigan, New York, Maine, Montana, North and South Dakota, Wyoming, Minnesota, and Wisconsin. More recent regional analogue studies, which assess impacts of climate change, are discussed in the following section.

1.3. Justification of the Billings region as analogue to the Medicine Hat region

Previous analogue studies for the Great Plains/Canadian Prairies

Previous studies (e.g. Newman, 1980; Rosenzweig, 1985; Parry and Carter, 1988; Mooney and Arthur, 1990; Mooney et al., 1994) have suggested that analogue regions for various locations in the Canadian prairies can be found in the northern United States. Newman (1980) simulated a +/- 1°C change in temperature, and an approximately 6 cm per °C change in potential evapotranspiration, to estimate the displacement of the North American "Corn Belt" along a warmer-drier/cooler-wetter gradient. He found a displacement gradient of 175 km per °C in a SSW-NNE direction. Rosenzweig (1985) used results from a doubled CO_2 run of the Goddard Institute for Space Studies General Circulation Model (GISS GCM) to generate a map of wheat regions under doubled CO_2 conditions. Although Rosenzweig's results showed that wheat regions in the United States remained essentially the same, they showed that the Canadian prairies would shift from an area growing predominantly spring wheat to one of predominantly winter wheat. From this, it would then be logical, from an agricultural point of view, to select an analogue for climate warming of the Medicine Hat area from the northern United States, as that region is currently growing winter wheat. Parry and Carter (1988) used temperature and precipitation changes suggested by the GISS GCM as a basis for selecting analogue regions for Iceland, Finland, the Leningrad and Cherdyn regions in Russia, northern Japan, and Saskatchewan (Fig. 1.3) Their map shows a potential shift in the climate of Saskatchewan to the southeast.

Mooney and Arthur (1990) used agroclimatic analogue areas to try to estimate the amount of crop migration which might occur under a 2 X CO_2 climate. Using output from the GISS GCM as projection of a 2 X CO_2 climate, cluster analysis was used to match doubled CO_2 scenario temperature and precipitation in areas of Manitoba with 1951-1980 normal temperature and precipitation in northern United States. The states of North Dakota, South Dakota, Minnesota, Montana, and Iowa were selected on the basis of previous studies of possible crop migration. Using cluster analysis on temperature alone suggested a south to north migration of climate of approximately 650 km, and clustering of precipitation alone suggested a northwesterly migration. Mooney and Arthur's results suggest a shift in climate of approximately 650 km to the northwest. The distance between Medicine Hat and Billings is approximately 500 km, in the same direction. The greater

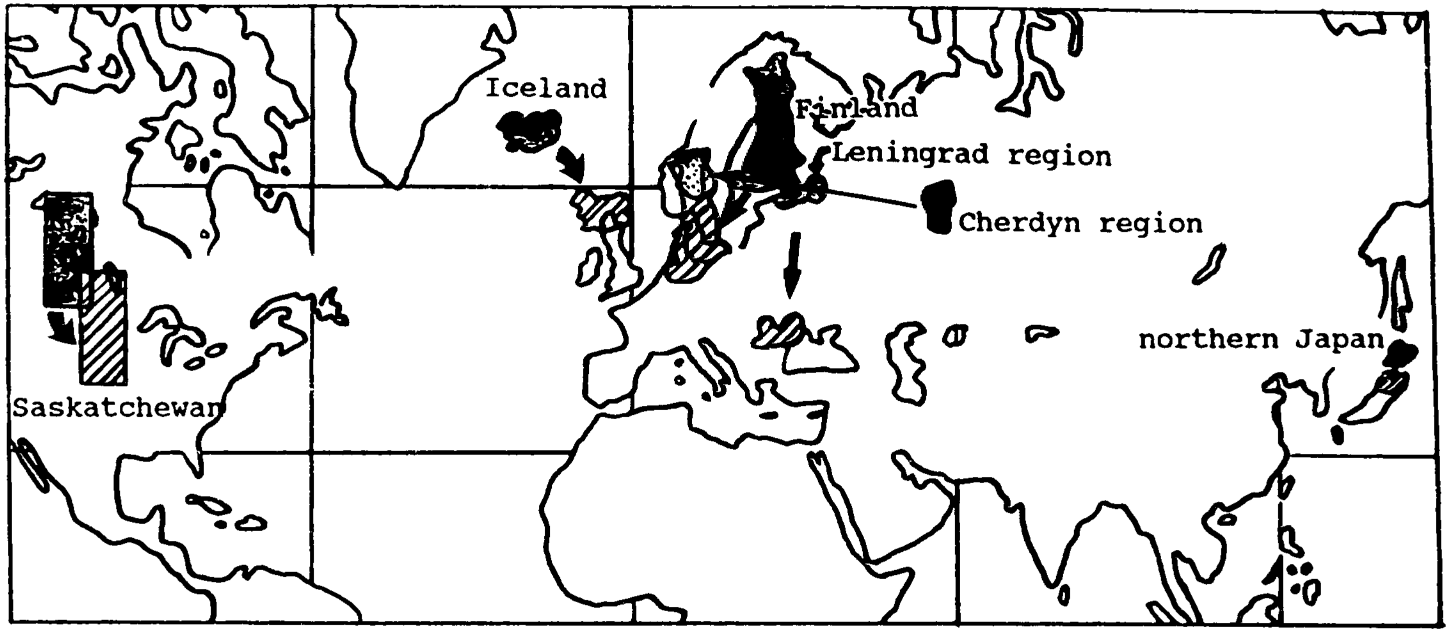


Figure 1.3. Analogous regions redrawn from Parry and Carter (1988).

distance of Mooney and Arthur's shift is likely due to the fact that they used GISS GCM results, which suggest a greater temperature increase (e.g. 4.6°C mean annual temperature for southern Alberta) than is being dealt with in this thesis (approximately 3°C mean annual temperature), to select their analogues. Further, Mooney et al. (1994) suggested that projected distances of climate shift resulting from cluster analysis are imprecise and may vary by up to 100 km, as the technique matches bands of climate, rather than specific sites. Mooney et al. (1994) used cluster analysis as in Mooney and Arthur, but matched projected 2 X CO_2 scenarios for Manitoba, Saskatchewan, and Alberta with stations in the northern United States (Figure 1.4). Mooney et al. (1994) also used agroclimatic data such as moisture availability, climate, soil type, and official crop reporting district boundaries to divide the Prairies into crop regions. Crop regions in Alberta were matched, using cluster analysis, with crop districts in Montana and Wyoming. Southeast Alberta was found to cluster with south central Montana, south east Montana, and north east Wyoming.

Consistency of non-climatic elements between regions

To reduce uncertainties in the impact assessment, as many elements of the natural environment as possible must be kept consistent between the analogue areas. This facilitates determining which changes in natural vegetation distribution, plant phenological development, agricultural land use, and crop yield are due to differences in climate between the two regions, and which are due to differences in other factors. It is difficult to control for differences in such things as day length or economically-directed agriculture policy, and, in general, "stringent validation of (analogue models) for impacts work is generally not possible..." (Williams et al., 1988, p. 253). Factors such as topography, soils, and agroeconomy should be reasonably consistent, but there are factors that can neither be controlled in the regional analogue model, nor in any other comparatively-based analogue.

At the macroscale, the topography of Billings is similar to that of Medicine Hat (Figures 1.5a-e). The elevations in the Medicine Hat area range from 610 m at the South Saskatchewan River approximately 50 km north of Medicine Hat, to 1465 m at the top of the Cypress Hills approximately 50 km southeast of Medicine Hat. Elevations in Billings range from approximately 915 m at the Yellowstone River 25 km northeast of Billings, to approximately 2689 m at East Pryor Mountain, approximately 70 km south of Billings. The terrain around Billings, like that around Medicine Hat, is rolling and dissected by coulees. Choosing an analogue region which displays topography similar to the study area helps to ensure that differences in land use, crop yield, and natural vegetation reflect differences in regional climate and not

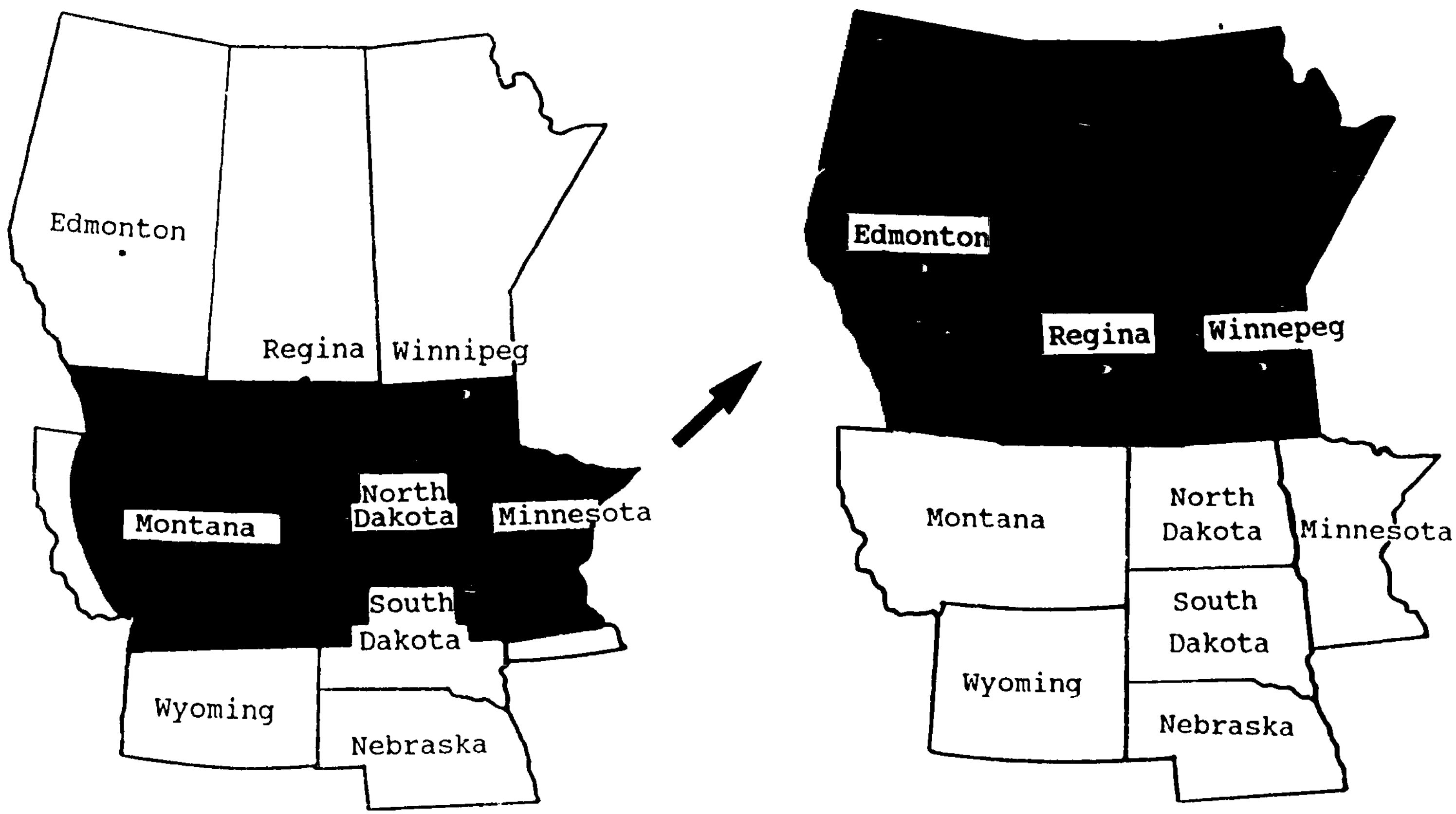


Figure 1.4. Analogue region for the Canadian Prairies, redrawn from Mooney et al. (1991).

Figure 1.5a. Similarity of agricultural landscapes in the Medicine Hat and Billings areas. Medicine Hat area, approximately 12 km north of the Cypress Hills (top), and Billings area, approximately 35 km northwest of Billings (bottom).

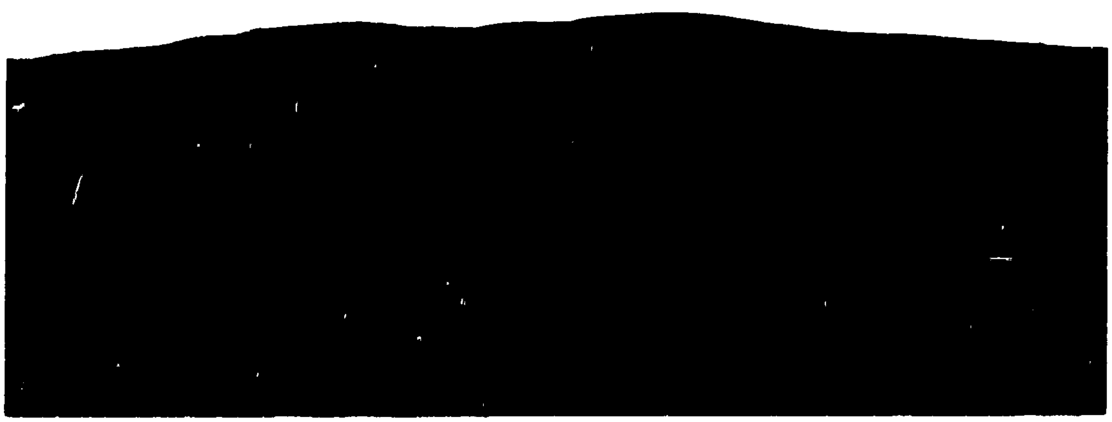


Figure 1.5b. Similarity of hilly rangeland landscapes in the Medicine Hat and Billings areas. Medicine Hat area, approximately 15 km southwest of the Cypress Hills (top), and Billings area, approximately 20 km south-southeast of Billings (bottom).

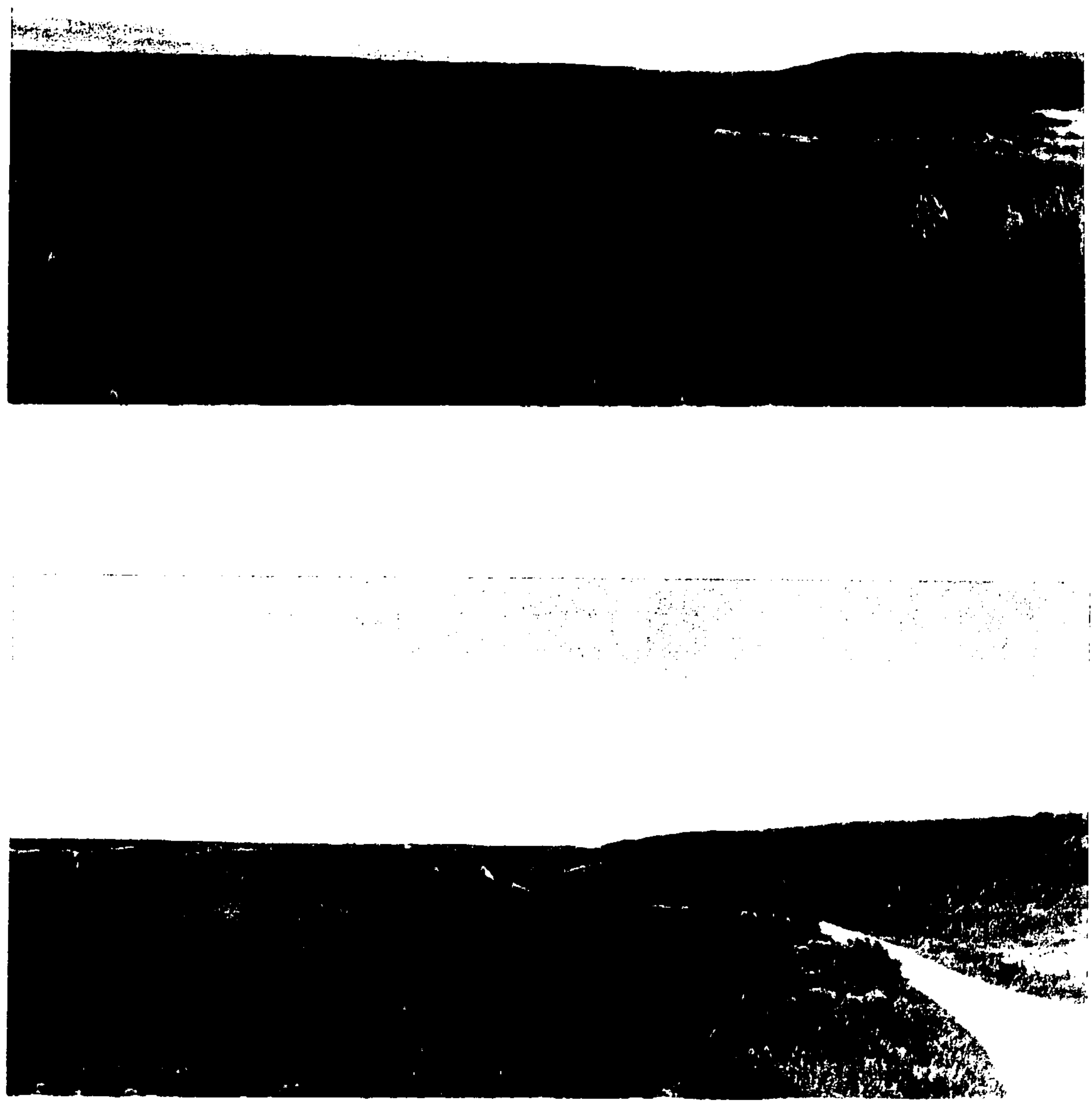


Figure 1.5c. Similarity of rolling landscapes in the Medicine Hat and Billings areas. Medicine Hat area, approximately 10 km east-southeast of Medicine Hat (top) and Billings area, approximately 20 km southwest of Billings (bottom).

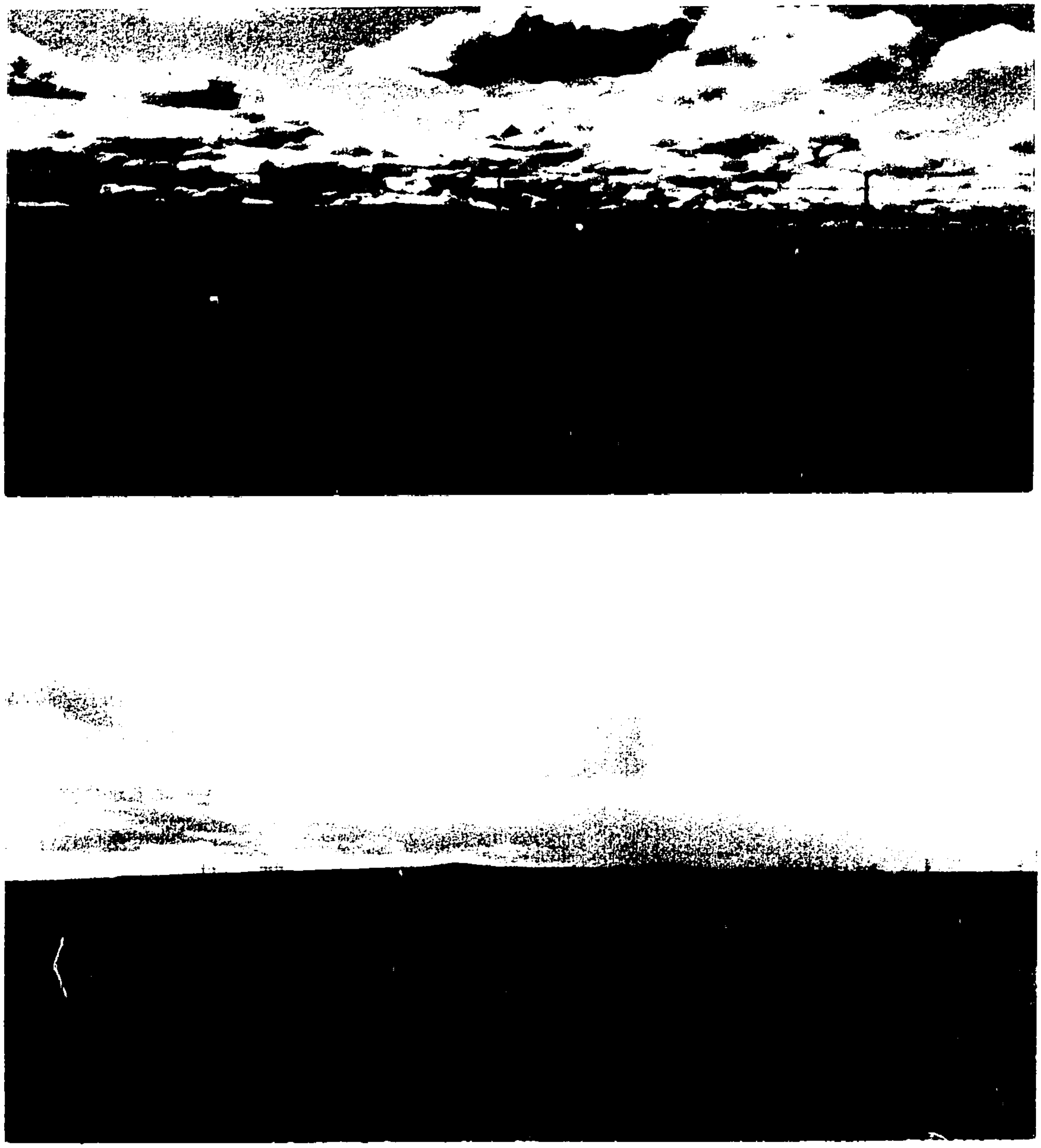
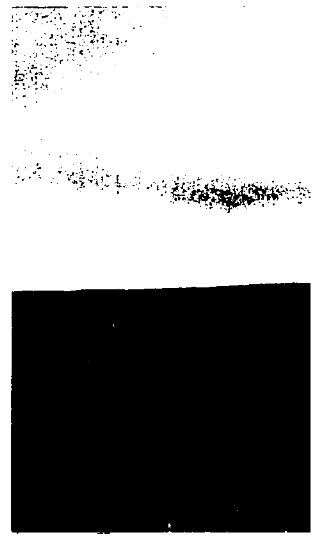


Figure 1.5d. Similarity of rolling landscapes in the Medicine Hat and Billings areas. Medicine Hat area, approximately 40 km northwest of Medicine Hat (top), and Billings area, approximately 25 km northwest of Billings (bottom).



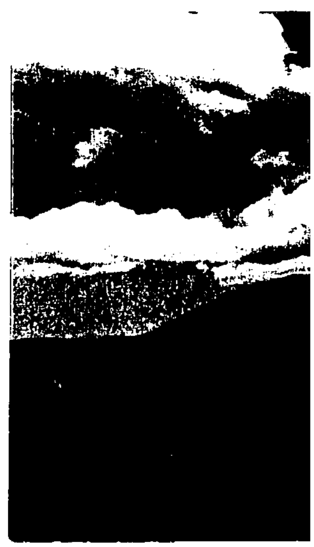


Figure 1.5e. Co
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parison of the Cypress Hills and Pryor ntains. Cypress Hills, approximately 50 km th-southwest of Medicine Hat (top), and or Mountains, approximately 50 km south of lings.

meso- and microscale climatic differences induced by topography.

One factor of the topography which differs is elevation of the regions as used in this study. The Billings weather station for example is 227 m higher than the Medicine Hat weather station (944 vs 717 m) which may influence comparisons made between vegetation and agriculture in the two regions. If the environmental lapse rate of 6.4°C per 1000 m (approximately 1.5°C in 227 m) were the sole determinant of temperature, a station at similar elevation to Medicine Hat's, at the latitude of Billings, could be 1.5°C warmer than Billings' current mean annual temperature.

The soil types around Billings and Medicine Hat are similar. Medicine Hat is in the Brown great soil group (Chernozemic order). According to Clayton et al. (1977), Brown Chernozemic soils are dominantly loamy in texture with some sandy and clayey areas, and are weakly calcareous. They develop mainly on glacial till, lacustrine, and fluvial deposits, but are also found on aeolian and alluvial surfaces. A horizons are greyish-brown to light brownish-grey. Billings is located in the entisol great group according the the soil taxonomy of the United States Department of Agriculture Soil Conservation Service (Soil Survey Staff, 1975). Entisols are recently formed and/or horizonless soils, which correspond to regosols in the Canadian System. Areas of Brown Chernozemic soils (Aridic Borolls in Soil Survey Staff, 1975) occur within Yellowstone County, in which Billings is located (Montagne et al., 1982). Two characteristic soils found in Yellowstone County are described in Montagne et al. (1982): Lisam soils in the northwest of the county, and Hesper soils in the south. Lisam soils are weakly developed, and occur on strongly sloping to steeply dissected areas of the sedimentary plains. They are clayey and calcareous, underlain by platy shale. Hesper soils develop on level to undulating upland terraces, as opposed to steep slopes. They have developed horizons, the A1 horizon being brownish-grey silt loam, the B2t horizon being brown silty clay loam or silty clay, and the Cca horizon being pale olive calcareous silty clay loam. They develop in uniform calcareous silt loam alluvium or loess. From the above descriptions, it seems that Hesper soils are similar to Brown Chernozemic soils. Given that Billings and Medicine Hat have similar soils, differences in land use, crop yields, and natural vegetation should reflect factors other than soil group.

Medicine Hat and Billings both have climatic records dating back to the beginning of the century. Data for Medicine Hat are available from 1883, and for Billings from 1911. The longer the climatic record, the more reliable it is for identifying long-term trends in climate and determining relationships between climate and vegetation or agriculture.

Temperature

Table 1.3 shows how the seasonal temperature differences between Medicine Hat and Billings compare to the temperature increases suggested by the Canadian Climate Centre General Circulation Model (CCC GCM). This model is reputed to be one of the best GCMs currently available (Nuttle, 1993; Cohen, pers. comm.). The CCC GCM figures in Table 1.3 were interpolated by eye from isotherm maps created by the Canadian Climate Centre (Appendix 1). The temperature difference between Medicine Hat and Billings is smaller than the temperature increase forecasted for southern Alberta by the CCC GCM (Table 1.3). The difference between Medicine Hat and Billings therefore represents a moderate case (as opposed to worst case) scenario of climate change conditions. However, Rosenzweig (1985) recommended using results of GCMs which suggest lower predictions of warming (than the GISS GCM), in order to do an impact assessment which is more restrained than a worst case scenario. Selection of an analogue region which does not represent as great a change as what the GCM suggests follows Rosenzweig's recommendation.

The comparative climate information for Medicine Hat and Billings is summarized in Figure 1.6. Climate normals for Medicine Hat are from Environment Canada (1993). Normals for Billings are from Owenby and Ezell (1992). Comparison of the distribution of temperatures between Medicine Hat and Billings shows that there is a greater difference in temperature in the winter months than in the summer months. The CCC GCM suggests that temperature increase will be greatest in the winter (Table 1.3). Thus, although the mean annual temperature difference between Medicine Hat and Billings is an underestimation of temperature change according to the GCM, the seasonal distribution of temperature differences between Medicine Hat and Billings corresponds with the pattern suggested by the CCC GCM.

Precipitation

Changes in precipitation were downplayed in the selection of an analogue, because there is not as much confidence in the scenarios for precipitation increase at the regional scale in the northern midlatitudes. This has been acknowledged by various authors (Wilks, 1988; Wong et. al., 1989; Mooney and Arthur, 1990; Cohen, 1991; Mitchell, 1991). One reason for the relatively poor reproduction of precipitation in climate models is that synoptic scale events which influence precipitation cannot be represented well. Further, Houghton (1991) points out that components of the hydrological cycle in relation to climatic change are not completely understood. Table 1.4 shows the seasonal precipitation changes forecasted for the Medicine Hat area, as compared with the difference between Medicine Hat and Billings precipitation. These were interpolated by inspection from isohyet maps created by the Canadian Climate Centre (Appendix 1). The Medicine Hat-

	DJF	MAM	JJA	SON
CCC GCM forecast for Medicine Hat[1]	7	5.5 - 6	4	3
Temperature difference between Medicine Hat and Billings	6	3	2	3

Table 1.3. Seasonal differences in temperature predicted for Medicine Hat, as compared with the difference in 1961-90 normal seasonal temperature between Medicine Hat and Billings. All temperatures in °C. (DJF = December/January/February; MAM = March/April/May; JJA = June/July/August; SON = September/October/November).

	DJF	MAM	JJA	SON
CCC GCM forecast for Medicine Hat[1]	>40%	50%	0 - -10%	0 - 10%
Precipitation difference between Medicine Hat and Billings	1.4%	43%	-16%	22.5%

Table 1.4. Forecasted precipitation changes according to the CCC GCM, as compared to the Medicine Hat - Billings difference.

[1]These figures have been approximated, using isotherm/isohyet maps of forecasted temperature/precipitation change according to the CCC GCM (see appendix 1).

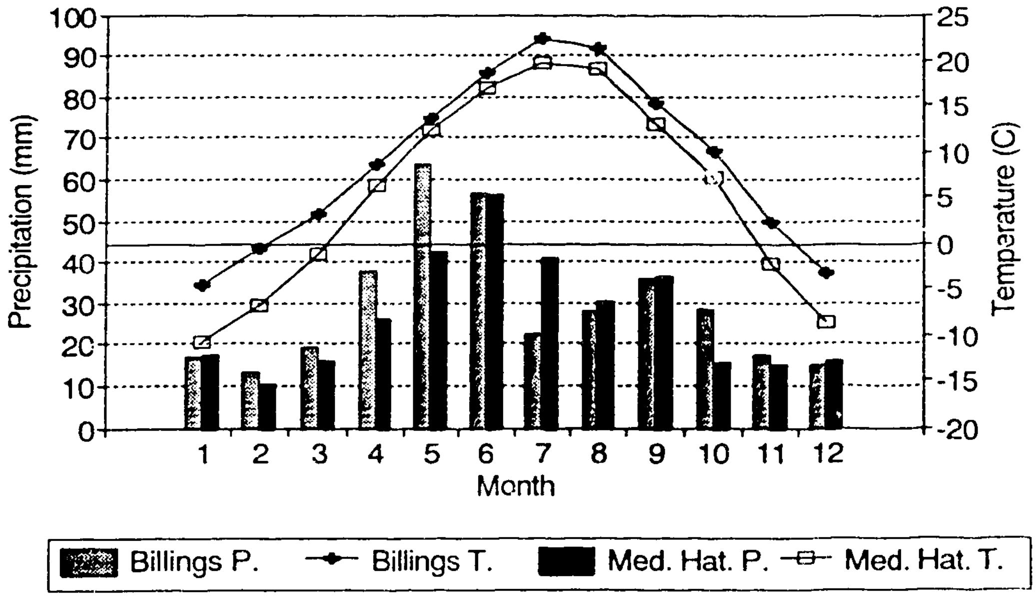


Figure 1.6. 1961-90 normal temperature and precipitation distributions of Medicine Hat and Billings.

Billings difference is less than the CCC GCM forecasts in all but September/October/November. As in the case of temperature, the pattern of precipitation is well-reproduced, although the exact amounts in the analogue model do not agree with the GCM forecast. The annual (1961-1990 normal) precipitation in Medicine Hat is 322.6 mm. Billings receives 353.8 mm of precipitation annually, 9.7% more than Medicine Hat. This represents an 8.3% underestimation of precipitation increase according to the GISS GCM results for southern Alberta, and a 2.7% overestimation according to GFDL and OSU GCM data (GISS, GFDL, and OSU GCM results from Wong et al., 1989). The direction of precipitation change between Medicine Hat and Billings is in agreement with GCMs, as all four GCMs show that annual precipitation will increase.

The projected isolines of temperature change for most of North America (Appendix 1), show that Billings and Medicine Hat are predicted to receive similar amounts of warming under 2 X CO_2. The fact that both areas might experience similar climate warming confirms that the characteristics that contribute to climate forcing in both locations are comparable.

As a result of the similarity of temperature differences between Medicine Hat and Billings to changes forecasted by the CCC GCM, consistency of non-climatic factors between the two regions, and similar analogue regions given in previous studies, the conclusion is that Billings is an appropriate analogue to Medicine Hat.

2. CHAPTER TWO

CLIMATIC ANALOGUES

2.1. Temperature

Two concepts are examined in this section: interannual variability between 1961 and 1990, and the question of whether or not there is evidence of a warming trend within the 57-year period between 1934 and 1990. Temperature data for Medicine Hat were obtained from the Meteorology Division, Department of Geography, University of Alberta (Thompson, pers. comm.). Temperature data for Billings were obtained from the National Climatic Data Center, Asheville, North Carolina.

Examining departures from 30-year normal (mean) temperature can provide a measure of interannual variability. Calculating departures from normal is a simple method of standardizing data. It allows easier recognition of variability than the use of raw temperatures because oscillations occur around a mean of zero, rather than around a different mean for each month or season (Halliwell, pers. comm.). Unless otherwise stated, the 30-year normal used throughout this thesis is 1961-90. Figures 2.1 and 2.2 show departures from normal temperature for Medicine Hat and Billings over the 1961-1990 period. Temperatures for January, February, and the previous year's December have been averaged into "winter months", and temperatures for June, July, and August have been averaged into "summer months". Winter and summer normals were determined by calculating averages of December-January-February and June-July-August normal temperatures. These were then subtracted from the averaged winter and summer temperatures for each year to obtain departures from normal winter and summer temperatures. Departure from normal mean annual temperature is also shown in Figures 2.1 and 2.2.

Means and standard deviations of departures from normal annual, winter, and summer temperatures were calculated. Means of departures from normal should equal zero; however, due to rounding of normals which were subtracted from raw monthly data, or rounding during conversion from Fahrenheit to Celsius in the case of Billings, some means are slightly greater or less than zero when rounded to one decimal place. In the case of missing monthly data, normal values were substituted. Table 2.1 shows means of departure from normal, standard deviations, and variances (squares of standard deviations) for Medicine Hat and Billings. Means, standard deviations, and variances were calculated using Quattro Pro (Appendix 2).

Anomalously high or low annual, winter, and summer temperature years were assessed for Medicine Hat and Billings. Departures from normal temperature which were greater than or equal to 2 standard deviations above or below the mean were considered anomalous. Figures 2.1 and 2.2 help to illustrate

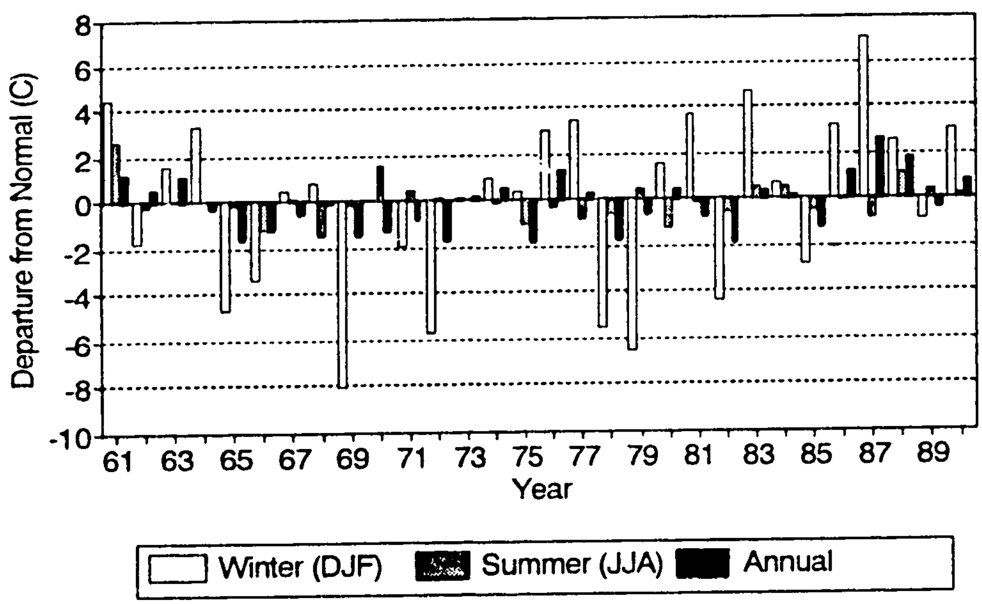


Figure 2.1. Departures from 1961-90 normal winter, summer, and annual temperatures by year, for Medicine Hat.

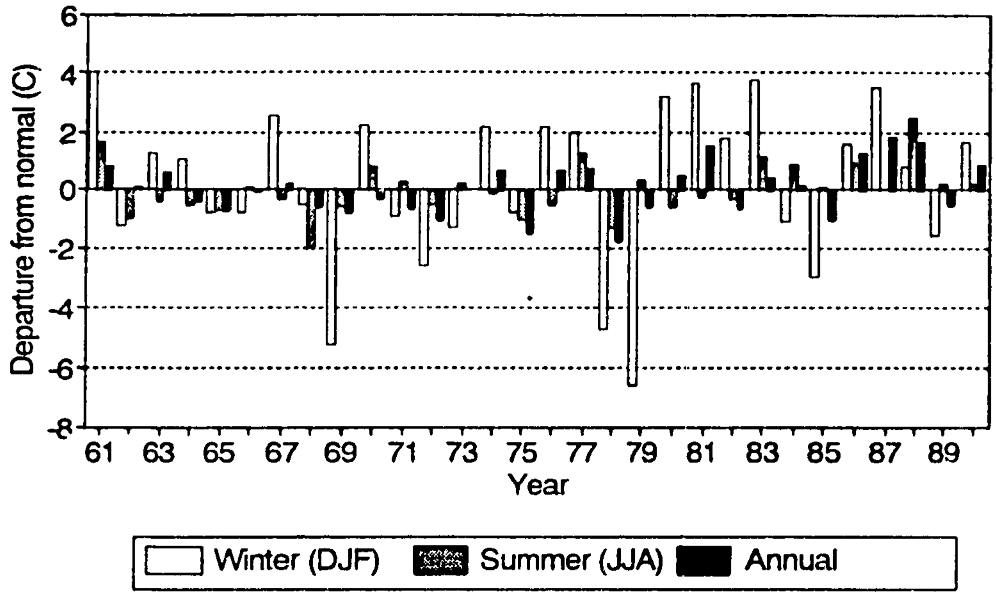


Figure 2.2. Departures from 1961-90 normal winter, summer, and annual temperatures by year, for Billings.

		ANNUAL	WINTER (DJF)	SUMMER (JJA)
MEAN	Medicine Hat	-0.1	0	0
	Billings	0	0.2	0
STANDARD DEVIATION	Medicine Hat	1.2	3.8	0.8
	Billings	0.9	2.8	0.9
VARIANCE	Medicine Hat	1.4	14.1	0.7
	Billings	0.8	7.6	0.8

Table 2.1. Means, standard deviations, and variances (squares of standard deviations) of departures from normal temperature for Medicine Hat and Billings, (1961-1990).
DJF = December/January/February; JJA = June/July/August. Means should equal zero, but may not because of error from rounding or conversion from Farenheit to Celsius.

years of temperature anomaly.

In Medicine Hat, the only year in which annual temperature is anomalously high (departure from normal of 2.3°C or above) is 1987, which has a departure from normal temperature of 2.7°C. There are no years when winter temperature is anomalously high (departure of 7.6°C or above), although 1987 is very close with a departure from normal of 7.0°C. There are 2 years in which summer temperature is anomalously high (departure of 1.6°C or above): 1961, which has a departure from normal of 2.7°C, and 1970, with a departure from normal of 1.6°C. In both Billings and Medicine Hat, 1987 is the only year in which annual temperature is anomalously high (departure of 1.8°C or above), with a departure from normal of 1.8°C. There are no years in Billings in which winter temperature is anomalously high (departure of 5.8°C or above), but summer temperature is anomalously high (departure of 1.8°C or above) in 1988, when the departure from normal is 2.5°C.

In Medicine Hat, there are no years in which annual temperature is anomalously low (departure from normal of -2.5°C or below). The only year when winter temperature is anomalously low (departure of -7.6°C or below) is 1969, with a departure from normal of -8.1°C. There are no years when summer temperature is low (departure of -1.6°C or below), but 1968 is close to being an anomaly at a departure from normal of -1.5°C. There is no year in which Billings' annual temperature is low (departure of -1.8°C or below), but 1978 is very close to being an anomaly at a departure from normal of -1.7°C. Winter temperature is low in Billings (departure of -5.4°C or below) in 1979 (departure of -6.6°C), and nearly anomalously low in 1969 (departure of -5.2°C). Summer temperature is low (departure of -1.8°C or below) in 1968 (departure of -1.9°C). The only years in which the temperature anomalies match in the two locations are 1987, when annual temperature is high in both locations, and 1968, when summer temperature is low. The frequency of temperature anomalies in each location is about the same: both have 1 year in which annual temperature is high and no years in which it is low; both have no years when winter temperature is high and 1 year when it is low. A difference in frequency occurs in summer temperature; Billings has 1 year when summer temperature is high and 1 year when it is low, while Medicine Hat has 2 years when summer temperature is high and none when it is low. Variance of annual temperature is greater in Medicine Hat. Variance of winter temperature is much greater in Medicine Hat, and variance of summer temperature is slightly greater in Billings.

In both Medicine Hat and Billings, variance of winter temperature is greater than variance of summer temperature or annual temperature. Winter temperatures during the 1961-90 period occurred up to 7 degrees above normal and up to 8 below normal in Medicine Hat, and up to 4 degrees above normal and 6.6 degrees below normal in Billings. Departures from summer temperatures occur within only 2.6 degrees above normal and 1.9 degrees below normal in both locations, and annual temperature departures occur within 1.9 degrees above or below normal.

Possibility of warming trends

Authors (e.g. Kerr, 1989; IPCC Working Group I, 1990; Jenne, 1991) have argued that there has been global warming of a few to several tenths of a degree over the last century. A linear fit of points of January, July, and mean annual temperature is presented in this section to examine the possibility of warming trends in Medicine Hat and Billings over the period 1934 to 1990. Figure 2.3 shows a linear fit of points of January temperature plotted against time. The time period, 1934-1990, was determined by the breaks in continuity in the Billings climate data record. The data within that period are continuous, but there is a gap in the data before 1934. The regression lines of Medicine Hat and Billings are drawn for the equations:

$T = (0.05)(Y) - 12.62$ (Medicine Hat; $R^2 = 0.02$)

and

$T = (0.004)(Y) - 4.38$ (Billings; $R^2 = 0.0003$)

where T=temperature
and Y=year.

The linear fit appears to show warming in both Medicine Hat and Billings; the amount of warming seems to be greater in Medicine Hat. The lines imply that over the 1961-90 period, Medicine Hat has conformed to the GCM forecast of milder winters, discussed in Chapter 1.

Figure 2.4 shows the linear fit of points of July temperature. The regression line equations for Medicine Hat and Billings are:

$T = (-0.03)(Y) + 21.13$ (Medicine Hat; $R^2 = 0.13$)

and

$T = (0.002)(Y) + 22.21$ (Billings; $R^2 = 0.0004$).

Medicine Hat's July temperature appears to have gone down, whereas Billings's July temperature has remained essentially the same.

Figure 2.5 shows apparent warming in mean annual temperature for the same time period. The regression line equations are:

$T = (0.01)(Y) + 5.03$ (Medicine Hat; $R^2 = 0.02$)

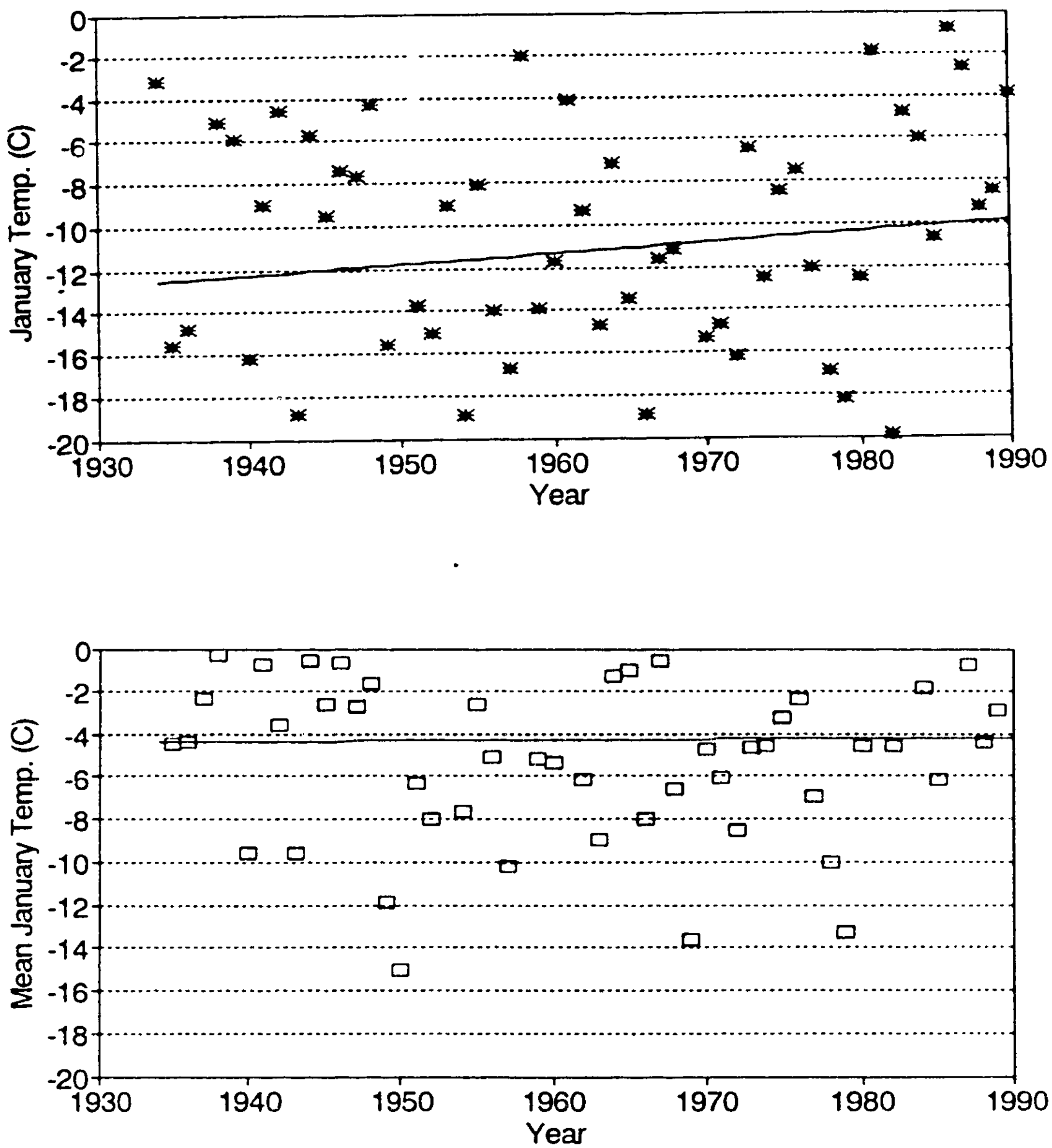


Figure 2.3. Linear fit of points of January temperature for Medicine Hat (top) and Billings (bottom), 1934-1990.

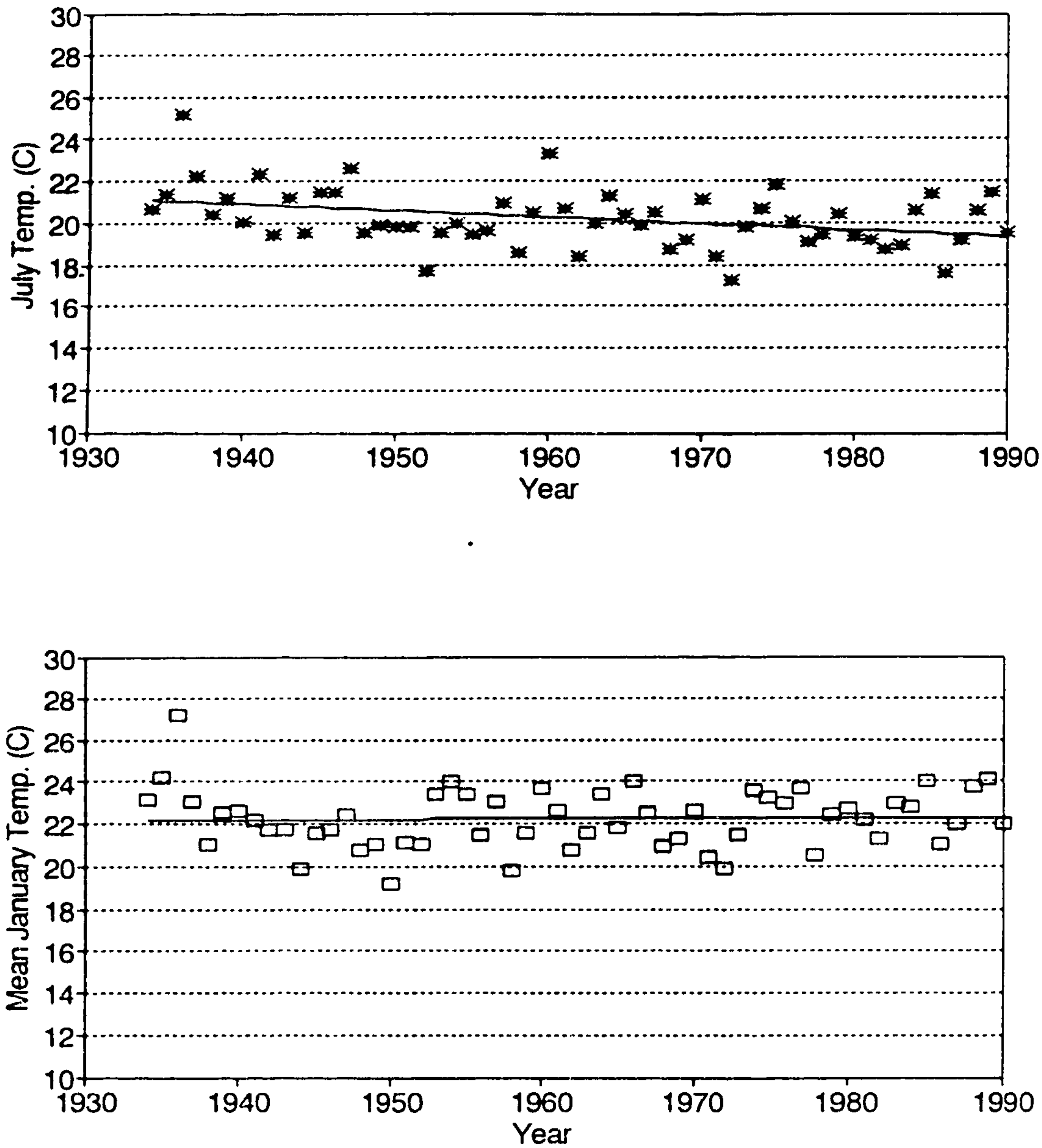
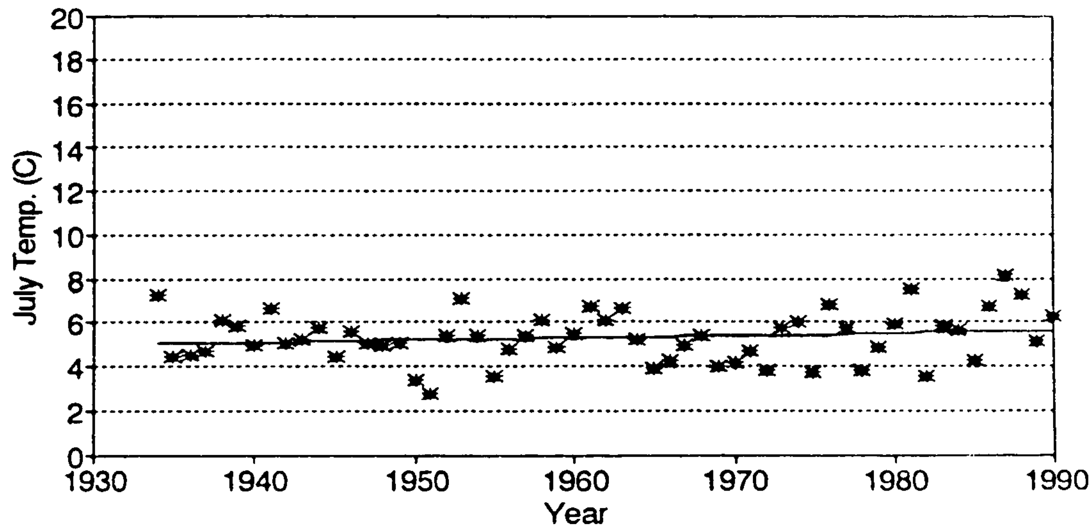


Figure 2.4. Linear fit of points of July temperature for Medicine Hat (top) and Billings (bottom), 1934-1990.



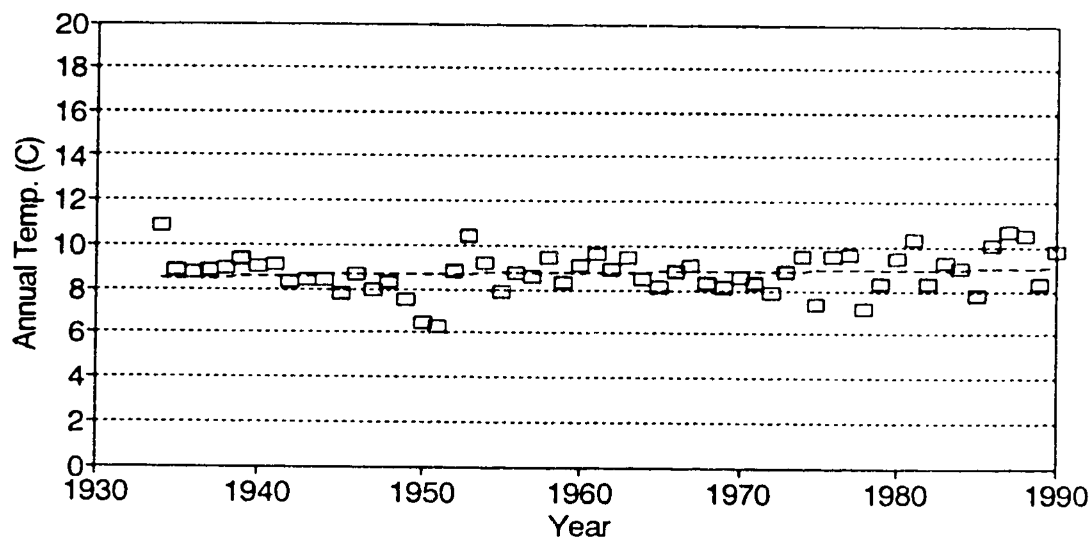


Figure 2.5. Linear fit of points of mean annual temperature for Medicine Hat (top) and Billings (bottom), 1934-1990.

and

$$T = (0.01)(Y)+8.50 \qquad \text{(Billings; } R^2 = 0.03)$$

Both Medicine Hat and Billings seem to have experienced warming in mean annual temperature.

R^2 values for the climate - year regressions are low, and are insignificant except in the case of Medicine Hat July temperature (Appendix 2). Attempts to determine climatic trends are problematic, because of (a) small databases due to the shortness of and gaps in the data record and (b) temporal climatic fluctuations in climate which lead to dispersion of data points. Nevertheless, it was desirable to try to determine if there was an evident warming trend. The linear fit lines are therefore interpreted as being illustrative, rather than as showing evidence of definite trends.

2.2. Precipitation

Departures from normal precipitation were used to give an indication of interannual variability of precipitation. Precipitation data for Medicine Hat and Billings were obtained from the same sources as temperature data (section 2.1). Figures 2.6 and 2.7 show both the growing season normals and departures from normal. Departures from normal growing season (May-August) precipitation were determined by first calculating an average of the May-August precipitation values for each year, then subtracting from that average a "growing season normal" determined by averaging the 1961-1990 normal values for each month. Departures from normal annual precipitation are shown in Figures 2.8 and 2.9.

In Medicine Hat, departures from normal growing season precipitation range from 20.1 mm above normal to 22.9 mm below normal (Figure 2.6). Mean departure from normal is -0.1, again unequal to zero because of rounding error. Sample standard deviation is 12.0, and variance is 144.9. In Billings, departures range from 41.1 mm above normal to 27.0 mm below normal (Figure 2.7). Mean departure is 0.1, sample standard deviation is 18.9, and variance is 358.3. Standard deviations and variances were calculated using Quattro Pro.

As in the case of departures from normal temperature, it was desirable to assess the number of years of anomalously high or low growing season precipitation. The threshold over or under which a departure value was considered an anomaly was 1.5 standard deviations above or below the mean, chosen because there is only one instance of values which are greater than or equal to 2 standard deviations above or below the mean. The instances in which values are greater than or equal to 1 standard deviation above or below the mean are too numerous to be considered anomalous (14 out of 30 in Medicine Hat and 10 out of 30 in Billings). In Medicine Hat, there are 2 years when precipitation is anomalously high: 1965, and

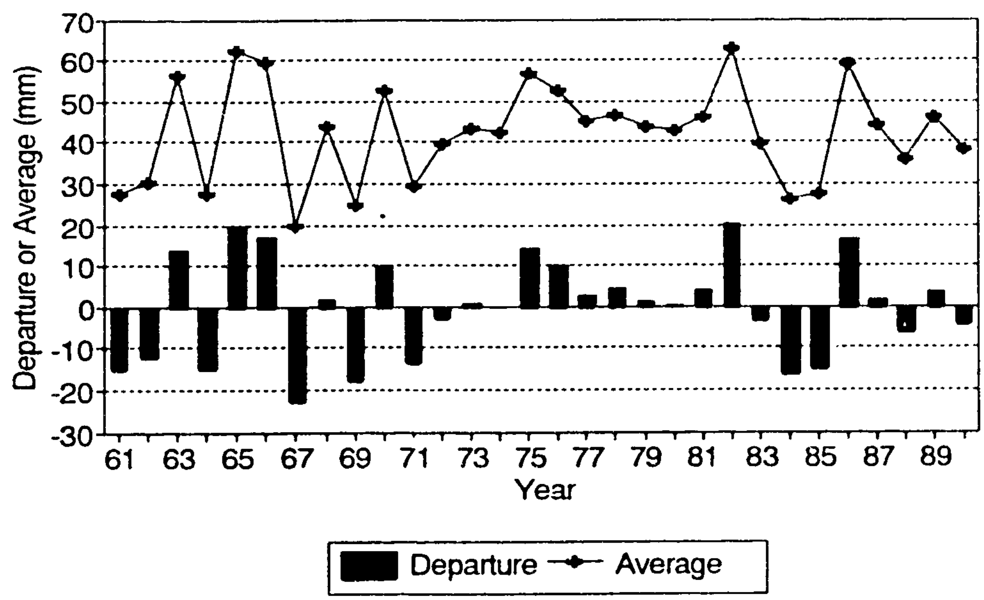


Figure 2.6. 1961-90 growing season (May-June-July-August) precipitation averages and departures from normal for Medicine Hat.

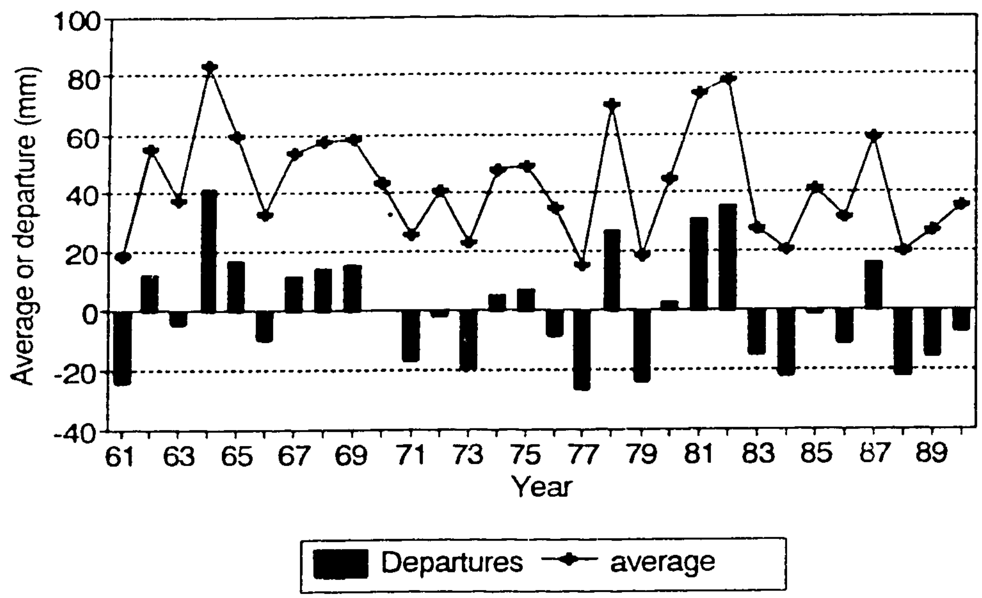


Figure 2.7. 1961-90 growing season (May-June-July-August) precipitation averages and departures from normal for Medicine Hat.

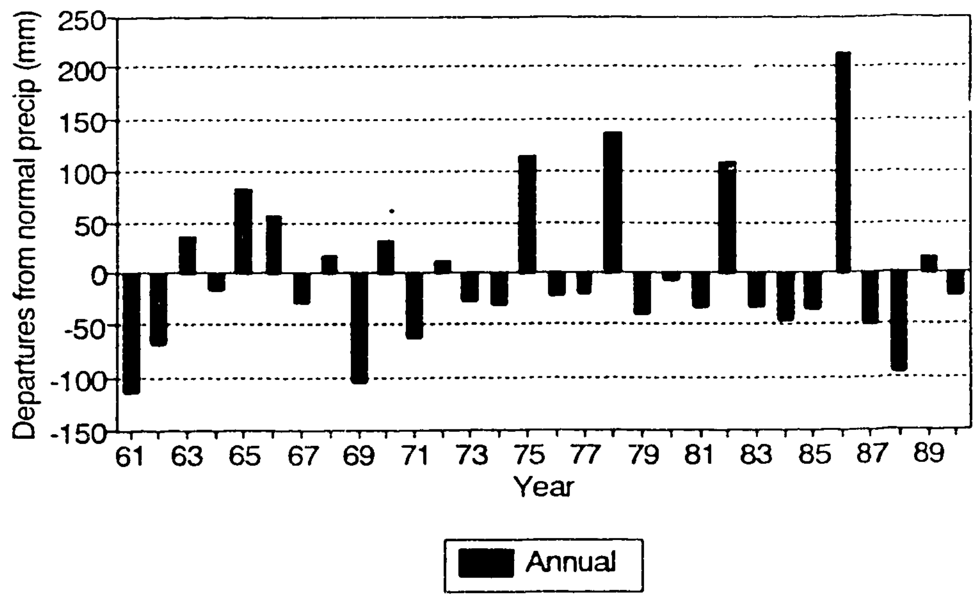


Figure 2.8. Departures from 1961-90 normal annual precipitation for Medicine Hat.

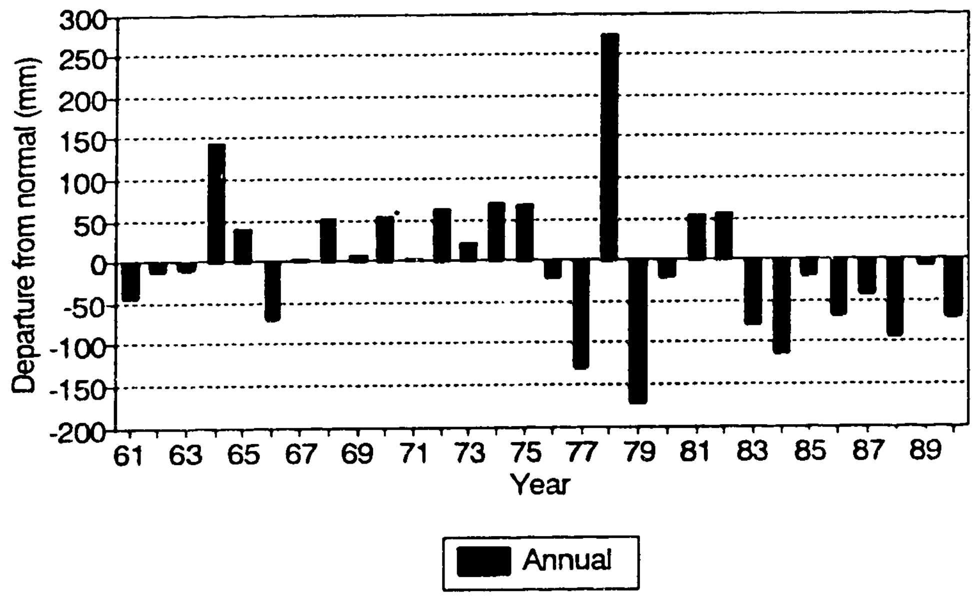


Figure 2.9. Departures from 1961-90 normal annual precipitation for Billings.

1982. There is one year, 1967, in which growing season precipitation is anomalously low. In Billings, precipitation is high in 3 years: 1964, 1981, and 1982. There are no years when precipitation is anomalously low. The only year when precipitation anomalies matched between the two locations was 1982, when precipitation was high. The frequency of high precipitation anomalies is about the same in both locations, and high precipitation anomalies are more frequent than low precipitation anomalies. Billings has one more high precipitation anomaly than Medicine Hat, but the reverse is true of low precipitation anomalies. Variance of growing season precipitation is greater in Billings.

Along with possible changes to precipitation with climatic change, there could be a change in the percentage of total precipitation which falls as snow. A change in the snow-rain ratio could affect the timing of runoff and peak streamflow and the amount of spring soil moisture. Whether the ratio of snow to rain will increase or decrease is not clear. For example, Gleick (1987) suggested a decrease in the snow-rain ratio in his study area in California, whereas Byrne and McNaughton (1991) suggested a heavier winter snowfall on the eastern slopes of the Rocky Mountains, if there is sufficient moisture. In Medicine Hat, approximately 33.5% of precipitation occurs as snowfall (108.2 cm snow out of 322.6 mm total precipitation). In Billings, approximately 39.8% of total precipitation occurs as snow (152.5 cm snow out of 383.0 mm total precipitation). The Billings figures are from the Billings airport, not the water plant weather station from which all other climate data were obtained, as the airport is the only weather station where snow data are recorded. Snowfall occurs in both locations from September through March.

2.3. Chinooks

Chinook winds are adiabatically warmed and dried winds blowing down leeward, rainshadow slopes. In North America chinooks are frequent along the eastern slopes of the Rocky Mountains, especially in the 320-480 km-wide (200-300 mile-wide, according to Glenn, 1961) "chinook belt" which extends along the eastern Rocky Mountain slopes from Alberta southward through central Montana, across eastern Wyoming and Colorado, and into northeast New Mexico (Glenn, 1961, p. 176).

Because Billings is closer to the mountains than Medicine Hat, one might expect a difference in chinook frequency. Prevailing wind directions both locations are similar; they experience mainly southwesterly winds with the exception of the months of May and December in Billings, when wind directions are northeast and west-southwest, respectively. Mean windspeed is slightly higher in Billings, where the annual windspeed is 18 km/h (1940-90 average), as opposed to 15 km/h (1961-90 normal) in Medicine Hat. Winter mean windspeeds are up to 6 km/h higher in Billings.

The frequency of chinooks in Medicine Hat has been quantified by Longley (1972) as approximately 20 days per winter. He defined a winter chinook day as a day in December, January, or February in which the maximum temperature reached 4.4°C (40°F). This definition is not suitable for Billings, as its milder climate yields the potential for many winter days to be 4.4°C or higher simply as a product of latitude, rather than chinooks.

Caprio and Nielsen (1992) defined a strong chinook as "a weather condition in which the maximum temperature of a given day is followed by a day in which the maximum temperature is at least 29°F (16°C) higher." (Caprio and Nielsen, 1992, p.52). They mapped chinook frequency in Montana in terms of number of strong chinooks per 100 years (Figure 2.10). Yellowstone county has 0-75 strong chinooks per 100 years in the southeast, 75-100 along the Yellowstone River, where the city of Billings is located, and 100-150 in the northwest. If the map is extrapolated northward into Alberta, the number of strong chinooks per 100 years in the Medicine Hat area lies between 150 and 225. In Montana chinooks appear to be most prominent just below the Canada-United States border, and slightly east of the Rocky Mountains, where there are up to 300 strong chinooks per 100 years. This pocket of high chinook frequency extends northward into Canada to the Lethbridge area. The United States National Climatic Data Center's Annual Local Climatological Data Summary indicates that winter temperatures in Billings become warmer with the occurrence of moderate to strong southwest winds, which are sometimes chinooks, but more often drainage winds moving down the Yellowstone Valley, bringing warmer Pacific air into the area (NCDC,1991). Thus, chinook frequency is greater in Medicine Hat, but the difference is not as pronounced as that between Billings and the pocket of heavy chinook activity in the northwest Montana-Lethbridge area. The drainage winds to which the NCDC publication refers may have the same effects in Billings as do chinooks in Medicine Hat.

Winter chinooks remove substantial amounts of snow through sublimation and reduce soil moisture in the following growing season. If so, there should be greater propensity for summer drought in the location where chinooks are more frequent, in this case, Medicine Hat. The following section discusses drought frequency in Medicine Hat and Billings.

2.4. Drought

Although annual precipitation may increase with future climate warming, summer soil moisture may decrease because of increased evapotranspiration (Gleik, 1987; Arthur, 1988; Williams et al., 1988; Mitchell et al., 1990; Cohen, 1991). In order to examine changes in drought frequency and magnitude which might occur in Medicine Hat, Palmer Drought Severity Index values from Medicine Hat are compared with those of

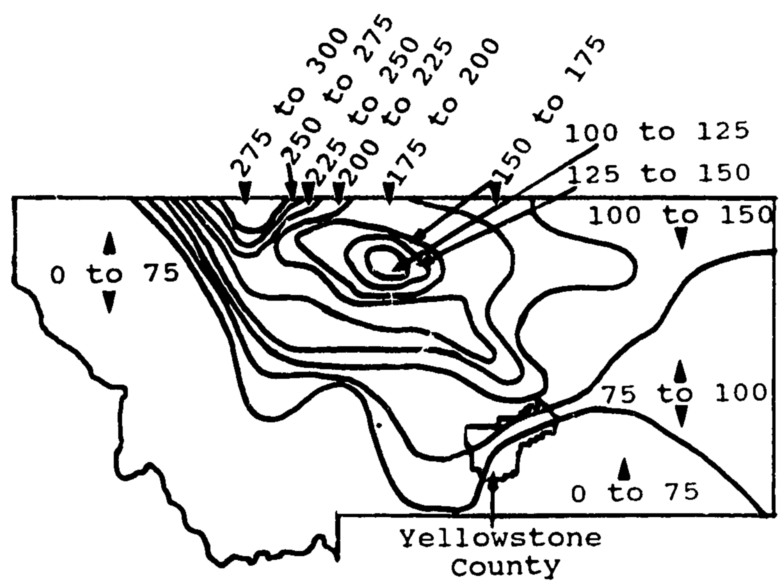


Figure 2.10. Number of strong chinooks per 100 years in Montana, adapted from Caprio and Nielsen (1992).

Billings for the period 1961-1990, and compared with those of southcentral Montana for the drought period of the late 1920s and early 1930s.

The Palmer Drought Severity Index (PDSI) was developed by Wayne C. Palmer in the 1960s. It is a cumulative index which combines successive, weekly values of the difference between actual evapotranspiration, which is based on actual temperature, precipitation, and soil moisture, and expected evapotranspiration, which is an adjusted value which depends on the departure of weekly temperature from normal (Palmer, 1968). The index is generally measured from -5 to +5, although these values may be exceeded in extreme cases. A value between 0 and -1 indicates normal to incipient drought conditions, between -1 and -2 indicates mild drought, between -2 and -3 indicates moderate drought, between -3 and -4 indicates severe drought, and anything less than -4 indicates extreme drought. Positive numbers indicate wetter than normal conditions, and are calibrated similarly to negative numbers. A value of 1-2 indicates slightly wetter than normal conditions, 2-3 indicates moderately wetter than normal, and so on.

PDSI data for Medicine Hat were obtained from the Canadian Climate Centre of the Atmospheric Environment Service, Environment Canada (Louie, pers. comm.). Data for Billings were obtained from the Climate Office at Montana State University's Department of Plant and Soil Science (Wraith, pers. comm.). In the Medicine Hat and Billings data sets, all values of -0.5 to 0.5 inclusive were set to zero.

An indication of significant drought conditions was obtained through examination of growing season drought conditions. Salter and Goode (1967), Bauer (1972), and Campbell et al. (1988) showed that wheat is most sensitive to moisture stress at or around the growth stage of heading when grain development occurs. In Billings, heading of winter wheat, the principal grain crop, occurs in June. Heading of spring wheat, the main grain crop grown in Medicine Hat, occurs in in July. These two months represent a crucial time in grain development so they were chosen for PDSI analysis.

Figure 2.11 shows 1961-1990 June PDSI values for Medicine Hat and Billings. Medicine Hat has a lower PDSI value than Billings 16 years out of 30, whereas Billings has a lower value than Medicine Hat 12 years out of 30. Isolating the 18 years in which values for one or both locations fall below zero shows that Medicine Hat has a lower value than Billings in 8 of the years, while Billings has a lower value than Medicine Hat in 10 of the years. Of the 9 years that both locations have values which fall below zero, there is only 1 year, 1961, in which Medicine Hat's value is lower than that of Billings. In all other mild to severe drought years, the severity of drought is greater in Billings.

In July (Figure 2.12), Medicine Hat's PDSI value falls below that of Billings in 15 years out of 30, whereas Billings

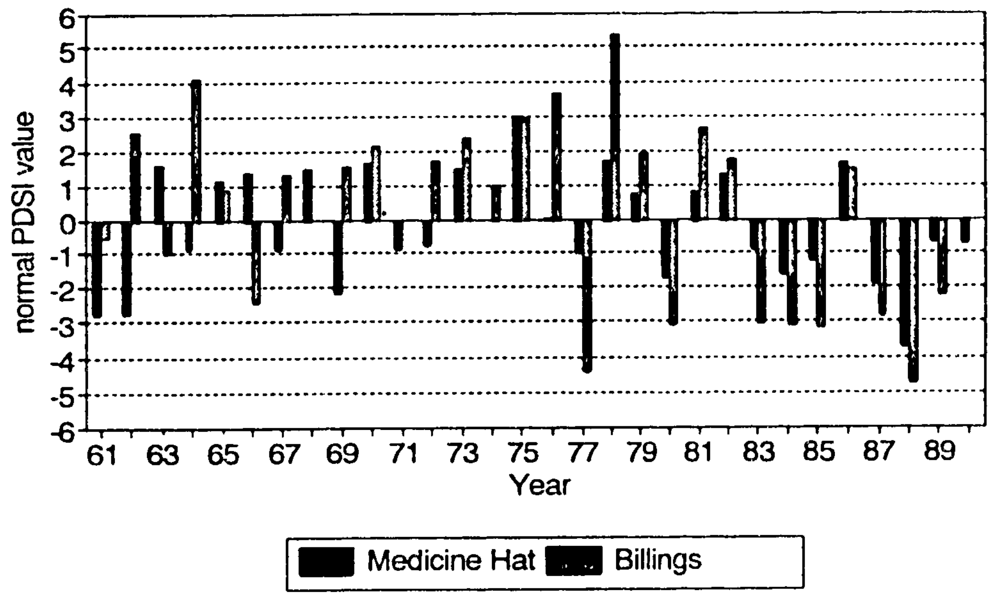


Figure 2.11. June PDSI values for Medicine Hat and Billings, 1961-1990.

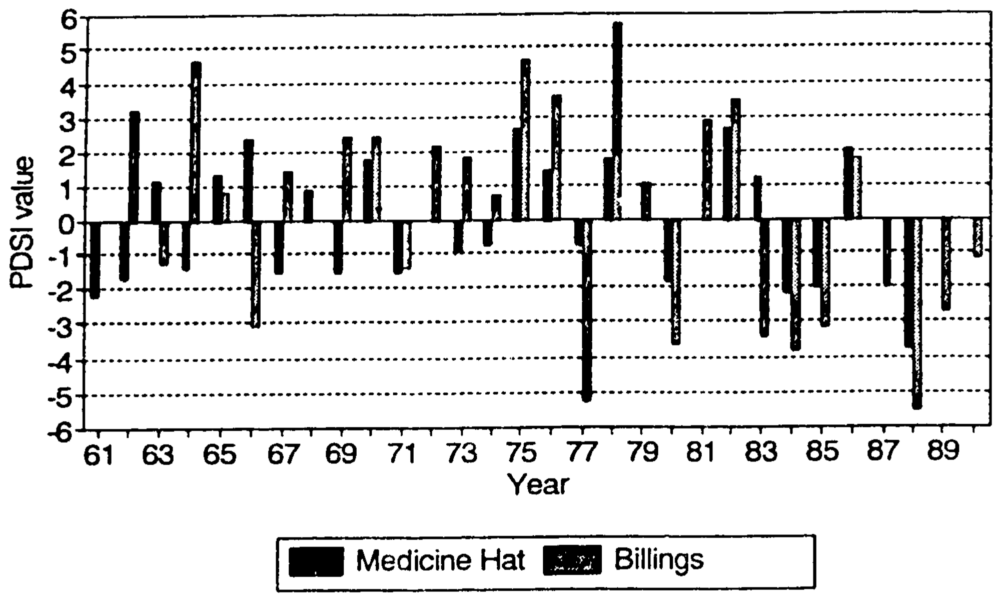


Figure 2.12. July PDSI values for Medicine Hat and Billings, 1961-1990.

falls below Medicine Hat 13 years out of 30. In the 19 years in which one or both stations has a value below zero, Medicine Hat has a lower value than Billings in 7 of the years, while Billings has a lower value than Medicine Hat in 11 of the years. There are 6 years in which both locations have values below zero; Medicine Hat's value is slightly below Billings' in only one of the years, 1971.

The number of years in each location with June and July PDSI values less than or equal to -3 were counted to compare the frequency of severe droughts between the two locations. In Medicine Hat, there is only 1 year, 1988, with a June value less than or equal to -3. In Billings, there are 6 years with a June value less than or equal to -3: 1977, 1980, 1983, 1984, 1985, and 1988. 1988 is the only year in which Medicine Hat has a July value less than or equal to -3. There are 7 years in which Billings has July values less than or equal to -3: 1966, 1977, 1980, 1983, 1984, 1985, and 1988.

Severe wet spells can be just as damaging to crops as severe drought. Years in which June and July PDSI values were greater than or equal to 3 were counted, to compare frequency of wet spells between the two locations. In Medicine Hat, there is one year, 1975, with a June value of greater than 3. In Billings, there are 3 such years: 1964, 1976, and 1978. There are no years in which Medicine Hat has a July value above or equal to 3. In Billings, there are 6 years whose values exceed or equal 3: 1962, 1964, 1975, 1976, 1978, and 1982.

Frequency of both severe droughts and wet spells is greater in Billings than in Medicine Hat, indicating more variability in June and July soil moisture. Referring back to chinook frequency discussed in the preceding section, it seems that the lower chinook frequency in Billings does not lead to its having fewer summer droughts than Medicine Hat, due to less sublimation of the snowpack.

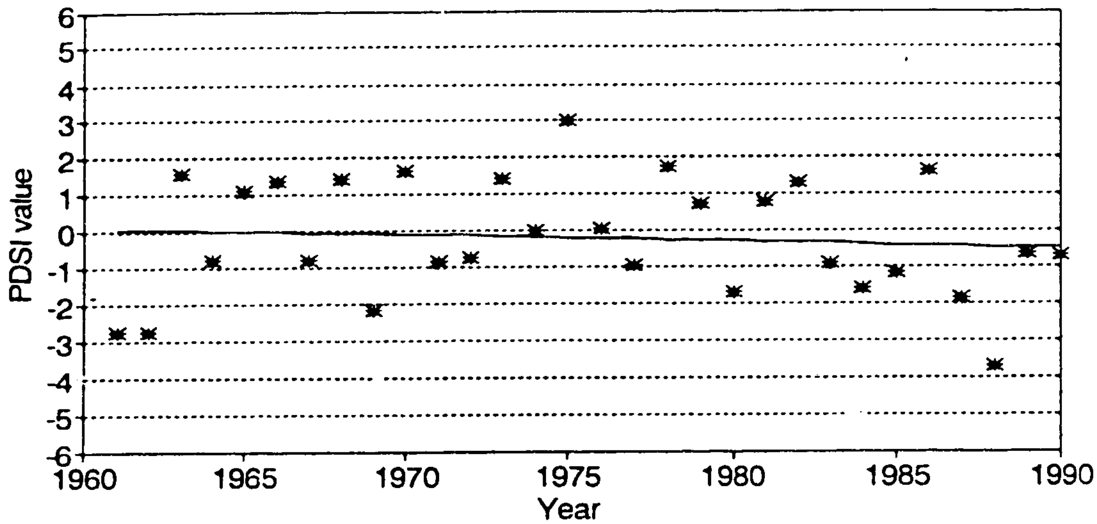
<u>Possibility of drying trends</u>

Identification of a trend in PDSI values is problematic for the same reasons as for identifying temperature trends discussed earlier. Linear fits of June and July PDSI values are presented for illustrative purposes, to explore the possibility of a trend towards drier conditions during the period of 1961 to 1990. Figure 2.13 shows a linear fit of points of June PDSI values plotted against time. Figure 2.14 shows July PDSI values vs. time. The June PDSI regression lines are drawn for the equations:

$$V = (-0.02)(Y)+0.10 \qquad \text{(Medicine Hat; } R^2 = 0.01\text{)}$$

and

$$V = (-0.11)(Y)+1.96 \qquad \text{(Billings; } R^2 = 0.14\text{)}$$



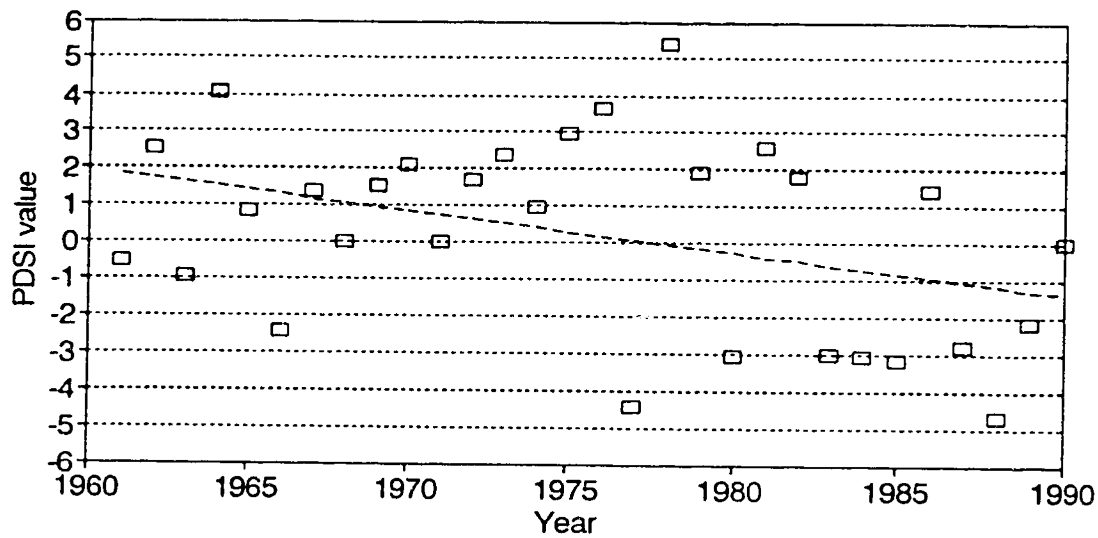
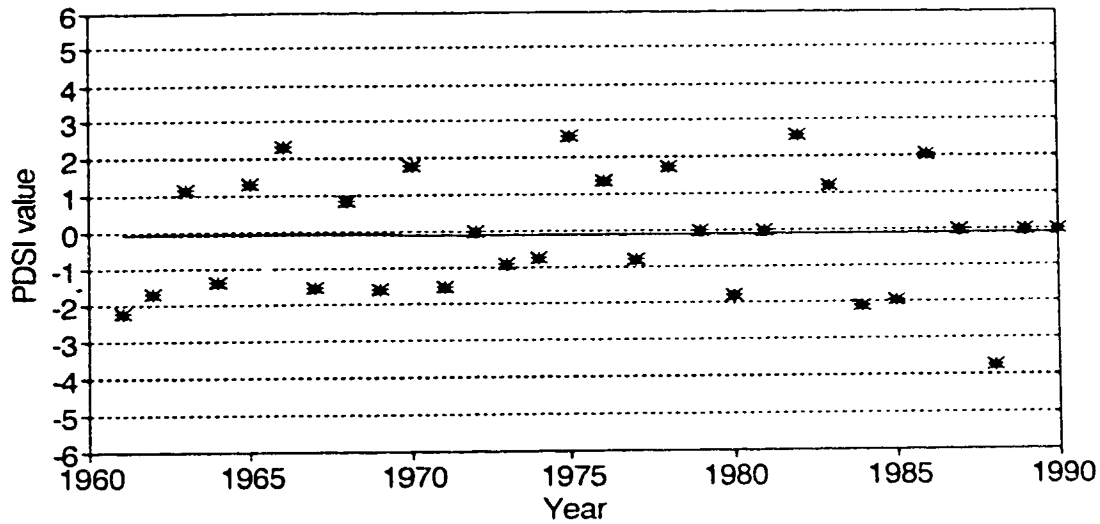


Figure 2.13. Linear fit of June PDSI points for Medicine Hat (top) and Billings (bottom), 1961-1990.



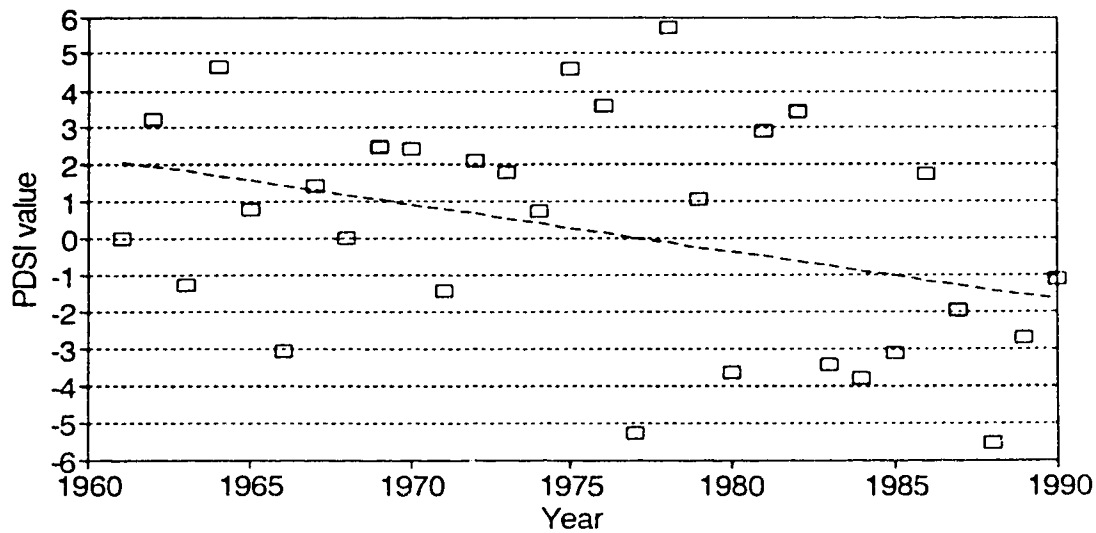


Figure 2.14. Linear fit of July PDSI points for Medicine Hat (top) and Billings (bottom), 1961-1990.

where V = PDSI value
and Y = year.

The July regression lines are drawn for the equations:

$$V = (-0.002)(Y)-0.07 \qquad \text{(Medicine Hat; } R^2 = 0.00009\text{)}$$

and

$$V = (-0.13)(Y)+2.22 \qquad \text{(Billings; } R^2 = 0.14\text{)}$$

Because the water balance calculation in PDSI involves surface and under-surface soil moisture capacity (observed from information on PDSI provided by Louie, pers. comm.), PDSI values were interpreted to be indicative of soil moisture conditions. The graphs thus imply that both Medicine Hat and Billings experienced a progression towards drier soil conditions between 1961 and 1990. The change in PDSI is more pronounced in Billings, progressing from wetter than normal conditions in 1961 to mild drought conditions in 1990. PDSI in Medicine Hat diverges slightly from normal in June, going from slightly above normal in 1961 to slightly below normal in 1990. In July, the trend begins at just below normal in 1961, and becomes slightly lower by 1990. R^2 values are significant in the case of Billings (Appendix 2).

Severe drought years

In 1988 there was a severe drought in both Medicine Hat and Billings. The drought was severe all across the Great Plains of North America, characterised as "disastrous" by Jones (1991), and was one of the most extensive in the United States (Trenberth et al., 1988). Dracup and Kendall (1990) note that the 1988 drought caused billions of dollars of property damage in the United States Midwest and a "yet to be determined" death toll (p.244). Figure 2.15 shows the progression of drought conditions throughout the 1988 year in both Medicine Hat and Billings. In both locations the year started off in January with already mild drought conditions. In Medicine Hat, the summer drought conditions attained a "severe" rating, with values between -3 and -4. In Billings, however, conditions became extremely severe, reaching a value of -6.05 in August. A factor that contributed greatly to the impacts of the drought in 1988 was the shortage of precipitation in the fall of 1987 (Appendix 3), since crops depend on moisture conditions at planting as well as during development.

Drought was also severe across the North American Great Plains in the 1930s. Drought conditions for the most severe drought year in each of Medicine Hat and southcentral Montana is shown in Figure 2.16. The most severe drought year during the 1930s in Medicine Hat was 1930, and in southcentral Montana it was 1937. In Medicine Hat, drought conditions were

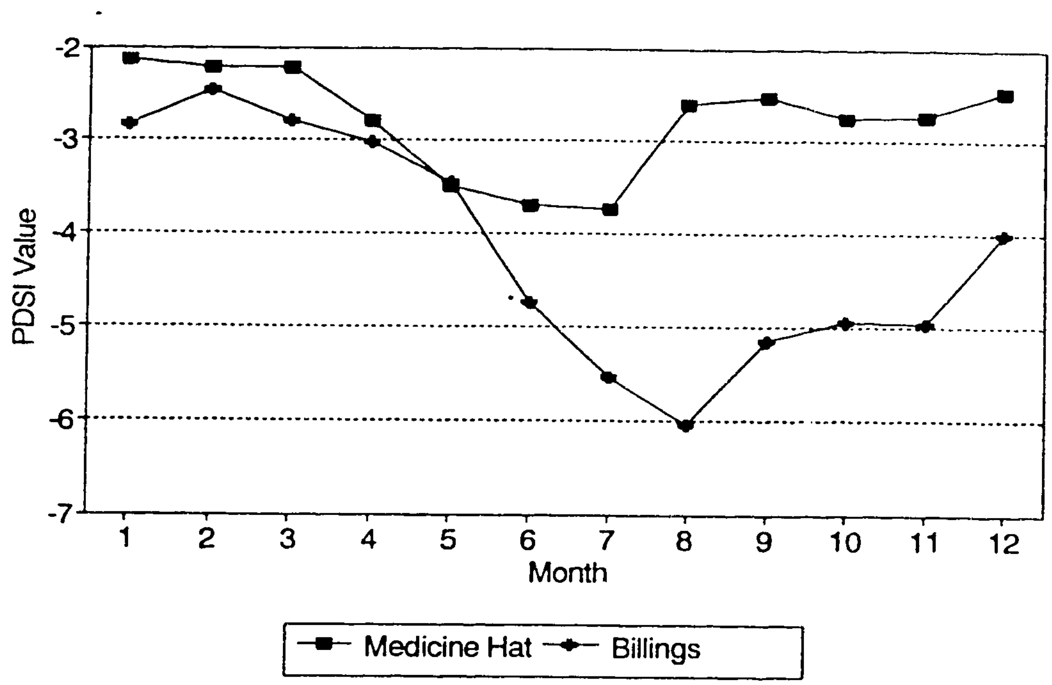


Figure 2.15. PDSI values during 1988 in Medicine Hat and Billings.

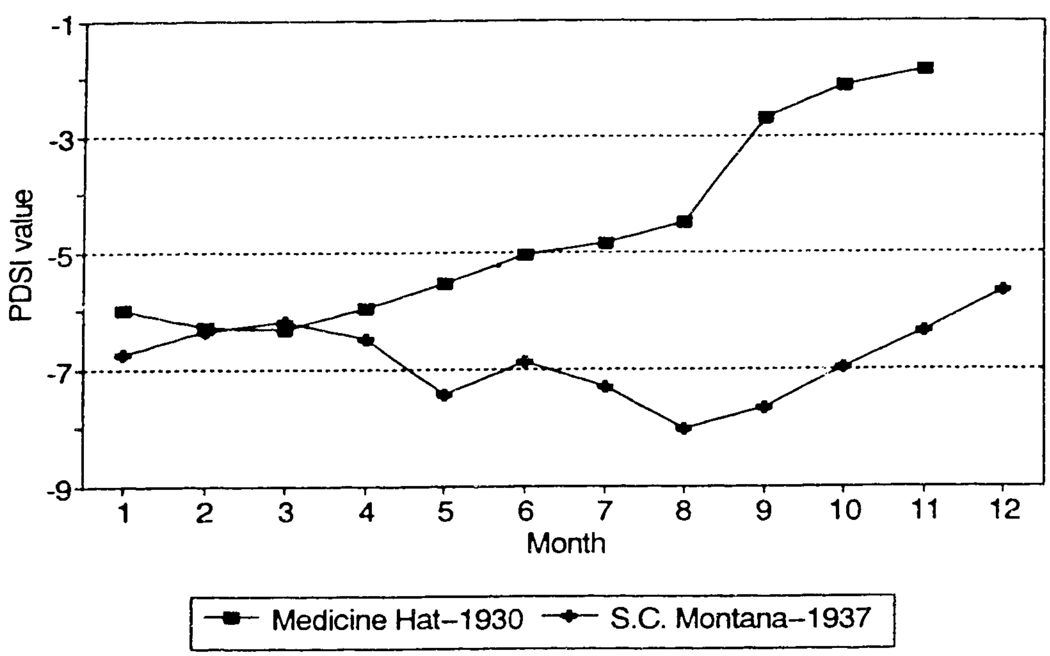


Figure 2.16. Comparison of PDSI values during the most severe drought years of the 1930s in Medicine Hat and Billings. 1930 was chosen for Medicine Hat and 1937 was chosen for Billings because those years had the lowest annual averages of PDSI values during the 1930s.

extremely severe in the late winter, spring, and summer months, but became progressively less severe into fall and early winter where drought conditions became mild. In southcentral Montana, drought conditions remained extremely severe all year, with an August value which exceeded -8.

Fig 2.17 shows the 1930 drought year in Medicine Hat as compared with the 1988 drought year of Billings. Both experienced extreme drought conditions in the summer months, and the mean annual PDSI value for both locations is approximately -4. Lilley and Webb (1990) suggested that water deficits in the Palliser Triangle could be worse than those of the 1930s under climate warming. Examination of the 1988 drought in the Northern United States Great Plains therefore serves as an indicator of potential drought conditions in the Palliser Triangle.

2.5. Growing season and frost free period

In this section, three indicators of growing season are examined: frost free period, freezeover and breakup of water bodies, and degree-days above 5°C.

Frost free period is an important determiner of the kinds of natural and agricultural vegetation that can grow in a given area. One way to compare frost free period between Medicine Hat and Billings is to simply compare the total number of frost free days in the two locations. The frost free period in the short grass ecoregion in which Medicine Hat is located ranges from 100 to 125 days (Strong and Leggat, 1981). In Yellowstone county, the number of frost free days ranges from 115-120 days on the uplands on either side of the Yellowstone River Valley, to 125-130 days in the Valley itself (Caprio and Nielsen, 1992). The mean frost free period is then approximately 10 days longer in Billings, with a range of 5 days to 30 days difference.

Another way to evaluate frost free period is to examine ice conditions on local water bodies. Nuttle (1993) suggested that higher temperatures due to climate warming will decrease the period of ice cover on rivers and lakes in Canada. Approximate dates of complete freezeover and complete ice breakup for Medicine Hat were obtained from The Hydrological Atlas of Canada (Fisheries and Environment Canada, 1978). Interpolated values from isochrone maps in the Atlas show that the approximate date of complete freezeover of rivers in the Medicine Hat region is about December 4; the date when rivers are completely ice-free is about March 30. Lakes in Medicine Hat freeze over on approximately December 15, and interpolated to be ice-free on approximately April 18. Dates of freezeover and breakup were not available in similar format for the Billings area. Freezeover and breakup dates were obtained for Canyon Ferry Reservoir (Felchle, pers. comm.) Canyon Ferry Reservoir is just outside of Helena, Montana (lat. 46°36'N; long. 112°00'W, elevation 1153.8 m, approximately 247 km

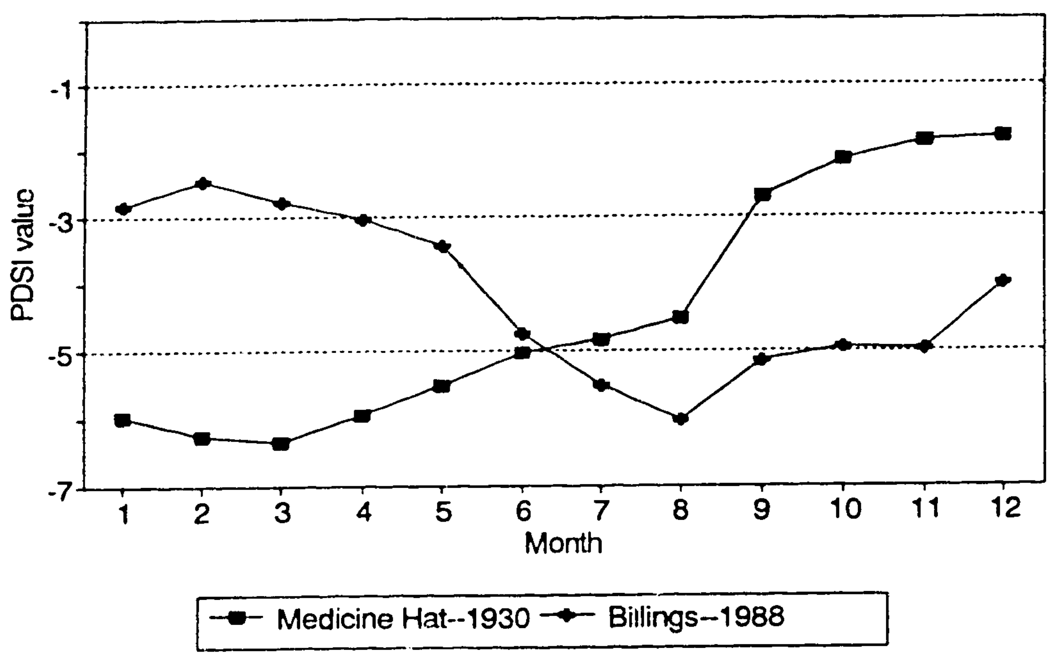


Figure 2.17. Comparison of PDSI values during 1930 in Medicine Hat with those during 1988 in Billings.

northeast of Billings). The Canyon Ferry Reservoir dates for freezing and thawing cover 39 years, from 1955 to 1993. The 39 year average shows the reservoir to be frozen over on approximately January 2, and ice-free on approximately April 7. These dates show a period of ice cover which is approximately one month shorter for Canyon Ferry Reservoir than for lakes in the Medicine Hat area. Because Helena is further north and at a higher elevation than Billings, it is likely that ice cover conditions would be shorter around Billings. A shorter period of ice cover could affect recreation and the flora and fauna of lakes, rivers, and wetlands. These results should be treated with caution; the dates from the Hydrological Atlas have been interpolated by eye from isochrones of average dates, and the dates from Canyon Ferry could be influenced by the human management of, and activity around, the reservoir. Given that the average difference in frost free period between Medicine Hat and Billings is approximately ten days, a one month difference in ice cover conditions might be an overestimation.

A third way growing season can be indicated is by growing degree-days. Growing degree-days are a cumulative measure of temperature above 5°C over a given time period. Williams et al. (1988) suggested possible increases in annual growing degree-day totals in Saskatchewan of between 3% and 50%, depending on whether the climate change scenario was historically-based (as in the smaller increase) or GCM-based (as in the larger increase).

Growing degree-days were previously calculated for Medicine Hat (Environment Canada, 1993), but had to be calculated for Billings. Daily maximum and minimum temperature data for Billings was provided by Jon Wraith of the Montana State University Climate Office (pers. comm). The daily data had been previously averaged over available years during the 1961-1990 period, into an approximate normal. A daily mean was calculated from the averaged daily minimum and maximum temperatures, then monthly degree-days were calculated (Appendix 5). Table 2.2 shows monthly totals of growing degree-days. In Medicine Hat, the annual growing degree-day total is 1971; in Billings, it is 2301.

The annual total of growing degree-days is approximately 17% higher in Billings than in Medicine Hat. The increase falls within the range of increase calculated for Saskatchewan by Williams et al. (1988), although it is below the GCM-generated total. Medicine Hat's growing degree-days are higher in the winter, early spring, and late fall. In April and October, however, Billings degree-day totals are higher than those of Medicine Hat.

The higher annual degree-day total, and the higher April and October degree-days, along with the decreased period of ice cover and shorter frost free period, indicate an earlier and longer growing season, with more heat units available to

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Medicine Hat	1.0	2.8	15.0	86.4	233.1	362.2	458.7	438.7	244.7	111.3	14.9	2.4	1971
Billings	0	0	3.3	109.8	270.4	405.3	536.3	504.6	310.0	156.1	5.0	0	2301

Table 2.2. Monthly and annual degree-day totals for Medicine Hat and Billings.

plants. These changes could have positive implications for agriculture at Medicine Hat, providing soil moisture does not decline and soil quality does not deteriorate as climate changes.

2.6. Summary of climate and growing season analogues

Variance of temperature, particularly during the winter months, was greater in Medicine Hat than in Billings. Winter temperature showed a higher variance than summer temperature in both locations. From 1934-1990, warming trends seem to have occurred in mean annual temperature and January temperature of both Medicine Hat and Billings. During the same time period, July temperature appears to have cooled in Medicine Hat and remained essentially the same in Billings. Variance of growing season precipitation was higher in Billings. The snow to rain ratio is 6.3% higher in Billings than in Medicine Hat.

Drought conditions are more variable in Billings than in Medicine Hat. During the 1961-1990 period, Billings had 5 more years than Medicine Hat with a severe PDSI drought rating in the month of June, and 6 more years with a severe drought rating in the month of July. Billings had 2 more years than Medicine Hat with a June PDSI value greater than or equal to 3, indicating much wetter than normal conditions. Billings had 6 more years than Medicine Hat in which July PDSI values are greater than or equal to 3. Medicine Hat and Billings are interpreted to have both experienced a progression towards drier soil conditions in the months of June and July, between 1961 and 1990. The progression seems more pronounced in Billings; PDSI values progress from wetter than normal conditions in 1961 to mild drought conditions in 1990, whereas in Medicine Hat, conditions are close to normal. During periods when both Medicine Hat and Billings reached severe drought conditions in the 1930s and in 1988, Billings' drought rating was more severe, reaching -6 to -8, when Medicine Hat reached -3 to -4. The 1930 drought year in Medicine Hat was comparable to the 1988 drought year in Billings, in terms of severity based on PDSI values.

Regardless of the fact that the methods used to compare growing seasons in Medicine Hat and Billings all give different results of the amount of difference in growing season length, all show an increase in length. Frost free period is approximately 10 days longer in Billings, but ranges from approximately 5-30 days longer. Ice-cover conditions on local water bodies at Helena, approximately 247 km northeast of Billings, last about 1 month less than at Medicine Hat. The annual growing degree-day total in Billings is approximately 17% higher than in Medicine Hat, falling within a range estimated for Saskatchewan by Williams et al. (1988).

3. CHAPTER THREE

NATURAL VEGETATION ANALOGUES

3.1. Plant phenology

Beaubien (1991) proposed the importance of phenology as an aid in examining changes to the environment as a result of climatic change. Phenology is the study of the seasonal timing of events in the life cycles of plants and animals, and its relation to the surrounding environment. Plant phenology examines the timing of various growth stages, such as leafing and flowering, and often attempts to relate them to climatic factors.

Hopp (1974) stated that:

> "Plants are excellent indicators of climatic differences because the time of occurrence of phenological events of many plants is, to a large degree, controlled by local climatological factors." (Hopp, 1974, p.29).

For this reason plant phenology was chosen as a possible indicator of impact of climatic differences between Medicine Hat and Billings.

Several authors have found that there is a correlation between flowering and temperature (see, for example, Lindsey and Newman, 1956; Basset et al., 1961; Caldwell, 1969; Anderson, 1974). Jackson (1966) stated that in species which flowered in spring and early summer, flowering was most closely correlated with temperature, whereas in species which flowered in late summer and fall, flowering was most closely correlated with photoperiod. Rathcke and Lacey (1985) indicated that flowering in most temperate woody species is in response to temperature, and both they and Larcher (1980) noted the importance of threshold temperatures which must be transcended before bloom will occur. Moss (1960) found that temperature was the principal factor affecting flowering of aspen, pin cherry (*Prunus pensylvanica*) and chokecherry in Edmonton. Johnson (1991b) examined the validity of using data from the May species count in Alberta to determine relative earliness or lateness of springs in the province, by comparing growing degree-days with number of species of plants in flower for several locations in Alberta for the period 1973--1989. He found that growing degree-days present a more accurate representation of earliness or lateness of the season; however, phenology can provide an alternative method for the general public, who may not have access to year-round temperature data.

The objective of this portion of the thesis was to determine whether date of lilac first bloom (date when first flower opens) in Billings is significantly earlier than in Medicine Hat, due to the temperature difference between the two locations. A difference in date of first bloom can give an indication of how growing season length might change as a result of climate warming.

History of the lilac monitoring programme in Montana

Monitoring of the phenology of the purple common lilac (*Syringa vulgaris*) was initiated in 1956 by the Montana Agricultural Experiment Station at Montana State University, Bozeman, in cooperation with the United States Weather Bureau and local garden clubs (Caprio, 1957). The purpose of the programme was to use lilac as an indicator to assess some relationships between climate and agriculture. Weather observers within the state of Montana were asked to record dates of occurrence of three phenological phases (phenophases): first bloom, peak of full bloom, and final withering of bloom. In 1957, the lilac project was extended to include the states of Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming, as part of the Western Regional Project W-48. Texas became part of the project in 1970. In 1967, two additional indicator plants, the Arnold Red honeysuckle (*Lonicera tatarica*) and the Zabeli honeysuckle (*Lonicera korolkowii* var. *zabelii*), were added to the network in order that, through monitoring the phases of the honeysuckle berry, a longer portion of the growing season could be monitored. Five phenophases are monitored in lilac between first leaf bud and withering of bloom, and nine phenophases are monitored in honeysuckle, starting with first leaf bud and ending with full shrivel of berries (Caprio, 1970). Since timing of lilac bloom tends to parallel that of many agricultural crops (Caprio, 1966) and the development of other plants and insects (Caprio and Nielsen, 1992), monitoring lilac first bloom is important; a map of average dates of lilac first bloom even appears in the Climate Atlas of Montana (Caprio and Nielsen, 1992).

Phenological monitoring in Alberta

An extensive lilac phenological survey such as the Montana lilac survey does not exist in Alberta, although individual studies have been conducted. Phenological studies in Alberta have focused mainly on wild plants. Moss (1960) collected flowering dates of several spring flowering species at Edmonton for the period 1926 to 1958 and correlated the dates with temperature in the form of degree days. Russel (1962) related development of native prairie plants to that of wheat from seeding time to harvest in Winnepeg, Saskatoon, and Edmonton for the period of 1936-1961. The Federation of Alberta Naturalists (FAN) is responsible for two more recent projects dealing with flowering of wild plants. A ten-year phenology project coordinated by FAN which recorded flowering dates for twelve "key" species in several areas of Alberta marked its final year in 1982 (Bird, 1983). FAN currently sponsors an annual province-wide species count, which includes plants in flower, on the last full weekend each May. The first of these May species count days was held in 1976 (Weseloh, 1976). The results of the May Day Count are published annually in the Alberta Naturalist (see, for example, Johnson, 1991a).

The only current, extensive Alberta phenological survey is that of Beaubien (1993). The project involves surveying flowering dates (10%, 50%, and 90% of flower buds open) of 15 Alberta wildflowers. 1987-1992 dates have been analyzed to this point (Beaubien and Johnson, 1994). The Alberta wildflower flowering date survey is Canada's only extensive phenology survey.

Hypothesis

Caprio (1957) found that there was a retardation of lilac bloom dates of about 1 day per 32 km (20 miles) of northward distance, and about 1 day per 30.5 m (100 feet) increase in elevation. Medicine Hat is approximately 500 km north of Billings, so dates will be retarded by 500/32=15.6 days. Police Point, where data were obtained at Medicine Hat, is approximately 432 m lower than Logan airport, where data were obtained at Billings; this would have the counter-effect of an advance of 432/30.5=14.2 days. Thus, the difference in bloom dates between Medicine Hat and Billings should be approximately 16 days due to the northward distance, minus 14 days due to Billings' higher elevation, equalling 2 days.

Methodology

Data for lilac phases from the Billings area were obtained from Montana State University. A lilac monitoring programme similar to that of Montana does not exist for southern Alberta, thus, a proxy species was used at Medicine Hat, and the number of days between first bloom dates for the proxy species and lilac was determined. The proxy species used was saskatoon (*Amelanchier alnifolia*). Data for saskatoon bloom at Police Point in Medicine Hat were obtained through Elisabeth Beaubien of the Devonian Botanic Garden, University of Alberta. The data at Police Point have been collected for the period 1987-1993. Data for 1991 are missing. To determine the number of days between saskatoon first bloom and lilac first bloom, bloom data were obtained for the two species from the same location. Data for the two species have been recorded for the period 1987-1993 just north of the Biological Sciences Building, University of Alberta (Beaubien, pers. comm.). The number of days between first bloom of lilac and saskatoon at that location ranged between 5 and 11 days (Table 3.1); the range was determined from comparison of dates from 1989, 1991, and 1993, as data are missing for either one or the other plant in the remaining years. The mean number of days between first bloom of saskatoon and lilac is 8; therefore, 8 days were added to the dates given for saskatoon at Medicine Hat to give an estimated mean lilac first bloom date there. Five days and 11 days were

	Saskatoon	Julian days	Lilac	Julian days	Number of days difference
1989	May 9-10e	129-130	May 15	135	5-6
1991	May 10	130	May 21e	141	11
1993	May 9	129	May 17-18	137-138	8-9
					mean (max+min/2)= 8

Table 3.1. First bloom dates for and number of days between saskatoon and lilac along Saskatchewan Drive, just north of the Biological Sciences Building, University of Alberta. "e" indicates estimated.

added to the saskatoon dates to give a range of estimated lilac first bloom dates. Lilac data from the Billings Weather Bureau at Billings airport are available for the period 1956-1991, and were obtained from the State Climate Office at Montana State University. Data are missing for 1990. Thus, the years available for comparison between Police Point in Medicine Hat and the airport at Billings are 1987, 1988, 1989; 1990 data are used from Medicine Hat and 1991 data are used from Billings, to enable the use of a fourth "year".

Table 3.2 shows that when the dates of lilac bloom in Billings and converted pseudolilac bloom in Medicine Hat are compared, the date of first bloom in Billings is 4 days earlier on average than in Medicine Hat. The minimum number of days between saskatoon and lilac first bloom is 1, and the maximum is 7. The results are consistent with the aforementioned predictions according to Caprio (1957). The difference in timing of lilac bloom between the two locations is not great, likely due to the difference in elevation. In Caprio (1966), maps of isophanes (lines connecting points where plants reach a given phenophase on the same date) show that lilac first bloom at the latitude of Billings, but at the elevation of Police Point, would occur sometime around April 30, or approximately one week before it actually occurred during the period examined above. Although the results give a wide range of actual amount of advancement of first bloom, they suggest that there would be some advancement of the lilac bloom season if Medicine Hat's climate became more like that of Billings.

3.2. Vegetation distribution

In this section, vegetation distribution in the immediate area of, and along an elevational gradient around, each of Medicine Hat and Billings is discussed. Comparing vegetation zonation between regions is problematic, for two main reasons: (a) Different authors use different systems to classify vegetation zones, depending on their objectives. The classification systems used in this study for Alberta and Montana differ in that the Montana system has more classes than the Alberta system. Even the vegetation within the Medicine Hat area has been classified differently by different authors; Strong and Leggat (1981) call the Medicine Hat area Short Grass Prairie, while Clayton et. al. (1977) show it as Mixed Grass Prairie. (b) The landscapes in both the Medicine Hat and Billings areas have been altered by agriculture and other human development. The vegetation distributions in the classifications used in this study represent the potential for the area, and may not be exactly what is present at any given time or place. Keeping these problems in mind, vegetation distribution was examined in the analogue regions for general comparison.

	Billings lilac	Medicine Hat saskatoon	Medicine Hat lilac equivalent			Number of days difference
			Saskatoon + 8 days (mean)	Saskatoon + 5 days (min)	Saskatoon + 11 days (max)	
1987	116	111	119	116	122	
1988	119	119	127	124	130	
1989	127	126	134	131	137	
1990/91	133 (91)	124 (90)	132	129	135	
mean	124	NA[1,2]	128[3]	NA	NA	4[4]
min	NA	NA	NA	125[3]	NA	1
max	NA	NA	NA	NA	131[3]	7

Table 3.2. Julian dates of Billings lilac, Medicine Hat saskatoon, and converted Medicine Hat "lilac".

[1] NA indicates not applicable.

[2] No mean, min, or max calculated for Medicine Hat saskatoon bloom dates because they required conversion to lilac equivalent to be useful for comparison.

[3] Mean, min, and max were calculated for Medicine Hat saskatoon + 8 days, 5 days, and 11 days (match mean, min, and max columns with rows) because number of days between lilac and saskatoon bloom days is not constant; mean difference in lilac and saskatoon bloom dates is 8 days; minimum difference is 5 days; and maximum difference is 11 days.

[4] Figures in Number of days difference column are differences between mean Billings lilac date (124 Julian days) and mean, min, and max Medicine Hat lilac equivalent dates.

Medicine Hat

Strong and Leggat's (1981) classification of ecoregions was used as the main determinant of the vegetation distribution in the Medicine Hat area (Figure 3.1). Alberta has 12 ecoregions based on climate and vegetation. The ecoregion is "...intended to be a broad level of generalization for classification of landscapes." (Strong and Leggat, 1981, p.1). The system specifies modal vegetation within each ecoregion, consisting of one to four species which occur on moderately well-drained, medium textured soils, and within modal temperature and moisture conditions. Species which occur under hotter and drier or cooler and moister conditions are also given. More specific information on the vegetation of the Cypress Hills was obtained from Breitung (1954), and Looman and Best (1979). Elevations have, unless otherwise stated, been approximated using 1:250 000 topographical maps. Common names for species listed in Breitung (1954) were obtained from Budd and Best (1964).

Immediate area

Medicine Hat is in the short grass prairie ecoregion (Strong and Leggat, 1981). The characteristic vegetation of the short grass prairie consists of drought-tolerant species. Budd and Best (1964) list the dominants of short grass prairie in the southwestern prairie zone to be blue grama (*Bouteloua gracilis*), spear grass (*Stipa comata*), June grass (*Koleria cristata*), Sandberg's bluegrass (*Poa secunda*), sedges (*Carex* spp.), little club moss (*Selaginella densa*), sage bush (*Artemisia* spp.), and cactus (family CACTACEAE). Strong and Leggat (1981) list the modal species as grama grass (*Bouteloua gracilis*) and spear grass (*Stipa comata*). Moss phlox (*Phlox hoodii*) is also common to the short grass ecoregion (Strong and Leggat, 1981). Shrubs such as buckbrush (*Symphoricarpos occidentalis*) and wolf willow (*Elaeagnus communtata*) occur where there is ample moisture. Cottonwood (*Populus* spp.), willow (*Salix* spp.), and water birch (*Betula occidentalis*) are found on stream banks and floodplains.

Elevational gradient

Figure 3.2 shows the distribution of vegetation along an elevational gradient from Medicine Hat southeastward to the Cypress Hills. The short grass ecoregion gives way to mixed grass prairie at approximately 1000 m. Mixed grass prairie combines short grass and tall grass species, the modal species being spear grass, grama grass, and wheat grass (*Agropyron* spp.) Common forbs are sagewort and moss phlox. Rough fescue (*Festuca scabrella*) and wheatgrass/junegrass ecosystems can occur under cooler/wetter conditions. As in the short grass ecoregion, buckbrush-wolf willow ecosystems occur where moisture supply is higher, and poplar (*Populus*, spp.), willow, and birch ecosystems occur in poorly-drained areas.

At the base of the Cypress Hills, at approximately

Legend for Figure 3.1.

Gs - Short grass prairie

Gm - Mixed grass prairie

APg - Aspen Parkland, Groveland Subregion

BF - Boreal Foothills

—·— - Boundary, Cypress Hills Provincial Park

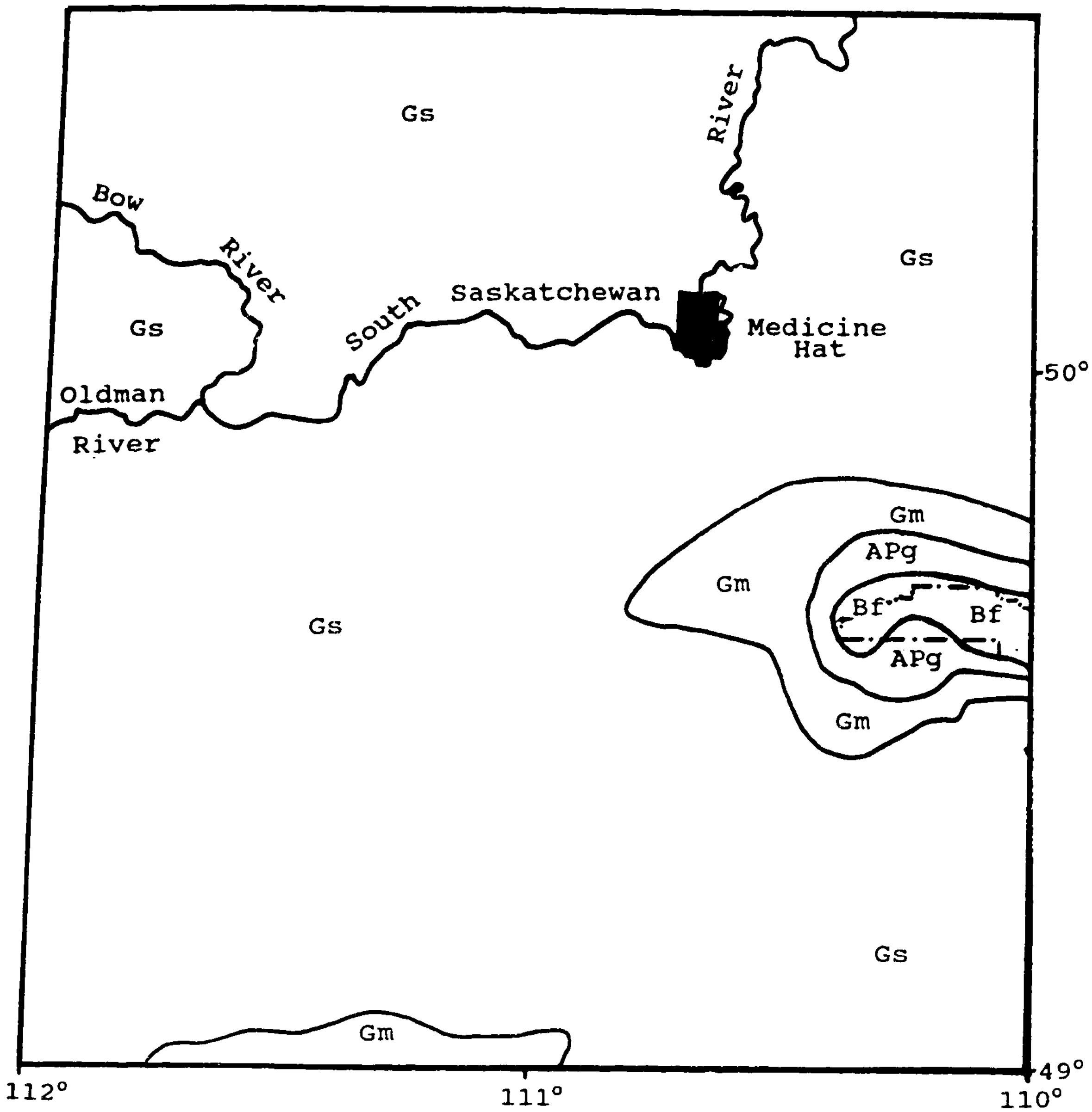


Figure 3.1. Vegetation distribution of the Medicine Hat area, adapted from Strong and Leggat (1981). Scale is approximately 1:1 000 000.

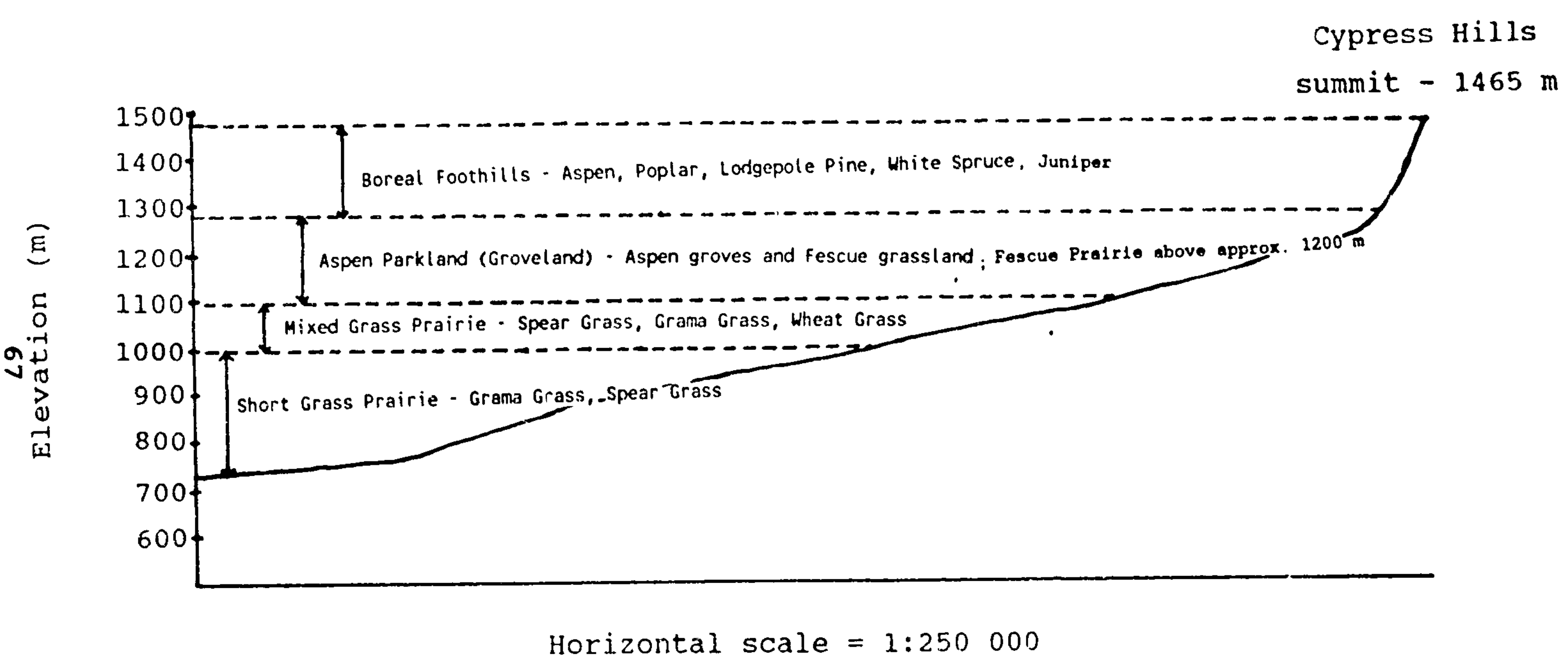


Figure 3.2. Elevational gradient of vegetation from Medicine Hat to the summit of the Cypress Hills. Profile is an approximation, based on 1:250 000 topographic maps.

1100 m, the mixed grass vegetation becomes aspen parkland (groveland subregion), in which approximately 15% of the cover is aspen (*Populus tremuloides*),and the remaining cover consists of fescue grassland and shrub communities. The grassland species in the groveland subregion include fescue, junegrass, spear grass, prairie smoke (*Geum triflorum*), sticky geranium (*Geranium viscossimum*), and bedstraw (*Galium boreale*). The shrub communities are typified by saskatoon (*Amelanchier alnifolia*), wild rose (*Rosa* spp.). buckbrush (*Symphocarpos occidentalis*), snowberry (*S. alba*), and silverberry (*Elaegnus commutata*). Looman and Best (1979) state that above 1200 m the grassland becomes pure fescue prairie. Breitung (1954) gives 1219 m to 1463 m (4000 to 4800 feet) as the elevational range of fescue grassland.

Breitung (1954) speaks of a narrow belt of "aspen woodland" (p. 66) which, in this part of the Cypress Hills, occurs along the lower edge of the higher coniferous forest. According to Breitung (1954), the understorey of the aspen woodland consists of three layers. The tallest layer is one of tall shrubs including saskatoon, willow, and chokecherry. The middle layer consists of shrubs and herbs, and the lowest layer is comprised of herbaceous plants. Buckbrush and rose thickets occur as a transition between aspen groves and grassland.

At approximately 1280 m (4200-foot contour line according to Breitung (1954), 1300 m according to Looman and Best (1979)), there is a sharp transition between grassland and forest, particularly noticeable on north-facing slopes. This forested area belongs to the Boreal Foothills ecoregion. The modal vegetation of the Boreal Foothills consists of aspen, balsam poplar (*Populus balsamifera*), lodgepole pine (*Pinus contorta*), and white spruce (*Picea glauca*). Breitung (1954) indicates that lodgepole pine is the dominant of these tree species, followed by aspen, white spruce, and balsam poplar. He divides the area covered by forest into the above-mentioned aspen woodland, a "lodgepole pine forest" (p.65) between approximately 1280 m and 1460 m, and an "Alberta spruce (*Picea glauca* var. *albertiana*) forest" (p.66) which occurs in cooler, moister areas within the forested area. The lodgepole pine forest has few understorey species, which consist of shrubs and herbaceous plants. Juniper (*Juniperus communis* var. *saxatilis*) is present on steep, south facing slopes. The white spruce forest, which contains balsam poplar and aspen, grades upslope towards drier conditions into lodgepole pine. Shrubs and herbs in the white spruce forest include red osier dogwood (*Cornus stolonifera*), lowbush cranberry (*Viburnum edule*), willow, northern black currant (*Ribes hudsonianum*), swamp gooseberry (*R. lacustre*), pinegrass, aster (*Aster* spp.), and baneberry (*Actaea* spp.). Several lower-growing species are also present.

Billings

The classification system of the Montana State University Climax Vegetation Base Map (MSU, 1994) was used to determine the vegetation distribution of the Billings area. The map was printed on request by the Department of Plant and Soil Science, Montana State University (Nielsen, pers. comm.), using a mainframe version of the Montana Agricultural Potentials System (MAPS) Mailbox Land and Climate Information System programme (Caprio et al., 1990). The base map consists of 62 classes of potential climax vegetation within Montana based on topography, climate, and soils. These are divided into Eastern Glaciated Plains, Western Glaciated Plains, Eastern Sedimentary Plains, Western Sedimentary Plains, and Foothills and Mountains. The characteristic species of the vegetation classes were obtained from Caprio et al. (1990). Figure 3.3 shows the vegetation of the Billings area. Because there are 62 classes of vegetation within the system of Caprio et al. (1990), grassland classes displaying similar species composition have been amalgamated to yield a generalized view of vegetation distribution, more compatible with that given for Alberta by Strong and Leggat (1981). Elevations were approximated using 1:250 000 topographic maps. Scientific names for species given in Caprio et al. (1990) were obtained from Weaver and Albertson (1956), Budd and Best (1964), Weber (1967), Montagne et al. (1982), and Beaubien (pers. comm.). An effort was made to use Canadian common names, if common names differ between Canada and the United States.

Immediate area

The vegetation within Yellowstone county belongs to the Eastern and Western Sedimentary Plains zone. Montagne et al. (1982) list the dominants of the vegetation of the Sedimentary Bedrock Plains and Hills as western wheatgrass, spear grass, and blue grama, with variations depending on soil texture. According to the MSU vegetation map, Yellowstone county is characterised by mixed grass species such as western, thickspike, and bluebunch wheatgrass (*Agropyron smithii*, *A. dasystachyum*, *A. spicatum*), spear grass, green needlegrass (*Stipa viridula*), junegrass, and sagebrush. Little bluestem (*Andropogon scoparius*) is a characteristic species in only the eastern part of the county. Montagne et al. (1982) use approximately 108° West longitude as the line west of which little bluestem becomes less common. Other mixed prairie species which occur in the county are basin wildrye (*Elymus cinerius*), threadleaf sedge (*Carex filfolia*), native legumes (family LEGUMINOSAE), blue grama, reed grass (*Calamagrostis* spp.), prairie sandreed (*Calamovilfa longifolia*), milkvetches (*Astralagus* spp.), and winterfat (*Eurotia* spp.). Nuttall's altriplex (*Atriplex nuttallii*), greasewood (*Sarcobatus vermiculatus*), Alkali grass (*Distichlis stricta*), and Sandberg's bluegrass (*Poa secunda*) are restricted to a small

Legend for Figure 3.3.

Gm	-	mixed grassland
Gfe	-	Fescue grassland
PJ-G	-	Ponderosa Pine/Rocky Mtn. Juniper/ grassland complex
F-G	-	Douglas Fir/grassland complex
C	-	Cottonwood/hardwood complex
JP	-	Rocky Mtn. Juniper/Limber Pine forest
FS	-	Subalpine Fir/Douglas Fir/Engelmann Spruce forest
FPS	-	Subalpine Fir/Douglas Fir/Ponderosa Pine/Engelmann Spruce forest
FP	-	Douglas fir/Ponderosa pine forest
---	-	Boundary, Foothill and Mountain vegetation
——	-	Boundary, Yellowstone County

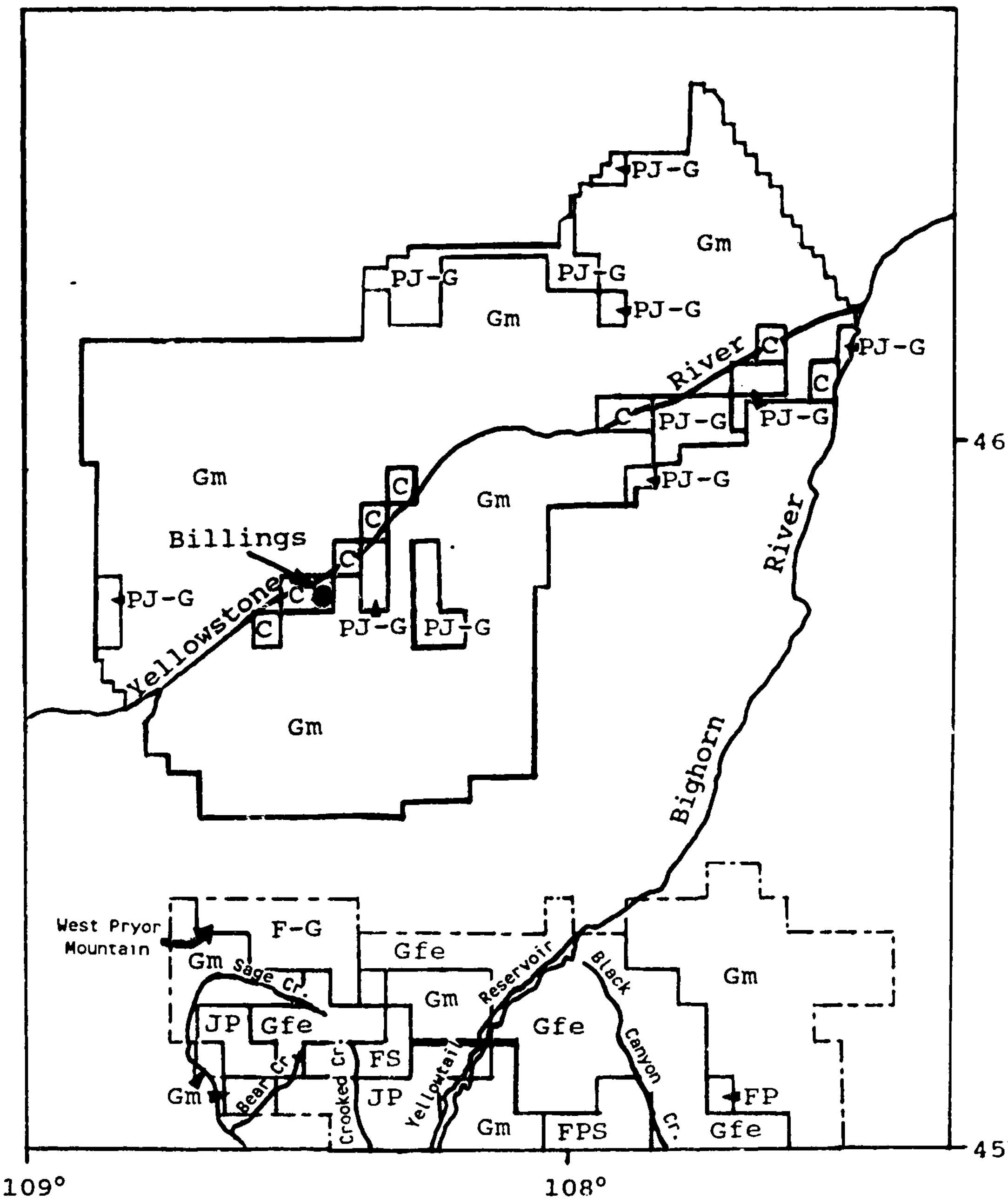


Figure 3.3. Vegetation distribution of Yellowstone County and adjacent foothills and mountains. Adapted from MSU (1994). Scale is approximately 1:1 000 000.

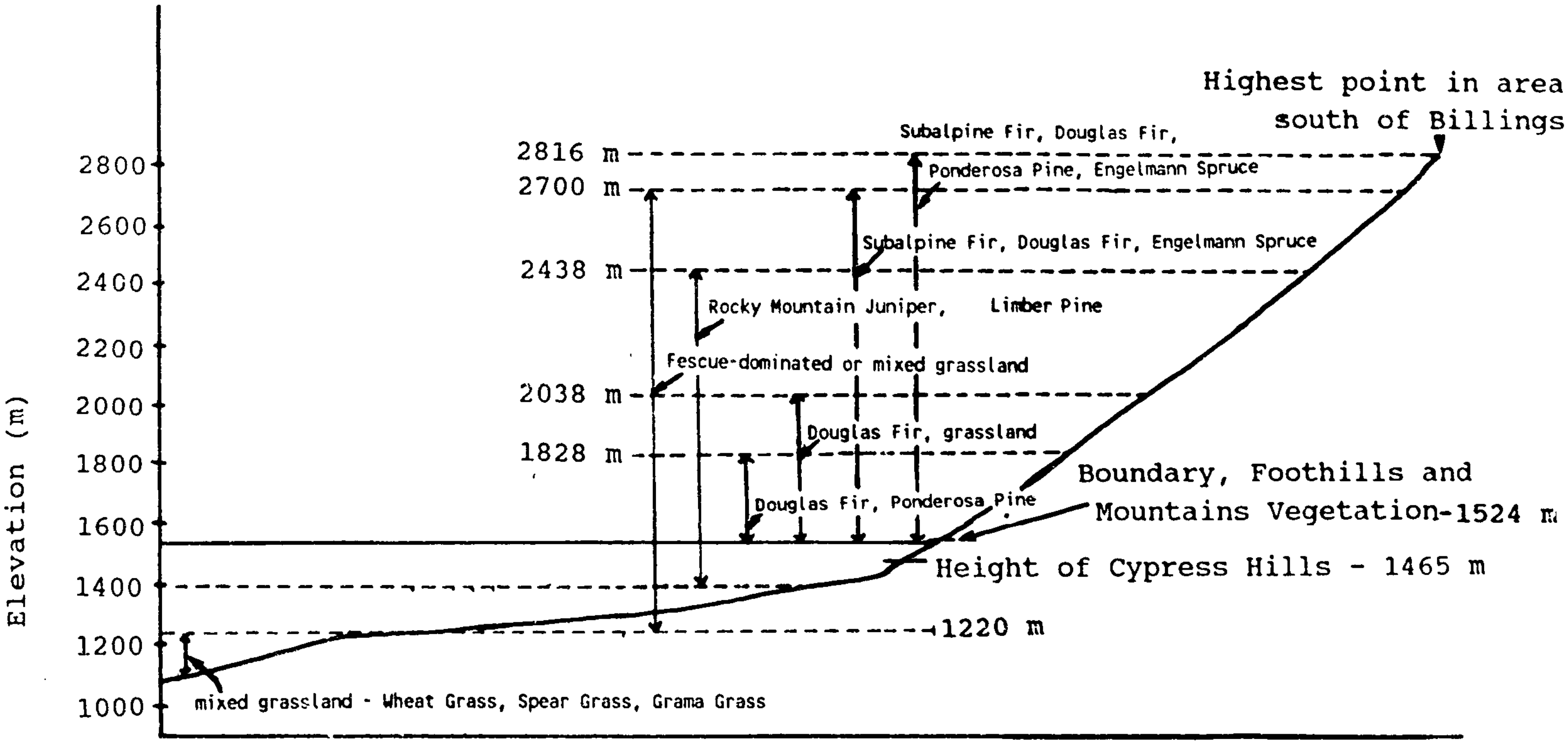
area in the west-central part of the county, and Alkali sacaton (*Sporobolus airoides*) and squirreltail (*Sitanion* spp.) are found on saline uplands within this area. Sticky geranium and prairie smoke occur in a very small area in the centre of the western fringe of the county, and between the most southerly boundary of the county and the adjacent Douglas fir-grassland complex. Shrub species in the county include skunkbush sumac (*Rhus trilobata*), common chokecherry in the west, and western snowberry in the east. A discontinuous community exists along the Yellowstone River in which the overstorey vegetation is 80% cottonwood and 20% other hardwoods. Spotted throughout the county is a 50% forest-50% grassland complex in which the grassland species composition is similar to that above, and the forest tree species are Ponderosa pine (*Pinus ponderosa*) and Rocky Mountain juniper (*Juniperus scopularum*). Montagne et al. (1982) suggest that the latter forested areas often occur on sandstone outcrops, as shown in Figure 3.4.

As the grassland species listed above fall into the Mixed Grass Ecoregion vegetation of Strong and Leggat (1981), it is ascertained that Billings falls into a mixed grass prairie region.

Elevational gradient

Figure 3.5 shows a generalized distribution along an elevational gradient between Billings and the Pryor and Bighorn Mountains. At approximately 1524 m asl., on the mountain slopes south of Billings, the vegetation changes from Sedimentary Plains communities to Foothills and Mountains communities. In areas of higher elevation forest units are interspersed amongst grassland units. Elevations within the Foothills and Mountains zone are as low as approximately 1220 m in some stream valleys, so elevational ranges of some species are shown to extend lower than 1524 m. Grassland units in the Foothills and Mountains zone contain similar species composition to that listed above, with the exception of a fescue grassland area which is interspersed with mixed prairie areas, nearly encircling the Pryor mountains (Figure 3.2). The species composition of the fescue grassland community is rough fescue, Idaho fescue (*Festuca idahoensis*), bluebunch wheatgrass, Columbia needlegrass, (*Stipa columbiana*) basin wildrye, spike fescue (*Leucopoa*, spp.), parry oat grass (*Danthonia parryi*), slender wheatgrass (*Agropyron trachycaulum*), lupine (*Lupinus* spp.), sticky geranium, arrowleaf balsamroot (*Balsamorhiza sagittata*), prairiesmoke, sagebrush, tall larkspur (*Delphinium glaucum*) prairie junegrass, timber danthonia (*Danthonia intermedia vasey*), and big bluegrass (*Poa ampla*). Grassland grades into a forest-grassland complex at West Pryor mountain (elevation approximately 1524 m - 2039 m), on the northern edge of the Foothills/mountains zone, in which forest constitutes 60% of the cover and grassland constitutes 40%. The grassland

Figure 3.4. Bedrock outcrop and overlying Ponderosa Pine - Rocky Mountain Juniper growth. This is an example of the sandstone outcrop vegetation noted in Montagne et al. (1982). Approximately 5 km north of Billings.



Horizontal scale is approximately 1:410 000

Figure 3.5. Elevational gradient of vegetation from Billings to the Pryor and Bighorn Mountains. Profile is schematic, based on 1:250 000 maps. Arrows represent elevational range, not sequence upslope.

species of this unit are wheatgrass and fescue-dominated, and the forest overstorey species is Douglas fir (*Pseudotsuga menziesii*). Snowberry, spiraea (*Spiraea* spp.), Oregon grape (*Berberis repens*), arnica, needlegrass, fescue, wheatgrass, and bearberry (*Arctostaphylos uva-ursi*) make up the understorey.

From West Pryor mountain southward forest becomes mixed or fescue grassland in the pass through which Sage Creek flows. The grassland area occurs at elevations ranging from approximately 1524 m to approximately 2700 m. Just southeast of the headwaters of Sage Creek, between approximately 1524 m and approximately 2705 m, grassland changes to a community in which the overstorey is 65% subalpine fir (*Abies lasiocarpa*), 25% Douglas fir, and 10% Engelmann spruce (*Picea engelmannii*). On the south and west-facing slopes between and southeast of Sage Creek and Bear Creek, and on the slopes northeast of the headwaters of Sage Creek, the overstorey vegetation is rocky mountain juniper and limber pine (*Pinus flexilis*). The juniper-pine unit occurs at elevations between approximately 1400 m and 2438 m. Further east, across an area of mixed grassland, is a unit on the Montana/Wyoming boundary which has an overstorey of 50% subalpine fir, 35% Douglas fir, 10% Ponderosa pine, and 5% Engelmann spruce. This unit is in the Bighorn Mountains, and ranges in elevation from 1524 m - 2816 m. A very small area containing overstorey of 60% Douglas fir and 40% Ponderosa pine occurs east of the fir/pine/spruce community, just north of the Montana/Wyoming boundary. The fir/pine unit occurs between approximately 1524 m and 1828 m, and is fully encircled by mixed and fescue grassland.

The grassland vegetation of the Billings area is similar to that of the Medicine Hat area at the genus level, although the composition is more towards mixed grass prairie in Billings and short grass prairie in Medicine Hat. Fescue grassland occurs at similar elevations in both regions. The elevational gradient of vegetation south of Billings is similar to the area around Pincher Creek, Alberta, where grassland grades directly into montane and subalpine vegetation. The Billings area lacks the belt of aspen groveland which is present between grassland and Boreal Foothills forest in the Cypress Hills. The higher elevation forest overstorey species in the Billings area are similar to those of the Cypress Hills in three genera: *Pinus* (pine), *Picea* (spruce), and *Juniperus* (juniper). The fir which occurs in the Pryor and Bighorn Mountains does not occur in the Cypress Hills. Factors other than climate will contribute to the elevational vegetation distribution of an area (see section 5.2). The difference in the elevational gradient of vegetation between the Cypress Hills and the Pryor and Bighorn Mountains does, however, reflect the climatic differences between the two areas.

3.3. Summary of natural vegetation analogues

Comparison of lilac first bloom dates in Medicine Hat and Billings revealed that first bloom occurs approximately 4 days earlier in Billings, but ranges from 1 to 7 days earlier. The comparison of first bloom dates gives an indication of growing season, but considers only the onset of the growing season, and not its end. Table 3.3 summarizes the differences in growing season determined by the indicators of frost free period, ice cover period, and growing degree day totals (Chapter 2), and lilac bloom dates. A minimum increase in growing season length from the indicators used above is 1 day, and a maximum is 1 month.

Vegetation distribution in the immediate areas of Medicine Hat and Billings is similar. Both areas are characterised by drought-tolerant grasses, such as spear grass and needle grass (*Stipa* spp.), blue grama (*Bouteloua* spp.), June grass *(Koleria* spp.), and, at slightly higher elevations in Medicine Hat and in the immediate area of Billings, wheatgrass (*Agropyron* spp.). Species occurring at higher elevations differ somewhat between the two locations. The aspen growth which occurs in the Cypress Hills near Medicine Hat is not found in the Pryor Mountains near Billings. The forest species which characterise the higher elevations of the Cypress Hills are aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), lodgepole pine (*Pinus contorta*), white spruce (*Picea glauca*), and juniper (*Juniperus communis* var. *saxatilis*). Forest species which characterise the Pryor Mountains are Douglas fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), Rocky Mountain juniper (*Juniperus scopularum*), ponderosa pine (*Pinus ponderosa*), and limber pine (*Pinus flexilis*). The elevational gradient of vegetation in Billings is more similar to the area around Pincher Creek, Alberta, than to the area around the Cypress Hills. Near Pincher Creek, grassland species grade directly into montane and subalpine species, without a belt of aspen, similarly to the area south of Billings.

Growing Season Indicator	Medicine Hat	Billings	increase	range (if applicable[1])
Frostfree period	112.5 days	122.5 days	10 days	5 to 30 days
Ice cover period	124 days (Dec 15 - Apr 18)	96 days (Jan 2 - Apr 7)	28 days	NA
Growing degree-day totals	1971	2301	17%	NA
Lilac bloom dates	128 Julian days	124 Julian days	4 days	1 to 7 days
Range in increase from all indicators	NA	NA	NA	1 to 30 days

Table 3.3. Synopsis of results from growing season indicators. NA indicates not applicable.

[1] Range is indicated only in cases where a range in the growing season indicator was given or calculated for each of Medicine Hat and Billings (Chapter 2). Means are given in the Medicine Hat and Billings columns in these cases.

4. CHAPTER FOUR

AGRICULTURAL ANALOGUES

4.1. Agroeconomy

The distribution of agricultural cash receipts among farm products in Medicine Hat and Billings is similar. A summary of 1991 cash receipts from agriculture illustrates the relative importance of agricultural products. Alberta statistics were obtained from the 1992 Alberta Agriculture Statistics Yearbook (Alberta Agriculture, 1992). Billings statistics are from the 1992 Montana Agriculture Statistics compilation (Montana Agricultural Statistics Service, 1992). Dollar figures are in local currency to avoid the problem of fluctuating exchange rates between Canada and the United States. In Alberta, cash receipts from the sale of farm products totalled $3 861.5 million. This total excludes Federal and Provincial Stabilization and supplementary payments, but includes other program payments and crop insurance. Of that total, crops made up 41.9% at $1618.9 million, and livestock and livestock products made up 58% at $2242.6 million. In Montana, cash receipts, excluding government payments, totalled $1531.169 million. Crop receipts made up 48.4% of the total, and livestock receipts made up 51.6%. In both Alberta and Montana, wheat is the principal crop. In Alberta, wheat cash receipts in 1991 totalled $677.7 million, constituting 41.9% of total crop receipts. Canola and barley are the other important crops in Alberta, comprising 20.7% and 13.4% of crop cash receipts, respectively. Wheat comprises 54.8% of crop receipts in Montana, at approximately $405.760 million. Barley is the other principal crop, at 21.1% of crop cash receipts.

4.2. Soil conservation practices

Areas of concern in agricultural soil conservation in Medicine Hat and Billings are very much the same. Decreased soil moisture is a serious issue, as is topsoil loss through wind and water erosion (Dumanski et al., 1986; Wheaton and Wittrock, 1992; Weber, pers.comm, 1993).

In both Medicine Hat and Billings, conservation tillage and residue management are the primary practices being encouraged to reduce erosion and maintain soil moisture. Conservation tillage involves disturbing the soil as little as possible during farming, through reduction or elimination of tillage operations. Residue management involves leaving some plant matter (residue) on the soil after harvesting.

According to Magleby and Schertz (1987), there are four types of conservation tillage: No-till (also called zero-till), ridge-till, strip-till, and mulch-till or reduced till. No-till virtually eliminates tillage, as seed is planted directly into stubble from the previous crop with a specialized seed drill. In ridge-till, seed is planted on cultivated soil ridges 10-16 cm high, which serve as wind breaks. Mulch-till and reduced till involve much the same procedures and equipment as conventional tillage, but tillage operations are performed less frequently. Unlike no-till, ridge-till, and strip-till, in which there is no disturbance to the soil before planting, the soil is tilled before planting in mulch till or reduced till. Weeds are controlled by both cultivation and herbicides in all but no-till, in which weeds are controlled only with herbicides.

A 1987 survey of Albertan farmers conducted by Jensen (1988) revealed that 45% of respondents practised reduced, minimum, or no-till. No-till made up only 1% of the 45%. In 1986, approximately 36% of cropland in the United States Northern Plains was in conservation tillage (Magleby and Schertz, 1988). According to Mr. Shad Weber of the United States Department of Agriculture Soil Conservation Service (USDA SCS) in Billings, farmers in the Billings area are being encouraged to adopt reduced till, no-till, and, on irrigated land, ridge-till (Weber, pers. comm.).

4.3. Wheat yields and climate

Previous studies

Several studies (Arthur, 1988; Wilks, 1988; Williams et al., 1988; Mooney and Arthur, 1990; Okamoto et al., 1991; Wheaton and Wittrock, 1992; Brklacich and Stewart 1993) have attempted to determine the impact of climatic change and/or increased CO_2 concentration on crop yields in the Canadian Prairies or United States Great Plains. The different studies have arrived at different results of yield changes under a doubled CO_2 climate, some suggesting increases in yield, others warning of the potential for decreased yields.

Arthur (1988) used GISS and GFDL GCM data and a series of weather and crop models to forecast yield changes of wheat, oats, barley, canola, and flax in the Prairie provinces. In Alberta, under the GISS scenario, yields of all crops either experienced insignificant change or increased, whereas under the GFDL scenario, yields showed either insignificant change, or decreased (except barley). Wilks (1988) used physiological crop models in conjunction with GCM data to determine impacts on winter wheat in Kansas, and spring wheat in North and South Dakota. Winter wheat yields were found to increase, while spring wheat yields decreased in some areas of the study area and increased in others. Williams et al. (1988) used historical scenarios given by the 1933-37 period and the year 1961, and two GISS GCM scenarios, one with changed temperature and precipitation and one with changed temperature and 1951-80 precipitation, to forecast yield changes in Saskatchewan. The 1961 scenario suggested yield decreases of 76% while the 1933-37 years suggested changes anywhere between a 58% yield reduction and a 26% yield increase. The GISS scenario with forecasted temperature and precipitation showed reductions of

18%, and the GISS scenario with forecasted temperature and 1951-80 precipitation showed a yield decrease of 28%. Mooney and Arthur (1990) used a biological weather crop-yield model to determine changes to crop yields under a 2 X CO_2 scenario in Manitoba. Their study showed a 20-30% reduction in crop yields, with wheat yields being reduced by 26.8 - 36%. Okamoto et al. (1991) used models incorporating different energy consumption scenarios to test the idea that increased CO_2 concentrations might be beneficial to crops. Under a temperature change of 4.2°C, wheat yields were shown to either increase up to 10% throughout the next century, or increase during the first part of the century, then decrease by up to 20-30% by the end of the next century.

Wheaton et al. (1992) have made a synopsis of impacts on Saskatchewan agriculture forecasted by various studies. They propose, with "low confidence", yield decreases for spring wheat, and with "moderate confidence", yield increases for winter wheat (p.121).

Brklacich and Stewart (1993) used the CERES-WHEAT model and GCM data to determine changes in wheat yields on the Canadian Prairies. They determined that impacts on wheat yields depend on the scenario used and the geographical location of the study area; different prairie sites may experience different yield impacts. Mooney et al. (1994) used yield changes outlined by their chosen analogous regions as an input into a linear programming model to assess changes to the agroeconomy of the Prairie provinces under doubled CO_2 conditions. The 9-year average (1981-89) spring wheat yield for Census Division #1, in the Medicine Hat area, was 25.2 bushels/acre. The average all-wheat yield (1984-89) in the analogue region, which included south central Montana, south eastern Montana, and north eastern Wyoming, was 20.15 bushels/acre, suggesting a yield reduction of approximately 20%.

Comparison of yields

Medicine Hat is primarily a spring wheat growing area. Spring wheat makes up approximately 71.6% of all wheat acreage in Alberta Census Division No.1 (CD 1, Figure 4.1) (1982-92 average). The remainder of CD 1 wheat acreage is comprised of durum wheat (20.7%) and winter wheat (7.5%) (from statistics provided by Su, pers. comm.). Billings has nearly the opposite composition, with 91.4% of all wheat acreage in Yellowstone County planted in winter wheat, and 8.6% planted in spring wheat (1982-92 average) (from statistics provided by Lund, pers. comm., and Montana Agricultural Statistics Service, 1982, 1984, 1986, 1988, 1990, and 1992).

The fact that there is both spring and winter wheat planted at Medicine Hat and Billings allows for comparison of yields between the two locations. It should be mentioned that the intention here is to give a generalized view of how

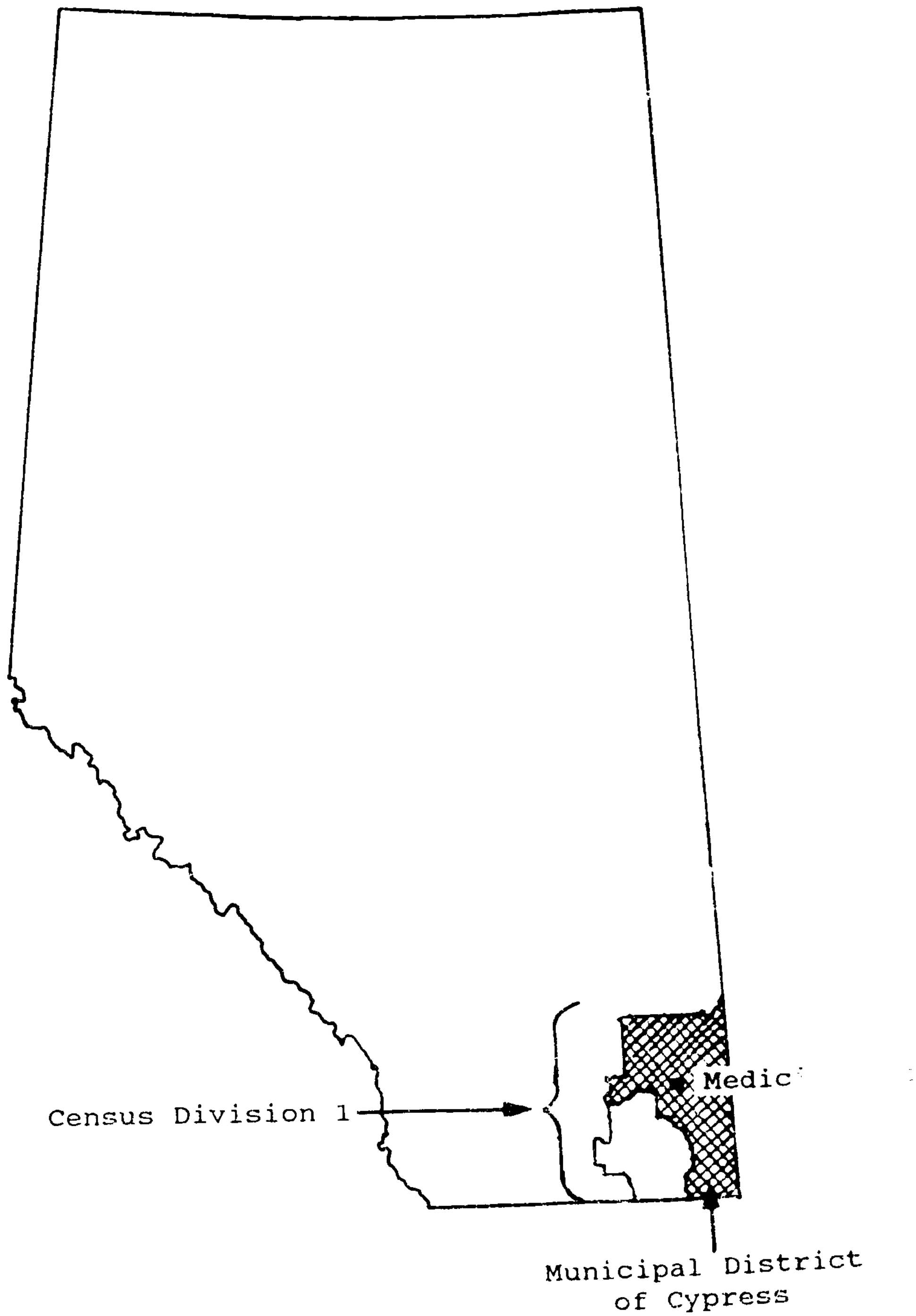


Figure 4.1. Location of Census Division 1 and Municipal District of Cypress.

climate affects wheat yields in the two study locations; wheat yield data are from an entire county or census district, whereas climate data are from an individual station, and will not be homogeneous across the area for which wheat yields are amalgamated.

Yield, acreage, and production data which distinguishes between irrigated vs. dryland spring and winter wheat are available for Yellowstone County (Lund, pers. comm.; Montana Agricultural Statistics Service, 1982, 1984, 1986, 1988, 1990, 1992). Spring wheat, winter wheat, and all wheat yield, acreage, and production data for CD 1 was provided by Su (pers. comm.) and Alberta Agriculture Statistics Yearbooks (Alberta Agriculture, 1982-92). The breakdown into irrigated and dryland wheat was not available for CD 1; however, yield, acreage, and production data for stubble, fallow, and irrigated spring and winter wheat were available for the Municipal District of Cypress (MD Cypress, Figure 4.1), in the Medicine Hat area, from the Agriculture Financial Services Corporation (Cruickshank, pers. comm.). Tables 4.1 and 4.2 show acreage of dryland and irrigated spring and winter wheat from 1982-92. Stubble and fallow yields were combined into total dryland for each of spring and winter wheat, by calculating production (yield x acreage) of each, combining productions of stubble and fallow to obtain total dryland production, then recalculating yield (total dryland production/total dryland acreage). Appendix 7 shows the raw stubble and fallow figures used in the calculations. Regression of total (irrigated + dryland) spring and winter wheat yields from MD Cypress on yields from CD 1 gave R^2 for spring wheat of 0.86 (11 observations), and R^2 for winter wheat of 0.63 (4 observations). Total spring and winter wheat yield figures used in the regressions were calculated in the same way as total dryland yields were calculated above: production of each of dryland and irrigated spring or winter wheat was calculated, the irrigated and dryland production figures were added to obtain total production, then yield was recalculated. The correlation between MD Cypress and CD 1 winter wheat is weak and there are few observations due to a shortage of data on irrigated winter wheat. Nevertheless, the MD Cypress winter wheat data were used, as they were all that was available to show a distinction between the yields of dryland and irrigated winter wheat.

Figures 4.2 - 4.5 show wheat yields for the period 1982-92. Wheat yields in Medicine Hat and Billings follow a very similar pattern. Because the yield fluctuations over the years are generally the same in both locations, it seems evident that climatic fluctuations, which are similar in the Medicine Hat and Billings areas (see Figures 2.1, 2.2, 2.7, 2.8, 2.13, and 2.14), are the primary control on yield fluctuations.

Table 4.3 shows 1982-92 yields of all wheat (includes

Year	MD Cypress				Yellowstone County			
	dryland	% total	irrigated	% total	dryland	% total	irrigated	% total
1982	115 389	98.7	1 563	1.3	7 000	95.9	300	4.1
1983	124 551	98.6	1 754	1.4	500	16.7	2 500	83.3
1984	115 701	97.8	2 597	2.2	3 400	56.7	2 600	43.3
1985	55 356	99.3	380	0.7	7 000	85.4	1 200	14.6
1986	133 157	98.9	1 495	1.1	4 700	78.3	1 300	21.7
1987	112 705	99.3	755	0.7	7 000	77.8	2 000	22.2
1988	108 405	99.3	796	0.7	3 500	70.0	1 500	30.0
1989	112 533	99.2	869	0.8	11 100	80.4	2 700	19.6
1990	117 550	99.0	1 160	1.0	3 800	47.5	4 200	52.5
1991	157 261	99.1	1 401	0.9	2 700	57.4	2 000	42.6
1992	156 543	99.8	331	0.2	3 900	54.2	3 300	45.8
mean	119 014	99.0	1 191	1.0	4 964	69.8	2 145	30.2

Table 4.1. Acreage of dryland and irrigated spring wheat in MD Cypress and Yellowstone County.

Year	MD Cypress				Yellowstone County			
	dryland	% total[1]	irrigated	% total[1]	dryland	% total	irrigated	% total
1982	1 520		NA		78 000	97.3	2 200	2.7
1983	3 396	96.6	120	3.4	74 400	97.9	1 600	2.1
1984	4 530	94.0	290	6.0	82 400	98.6	1 200	1.4
1985	590		NA		60 000	95.5	2 800	4.5
1986	7 706		NA		74 300	99.1	700	0.9
1987	8 273	97.0	260	3.0	78 400	98.0	1 600	2.0
1988	13 633		NA		64 100	98.6	900	1.4
1989	2 698		NA		70 300	99.0	700	1.0
1990	5 336	97.4	145	2.6	87 400	99.3	600	0.7
1991	4 191		NA		67 300	98.8	800	1.2
1992	1 637		NA		82 600	98.6	1 200	1.4
mean	4 865	96.0	204	4.0	74 473	98.3	1 300	1.7

Table 4.2. Acreage of dryland and irrigated winter wheat in MD Cypress and Yellowstone County. NA indicates not available.

[1] spaces have been left blank where inavailability of winter wheat data has precluded calculation of a total and per centage of total.

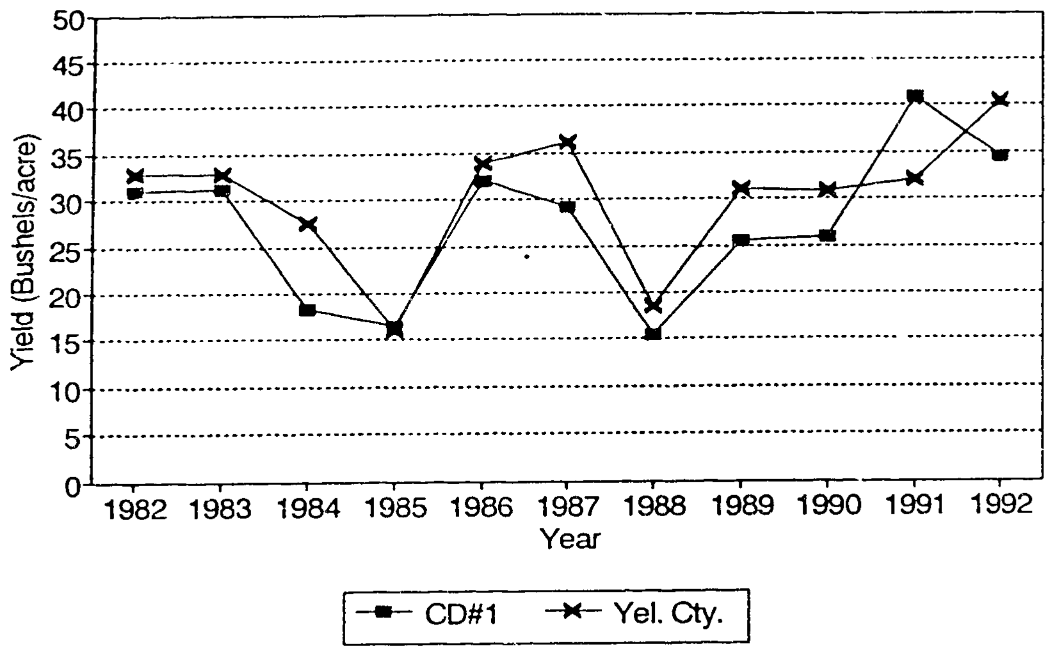


Figure 4.2. All wheat yields for Census Division 1 (CD #1) and Yellowstone County (Yel. Cty).

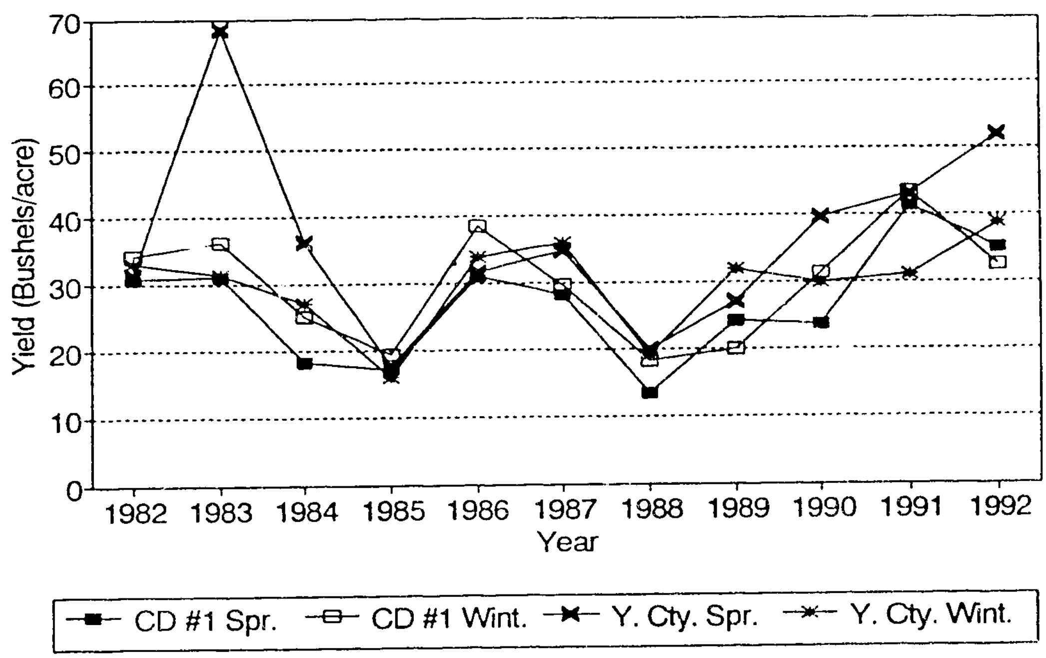


Figure 4.3. Spring (spr.) and winter (wint.) wheat yields for Census Division 1 (CD #1) and Yellowstone County (Y.Cty.).

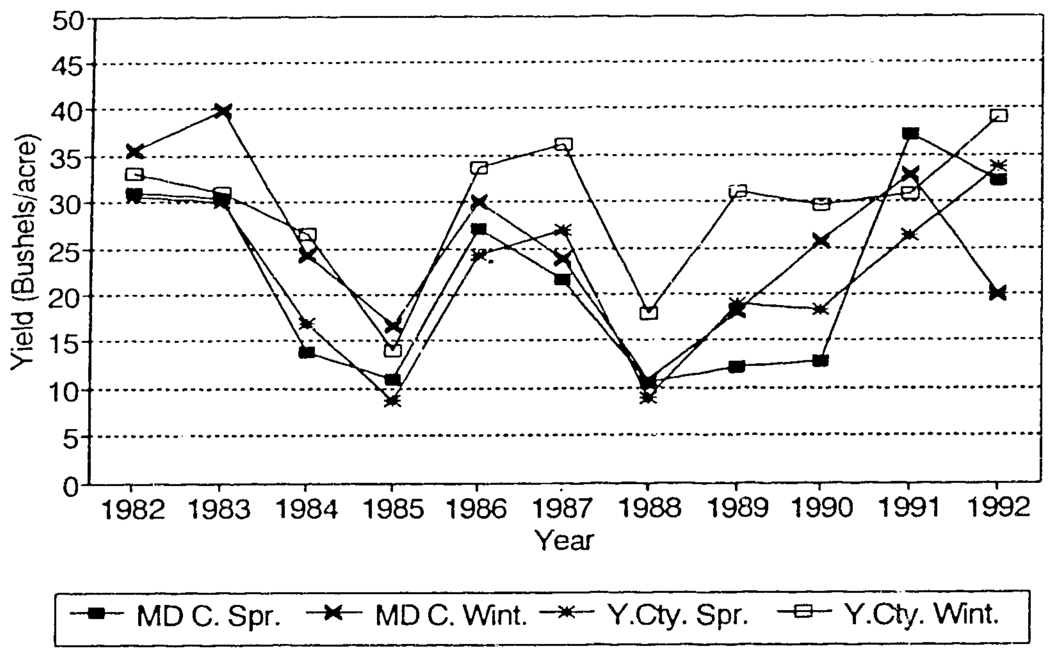


Figure 4.4. Dryland spring (spr.) and winter (win..) wheat yields for Municipal District of Cypress (MD C) and Yellowstone County (Y.Cty.).

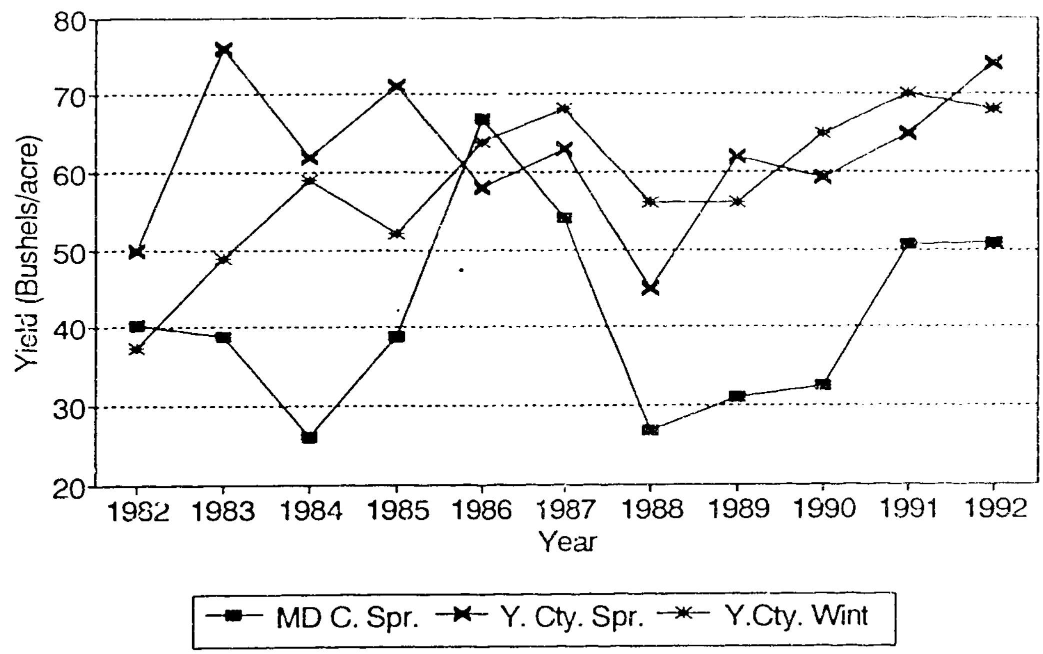


Figure 4.5. Irrigated spring (spr.) and winter (wint.) wheat yields for Municipal District of Cypress (MD C) and Yellowstone County (Y.Cty.). Irrigated winter wheat in MD Cypress is not shown due to lack of data.

Year	CD **#1**	**Yellowstone County**
1982	31.0	32.9
1983	31.3	32.8
1984	18.4	27.6
1985	16.4	16.0
1986	32.0	33.9
1987	29.2	36.2
1988	15.4	18.6
1989	25.5	31.0
1990	26.0	30.7
1991	40.9	32.1
1992	34.6	40.5
mean	27.3	30.2
standard deviation	8.0	7.2

Table 4.3. Yields of all wheat in the Medicine Hat area (CD #1) and the Billings area (Yellowstone County). Yields are in bushels/acre.

spring wheat, winter wheat, irrigated, and dryland) in CD 1 and Yellowstone County. Table 4.4 shows yields for the same two areas, distinguishing between spring and winter wheat. Table 4.5 shows yields of irrigated spring and winter wheat for MD Cypress and Yellowstone County, and Table 4.6 shows dryland spring and winter wheat yields for these two areas. In terms of all wheat, Yellowstone County has received yields approximately 10.6% higher on average than those of CD 1. A likely explanation for the yield difference lies in the fact that the major wheat crop in Yellowstone County is winter wheat and in CD 1, it is spring wheat. Winter wheat yields in Yellowstone County are approximately 11.2% higher than CD 1 spring wheat yields. Winter wheat is typically higher yielding than spring wheat, however, with yields about 10-15% higher than spring wheat yields (Alberta Agriculture, 1987b). Even within CD 1 itself, winter wheat yields are 11.6% higher than spring wheat yields (Table 4.4).

Irrigation can increase yields significantly; MD Cypress's irrigated spring wheat yields are nearly twice as high as its dryland spring wheat yields. Yellowstone County's yields of irrigated spring wheat are nearly 3 times that of dryland spring wheat yields. Winter wheat in Yellowstone County, although still subject to increases in yield with irrigation, does not show as pronounced an increase as spring wheat. Irrigated winter wheat yields in the county are nearly twice those of dryland winter wheat yields, as opposed to the nearly threefold increase of spring wheat. In MD of Cypress, winter wheat yield, like spring wheat yield, approximately doubles with irrigation.

Spring wheat yields are 36.6% higher in Yellowstone County than in CD 1 (Table 4.4). A likely explanation for the higher yield in Yellowstone County is that the proportion of acreage of irrigated spring wheat is increasing the mean. Thirty per cent of the spring wheat acreage in Yellowstone County is irrigated (1982-92 average), as compared to only 1% in MD Cypress (1982-92 average). Comparison of dryland spring wheat yields in Yellowstone County and MD Cypress (Table 4.6) reveals a negligible difference in yield of 1.4%, whereas irrigated spring wheat yield is 50.1% higher in Yellowstone County (Table 4.5). Thus, irrigated spring wheat is highly productive in Yellowstone County; however, dryland spring wheat in the County does not show much improvement over that of the Medicine Hat area.

Winter wheat in CD 1 and Yellowstone County produces very similar yields (Table 4.4). Comparison of both irrigated and dryland crops in MD Cypress and Yellowstone County (Tables 4.5 and 4.6), however, shows that yields are higher in the latter region.

Yields appear to be higher on average in Billings. The standard deviations of each crop show, however, that yields in Billings are significantly higher (higher than an increase of 1 standard deviation of Medicine Hat's yield) only in the

Year	Spring Wheat		Winter Wheat	
	CD #1	Yellowstone County	CD #1	Yellowstone County
1982	30.8	31.4	34.2	33.1
1983	31.0	68.3	36.2	31.4
1984	18.3	36.4	25.0	27.0
1985	17.0	17.8	19.3	15.8
1986	31.1	31.7	38.6	34.0
1987	28.3	35.0	29.8	36.0
1988	13.2	20.0	18.0	19.0
1989	24.3	27.0	20.0	32.0
1990	23.8	39.8	31.5	29.9
1991	41.5	43.0	43.3	31.0
1992	35.3	52.0	32.7	39.0
mean	26.8	36.6	29.9	29.8
standard deviation	8.4	14.4	8.4	6.9

Table 4.4. Yields of spring and winter wheat in the Medicine Hat area (CD#1) and the Billings area (Yellowstone County). Yields are in bushels/acre.

Year	Spring Wheat		Winter Wheat	
	MD Cypress	Yellowstone County	MD Cypress	Yellowstone County
1982	40.2	50.0	NA	37.5
1983	38.8	76.0	20.0	49.0
1984	26.1	62.0	55.0	59.0
1985	38.8	71.0	NA	52.0
1986	66.8	58.0	NA	64.0
1987	54.1	63.0	52.1	68.0
1988	26.8	45.0	NA	56.0
1989	30.9	62.0	NA	56.0
1990	32.3	59.3	63.5	65.0
1991	50.5	65.0	NA	70.0
1992	50.1	74	NA	68.0
mean	41.5	62.3	47.7	58.6
standard deviation	12.8	9.4	19.1	9.9

Table 4.5. Yields of irrigated spring and winter wheat, in Municipal District of Cypress and Yellowstone County. Yields are in bushels/acre. NA indicates not available.

Year	Spring Wheat		Winter Wheat	
	MD Cypress	Yellowstone	MD Cypress	Yellowstone
1982	31.1	30.6	35.5	33.0
1983	30.4	30.0	39.7	31.0
1934	13.7	16.8	24.4	26.5
1985	10.9	8.7	16.6	14.1
1986	27.1	24.4	29.9	33.7
1987	21.7	27.0	23.8	36.0
1988	10.6	9.0	10.8	18.0
1989	12.2	19.0	18.1	31.0
1990	12.8	18.2	25.8	29.7
1991	37.1	26.3	32.8	30.9
1992	32.4	33.6	20.0	39.0
mean	21.8	22.1	25.2	29.4
standard deviation	10.1	8.5	8.7	7.4

Table 4.6. Dryland wheat yields in the Medicine Hat area (CD#1) and the Billings area (Yellowstone County). Yields are in bushels/acre.

cases of total (irrigated + dryland) spring wheat, and irrigated spring wheat.

Two years in which yields were well below average (1982-92) in both Medicine Hat and Billings are 1985 and 1988. In 1985, CD 1's all-wheat yields were reduced by 39.9% from the 1982-92 average, and Yellowstone County's yields were reduced by 47%. In 1988, yield reduction was greater in CD 1, where yields were reduced by 43.6% from average, while in Yellowstone County, yields were reduced by 38.4%. Examination of yields of the major wheat crops in each region, spring wheat in CD 1 and winter wheat in Yellowstone County, mirror the yield reductions of all-wheat in 1985 and 1988. CD 1 spring wheat yields were reduced by 36.6% from average in 1985, while Yellowstone County's winter wheat yields were reduced by 47% from average. In 1988, CD 1 spring wheat yields suffered reductions of 50.7 % from average, and in Yellowstone County, reduction in winter wheat yields was 36.2% below average. Spring wheat yields in Yellowstone County in 1985 and 1988 encountered much the same reductions as CD 1 spring wheat yields. In 1985, yields were reduced by 51.4%, and in 1988, yields were reduced by 45.4%. Winter wheat yields in CD 1 were also reduced: by 35.5% in 1985, and by 39.8% in 1988.

The low yields in these years appear to have resulted from, at least in part, moisture stress. PDSI values during the 1985 and 1988 growing seasons (May-August) were low (see Figures 2.11 and 2.12, and Appendix 4). Growing season precipitation (Figures 2.6 and 2.7) was also low. Summer temperatures were above normal in both locations in 1988. In 1985, summer temperatures were below normal in Medicine Hat but above normal in Billings. The high temperatures combined with precipitation shortage would create moisture stress reflected in PDSI values. The below normal summer temperatures in Medicine Hat in 1985 may explain why yield reductions are not as great as those in Billings during that year.

Other factors, in addition to moisture stress, added to yield reductions. For example, grasshopper infestation and winds were a problem in both Medicine Hat and Billings in 1985 (Alberta Agriculture, 1985; Montana Agriculture Statistics Service, 1986), contributing to the low yields in both locations in that year. Rosenberg (1992) points out that grasshopper populations grow during warm dry periods; thus, the drought conditions that existed in 1985 made it possible for grasshoppers to become a problem, and exacerbate climatically-induced crop stresses. It appears that wheat yields in the Medicine Hat and Billings areas are reduced by similar amounts when subjected to stress factors such as moisture shortage and pests.

4.4. Summary of agricultural analogues

Agriculturally, the Billings and Medicine Hat areas are very similar. Distribution of cash receipts among farm products in Alberta and Montana is analogous; in 1991 crops made up 41.9% of cash receipts from the sale of farm products in Alberta, and 48.4% in Montana. Wheat cash receipts in 1991 constituted 41.9% of total crop receipts in Alberta, and 54.8% in Montana. Soil erosion by wind and water are of concern in both areas, and conservation tillage and residue management are being encouraged. Comparison of wheat yields in the two locations reveals that, on average, yields are higher in the Billings area; however, yields in Billings are only significantly higher (higher than an increase of 1 standard deviation of Medicine Hat's yield) in the case of total (irrigated + dryland) spring wheat, and irrigated spring wheat. All-wheat yields are higher in Billings due to higher proportions of winter wheat and irrigated spring wheat, both of which are higher-yielding than dryland spring wheat, which is the main wheat crop in the Medicine Hat area.

5. CHAPTER FIVE

FINAL ASSESSMENT

The final question arises: what are the potential effects of climatic warming for the Medicine Hat region as indicated by the regional analogue study? This closing chapter interprets the study results to give a final assessment of the implications of climatic change for the Medicine Hat region, using regional analogue methodology.

5.1. Summary of study and results

The objective of this thesis was to examine possible effects of climatic change on selected aspects of the environment of the Alberta portion of the Palliser Triangle. The regional analogue method was used. The study area was that around Medicine Hat, in the centre of the Alberta portion of the Triangle. The 2 X CO_2 analogue region was the area around Billings, Montana, approximately 500 km south-by-southeast of Medicine Hat. The Billings area was selected as an analogue region on the basis of temperature, precipitation, previous studies which suggested similar regional shift under 2 X CO_2 conditions, similarity of agricultural land use, topography, soils, and length of climatic record.

5.2. Discussion

Interpretation of results

The evidence indicates that if, as a result of climatic change, the climate of the Medicine Hat region were to resemble that of the Billings region, the differences in the environment would not be drastic. Some climatic changes, such as a lengthened growing season, have positive implications. Other changes, such as increased drought frequency and intensity leading to reduction in crop yield, may cause problems.

The examination of vegetation distribution in Chapter 2 shows that if the climate, and thus vegetation, of Medicine Hat became more like that of Billings, the potential natural vegetation of the immediate areas of the two cities would not be significantly altered. The Billings area is more characteristic of the mixed-grass vegetation at slightly higher elevations in the Medicine Hat area, than the short grass species in the area immediately around Medicine Hat. This is because Billings is at roughly the same elevation as the mixed grass area between Medicine Hat and the Cypress Hills. If summer soil moisture became more variable, (Chapter 3), species composition would become more variable over time, following a gradient such as Strong and Leggat's (1981) cool/wet -- hot/dry environmental gradient of vegetation. Strong and Leggat's environmental gradient shows that grama grass becomes more prevalent in drier years, and spear and wheat grass become more prevalent in wetter years.

The Aspen Parkland Groveland Subregion is, according to Strong and Leggat (1981), a "tension zone between the Fescue and Mixed Grass Ecoregions, and the Aspen Subregion" (p. 15). Strong and Leggat (1981) show a difference in precipitation distribution separating the Fescue Grass Ecoregion and the Aspen Parkland Ecoregion (Figure 5.1). The apparent lack of a prominent aspen growth in the Pryor and Bighorn Mountains could be a product of a difference in precipitation distribution; although they are further north and at lower elevations than the higher elevation fescue/aspen sites, Medicine Hat and Billings have precipitation distributions that roughly match the aspen and fescue distributions, respectively. Strong and Leggat (1981) also show that rough fescue grassland is more towards the dry/warm side of the environmental gradient, while aspen parkland is more towards the cool/wet side. Thus, the warmer climate of Billings means less aspen growth in the Billings area than around Medicine Hat. Aspen groves occur in the Groveland Subregion of the Cypress Hills only in areas where moisture is sufficient, such as north-facing slopes and stream banks. Therefore, one of two factors could contribute to the apparent non-existence of aspen in the foothills and mountains south of Billings: (a) there is insufficient moisture to sustain aspen, or (b) the classification system of the MSU climax vegetation map does not detect small groves of aspen which are actually present.

The same forest species in the Cypress Hills are not present in the Pyor and Bighorn Mountains, although species belonging to the *Pinus* (pine), *Picea* (spruce), and *Juniperus* (juniper) genera are present in both areas. The vegetation gradient on higher slopes of the Pryor and Bighorn Mountains is expected to be somewhat different from that of the Cypress Hills, due to the higher elevation. The difference in tree species between the Cypress Hills and the lower slopes of the Pryor/Bighorn Mountains reflects the difference in climate between the two areas; however, other factors contribute to growth of species on slopes. Differences in slope gradient, aspect, and soil drainage characteristics will play a part in the prominence of forest species in the Cypress Hills and the low slopes of the Pryor and Bighorn Mountains. Fishburn (pers. comm.) suggests that the limber pine of the Pryor Mountains may have been planted by early indigenous peoples. It is possible that over time, the vegetation of the Cypress Hills could become more like that of the Pryor and Bighorn Mountains, but because of the above inconsistencies, and uncertainties in ability of plant species to migrate northward (see below), that idea cannot be proposed with a high degree of certainty.

A change from spring wheat to higher-yielding winter wheat could prove to be profitable, depending on how crop prices and agricultural policies are regulated or changed in the future. According to Williams et al. (1988) winter wheat

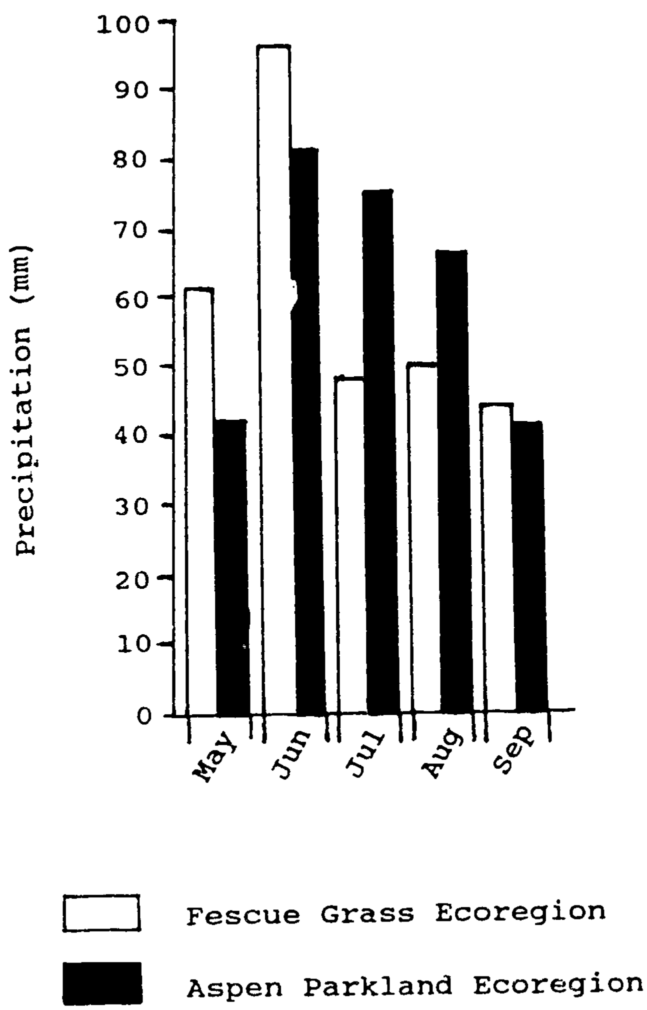


Figure 5.1. May - September precipitation distribution in the Fescue Grass and Aspen Parkland Ecoregions. Redrawn from Strong and Leggat (1981).

can already be grown in Saskatchewan, having become more popular in the 1980s. Williams points out that winter wheat is hardier than spring wheat because it is able to use fall, winter, and early spring moisture which is not available to spring wheat, and because it is more mature than spring wheat when late frosts occur and thus not as susceptible to frost damage. He suggests that the expansion of winter wheat in Saskatchewan is due to a changing agricultural market, a desire of farmers to spread their workload by planting both fall- and spring-seeded crops, a push to use a spring cover crop to reduce soil erosion, and less severe winters during the 1980s. The threat of winter kill of winter wheat is not absent in the Billings area; when winter kill occurs, fields are replanted in spring wheat (observed from yield data provided by Lund, pers. comm.). Dryland spring wheat in the Billings area performs as well as in the Medicine Hat area (Chapter 4). The ability to plant winter wheat in Medicine Hat as a result of warmer winters, and the assurance of being able to replant in spring wheat if winter kill occurred, would have favourable implications, unless crop prices and crop insurance made these options less attractive.

Both Alberta and Montana are currently encouraging conservation tillage practices. Under changed climate conditions, and the possibility of more frequent and intense summer droughts (Chapter 3), topsoil may be more at risk. Montana does not seem to be any more stringent in its use of conservation tillage than Alberta, and according to Mr. Shad Weber of the USDA SCS, Billings area farmers are not terribly concerned about possible effects of climatic change (Weber, pers. comm.). Nevertheless, a future increase in severe drought years might lead to an even greater push to adopt conservation tillage. Conversion of cropland to rangeland, as has already occurred in both the Billings area and the Medicine Hat area, may be encouraged.

Areas of uncertainty

There are some uncertainties in regional analogue-based climate change impact studies. The first and most fundamental of the potential areas for uncertainty is General Circulation Model output, as GCMs serve as the basis for selection of an analogue region. GCMs have limitations resulting from limitations of computer capabilities and the assumptions and parameters incorporated into the models. Thus, every aspect of climate over time and space cannot be taken into consideration in model input, and is therefore less certain in output. This affects the selection of an analogue region; if future GCMs are found to better represent a CO_2-warmed climate, new analogue regions might have to be selected.

In this study, GCM temperature output served as the main criterion for selecting a climate change analogue region to the Medicine Hat area. Although the choice of analogue region in this case is believed to be sound, an even more thorough impact assessment would involve selection and examination of several analogue regions. The analogue regions either would represent several different, plausible climate change scenarios for a given area, or would each be chosen to represent a GCM-based climate change scenario for a given area as closely as possible. No analogue region will represent every aspect of GCM output exactly. Such a comprehensive, multiple-region analogue approach would be an ambitious task, and is beyond the scope of this study.

Contemporary regional analogue analysis cannot account for plant physiological response to increased amounts of CO_2. Because increased atmospheric CO_2 causes stomatal closure in plants (Rosenberg, 1981; Idso and Brazel, 1984; Brklacich and Stewart, 1993), moisture loss by transpiration is lessened. Thus, a higher concentration of atmospheric CO_2 could have beneficial effects. Increased CO_2 also stimulates photosynthesis in some plant species (Rosenberg 1981; Okamoto et al., 1991; Brklacich and Stewart, 1993) which could have positive implications. It is uncertain at this time whether the beneficial effects of increased CO_2 would be outweighed by the detrimental effects of increased temperature. A change in plant photosynthesis or transpiration rate resulting from altered CO_2 levels would affect crop yield and would contribute to the ability of naturally-occurring species to survive in warmer climates or migrate northward.

5.3. Conclusions

The climate of Billings has milder winters and is higher in precipitation than that of Medicine Hat. Billings has a higher proportion of precipitation occurring as snow. Variance of annual and winter temperature is lower in Billings, while variance of growing season precipitation is greater. Frequency of temperature and precipitation anomalies is about the same in the two locations. Chinook frequency is lower in Billings.

If future climatic change causes the climate of Medicine Hat to be like that of Billings, what will happen?

1. Frostless period and growing season will be lengthened by anywhere from 1 day to 1 month.
2. Summer soil moisture conditions, as indicated by PDSI data, will become more variable over time.
3. Summer (June and July) droughts should become more frequent and intense, possibly reflecting those of the 1930s.

If the changes in temperature, precipitation, temperature and precipitation variability, growing season, and drought outlined above result in the environment of Medicine Hat's becoming more like that of Billings:

1. Changes in prairie vegetation species may occur in

the immediate area of Medicine Hat, but vegetation would generally remain the same at the genus level, and still be classified as short to mixed grass prairie.

2. More variable summer soil moisture conditions would lead to more temporally variable species composition.

3. Elevational gradient of vegetation could change, with upslope migration and, perhaps, loss of the aspen belt.

4. Higher elevation forest overstorey species might change to those characteristic of the lower slopes around the Billings area; this possibility and 3., above are uncertain because of inconsistencies in slope gradient, aspect, and drainage, and uncertainties in plant physiological response to climate change and increased levels of CO_2.

If the climatic changes outlined above result in agriculture of Medicine Hat being more like that of Billings:

1. Crops would continue to constitute slightly less than half of agricultural cash receipts.

2. Wheat would likely continue to be the main cash crop, although a switch from spring wheat to winter wheat would occur, providing crop prices made it profitable to do so.

3. Wheat yields would increase, but not more than one standard deviation over Medicine Hat's 1982-92 average yield.

4. Drought and pests would continue to have detrimental effects on crops, reducing yields by the same, or possibly higher degree as was seen in 1985 and 1988.

The conclusions concerning agriculture are less certain than those concerning other sectors. Agricultural technology, market, and policy changes made during the course of climatic change would affect chosen agricultural products, crop mix, and crop yields. A current example of how profits determine crop mix is shown by the fact that although wheat is the most drought tolerant crop grown in Alberta, less drought tolerant crops such as canola are becoming more popular because of higher profits, even though they carry a higher risk of drought losses.

Policy implications

The economic, political, and social effects of climatic change may be more significant than the environmental impacts. The obvious area of political, economic, and social concern with regard to climatic change in the Medicine Hat region is agriculture. Table 5.1. shows some possible policy implications of climatic change in the Medicine Hat area, if the environmental changes highlighted in this thesis take place. Changes in policy will occur primarily in agriculture, as it is such an important land use and consumer of natural resources in the Medicine Hat area. A switch from spring to winter wheat implies changes in marketing strategies and possibly in crop insurance plans. Staying with spring wheat

CLIMATIC/ENVIRONMENTAL AREA	POLICY IMPLICATION
DROUGHT/WET SPELLS	-WATER RESOURCES MANAGEMENT -agricultural consumption -municipal consumption
GROWING SEASON/ FROSTFREE PERIOD	-AGRICULTURAL POTENTIAL -switch to higher yielding winter wheat
	-INITIATION OF A PHENOLOGICAL NETWORK?? -citizen participation -phenology correlated with agricultural operations, useful for climate change detection, etc.
	-RECREATION -summer vs. winter recreation; rec. facility development
VEGETATION DISTRIBUTION	-NATURAL AREAS DECISIONS -areas taken out of agricultural production?
AGRICULTURE	-CHANGE IN CROP MIX -marketing, crop insurance decisions
	-SOIL MANAGEMENT -erosion control, conservation tillage, education -conversion of marginal cropland to rangeland?

Table 5.1. Policy implications of climatic change and associated environmental implications, under the assumption of a transition of Medicine Hat's current climate to one more like Billings.

means irrigation, leading to decision-making on agricultural water resources management. An increase in drought frequency and intensity would elevate the need for soil management education and policy. Any large-scale changes to agricultural policy would have repercussions for many people in the Medicine Hat region whose livelihood depends on agriculture. In addition to agriculture, the areas of water resources management and recreation would be affected by climatic change, calling for examination of policy in municipal and residential water consumption and development of recreation facilities.

The conclusions discussed above paint a fairly benign picture of the effects of climatic change on the Medicine Hat region. More study is needed on the effects of a warmer climate and increased CO_2 levels on plant physiology. A crucial problem concerns the rate at which CO_2 levels will continue to increase and thus the rate at which climate will change, and the effects of increased CO_2 on individual aspects of climate. Such information is required to be able to fully understand what the absolute effects of climatic change will be on the Medicine Hat region. Regional analogy provides an essential starting point as to possible effects of and adaptations to a warmer climate.

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PERSONAL COMMUNICATIONS

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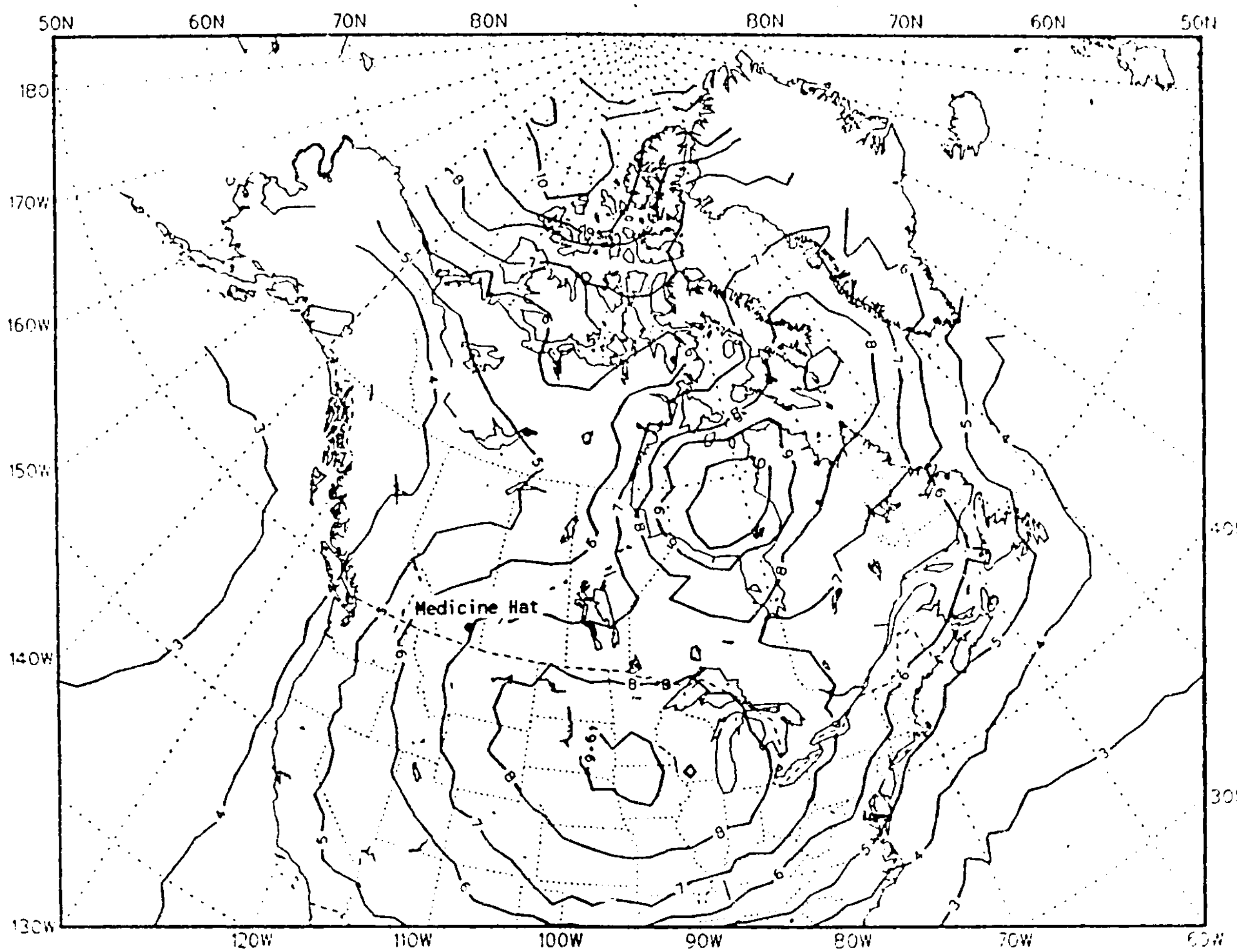
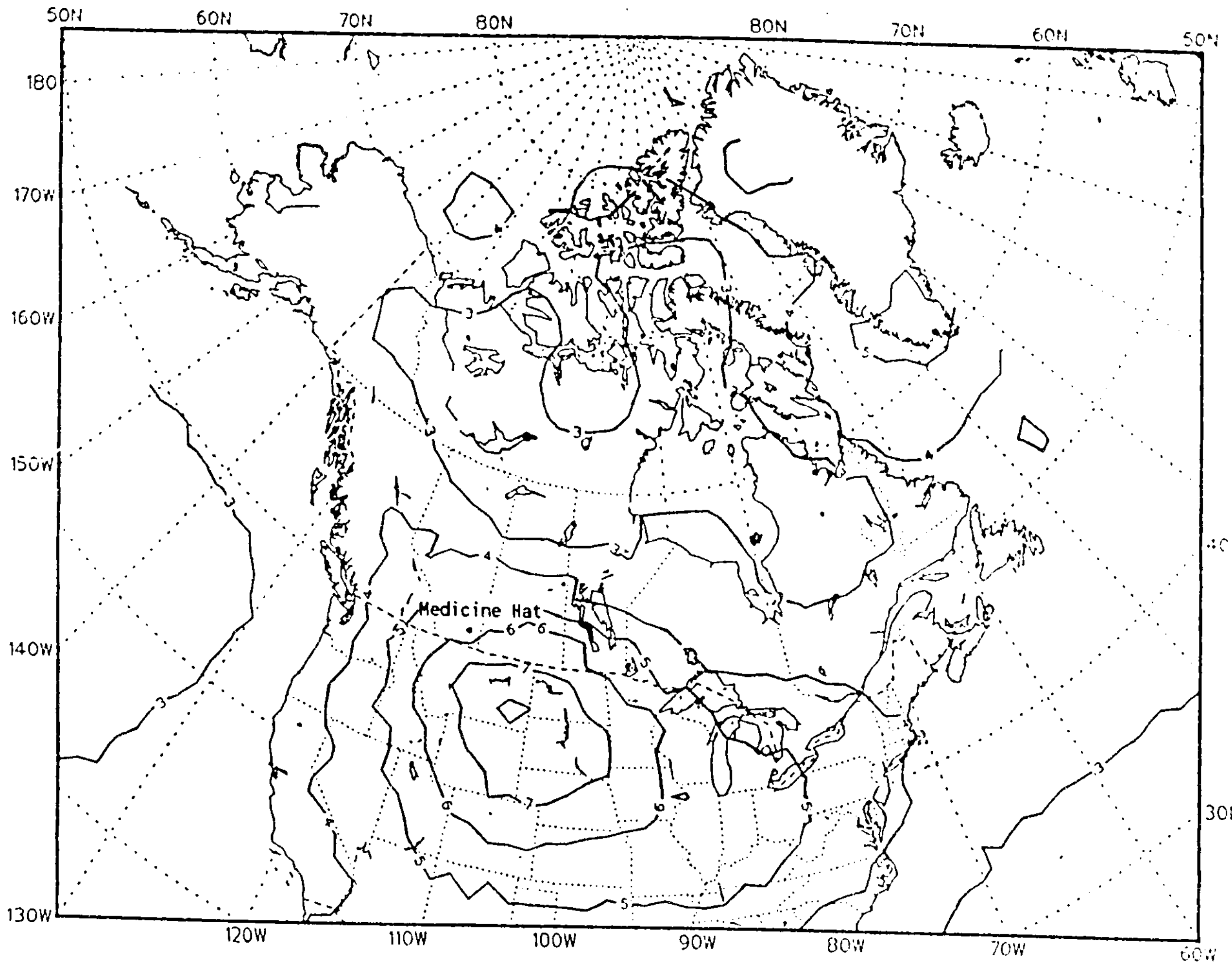
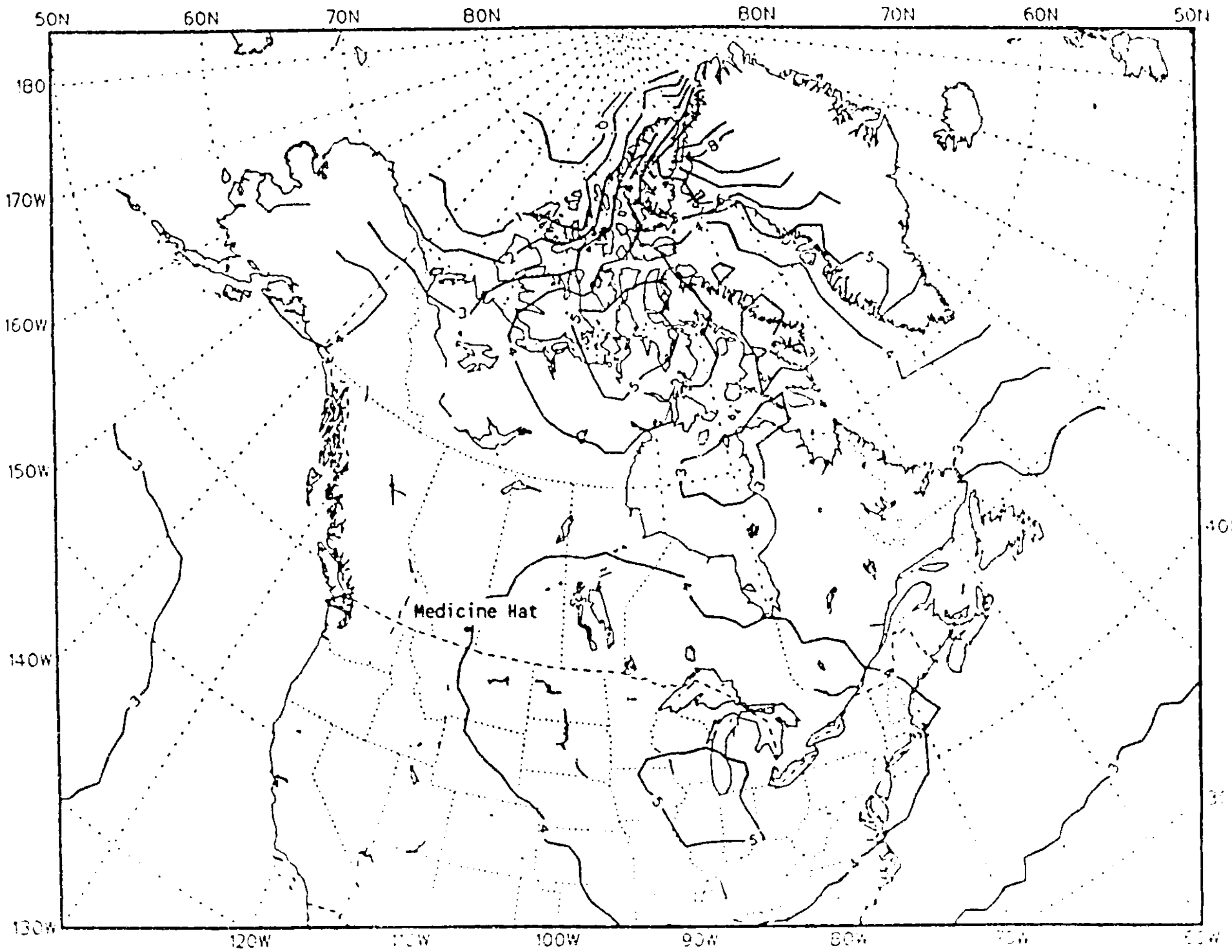
Appendix 1. Isotherm maps showing forecasted amount of precipitation and temperature change for Canada and the northern United States, according to the CCC GCM. Adapted from maps generated by Canadian Climate Centre, Environment Canada, Atmospheric Environment Service. Source: Webb (pers. comm.).



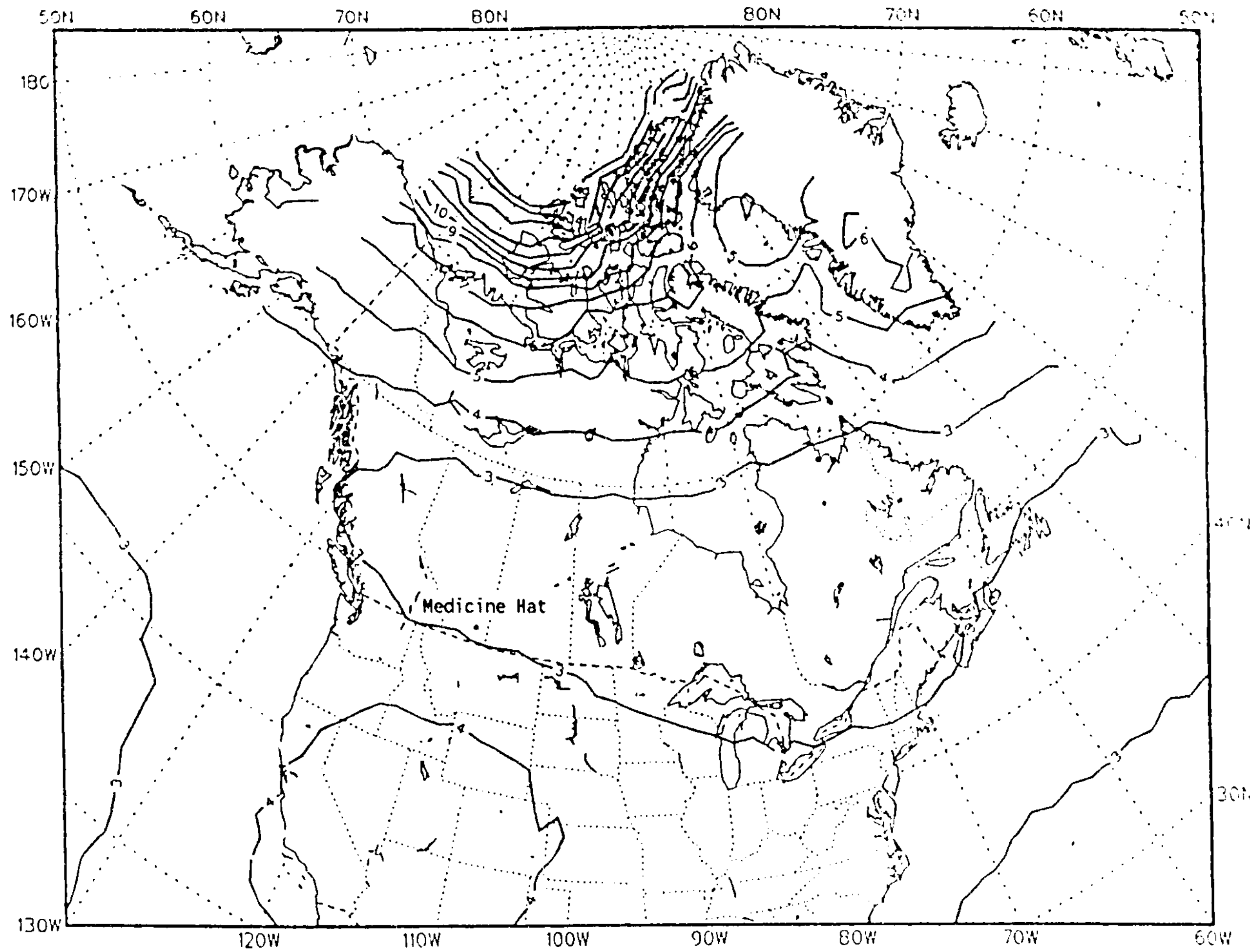
Temperature change (DJF). Scale at 60°N is approximately 1:45 125 000.



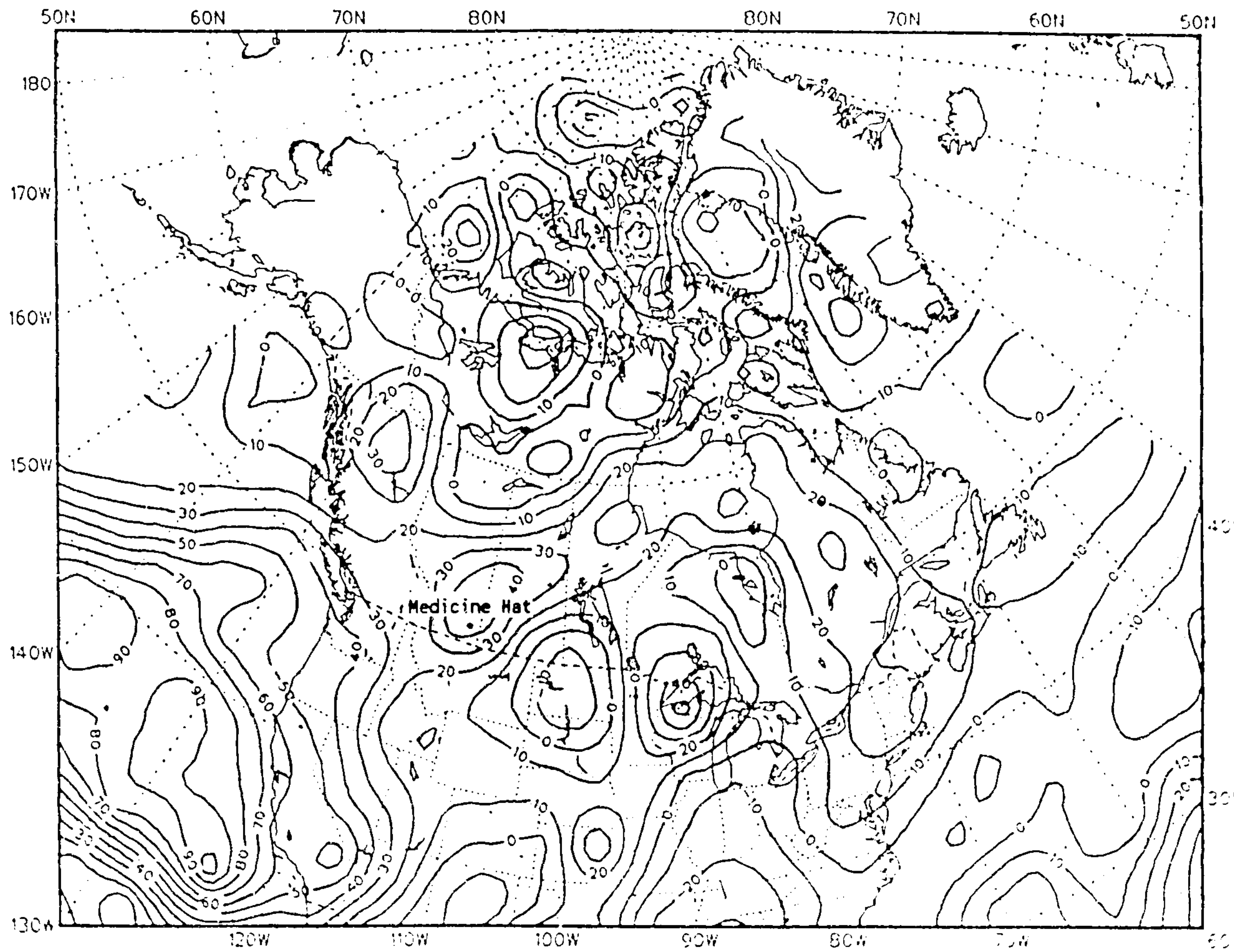
Temperature change (MAM). Scale at 60°N is approximately 1:45 125 000.



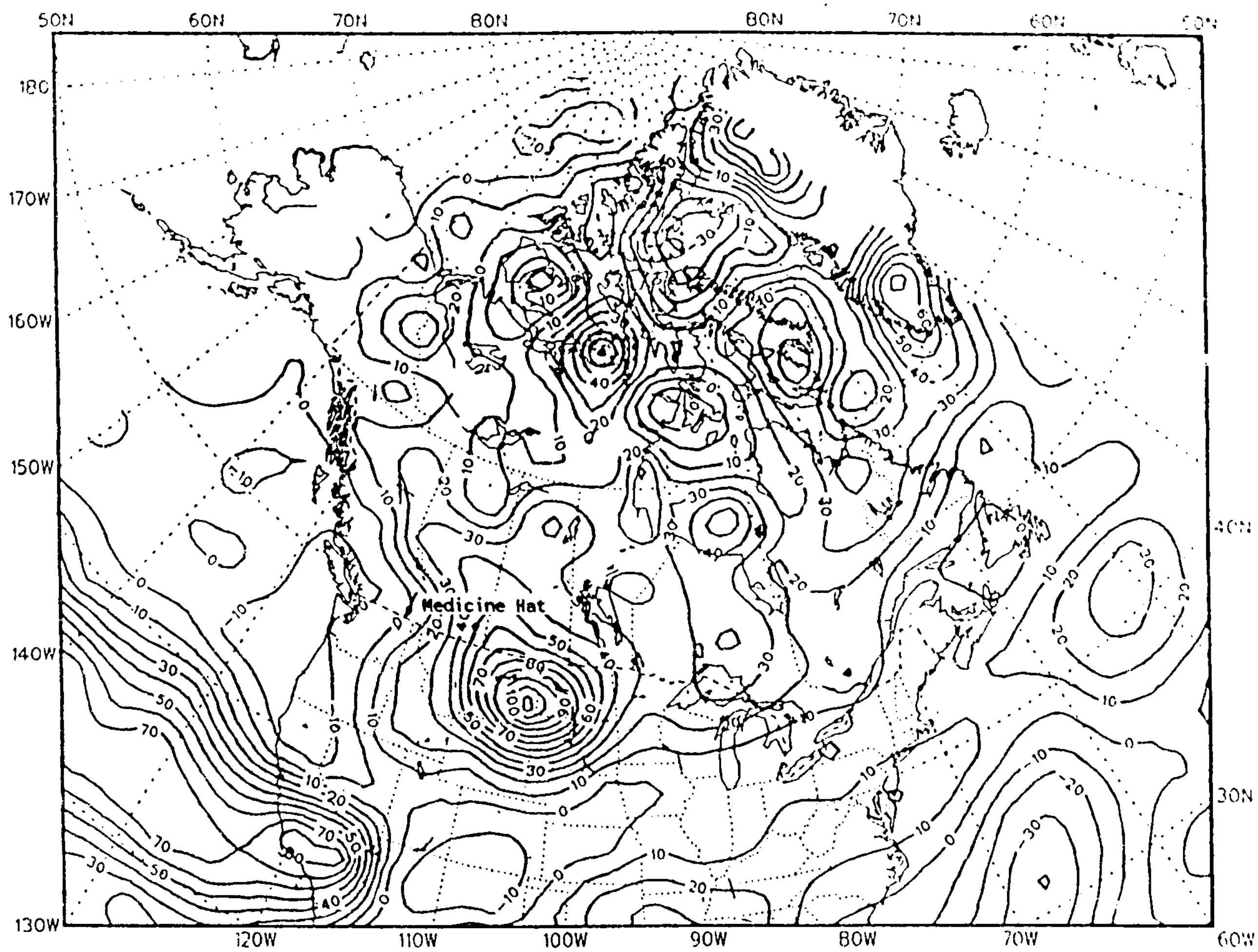
Temperature change (JJA). Scale at 60°N is approximately 1:45 125 000.



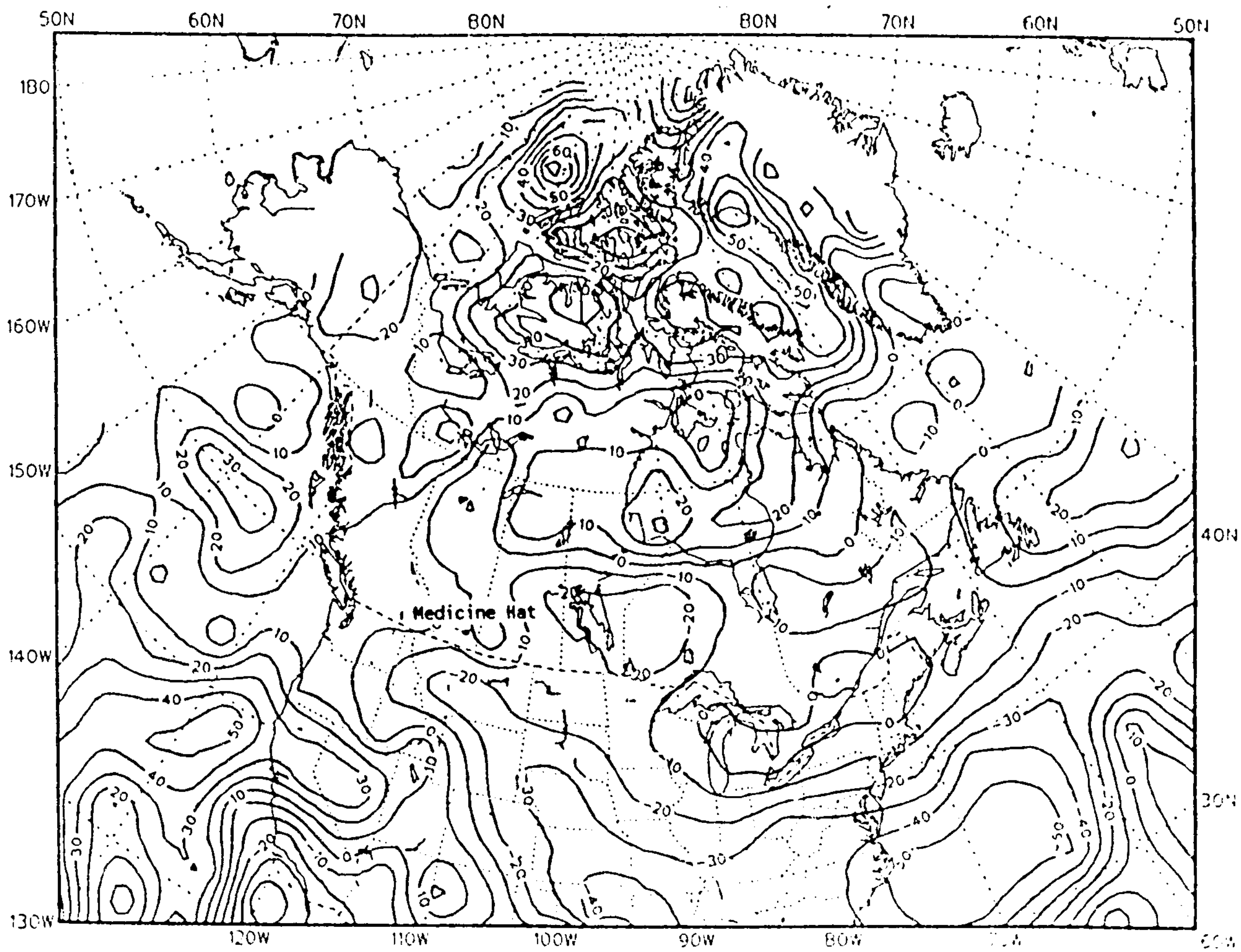
Temperature change (SON). Scale at 60°N is approximately 1:45 125 000.



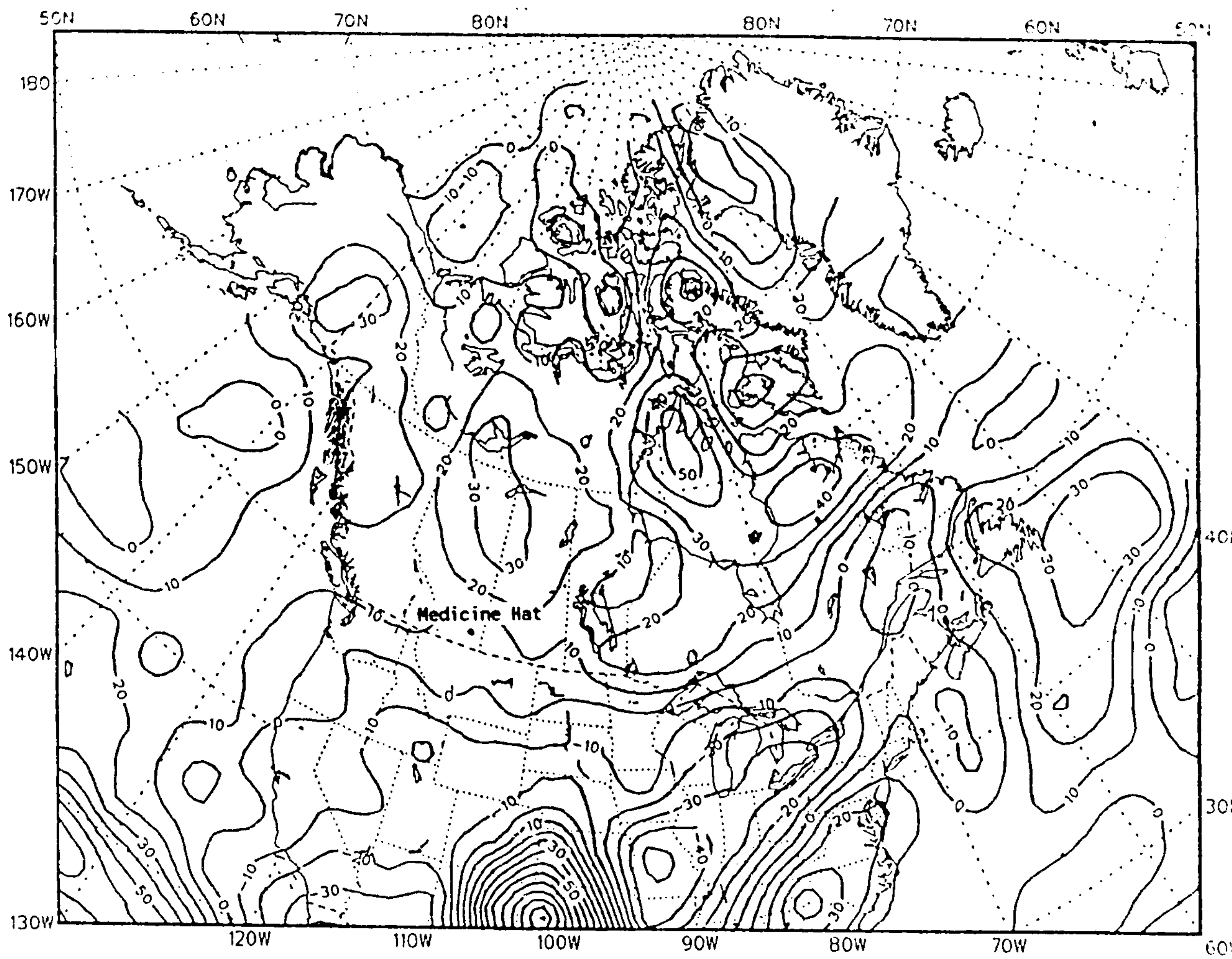
Precipitation change (DJF). Scale at 45°N is approximately 1:41 250 000. Numbers indicate per cent change; positive numbers indicate increase, negative numbers indicate decrease.



Precipitation change (MAM). Scale at 45°N is approximately 1:41 250 000. Numbers indicate per cent change; positive numbers indicate increase, negative numbers indicate decrease.



Precipitation change (JJA). Scale at 45°N is approximately 1:41 250 000. Numbers indicate per cent change; positive numbers indicate increase, negative numbers indicate decrease.



Precipitation change (SON). Scale at 45°N is approximately 1:41 250 000. Numbers indicate per cent change; positive numbers indicate increase, negative numbers indicate decrease.

Appendix 2: Temperature data for Medicine Hat and Billings, departures from normal, and statistics.

Mean Monthly and annual Temps--Med. Hat

YEAR	JAN	FEB			MAR	APR	MAY	JUN	JUL	AUG			SEP	OCT	NOV	DEC	MODDEC	ANN	MODANN	
1934	-3.1	-1.7			-0.5	9.1	16.1	15.8	20.7	19.4			9.4	9	1.5	-8.8	-8.8	7.2	7.2	
1935	-15.6	-4.2			-5.2	2.6	10.5	15.9	21.4	18			14.1	6.2	-6.5	-3.8	-3.8	4.5	4.5	
1936	-14.8	-26.6			-1.7	4.7	16.5	18.3	25.2	20.6			13.5	8	0.8	-9.9	-9.9	4.6	4.6	
1937	-21	-14.4			-2.2	8.5	13.6	17.9	22.3	18.9			14.3	9.4	-3.1	-7.9	-7.9	4.7	4.7	
1938	-5.1	-14.4			-0.4	6.3	11.8	17.8	20.4	17.8			18	9.1	-2.4	-5.9	-5.9	6.1	6.1	
1939	-5.9	-16.7			-4.1	7.2	13.9	13.4	21.2	19.6			13.5	5	5.6	-1.8	-1.8	5.9	5.9	
1940	-16.2	-10.9			-2.6	3.4	14.2	16.8	20.1	20			16.8	10.1	-8.1	-3.8	-3.8	5.0	5.0	
1941	-9	-6.1			-1.2	8.5	13	17.3	22.4	19.7			10.3	7.8	1.9	-4.7	-4.7	6.7	6.7	
1942	-4.5	-11.4			0.5	7.3	11	14.1	19.5	18.2			12.4	7.4	-5	-8.8	-8.8	5.1	5.1	
1943	-18.8	-6.5			-8.3	9.7	10.4	14.2	21.2	19.2			13.5	9.6	1.4	-2.6	-2.6	5.3	5.3	
1944	-5.7	-7			-6.2	9	14.4	15.5	19.6	18.1			14.3	10.7	-5.1	-8	-8	5.8	5.8	
1945	-9.5	-9.4			0.3	2.7	10.3	14.9	21.5	20.1			11.4	8	-6.4	-11.3	-11.3	4.4	4.4	
1946	-7.4	-7.2			4.5	9.6	10.7	16	21.5	17.6			12.7	4.1	-6.5	-8.8	-8.8	5.6	5.6	
1947	-7.6	-11.9			-6.7	7.1	11.5	14.8	22.6	18.3			12.1	9.7	-4.3	-5.2	-5.2	5.0	5.0	
1948	-4.3	-13.4			-7.3	3.2	13.2	17.3	19.6	19.8			15	8.5	0.3	-12.6	-12.6	4.9	4.9	
1949	-15.6	-15.9			-1.2	10.3	14.1	16.4	19.9	20.8			14.1	5.4	6.1	-13.2	-13.2	5.1	5.1	
1950	-27.6	-6.7			-4	5.2	11	16.5	19.8	17.3			13.8	6.4	-4.5	-6.6	-6.6	3.4	3.4	
1951	-13.7	-12			-10.9	4.6	13.6	13	19.8	16.8			11.2	3.4	-0.7	-12.1	-12.1	2.8	2.8	
1952	-15	-6.9			-6.7	10.1	13.4	15.6	17.7	18.1			14.8	8.8	0.2	-4.9	-4.9	5.4	5.4	
1953	-9.1	-2.6			-1.4	2.7	11.2	15.7	19.6	20.1			15	11.2	4.6	-2.1	-2.1	7.1	7.1	
1954	-18.9	1.1			-5.7	0.2	11.6	14.2	20	18			12.6	7.4	5.4	-1.4	-1.4	5.4	5.4	
1955	-8.1	-9.9			-7.1	5.7	10.1	16.3	19.5	19.4			11.8	8.5	-11	-12.2	-12.2	3.6	3.6	
1956	-14	-12.8			-3.5	4.2	12.7	17.1	19.7	18.3			13.3	7.5	1.6	-6.5	-6.5	4.8	4.8	
1957	-16.7	-9.4			-0.4	5.5	14	16.2	20.9	17.8			14.3	3.5	0.9	-1.2	-1.2	5.5	5.5	
1958	-2	-10.9			-5.5	6.7	16	15.9	18.6	20.8			13.7	8.6	-2.4	-6	-6	6.1	6.1	
1959	-13.9	-12.7			2.2	6.1	9.5	17.1	20.5	17.3			12	5.1	-3.5	-0.8	-0.8	4.9	4.9	
1960	-11.7	-8.5			-3.9	6.3	11.4	16.1	23.3	18.6			14.1	9.1	-2.7	-6.2	-6.2	5.5	5.5	
1961	-4.1								20.7									6.7	6.7	
1962	-9.3	FEB	DJF	DEPDJF	MAR	APR	MAY	JUN	18.4	AUG	JJA	DEPJJA	SEP	OCT	NOV	DEC	MODDEC	6.1	6.1	DEPMOD
1963	-14.7	-2.5	-4.26667	4.423333	2.6	4.6	13.2	21.4	20	22	21.36667	2.666667	10.1	6.9	-2.4	-11.9	-11.9	6.7	6.7	1.216667
1964	-7.1	-10.4	-10.5333	-1.83333	-7.1	9	12	18.1	21.3	19.1	18.53333	-0.16667	13.6	9.9	3.7	-3.9	-3.9	5.2	5.2	0.591667
1965	-13.4	-3	-7.2	1.5	3.3	6.9	12.1	17	20.4	19.3	18.76667	0.066667	17.6	11.3	-1	-9	-9	3.9	3.9	1.15
1966	-18.9	-0.2	-5.43333	3.266667	-4.3	5.9	12.4	16.8	19.9	18	18.7	0	10.6	9.4	-2.4	-18.1	-18.1	4.3	4.3	-0.30833
1967	-11.6	-8.8	-13.4333	-4.73333	-7.9	6	11.2	15.6	20.5	19.7	18.56667	-0.13333	7.1	10.1	-5.9	-7.1	-7.1	4.9	4.9	-1.58333
1968	-11.1	-10.2	-12.0667	-3.36667	0.8	3.5	13.5	15	18.8	17.7	17.53333	-1.16667	16.1	6.7	-6.2	-6	-6	5.4	5.4	-1.175
1969	-25.5	-7	-8.2	0.5	-5.4	-0.2	10.3	15.2	19.2	20.9	18.86667	0.166667	17.7	8	-0.7	-8.4	-8.4	4.0	4.0	-0.55833
1970	-15.3	-4.2	-7.9	0.8	4	5	10.8	15.6	21.1	17.2	17.2	-1.5	13.5	7.3	0.1	-12.1	-12.1	4.2	4.2	-0.09167
1971	-14.7	-12.7	-16.7667	-8.06667	-6.4	9.2	13	15.8	18.4	20.7	18.56667	-0.13333	14.8	2.4	1.9	-4.4	-4.4	4.7	4.7	-1.5
1972	-16.2	-6.4	-8.7	-1.8E-15	-4.6	4.4	12.4	19.6	17.3	20.1	20.26667	1.566667	11.7	4.7	-5.9	-11.5	-11.5	3.8	3.8	-1.30833
1973	-6.4	-5.8	-10.6667	-1.96667	-2.9	6.8	13.2	16.1	19.8	23	19.16667	0.466667	11.5	5.9	-1.2	-14	-14	5.8	5.8	-0.80833
1974	-12.5	-12.9	-14.3667	-5.66667	-0.9	5.7	12.9	18.1	20.7	21	18.8	0.1	9.5	4	-0.2	-12.5	-12.5	6.0	6.0	-1.68333
1975	-8.4	-6.9	-8.6	0.1	3.4	4.1	13.1	16.7	21.8	19.8	18.76667	0.066667	13	8.1	-8.7	-6.8	-6.8	3.7	3.7	0.266667
1976	-7.5	-4	-7.76667	0.933333	-3.8	8	9.7	18.7	20.1	16.4	18.6	-0.1	11.8	9.3	0.5	-2.4	-2.4	6.8	6.8	0.533333
1977	-12	-14.3	-8.36667	0.333333	-5.9	-0.5	10.9	15.1	19.1	16.2	17.7	-1	13.2	6.5	-2.4	-7.4	-7.4	5.8	5.8	-1.76667
1978	-16.9	-2.1	-6.66667	3.033333	-2.7	8.7	14.2	15.2	19.5	20	18.43333	-0.26667	15.7	5.9	-1.3	-4.7	-4.7	3.8	3.8	1.291667
1979	-18.2	0.9	-5.26667	3.433333	1.4	9.3	12.9	18.6	20.4	16	17.9	-0.8	12	7.8	-3.5	-12.7	-12.7	4.9	4.9	0.316667
1980	-12.5	-13.1	-14.2333	-6.53333	-2.4	6.3	12.1	17.1	19.4	17.6	18.06667	-0.63333	14	8.5	-6	-10.8	-10.8	5.9	5.9	-1.675
1981	-1.8	-16.7	-15.2333	-6.53333	0.4	3.4	10.6	16.9	19.2	20.1	19.13333	0.433333	16.1	9.3	-1.3	-2	-2	7.6	7.5	-0.58333
1982	-19.9	-7	-7.16667	1.533333	-2.8	11.2	14.7	17	18.8	16.2	17.53333	-1.16667	13.3	8.2	2.6	-9.2	-9.2	3.6	3.6	0.425
1983	-4.7	-4.1	-5.03333	3.666667	3.1	8	13	14.8	19	21.7	18.56667	-0.13333	15.2	6.4	3.2	-9999.9	-8.6	5.9	5.9	-0.73333
1984	-6	-10.9	-13.1333	-4.43333	-3.9	3.7	10.6	17.2	20.6	18.4	18.13333	-0.56667	12.6	6.9	-4.5	-5.7	-5.7	5.7	5.7	-1.89167
1985	-10.6	-1.6	-4	4.7	0.7	6	11.9	16.6	21.4	22.2	19.26667	0.566667	12	9	-0.3	-20.2	-20.2	4.3	4.3	0.383333
1986	-0.7	2.2	-8	0.7	-1.1	8.1	11.7	16.3	17.6	20.9	19.26667	0.566667	9.8	3.5	-4	-13.6	-13.6	6.8	6.8	0.2
1987	-2.6	-10.4	-11.5333	-2.83333	0.7	7.7	11.1	15.7	19.2	17.6	18.23333	-0.46667	8.9	6.6	-13.3	-6.6	-6.6	8.2	8.2	-1.18333
1988	-9.2	-9.1	-5.46667	3.233333	4.4	6.3	11.8	18.5	20.6	19.9	18.66667	-0.03333	9.8	8.7	-4.7	-2.5	-2.5	7.3	7.3	1.25
1989	-8.4	0.1	-1.66667	7.033333	0.7	10.3	11.4	18.8	21.5	15.8	17.93333	-0.70667	14.8	7.6	2.4	-3.7	-3.7	5.2	5.2	2.65
1990	-3.8	-5.7	-6.2	2.5	2.5	8.4	15.8	20.[illegible]	19.6	18.3	19.86667	1.166667	13.5	8.7	-0.5	-5.7	-6.7	6.3	6.3	1.783333
		-14.6	-9.56667	-0.86667	-4.1	6.3	12.[illegible]	17.3		18.3	19.03333	0.333333	13.3	7.7	-0.7	-7.1	-7.1			-0.35
		-6.1	-5.66667	3.033333	1.5	6.6	11.7	16.7		20.4	18.9	0.2	16.6	6.3	-2.3	-11.4	-11.4			0.816667
			MEAN	STDS							MEAN	STDS							MEAN	STDS
			-0.03667	3.755643							-0.02222	0.839966							-0.14417	1.190637
				14.10485							VAR	0.705543							VAR	1.417616

MONTHLY TEMPERATURES, BILLINGS

YEAR	JAN	ModJAN	FEB	DJF	DepDJF	MAR	APR	MAY	JUN	JUL	AUG	JJA	DepJJA	SEP	OCT	NOV	ModNOV	DEC	ANN	ModANN		
1934	1.2	1.2	2.0	0.907407	3.707407	3.7	10.9	18.1	18.8	23.2	21.5	21.18519	0.485185	13.4	12.1	6.0	6.0	-0.4	10.9	10.9		
1935	-4.4	-4.4	2.3	-0.66667	2.133333	0.6	5.4	11.3	17.9	24.3	22.0	21.38889	0.688889	17.4	9.1	0.4	0.4	0.2	8.9	8.9		
1936	-4.4	-4.4	-16.3	-7.61111	-4.81111	2.2	7.2	18.1	21.2	27.2	22.6	23.66667	2.966667	16.7	10.3	2.9	2.9	-2.1	8.8	8.8		
1937	NA	-2.4	NA	-1.78704	1.012963	NA	NA	14.6	17.3	23.1	20.8	20.38889	-0.31111	16.6	10.2	1.6	1.6	-3.0	NA	8.9		
1938	-0.3	-0.3	-2.4	-1.18519	1.614815	2.7	8.3	12.1	18.2	21.1	20.0	19.74074	-0.95926	17.8	10.4	1.0	1.0	-0.8	9.0	9.0		
1939	0.8	0.8	-7.3	-1.31481	1.485185	3.2	9.8	15.7	15.9	22.6	19.8	19.42593	-1.27407	15.3	9.7	4.8	4.8	2.6	9.4	9.4		
1940	-9.6	-9.6	-1.2	-3.37037	-0.57037	4.7	7.3	15.0	18.9	22.7	21.4	21	0.3	18.3	11.6	-1.4	-1.4	0.7	9.0	9.0		
1941	-0.8	-0.8	-0.4	-1.03704	1.762963	3.2	8.2	15.6	18.1	22.2	21.3	20.53704	-0.16296	12.3	7.8	3.9	3.9	-1.9	9.1	9.1		
1942	-3.6	-3.6	-4.7	-3.14815	-0.34815	3.1	10.0	11.4	16.0	21.8	19.9	19.24074	-1.45926	15.0	10.1	1.9	1.9	-1.2	8.3	8.3		
1943	-9.6	-9.6	0.7	-2.83333	-0.03333	-2.6	11.6	11.3	16.1	21.7	20.8	19.53704	-1.16296	15.3	10.7	4.0	4.0	0.3	8.4	8.4		
1944	-0.6	-0.6	-2.9	-2.11111	0.688889	0.2	9.6	15.3	15.7	19.9	19.1	18.24074	-2.45926	14.6	10.7	1.9	1.9	-2.9	8.4	8.4		
1945	-2.6	-2.6	-2.0	-3.18519	-0.38519	3.7	5.4	11.4	14.8	21.6	20.3	18.88889	-1.81111	13.7	10.4	1.4	1.4	-5.0	7.8	7.8		
1946	-0.7	-0.7	-0.4	-1.07407	1.725926	6.1	11.2	11.6	17.0	21.8	19.1	19.27778	-1.42222	14.0	6.3	0.2	0.2	-2.1	8.7	8.7		
1947	-2.7	-2.7	-3.4	-2.88889	-0.08889	-0.6	7.9	13.3	15.6	22.4	20.4	19.48148	-1.21852	14.4	11.1	-0.2	-0.2	-2.6	8.0	8.0		
1948	-1.7	-1.7	-3.7	-3.88889	-1.08889	-0.3	9.3	14.3	18.2	20.8	20.9	19.96296	-0.73704	16.3	9.1	2.9	2.9	-6.3	8.3	8.3		
1949	-11.9	-11.9	-6.9	-7.98148	-5.18148	0.7	11.6	14.6	17.4	21.0	20.8	19.75926	-0.94074	13.9	6.1	7.8	7.8	-5.2	7.5	7.5		
1950	-15.1	-15.1	0.6	-5.07407	-2.27407	-0.4	6.7	10.3	15.6	19.2	19.0	17.92593	-2.77407	13.2	9.9	-0.3	-0.3	-0.8	6.5	6.5		
1951	-6.3	-6.3	-1.7	-5.01852	-2.21852	-4.4	6.2	13.7	13.7	21.2	19.0	17.96296	-2.73704	12.3	7.1	1.7	1.7	-7.1	6.3	6.3		
1952	-7.9	-7.9	-1.6	-3.2963	-0.4963	0.8	11.3	14.4	18.8	21.1	21.3	20.37037	-0.32963	17.2	10.5	0.7	0.7	-0.3	8.8	8.8		
1953	2.4	2.4	1.3	1.5	4.3	4.8	5.7	11.4	17.8	23.4	21.8	21.01852	0.318519	17.2	12.3	5.9	5.9	0.7	10.4	10.4		
1954	-7.6	-7.6	5.1	-0.72222	2.077778	-1.3	7.6	12.7	16.9	24.1	20.7	20.55556	-0.14444	15.7	8.9	6.8	6.8	0.3	9.2	9.2		
1955	-2.6	-2.6	-5.5	-4.44444	-1.64444	-1.4	7.6	13.7	17.3	23.4	23.6	21.44444	0.744444	15.3	11.7	-3.3	-3.3	-5.2	7.9	7.9		
1956	-5.1	-5.1	-3.6	-2.88889	-0.08889	2.8	6.7	13.7	20.4	21.4	19.4	20.42593	-0.27407	16.1	10.7	2.4	2.4	0.1	8.7	8.7		
1957	-10.2	-10.2	-1.7	-2.88889	-0.08889	2.7	6.9	14.6	17.7	23.1	21.6	20.77778	0.077778	14.9	8.2	1.7	1.7	3.3	8.6	8.6		
1958	1.4	1.4	-2.4	-1.05556	1.744444	2.2	7.9	17.6	16.7	19.8	22.7	19.72222	-0.97778	16.2	10.6	2.9	2.9	-2.1	9.4	9.4		
1959	-5.2	-5.2	-5.5	-3.16667	-0.36667	4.8	7.7	11.4	19.7	21.6	20.7	20.66667	-0.03333	14.7	9.1	-0.6	-0.6	1.2	8.3	8.3		
1960	-5.3	-5.3	-2.5	-2.87037	-0.07037	2.7	8.3	14.2	18.7	23.7	19.9	20.75926	0.059259	16.4	10.8	3.0	3.0	-0.8	9.1	9.1		
1961	0.1	0.1	4.4	1.222222	4.022222	5.3	7.3	14.5	21.4	22.6	23.0	22.33333	1.633333	11.8	8.5	0.7	0.7	-3.4	9.7	9.7	0.771296	
1962	-6.2	-6.2	-2.4	-4.01852	-1.21852	0.4	10.8	13.2	18.3	20.8	20.2	19.75926	-0.94074	14.8	11.9	4.8	4.8	0.9	9.0	9.0	0.072222	
1963	-9.0	-9.0	3.3	-1.59259	1.207407	5.0	8.2	13.5	17.9	21.6	21.6	20.33333	-0.36667	18.9	13.1	4.3	4.3	-4.6	9.5	9.5	0.576852	
1964	-1.3	-1.3	0.7	-1.74074	1.059259	1.3	8.6	14.4	17.4	23.4	19.6	20.14815	-0.55185	14.2	11.1	0.3	0.3	-7.3	8.5	8.5	-0.36296	
1965	-1.0	-1.0	-2.6	-3.61111	-0.81111	-3.9	8.8	12.3	17.3	21.9	20.8	20.01852	-0.68148	9.3	11.8	4.5	4.5	-1.1	8.2	8.2	-0.71019	
1966	-7.9	-7.9	-1.7	-3.57407	-0.77407	4.1	6.7	14.9	17.8	24.1	20.4	20.75926	0.059259	18.2	10.4	1.2	1.2	-2.2	8.8	8.8	-0.06204	
1967	-0.6	-0.6	2.0	-0.25926	2.540741	0.9	6.9	12.3	16.6	22.6	22.0	20.38889	-0.31111	17.9	11.1	2.4	2.4	-4.7	9.1	9.1	0.225	
1968	-6.6	-6.6	1.3	-3.33333	-0.53333	6.8	7.2	11.9	16.2	20.9	19.1	18.75926	-1.94074	15.6	10.7	3.2	3.2	-6.4	8.3	8.3	-0.56667	
1969	-13.6	-13.6	-4.1	-8.03704	-5.23704	0.6	11.0	14.4	15.9	21.3	23.1	20.11111	-0.58889	17.6	6.1	5.1	5.1	0.2	8.1	8.1	-0.76574	
1970	-4.7	-4.7	2.7	-0.61111	2.188889	1.0	5.4	13.9	19.2	22.7	22.7	21.5	0.8	13.9	8.1	1.7	1.7	-3.6	8.6	8.6	-0.32593	
1971	-6.1	-6.1	-1.4	-3.68519	-0.88519	2.8	8.3	13.3	18.2	20.4	24.3	20.96296	0.262963	14.2	8.2	3.3	3.3	-6.1	8.3	8.3	-0.59907	
1972	-8.6	-8.6	-1.6	-5.40741	-2.60741	5.9	8.0	13.1	19.1	19.9	21.5	20.18519	-0.51481	13.4	8.3	2.4	2.4	-6.9	7.9	7.9	-1.02037	
1973	-4.6	-4.6	-0.7	-4.09259	-1.29259	4.6	6.1	12.9	18.8	21.5	22.4	20.90741	0.207407	14.8	11.1	-0.1	-0.1	0.1	8.9	8.9	0.002778	
1974	-4.6	-4.6	2.6	-0.62963	2.17037	3.7	10.4	11.5	19.4	23.6	18.8	20.59259	-0.10741	14.1	11.7	3.8	3.8	0.0	9.6	9.6	0.683333	
1975	-3.3	-3.3	-7.4	-3.55556	-0.75556	0.8	4.1	11.5	16.3	23.3	19.3	19.62963	-1.07037	14.7	9.6	1.1	1.1	-1.3	7.4	7.4	-1.51111	
1976	-2.3	-2.3	1.8	-0.62963	2.17037	1.3	9.6	14.9	16.6	22.9	20.9	20.16667	-0.53333	16.2	9.0	2.8	2.8	0.6	9.5	9.5	0.632407	
1977	-6.9	-6.9	3.7	-0.85185	1.948148	3.7	11.3	15.5	22.1	23.7	20.1	21.96296	1.262963	16.2	10.8	0.1	0.1	-4.7	9.6	9.6	0.738889	
1978	-10.0	-10.0	-7.9	-7.55556	-4.75556	2.5	9.3	13.3	18.1	20.5	19.6	19.37037	-1.32963	16.4	10.6	NA	2.3	-8.8	7	7.2	-1.7	
1979	-13.3	-13.3	-6.2	-9.40741	-6.60741	3.2	7.7	13.2	18.9	22.4	21.7	21.01852	0.318519	18.2	11.4	1.0	1.0	1.4	8.3	8.3	-0.58056	
1980	NA	-4.5	-0.9	-1.33333	3.166667	1.9	11.6	15.3	18.9	22.7	18.7	20.11111	-0.58889	15.8	9.7	4.3	4.3	-0.6	9.8	9.4	0.5	
1981	2.2	2.2	0.9	0.87037	3.67037	5.8	10.3	13.7	17.3	22.2	21.9	20.46296	-0.23704	18.3	8.6	4.7	4.7	-1.6	10.4	10.4	1.47037	
1982	NA	-4.5	-2.1	-2.72222	1.777778	1.8	6.3	12.2	17.4	21.3	22.4	20.38889	-0.31111	15.1	9.9	1.0	1.0	-1.7	8.6	8.3	-0.6	
1983	1.2	1.2	3.5	0.981481	3.781481	5.3	7.4	12.1	17.8	23.0	24.6	21.81481	1.114815	15.1	10.6	3.5	3.5	-12.8	9.3	9.3	0.368519	
1984	-1.8	-1.8	3.0	-3.88889	-1.08889	4.3	8.3	14.1	18.2	22.8	23.6	21.55556	0.855556	12.9	7.2	2.8	2.8	-7.1	9.0	9.0	0.137037	
1985	-6.2	-6.2	-4.2	-5.81481	-3.01481	2.0	11.2	16.7	18.4	24.1	19.9	20.7963	0.096296	13.2	9.7	-7.6	-7.6	-3.1	7.8	7.8	-1.05278	
1986	2.8	2.8	-3.4	-1.24074	1.559259	9.1	8.4	13.6	21.8	21.1	22.1	21.62963	0.92963	13.7	10.6	1.1	1.1	0.6	10.1	10.1	1.215741	
1987	-0.8	-0.8	2.3	0.703704	3.503704	4.7	12.7	16.4	20.3	22.1	19.7	20.7037	0.003704	16.6	10.4	4.8	4.8	-0.8	10.7	10.7	1.799074	
1988	-4.3	-4.3	-0.9	-2.01852	0.781481	5.4	10.8	16.2	23.8	23.8	22.1	23.2037	2.503704	15.0	11.8	3.7	3.7	-1.0	10.5	10.5	1.609259	
1989	-2.9	-2.9	-8.1	-4.33333	-1.53333	0.2	8.3	14.2	18.1	24.1	20.5	20.90741	0.207407	15.5	9.5	5.0	5.0	-3.2	8.3	8.3	-0.95278	
1990	0.8	0.8	-1.0	-1.12963	1.67037	4.1	9.7	13.0	18.4	22.0	22.3	20.88889	0.188889	19.2	10.0	5.1	5.1	-6.3	9.8	9.8	0.863889	
					dif stds								JJA STDS								0.041883	ANNMEA
			mean	0.203457	2.755699						mean	0.012346	0.91508								0.896336	STDS
				var	7.593878							var	0.837371								0.803418	VARS

mh jan t vs yr

Regression Output		
Constant		-12.616
Std Err of Y Est		6.025094
R Squared		0.017915
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	0.048587	
Std Err of Coef	0.048508	

mh jul t vs yr

Regression Output		
Constant		21.12644
Std Err of Y Est		1.318706
R Squared		0.134956
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	-0.0311	
Std Err of Coef	0.010617	

mh annt vs yr

Regression Output		
Constant		5.026258
Std Err of Y Est		1.142399
R Squared		0.02245
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	0.010337	
Std Err of Coef	0.009197	

bill jan t vs time

Regression Output		
Constant		-4.38128
Std Err of Y Est		4.276343
R Squared		0.000252
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	0.004056	
Std Err of Coef.	0.034428	

bill jul t vs time

Regression Output		
Constant		22.20548
Std Err of Y Est		1.421854
R Squared		0.000427
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	0.001754	
Std Err of Coef.	0.011447	

bill ann t vs time

Regression Output		
Constant		8.503987
Std Err of Y Est		0.931466
R Squared		0.02948
No. of Observations		57
Degrees of Freedom		55
X Coefficient(s)	0.009693	
Std Err of Coef.	0.007499	

Testing for significance of R^2

For each test:

H_o: $r = 0$
H_1: $r \neq 0$

$$F = \frac{r^2 (n-2)}{1-r^2}$$

critical value of F = 4.02.

<u>Medicine Hat January temperature</u>

$$F = \frac{0.02 (57-2)}{1 - 0.02}$$

F = 1.12; accept H_o.

<u>Medicine Hat July temperature</u>

$$F = \frac{0.13 (57-2)}{1 - 0.13}$$

F = 8.2; accept H_1.

<u>Medicine Hat mean annual temperature</u>

$$F = \frac{0.02 (57-2)}{1 - 0.02}$$

F = 1.12; accept H_o.

<u>Billings January temperature</u>

$$F = \frac{0.0003 (57-2)}{1 - 0.0003}$$

F = 0.02; accept H_o.

<u>Billings July temperature</u>

$$F = \frac{0.0004 (57-2)}{1 - 0.0004}$$

F = 0.02; accept H_o.

<u>Billings mean annual temperature</u>

$$F = \frac{0.03 (57-2)}{1 - 0.03}$$

F = 1.7; accept H_o.

Appendix 3: Precipitation data for Medicine Hat and Billings and departures from normal.

Total Monthly Precip--Medicine Hat

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	MJJA	AMJJA	DEPMJJA	SEP	OCT	NOV	DEC	ANN	DEPANN
61	7.1	7.1	6.4	13.7	26.7	24.6	49.3	10.2	27.7	124.5	-14.9	9.7	28.4	8.1	16	207.3	-115.3
62	16	15.2	18	6.6	26.2	26.4	65	4.1	30.425	128.3	-12.175	52.6	14.7	3.6	7.4	255.8	-66.8
63	45.7	13	5.3	9.1	19.8	123.7	29.2	53.6	56.575	235.4	13.975	34	0.5	1.5	24.4	359.8	37.2
64	20.8	6.1	16.5	25.1	55.6	23.4	16.5	14.7	27.55	135.3	-15.05	60.7	4.3	19.1	43.2	306	-16.6
65	13.7	15.5	14.5	21.3	33.3	103.6	51.1	61.2	62.3	270.5	19.7	49.5	1.3	32	7.4	404.4	81.8
66	36.3	8.1	1.8	39.6	19.6	91.7	79	48	59.575	277.9	16.975	9.9	12.2	22.9	10.2	379.3	56.7
67	29	30.7	25.4	88.4	30	29.7	10.7	8.4	19.7	167.2	-22.9	3	10.4	9.7	17.8	293.2	-29.4
68	7.1	5.1	7.1	43.9	34.5	106.9	21.8	13	44.05	220.1	1.45	61.5	17.5	2.5	19.3	340.2	17.6
69	34	6.1	9.9	10.4	25.9	19.1	51.3	4.1	25.1	110.8	-17.5	19.1	27.9	2.8	7.1	217.7	-104.9
70	37.6	4.8	11.2	24.1	22.9	127.8	51.1	9.1	52.725	235	10.125	21.3	15.2	17.3	11.9	354.3	31.7
71	42.7	7.4	16.3	9.4	45.7	41.1	9.4	20.8	29.25	126.4	-13.35	26.9	18.3	9.1	12.7	259.8	-62.8
72	21.8	23.4	8.4	20.1	39.6	41.4	44.2	33.3	39.625	178.6	-2.975	48	20.1	4.3	30	334.6	12
73	1.8	8.6	0.8	30.7	5.8	124	6.6	37.3	43.425	204.4	0.825	19.6	17.5	23.9	19.1	295.7	-26.9
74	14.5	17.5	27.7	44.7	53.1	45.2	23.1	48.3	42.425	214.4	-0.175	3.3	5.1	1.5	7.6	291.6	-31
75	7.6	20.6	36.6	53.3	85.9	70.1	37.1	34.3	57.1	281.7	14.5	23.1	14.5	25.9	25.7	435.7	113.1
76	3	9.4	21.1	26.7	23.1	59.2	87.1	41.1	52.625	237.2	10.025	4.8	6.9	14.2	5.3	301.9	-20.7
77	18	0.7	6.2	6.7	80.5	19	41.2	40.6	45.325	188	2.725	39.3	1.8	17.9	31	302.9	-19.7
78	18.9	16.2	8.7	72.4	55.4	53.4	44.9	33.9	46.9	260	4.3	92.6	31.4	22.6	8.5	458.9	136.3
79	5.7	16.3	8	26.1	45.9	76.2	32.4	20.4	43.725	201	1.125	14.9	18.4	6.7	10.8	281.8	-40.8
80	23.4	8	13.7	10.8	42	64.7	28.4	36.4	42.875	182.3	0.275	23.4	37.6	5.1	23.2	316.7	-5.9
81	10.6	0.6	17	18.3	68.5	59.8	37.3	20	46.4	203.9	3.8	11.2	35.4	11	16.2	305.9	-32.9
82	22.9	10.9	25.7	17.3	88.1	54.4	88.3	20	62.7	268.1	20.1	62.7	18.7	11.5	10.4	430.9	108.3
83	14.5	3.4	29.4	30.7	30	31.1	81.4	15.4	39.475	188.6	-3.125	18.8	3.1	15.6	16.1	289.5	-33.1
84	16.7	2.2	26.5	17.8	33	51.6	14.2	5.8	26.15	122.4	-16.45	52.1	27.2	10.3	20.5	277.9	-44.7
85	4.8	10.9	12.8	37.8	47	8.7	7.7	46.6	27.5	147.8	-15.1	63.9	23	22.5	3.1	288.8	-33.8
86	3.1	9	26.8	5.7	84	82.9	57.2	12.3	59.1	242.1	16.5	197.6	25.2	23.3	9.3	536.4	213.8
87	6.8	3.8	33.8	18.5	18.6	21.9	45.4	91.9	44.45	196.3	1.85	9.4	8.6	5	8.6	272.3	-50.3
88	5.6	7.6	13.9	0.9	12.6	48	24.3	60	36.225	145.8	-6.375	27.8	2.5	8.7	15.5	227.4	-95.2
89	15.1	16.6	10.1	25.2	58.2	32.4	45.4	48.4	46.1	209.6	3.5	27.8	4.7	27.9	25.6	337.4	14.8
90	14.6	3.4	20.8	22.8	55.2	28.6	46.4	23.2	38.35	176.2	-4.25	1.2	15.2	48.3	21.6	301.3	-21.3
									MEAN		MEAN						
									42.51417		-0.08583						
									STDS		STDS						
									12.03814		12.03814						
											144.9168						

Metric monthly precip—Billings

	JAN	DEPJAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	MJJA	DEPMJJA	AMJJA	SEP	OCT	NOV	DEC	ANN	DEPANN
61	3.302	-13.458	3.81	11.684	52.832	41.402	8.128	21.336	3.81	18.669	-24.031	127.508	109.22	29.464	21.844	3.302	310.134	-43.666
62	30.226	13.466	22.098	20.066	1.016	93.98	52.324	39.624	32.766	54.6735	11.9735	219.71	26.162	8.128	13.208	1.524	341.122	-12.678
63	39.37	22.61	7.112	6.096	59.944	58.166	69.342	20.066	2.54	37.5285	-5.1715	210.058	47.498	8.636	0.508	26.162	345.44	-8.36
64	0.762	-15.998	5.842	16.002	110.744	115.824	140.716	0.508	78.232	83.82	41.12	446.024	1.524	6.35	11.684	8.636	496.824	143.024
65	14.986	-1.774	18.542	12.192	23.622	56.388	59.69	34.544	87.884	59.6265	16.9265	262.128	60.706	2.286	10.414	11.43	392.684	38.684
66	6.858	-9.902	5.08	25.908	26.162	18.034	63.246	18.034	32.258	32.893	-9.807	157.734	38.862	15.24	21.082	13.97	284.734	-69.066
67	6.604	-10.156	10.16	20.32	34.544	41.656	146.812	3.556	24.13	54.0385	11.3385	250.698	17.018	24.638	11.684	16.764	357.886	4.086
68	26.67	9.91	11.684	8.89	30.48	50.546	107.95	5.842	64.77	57.277	14.577	259.588	38.354	10.414	34.544	14.986	405.13	51.33
69	21.336	4.576	3.81	9.906	31.75	24.638	160.274	37.084	9.652	57.912	15.212	263.398	6.858	35.306	13.97	6.096	360.68	6.88
70	15.494	-1.266	21.082	27.178	62.484	96.774	57.912	12.446	4.318	42.8625	0.1625	233.934	61.468	21.844	18.796	8.382	408.178	54.378
71	21.59	4.83	11.684	18.542	37.592	47.752	41.91	10.414	3.556	25.908	-16.792	141.224	49.022	94.234	2.032	17.526	355.854	2.054
72	53.086	36.326	17.272	11.43	36.068	47.498	22.86	48.768	43.688	40.7035	-1.9965	198.882	30.226	62.23	26.162	18.796	418.084	64.284
73	18.288	1.528	2.286	42.926	71.882	25.654	25.908	11.43	29.718	23.1775	-19.5225	164.592	57.404	20.574	29.21	39.878	375.158	21.358
74	13.208	-3.552	3.556	20.32	40.132	63.5	40.64	24.638	63.246	48.006	5.306	232.156	51.562	85.598	10.922	5.08	422.402	68.602
75	34.29	17.53	14.986	11.176	35.814	78.74	46.228	63.754	8.636	49.3395	6.6395	233.172	6.604	66.294	26.67	27.432	420.624	66.824
76	13.208	-3.552	8.89	11.938	89.662	46.99	74.168	0	16.764	34.4805	-8.2195	227.584	28.448	24.638	10.16	7.366	332.232	-21.568
77	27.178	10.418	0	26.416	7.62	34.036	6.096	6.35	16.256	15.6845	-27.0155	70.358	14.224	23.622	27.432	35.56	224.79	-129.01
78	28.702	11.942	52.324	4.064	76.962	197.358	41.91	27.432	12.192	69.723	27.023	355.854	109.728	4.064	53.594	19.05	627.38	273.58
79	18.288	1.528	13.716	16.764	15.494	17.018	21.844	10.16	24.892	18.4785	-24.2215	89.408	14.478	21.336	6.858	2.54	183.388	-170.412
80	21.336	4.576	12.446	25.908	2.286	90.424	31.496	12.192	45.974	45.0215	2.3215	182.372	22.352	51.308	4.318	12.954	332.994	-20.806
81	3.81	-12.95	4.826	16.764	21.59	186.436	85.852	12.192	11.176	73.914	31.214	317.246	6.858	41.91	6.858	8.382	406.654	52.854
82	0	-16.76	7.112	24.892	14.478	66.548	163.068	65.532	18.542	78.4225	35.7225	328.168	13.97	8.89	10.668	15.494	409.194	55.394
83	2.032	-14.728	4.826	21.59	14.986	52.07	18.796	27.432	11.938	27.559	-15.141	125.222	57.658	29.21	8.89	27.178	276.606	-77.194
84	12.446	-4.314	18.542	10.668	39.37	21.336	37.846	6.35	17.018	20.6375	-22.0625	121.92	25.654	12.7	19.812	19.304	241.046	-112.754
85	10.668	-6.092	7.62	48.514	4.572	33.02	43.688	38.608	50.038	41.3385	-1.3615	169.926	57.404	3.556	31.242	6.096	335.026	-18.774
86	6.858	-9.902	43.434	14.986	57.404	45.212	56.6	19.558	5.842	31.803	-10.897	184.616	36.576	21.336	35.052	1.778	288.036	-65.764
87	2.286	-14.474	10.922	22.352	6.858	84.074	30.48	79.502	40.894	58.7375	16.0375	241.808	23.876	0.254	6.096	5.842	313.436	-40.364
88	8.382	-8.378	18.796	10.414	33.528	57.912	17.018	6.35	0.254	20.3835	-22.3165	115.062	49.022	22.606	16.764	18.796	259.842	-93.958
89	20.828	4.068	10.414	40.386	43.942	43.688	16.002	7.874	41.148	27.178	-15.522	152.654	12.7	68.834	12.7	27.94	346.456	-7.344
90	4.572	-12.188	14.986	22.098	44.196	68.834	21.844	5.334	44.958	35.2425	-7.4575	185.166	1.016	28.194	11.938	16.256	284.226	-69.574
1991	18.034	1.274	10.414	12.192	76.962	53.848	124.714	11.176	9.398			276.098	78.486	34.29	20.828	8.636	458.978	105.178
1992	1.016	-15.744	1.778	23.876	54.356	42.418	87.63	46.482	8.128			239.014	18.288	10.16	6.096	11.938	312.166	-41.634

MJJA MEAN 42.83463

MEAN 0.134633

STDS 18.92899

VAR 358.3067

Appendix 4: PDSI data and statistics for Medicine Hat, Billings, and southcentral Montana.

Med Hat PDSI

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
1928	-0.55	-0.94	-1.47	-1.7	-2.72	-1.91	-1.1	-1.69	-2.52	-2.68	-3.31	-3.95	-2.045
1929	-4.33	-4.57	4.73	-3.45	-3.65	-3.28	-3.64	-4.2	-4.63	-4.94	-5.16	-5.6	-3.55999
1930	-5.99	-6.28	-6.35	-5.96	-5.52	-5.04	-4.84	-4.51	-2.7	-2.13	-1.86	-1.81	-4.41568
1931	-2.22	-2.58	-2.48	-2.89	-3.27	-3.05	-3.21	-3.66	-3.15	-3.25	0.67	1.98	-2.25814
1932	1.58	1.56	1.25	1.78	1.72	0.97	1.59	2.01	2.87	2.86	3.13	2.72	1.983195
1933	2.31	1.91	1.77	1.96	2.19	-0.17	-1.1	-1.21	-1.57	1.05	1.36	2.48	0.844615

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
61	-1.32	-1.45	-1.81	-1.89	-2.09	-2.76	-2.21	-2.7	-3.1	-2.55	-2.44	-2.09	-2.20083
62	-1.91	-1.67	-1.47	-1.95	-2.19	-2.74	-1.69	-2.32	-1.77	-1.73	-1.99	-2.15	-1.965
63	-0.88	-0.83	-1.33	-1.68	-2.06	1.58	1.16	1.57	0	-0.79	-1.31	-1.16	-0.4775
64	-0.9	-1.11	-0.02	0.04	0	-0.83	-1.39	-1.76	0.71	0	0	1.3	-0.33167
65	0	0	0	0	-0.51	1.13	1.34	1.94	2.35	1.5	1.85	1.44	0.92
66	1.99	1.56	0.81	1.29	0.57	1.36	2.34	2.53	1.55	1.17	1.29	1.04	1.458333
67	1.36	1.85	1.94	3.92	0	-0.83	-1.55	-2.25	-3.19	-3.51	-3.89	-4.12	-0.85583
68	-4.33	-4.45	-4.59	0	0	1.46	0.86	0	0.89	0.84	0	0.64	-0.72333
69	1.19	0	-0.63	-1.09	-1.39	-2.16	-1.57	-2.26	-2.64	-1.99	-2.14	-2.17	-1.40417
70	0.74	0	-0.53	0	-0.84	1.62	1.77	-0.7	-1.04	-0.01	0	0	0.084167
71	1.03	0	0	-0.75	-0.52	-0.85	-1.55	-1.95	-2	0.09	0.04	0.01	-0.5375
72	0	0.52	0	0	0	-0.75	0	0	0.61	0.81	0.52	1.06	0.230833
73	-0.75	-0.88	-1.54	-1.24	-2.07	1.45	-0.9	-0.88	-1.15	0.02	0	0.63	-0.60917
74	0	0.56	0.87	1.36	1.68	0	-0.76	0	-0.95	-1.42	-1.97	-2.48	-0.25917
75	-2.79	0	0.78	1.8	2.99	3.01	2.61	2.43	1.9	1.68	2.05	2.28	1.561667
76	-0.51	-0.63	0	0	-0.87	0.06	1.4	1.44	-0.84	-1.16	-1.23	-1.54	-0.32333
77	-1.37	-1.77	-2.06	-2.49	1.07	-0.97	-0.78	0	0	-0.68	0.08	0.7	-0.68917
78	0.69	0.7	0	1.77	20.5	1.72	1.73	1.59	2.96	3.12	3.22	0	3.166667
79	-0.58	0	-0.74	0	0	0.77	0	-0.56	-1.12	-1.65	-2	-2.29	-0.68083
80	-1.94	-1.97	-1.9	-2.28	-2.09	-1.71	-1.82	-1.48	-1.6	0.68	0	0.62	-1.29083
81	0	-0.72	-0.81	-0.97	0.8	0.8	-0.02	0	-1.13	0.52	0	-0.6	-0.1775
82	0	0.07	0	0	1.59	1.34	2.61	1.99	2.55	2.39	0.03	0	1.0475
83	0	-0.58	0	0.57	0	-0.87	1.22	-1.36	-1.67	-2.08	-2.02	-1.87	-0.72167
84	-1.69	-2.05	-1.52	-1.62	-1.62	-1.59	-2.13	-2.79	0	0.85	0.76	0.93	-1.03917
85	0	-0.52	-0.66	0	-0.03	-1.19	-1.97	0	1.08	1.23	1.52	0	-0.045
86	-0.85	-0.95	-0.73	-1.23	1.21	1.65	2.05	1.24	5.45	5.13	5.05	0	1.501667
87	-0.51	-0.85	0	-0.5	-1.09	-1.88	0	1.86	-0.69	-0.98	-1.43	-1.8	-0.65583
88	-2.14	-2.21	-2.23	-2.78	-3.49	-3.69	-3.74	-2.61	-2.51	-2.75	-2.72	-2.46	-2.7775
89	-2.28	-1.95	-2.01	0.03	0.56	-0.62	0	0.55	0	-0.53	0	0.86	-0.44917
90	0.68	0	0	0	0.6	-0.7	0	-0.69	-1.59	-1.64	1.02	1.21	-0.0925
1991	0.89	0.97	1.07	1.68	2.26	3.02	0	0	-0.62	0	-0.58	-0.89	0.65
1992	-1.03	-1.19	-1.89	-2.11	-2.01	0.75	1.78	1.99	2.14	2.91	2.81	0	0.345833

mh jun pd vs time

Regression Output

Constant	0.102115
Std Err of Y Est	1.659732
R Squared	0.011407
No. of Observations	30
Degrees of Freedom	28
X Coefficient(s)	-0.0199
Std Err of Coef.	0.03501

mh jul pd vs time

Regression Output

Constant	-0.07156
Std Err of Y Est	1.701977
R Squared	9.11E-05
No. of Observations	30
Degrees of Freedom	28
X Coefficient(s)	-0.00181
Std Err of Coef	0.035901

Billings PDSI

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
1961	0	0	0	0	0	-0.52	0	-1.49	1.97	2.34	2.49	2.07	0.571667
1962	2.46	2.77	3.05	2	2.6	2.54	3.21	3.41	2.89	1.95	1.45	0.78	2.425833
1963	1.25	0.77	-1.57	-1.06	-1.07	-0.97	-1.26	-2	-1.79	-2.37	-2.79	-2.2	-1.255
1964	-2.53	-2.58	-2.37	-0.62	2.49	4.06	4.67	5.85	4.55	3.43	3.04	2.52	1.875833
1965	2.14	2.1	1.89	1.34	1.08	0.85	0.73	2.44	3.17	2.43	1.79	1.44	1.788333
1966	0.89	-1.37	-1.23	-1.27	-2.33	-2.43	-3.09	-2.79	-2.64	-2.31	-2.35	-2.14	-1.96333
1967	-2.27	-2.21	-1.81	-1.55	-1.68	1.35	1.43	1.23	0	0	0	0	-0.45917
1968	0	0	-1.14	-1.19	-1.25	0	0	1.33	1.23	0.56	0.91	0.86	0.109167
1969	0.93	0.64	0	0	-1.41	1.54	2.45	2.16	1.1	1.36	1.01	0.61	0.865833
1970	0	0	0	1.28	1.97	2.12	2.43	1.38	1.91	1.63	1.53	1.15	1.283333
1971	1.11	0.97	0.86	0.76	0	0	-1.42	-2.27	-1.68	2.06	1.52	1.6	0.2925
1972	2.73	2.93	2.5	2.45	2.19	1.69	2.13	2.57	2.31	3.01	3.08	3.05	2.553333
1973	2.97	2.54	3.04	3.82	3	2.38	1.82	1.54	1.93	1.4	1.73	2.42	2.3825
1974	2.2	1.73	1.59	1.33	1.45	0.98	0.72	1.67	1.95	3.01	2.58	2.09	1.775
1975	2.46	2.44	2.3	2.46	2.92	2.93	4.62	4.2	3.15	3.78	3.85	4.03	3.261667
1976	3.74	3.38	3.16	4.01	3.42	3.67	3.59	2.73	1.78	1.5	1.07	0.62	2.7225
1977	0.74	-1.64	-1.41	-2.3	-3.11	-4.45	-6.27	-5.21	-5.31	-5	-4.06	-2.93	-3.32917
1978	-2.15	2.76	2.42	3.15	5.79	5.38	5.69	5.01	6.27	5.39	6.08	5.78	4.2975
1979	5.46	5.1[illegible]	4.79	4.02	2.89	1.92	1.04	0.65	-2.64	-2.7	-2.67	-2.93	1.250833
1980	-2.65	-2.45	-1.96	-2.9	-2.46	-3.06	-3.63	-2.8	-2.9	-2.06	-2.27	-2.14	-2.60667
1981	-2.54	-2.64	-2.84	-3.34	0.88	2.62	2.89	2.2	1.04	1.32	0.79	-1.23	-0.2175
1982	-1.2	-1.3	-0.96	-1.18	-0.9	1.77	3.46	3.79	2.94	2.16	1.82	1.64	1.003333
1983	0.91	-1.65	-1.74	-2.08	-2.15	-3.03	-3.45	-3.95	-3.04	-2.82	-2.89	-2.27	-2.34667
1984	-2.22	-1.98	-2.16	-1.94	-2.67	-3.07	-3.8	-4.05	-3.77	-3.66	-3.28	-2.82	-2.95167
1985	-2.75	-2.63	-1.37	-2.13	-2.92	-3.17	-3.11	-2.21	-1.36	-1.87	-1.14	-1.26	-2.16
1986	-1.63	0	0	0	0	1.45	1.73	1.08	1.09	0.7	1.22	0.7	0.528333
1987	0	0	0	-2.06	-2	-2.8	-1.95	-1.42	-1.69	-2.29	-2.59	-2.7	-1.625
1988	-2.83	-2.46	-2.78	-3.02	-3.45	-4.74	-5.54	-6.05	-5.14	-4.95	-4.96	-4.01	-4.16083
1989	-3.53	-3.22	-2.01	-1.58	-1.71	-2.19	-2.71	-2.23	-2.64	-1.39	-1.44	-0.82	-2.1225
1990	-1.04	-0.79	-0.63	0	0	0	-1.1	-0.7	-1.76	-1.61	-1.86	-1.7	-0.9325
1991	-1.59	-1.85	-2.14	-1.13	-1.23	1.34	1.11	0	0	1.01	1.09	0.76	-0.21917
1992	0	-1.43	-1.88	-1.82	-2.45	-2.28	-2.05	-2.51	-2.74	-3.03	-3.12	-2.05	-2.11417

SOUTH CENTRAL MONTANA PDSI

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
1930	-0.21	-0.61	-0.74	-1.14	-1.43	-2.19	-2.82	-2.46	-2.06	-1.06	-0.96	-1.37	-1.4375
1931	-1.77	-1.98	-2.38	-2.79	-3.61	-4.8	-5.6	-6.22	-5.75	-5.48	-5.12	-5.16	-4.22167
1932	-4.98	-5.06	-4.33	-4.02	-4.43	-3.87	-4.2	-4.34	-4.67	-3.17	-3.16	-3.01	-4.10333
1933	-2.78	-2.59	-2.96	-2.4	-2.21	-3.51	-4.5	-3.06	-3.67	-3.65	-3.86	-3.53	-3.22667
1934	-3.87	-4.01	-3.99	-5	-6.68	-6.72	-7.5	-8.07	-7.52	-7.56	-7.85	-7.27	-6.33667
1935	-7.25	-7.27	-6.44	-5.93	-5.04	-5.26	-5.16	-5.21	-5.65	-5.55	-5.21	-5.12	-5.7575
1936	-5.04	-4.35	-4.71	-4.75	-6.22	-6.76	-7.92	-6.08	-7.66	-7.3	-6.96	-6.75	-6.375
1937	-6.75	-6.37	-6.21	-6.49	-7.46	-6.88	-7.32	-8.02	-7.68	-6.98	-6.37	-5.68	-6.85083
1938	-5.58	5.54	-4.94	-5.04	-3.74	-3.23	-2.4	-2.16	-3.02	-2.03	-1.64	-1.81	-3.4275
1939	-1.91	-1.89	-2.13	-2.57	-3.09	-1.93	-2.39	-2.46	-3.02	-3.03	-3.74	-3.91	-2.6725

bill jun pd vs time

Regression Output

Constant	1.967678
Std Err of Y Est	2.52677
R Squared	0.136812
No. of Observations	30
Degrees of Freedom	29
X Coefficient(s)	-0.11229
Std Err of Coef	0.052099

bill jul pd vs time

Regression Output

Constant	2.215747
Std Err of Y Est	2.929554
R Squared	0.135251
No. of Observations	30
Degrees of Freedom	28
X Coefficient(s)	-0.12932
Std Err of Coef	0.061796

Testing for significance of R^2

For each test:

H_0: $r = 0$
H_1: $r \neq 0$

$$F = \frac{r^2 (n-2)}{1-r^2}$$

critical value of F = 4.20.

Medicine Hat June PDSI

$$F = \frac{0.01 (30-2)}{1 - 0.01}$$

F = 0.28; accept H_0.

Medicine Hat July PDSI

$$F = \frac{0.00009 (30-2)}{1 - 0.00009}$$

F = 0.003; accept H_0.

Billings June PDSI

$$F = \frac{0.14 (30-2)}{1 - 0.14}$$

F = 4.56; accept H_1.

Billings July PDSI

$$F = \frac{0.14 (30-2)}{1 - 0.14}$$

F = 4.56; accept H_1.

Appendix 5: Daily temperatures and calculated growing degree days for Billings.

Billings Daily

MONTH	DAY	T_MAX	T_MIN	T_MEAN	MEANC	DEGDAY	MONTHL
1	1	35.9	10.6	23.25	-4.86111	0	
1	2	35.7	11.1	23.4	-4.77778	0	
1	3	35.8	10.4	23.1	-4.94444	0	
1	4	33.9	10.1	22	-5.55556	0	
1	5	33.4	11.9	22.65	-5.19444	0	
1	6	36.7	11.9	24.3	-4.27778	0	
1	7	34.7	11.9	23.3	-4.83333	0	
1	8	34.4	8.7	21.55	-5.80556	0	
1	9	34	7.4	20.7	-6.27778	0	
1	10	33	10.3	21.65	-5.75	0	
1	11	33.7	9.5	21.6	-5.77778	0	
1	12	35.4	8	21.7	-5.72222	0	
1	13	38.9	12.4	25.65	-3.52778	0	
1	14	38.9	12.9	25.9	-3.38889	0	
1	15	40.6	14.9	27.75	-2.36111	0	
1	16	41.5	14.8	28.15	-2.13889	0	
1	17	40	15.4	27.7	-2.38889	0	
1	18	39.6	13.4	26.5	-3.05556	0	
1	19	37.5	10.6	24.05	-4.41667	0	
1	20	38.2	12.4	25.3	-3.72222	0	
1	21	39	14.7	26.85	-2.86111	0	
1	22	40.6	15.3	27.95	-2.25	0	
1	23	39.6	16.6	28.1	-2.16667	0	
1	24	39.2	16.1	27.65	-2.41667	0	
1	25	36.9	14.1	25.5	-3.61111	0	
1	26	34	12.6	23.3	-4.83333	0	
1	27	35.2	11.[illegible]	23.15	-4.91667	0	
1	28	36.5	12.8	24.65	-4.08333	0	
1	29	35.9	14.5	25.2	-3.77778	0	
1	30	37.5	11.2	24.35	-4.25	0	
1	31	37.2	10.3	23.75	-4.58333	0	
2	1	36.7	12.3	24.5	-4.16667	0	
2	2	36.9	10.6	23.75	-4.58333	0	
2	3	38.6	12.8	25.7	-3.5	0	
2	4	39.5	12.6	26.05	-3.30556	0	
2	5	37.8	13.1	25.45	-3.63889	0	
2	6	39.4	12.9	26.15	-3.25	0	
2	7	40.5	14.6	27.55	-2.47222	0	
2	8	41.9	14.8	28.35	-2.02778	0	
2	9	42.4	15.7	29.05	-1.63889	0	
2	10	42.7	16.1	29.4	-1.44444	0	
2	11	44.4	16.8	30.6	-0.77778	0	
2	12	43.3	19.4	31.35	-0.36111	0	
2	13	41.9	18.6	30.25	-0.97222	0	
2	14	42.9	17.4	30.15	-1.02778	0	
2	15	40.8	14.4	27.6	-2.44444	0	
2	16	43.2	16.8	30	-1.11111	0	
2	17	44.3	18.2	31.25	-0.41667	0	
2	18	44.2	17.7	30.95	-0.58333	0	
2	19	45.1	21.9	33.5	0.833333	0	
2	20	47.9	21.3	34.6	1.444444	0	
2	21	47.4	20.7	34.05	1.138889	0	
2	22	48.1	22	35.05	1.694444	0	
2	23	45.6	19.7	32.65	0.361111	0	
2	24	47.1	19.8	33.45	0.805556	0	
2	25	49.6	21.2	35.4	1.888889	0	
2	26	48.2	21.9	35.05	1.694444	0	
2	27	47.9	23.8	35.85	2.138889	0	
2	28	48	21.2	34.6	1.444444	0	
2	29	50.1	21	35.55	1.972222	0	
3	1	46.4	20.2	33.3	0.722222	0	
3	2	44.5	19.3	31.9	-0.05556	0	
3	3	42.6	15.5	29.05	-1.63889	0	
3	4	44.4	14.1	29.25	-1.52778	0	
3	5	46.3	16.8	31.55	-0.25	0	
3	6	49.4	22.4	35.9	2.166667	0	
3	7	48.4	21.5	34.95	1.638889	0	
3	8	50.7	21.4	36.05	2.25	0	
3	9	53.4	24.5	38.95	3.861111	0	
3	10	51.9	24.2	38.05	3.361111	0	
3	11	51.9	21.8	36.85	2.694444	0	
3	12	51.7	22.3	37	2.777778	0	
3	13	52.2	22.9	37.55	3.083333	0	
3	14	51.5	25.5	38.5	3.611111	0	
3	15	51.6	24.3	37.95	3.305556	0	
3	16	53.4	24.8	39.1	3.944444	0	
3	17	52.8	26.6	39.7	4.277778	0	
3	18	51.8	26.2	39	3.888889	0	
3	19	51.8	25.4	38.6	3.666667	0	
3	20	52.8	25.2	39	3.888889	0	
3	21	55.3	25.8	40.55	4.75	0	
3	22	54.5	24.6	39.55	4.194444	0	
3	23	52.8	25	38.9	3.833333	0	
3	24	54.9	24.2	39.55	4.194444	0	
3	25	54.7	24	39.35	4.083333	0	
3	26	54.7	25.5	40.1	4.5	0	
3	27	55.1	27.4	41.25	5.138889	0.138889	
3	28	52.3	26.9	39.6	4.222222	0	
3	29	53.7	24.3	39	3.888889	0	
3	30	58.1	28.4	43.25	6.25	1.25	
3	31	60	28.9	44.45	6.916667	1.916667	3.305556
4	1	57	28.2	42.6	5.888889	0.888889	
4	2	57.9	29.6	43.75	6.527778	1.527778	
4	3	55.5	28	41.75	5.416667	0.416667	
4	4	58.7	27.7	43.2	6.222222	1.222222	
4	5	60.6	28.7	44.65	7.027778	2.027778	
4	6	63.7	30.6	47.15	8.416667	3.416667	
4	7	61.5	31.1	46.3	7.944444	2.944444	
4	8	60.6	28.9	44.75	7.083333	2.083333	
4	9	62.7	30.3	46.5	8.055556	3.055556	
4	10	63.3	33.8	48.55	9.194444	4.194444	
4	11	60.7	33.7	47.2	8.444444	3.444444	
4	12	61.6	31.4	46.5	8.055556	3.055556	
4	13	62.1	30.4	46.25	7.916667	2.916667	
4	14	64.3	29.8	47.05	8.361111	3.361111	
4	15	66.6	34.1	50.35	10.19444	5.194444	
4	16	66.5	33.2	49.85	9.916667	4.916667	
4	17	63.1	32.5	47.8	8.777778	3.777778	
4	18	64.6	33.1	48.85	9.361111	4.361111	
4	19	64.2	35.1	49.65	9.805556	4.805556	
4	20	62.8	33.9	48.35	9.083333	4.083333	
4	21	62.9	33.1	48	8.888889	3.888889	
4	22	65.8	34.1	49.95	9.972222	4.972222	
4	23	67.2	35.4	51.3	10.72222	5.722222	
4	24	67.2	36	51.6	10.88889	5.888889	
4	25	65	36.3	50.65	10.36111	5.361111	
4	26	60.5	36.5	48.5	9.166667	4.166667	
4	27	61.2	34.3	47.75	8.75	3.75	
4	28	63	34.9	48.95	9.416667	4.416667	
4	29	63.5	35.3	49.4	9.666667	4.666667	
4	30	65.8	35.3	50.55	10.30556	5.305556	109.8333
5	1	68.6	36.9	52.75	11.52778	6.527778	
5	2	69.7	38.1	53.9	12.16667	7.166667	
5	3	69.2	38.6	53.9	12.16667	7.166667	
5	4	70.7	39.4	55.05	12.80556	7.805556	
5	5	69.3	40.2	54.75	12.63889	7.638889	
5	6	69.2	38.8	54	12.22222	7.222222	
5	7	67.2	40.7	53.95	12.19444	7.194444	
5	8	65.6	39.2	52.4	11.33333	6.333333	
5	9	69.2	39.5	54.35	12.41667	7.416667	
5	10	69.5	40.5	55	12.77778	7.777778	
5	11	66.3	37.9	52.1	11.16667	6.166667	
5	12	67.7	38.6	53.15	11.75	6.75	
5	13	71	39.6	55.3	12.94444	7.944444	
5	14	71.8	41.1	56.45	13.58333	8.583333	
5	15	72.2	41.1	56.65	13.69444	8.694444	
5	16	73.3	43.2	58.25	14.58333	9.583333	
5	17	71.3	42.7	57	13.88889	8.888889	
5	18	71.1	42.3	56.7	13.72222	8.722222	
5	19	72.3	41.9	57.1	13.94444	8.944444	
5	20	72	43.2	57.6	14.22222	9.222222	
5	21	72.2	43.4	57.8	14.33333	9.333333	
5	22	73.5	43.7	58.6	14.77778	9.777778	
5	23	75	43.5	59.25	15.13889	10.13889	
5	24	76.1	43.7	59.9	15.5	10.5	
5	25	75.5	45.6	60.55	15.86111	10.86111	
5	26	74.3	44.4	59.35	15.19444	10.19444	
5	27	76.1	45.8	60.95	16.08333	11.08333	
5	28	75.8	45.6	60.7	15.94444	10.94444	
5	29	74.7	46.7	60.7	15.94444	10.94444	
5	30	74.6	45.9	60.25	15.69444	10.69444	
5	31	73.6	45	59.3	15.16667	10.16667	270.3889
6	1	74.6	43.4	59	15	10	
6	2	76.7	45.3	61	16.11111	11.11111	
6	3	78.1	47.4	62.75	17.08333	12.08333	
6	4	77.9	46.7	62.3	16.83333	11.83333	
6	5	78.3	48.6	63.45	17.47222	12.47222	
6	6	80	49	64.5	18.05556	13.05556	
6	7	79.1	49.3	64.2	17.88889	12.88889	
6	8	78.9	48.4	63.65	17.58333	12.58333	
6	9	78.3	49.1	63.7	17.61111	12.61111	
6	10	79.1	48.6	63.85	17.69444	12.69444	
6	11	78	47.8	62.9	17.16667	12.16667	
6	12	78.2	47.7	62.95	17.19444	12.19444	
6	13	79	47.9	63.45	17.47222	12.47222	
6	14	77.6	49.2	63.4	17.44444	12.44444	
6	15	77.6	49.6	63.6	17.55556	12.55556	
6	16	80.1	49.6	64.85	18.25	13.25	
6	17	80.2	49.5	64.85	18.25	13.25	
6	18	80.8	50.2	65.5	18.61111	13.61111	
6	19	83.3	50.2	66.75	19.30556	14.30556	
6	20	83.2	51.4	67.3	19.61111	14.61111	
6	21	82.3	51.1	66.7	19.27778	14.27778	
6	22	83	50.9	66.95	19.41667	14.41667	
6	23	83.2	51.6	67.4	19.66667	14.66667	
6	24	84.5	52.2	68.35	20.19444	15.19444	
6	25	84.3	52.3	68.3	20.16667	15.16667	
6	26	85.5	52.6	69.05	20.58333	15.58333	
6	27	87.5	54.1	70.8	21.55556	16.55556	
6	28	87	52.7	69.85	21.02778	16.02778	
6	29	85.8	52.8	69.3	20.72222	15.72222	
6	30	86.5	51.4	68.95	20.52778	15.52778	405.3333

7	1	87.3	53	70.15	21.19444	16.19444	
7	2	87.3	54	70.65	21.47222	16.47222	
7	3	86.7	54.4	70.55	21.41667	16.41667	
7	4	88.6	53.2	70.9	21.61111	16.61111	
7	5	89.3	53.5	71.4	21.88889	16.88889	
7	6	89.5	54.5	72	22.22222	17.22222	
7	7	89.8	55.3	72.55	22.52778	17.52778	
7	8	89.4	54	71.7	22.05556	17.05556	
7	9	90.1	56.1	73.1	22.83333	17.83333	
7	10	89.8	57	73.4	23	18	
7	11	88.2	55	71.6	22	17	
7	12	88.4	54.5	71.45	21.91667	16.91667	
7	13	88.3	54.9	71.6	22	17	
7	14	87.7	53.9	70.8	21.55556	16.55556	
7	15	90.1	53.9	72	22.22222	17.22222	
7	16	90	55.1	72.55	22.52778	17.52778	
7	17	88.5	55.8	72.15	22.30556	17.30556	
7	18	87.6	54.5	71.05	21.69444	16.69444	
7	19	88.7	55.2	71.95	22.19444	17.19444	
7	20	88	56.5	72.25	22.36111	17.36111	
7	21	89.9	56.2	73.05	22.80556	17.80556	
7	22	90	55.6	72.8	22.66667	17.66667	
7	23	89.7	55.7	72.7	22.61111	17.61111	
7	24	90.5	56.2	73.35	22.97222	17.97222	
7	25	89.7	57.2	73.45	23.02778	18.02778	
7	26	88.7	56	72.35	22.41667	17.41667	
7	27	89.4	55.7	72.55	22.52778	17.52778	
7	28	90.2	55.9	73.05	22.80556	17.80556	
7	29	91.1	56.3	73.7	23.16667	18.16667	
7	30	90.5	55.5	73	22.77778	17.77778	
7	31	89.3	55.7	72.5	22.5	17.5	536.2778
8	1	90	55.1	72.55	22.52778	17.52778	
8	2	90.7	53.9	72.3	22.38889	17.38889	
8	3	89.1	54.5	71.8	22.11111	17.11111	
8	4	89.7	54.8	72.25	22.36111	17.36111	
8	5	90.8	55.3	73.05	22.80556	17.80556	
8	6	91.2	55.4	73.3	22.94444	17.94444	
8	7	91	54.9	72.95	22.75	17.75	
8	8	89.2	54.9	72.05	22.25	17.25	
8	9	88.5	53.7	71.1	21.72222	16.72222	
8	10	87.9	53.6	70.75	21.52778	16.52778	
8	11	89.5	53.8	71.65	22.02778	17.02778	
8	12	88.8	54.1	71.45	21.91667	16.91667	
8	13	88.1	53.6	70.85	21.58333	16.58333	
8	14	87.1	53.8	70.45	21.36111	16.36111	
8	15	88.4	53.1	70.75	21.52778	16.52778	
8	16	89.3	54.1	71.7	22.05556	17.05556	
8	17	87.8	53.3	70.55	21.41667	16.41667	
8	18	88.1	53.7	70.9	21.61111	16.61111	
8	19	87.2	52.8	70	21.11111	16.11111	
8	20	86.1	52.9	69.5	20.83333	15.83333	
8	21	85.7	52.6	69.15	20.63889	15.63889	
8	22	86	52.8	69.4	20.77778	15.77778	
8	23	85.3	50.8	68.05	20.02778	15.02778	
8	24	85.9	50.7	68.3	20.16667	15.16667	
8	25	87.6	50.4	69	20.55556	15.55556	
8	26	85.1	52.6	68.85	20.47222	15.47222	
8	27	85.6	50.6	68.2	20.11111	15.11111	
8	28	85.7	50.4	68.05	20.02778	15.02778	
8	29	84.3	50	67.15	19.52778	14.52778	
8	30	83.4	50.2	66.8	19.33333	14.33333	
8	31	83.3	49.4	66.35	19.08333	14.08333	504.5556

9	1	82.2	48.3	65.25	18.47222	13.47222	
9	2	82.3	49.7	66	18.88889	13.88889	
9	3	81.6	46.8	64.2	17.88889	12.88889	
9	4	82.4	45.3	63.85	17.69444	12.69444	
9	5	83.4	45.9	64.65	18.13889	13.13889	
9	6	82.7	47.4	65.05	18.36111	13.36111	
9	7	81.8	47.6	64.7	18.16667	13.16667	
9	8	81.3	46	63.65	17.58333	12.58333	
9	9	80.1	46.6	63.35	17.41667	12.41667	
9	10	79.4	45.9	62.65	17.02778	12.02778	
9	11	75.7	44.4	60.05	15.58333	10.58333	
9	12	73	44.5	58.75	14.86111	9.861111	
9	13	72.9	42.4	57.65	14.25	9.25	
9	14	73.9	42.4	58.15	14.52778	9.527778	
9	15	74.4	41.7	58.05	14.47222	9.472222	
9	16	75.1	43	59.05	15.02778	10.02778	
9	17	75.6	42.4	59	15	10	
9	18	75	43.1	59.05	15.02778	10.02778	
9	19	72.3	42.8	57.55	14.19444	9.194444	
9	20	70.5	41.4	55.95	13.30556	8.305556	
9	21	71.5	40.4	55.95	13.30556	8.305556	
9	22	72.6	39.4	56	13.33333	8.333333	
9	23	73.6	39.2	56.4	13.55556	8.555556	
9	24	73.6	39.3	56.45	13.58333	8.583333	
9	25	75.3	40.5	57.9	14.38889	9.388889	
9	26	74.3	40.6	57.45	14.13889	9.138889	
9	27	71.9	38.7	55.3	12.94444	7.944444	
9	28	71.2	38.9	55.05	12.80556	7.805556	
9	29	71.7	38.5	56.1	12.83333	7.833333	
9	30	72.6	39	56.8	13.22222	8.222222	310
10	1	74.4	38.8	56.6	13.66667	8.666667	
10	2	72.8	38	55.4	13	8	
10	3	70.8	37.3	54.05	12.25	7.25	
10	4	71.6	38.3	54.95	12.75	7.75	
10	5	70.3	36.6	53.45	11.91667	6.916667	
10	6	69.5	37.8	53.65	12.02778	7.027778	
10	7	69	37.9	53.45	11.91667	6.916667	
10	8	68	36.7	52.35	11.30556	6.305556	
10	9	67.2	34.9	51.05	10.58333	5.583333	
10	10	68.5	36.4	52.45	11.36111	6.361111	
10	11	66.7	35.7	51.2	10.66667	5.666667	
10	12	68.3	36.1	52.2	11.22222	6.222222	
10	13	67.4	35.2	51.3	10.72222	5.722222	
10	14	65.9	35.2	50.55	10.30556	5.305556	
10	15	64.5	34.8	49.65	9.805556	4.805556	
10	16	63	34.6	48.8	9.333333	4.333333	
10	17	64.1	32.7	48.4	9.111111	4.111111	
10	18	63.4	31.2	47.3	8.5	3.5	
10	19	66.1	32.8	49.45	9.694444	4.694444	
10	20	66.7	33.6	50.15	10.08333	5.083333	
10	21	65.6	33.3	49.45	9.694444	4.694444	
10	22	63.4	33.3	48.35	9.083333	4.083333	
10	23	63.6	31	47.3	8.5	3.5	
10	24	63.3	32.9	48.1	8.944444	3.944444	
10	25	64.4	32.6	48.5	9.166667	4.166667	
10	26	64.8	33.5	49.15	9.527778	4.527778	
10	27	61.1	29.5	45.3	7.388889	2.388889	
10	28	62.3	30.5	46.4	8	3	
10	29	61.3	29.3	45.3	7.388889	2.388889	
10	30	58.7	29.1	43.9	6.611111	1.611111	
10	31	57.1	30.6	43.85	6.583333	1.583333	156.1111

11	1	56.9	29.3	43.1	6.166667	1.166667	
11	2	55.4	28.1	41.75	5.416667	0.416667	
11	3	55.8	27.9	41.65	5.472222	0.472222	
11	4	57.9	28.9	43.4	6.333333	1.333333	
11	5	58.5	28.4	43.45	6.361111	1.361111	
11	6	55.2	27.6	41.4	5.222222	0.222222	
11	7	52.5	26.3	39.4	4.111111	0	
11	8	51.5	26.4	38.95	3.861111	0	
11	9	51.7	25.4	38.55	3.638889	0	
11	10	52.2	25.9	39.05	3.916667	0	
11	11	51.3	26	38.65	3.694444	0	
11	12	51.8	25.5	38.65	3.694444	0	
11	13	51	25.9	38.45	3.583333	0	
11	14	50.4	24.9	37.65	3.138889	0	
11	15	51.8	25.3	38.55	3.638889	0	
11	16	50	24.5	37.25	2.916667	0	
11	17	48	24.1	36.05	2.25	0	
11	18	45.4	22.7	34.05	1.138889	0	
11	19	47.2	22.6	34.9	1.611111	0	
11	20	47.8	21.3	34.55	1.416667	0	
11	21	44.9	19.2	32.05	0.027778	0	
11	22	45.6	19.7	32.65	0.361111	0	
11	23	45.9	18.9	32.4	0.222222	0	
11	24	48.4	21.4	34.9	1.611111	0	
11	25	44.9	21.1	33	0.555556	0	
11	26	40.7	19.3	30	-1.11111	0	
11	27	38.3	15.8	27.05	-2.75	0	
11	28	40	16.5	28.25	-2.08333	0	
11	29	43	17.4	30.2	-1	0	
11	30	42.9	18.5	30.7	-0.72222	0	4.972222
12	1	42.9	17.5	30.2	-1	0	
12	2	42.8	16.5	29.65	-1.30556	0	
12	3	43.6	17.1	30.35	-0.91667	0	
12	4	44.9	21.5	33.2	0.666667	0	
12	5	42.7	18.8	30.75	-0.69444	0	
12	6	40.8	16.4	28.6	-1.88889	0	
12	7	38.9	16.1	27.5	-2.5	0	
12	8	38.1	13.8	25.95	-3.36111	0	
12	9	39.9	14.5	27.2	-2.66667	0	
12	10	41.9	14.5	28.2	-2.11111	0	
12	11	42.2	15.1	28.65	-1.85111	0	
12	12	39.6	16.4	28	-2.22222	0	
12	13	38.4	14.9	26.65	-2.97222	0	
12	14	40.3	15.6	27.95	-2.25	0	
12	15	40.6	12.9	26.75	-2.91667	0	
12	16	38	13.9	25.95	-3.36111	0	
12	17	39.2	14.1	26.65	-2.97222	0	
12	18	38.2	13.9	26.05	-3.30556	0	
12	19	34.7	13.1	23.9	-4.5	0	
12	20	34.4	12.4	23.4	-4.77778	0	
12	21	36.7	13.1	24.9	-3.94444	0	
12	22	37.1	12.5	24.8	-4	0	
12	23	36.2	13.7	24.95	-3.91667	0	
12	24	32.7	10.3	21.5	-6.83333	0	
12	25	35.6	9.8	22.7	-6.16667	0	
12	26	35.9	13.6	24.75	-4.02778	0	
12	27	36.8	12.3	24.55	-4.13889	0	
12	28	35.5	10.8	23.15	-4.91667	0	
12	29	32.4	8.1	20.25	-6.52778	0	
12	30	34.4	12.7	23.55	-4.69444	0	
12	31	34.9	11.7	23.3	-4.83333	0	
						2300.778	2300.778

Appendix 6: Wheat yield data and statistics for CD 1, MD Cypress, and Yellowstone County.

Medicine Spring	Hat Wheat	cd 1 Yield
Year	bushels/acre	
1982	30.8	
1983	31.0	
1984	18.3	
1985	17	
1986	31.1	
1987	28.3	
1988	13.2	
1989	24.3	
1990	23.8	
1991	41.5	
1992	35.3	
	MEAN	STDS
	26.78182	8.433364

Winter	Wheat	Yield
Year	bushels/acre	
1982	34.2	
1983	36.2	
1984	25	
1985	19.3	
1986	38.6	
1987	29.8	
1988	18	
1989	20	
1990	31.5	
1991	43.3	
1992	32.7	
	MEAN	STDS
	29.87273	8.365535

Billings Spring	Yell. cty. Wheat	Yield
Year	bushels/acre	
1982	31.4	
1983	68.3	
1984	36.4	
1985	17.8	
1986	31.7	
1987	35	
1988	20	
1989	27	
1990	39.8	
1991	43	
1992	52	
	MEAN82-	STDS
	36.58182	14.38074

Winter	Wheat	Yield
Year	bushels/acre	
1982	33.1	
1983	31.4	
1984	27	
1985	15.8	
1986	34	
1987	36	
1988	19	
1989	32	
1990	29.9	
1991	31	
1992	39	
	MEAN 82	STDS
	29.83636	6.934879

	MEDHATALL	BILLALL		BILLSPR NOT IRRI	BILLWINT NOT IRRI
1982	31	32.9	82	30.6	33
1983	31.3	32.8	83	30	31
1984	18.4	27.6	84	16.8	26.5
1985	16.4	16	85	8.7	14.1
1986	32	33.9	86	24.4	33.7
1987	29.2	36.2	87	27	36
1988	15.4	18.6	88	9	18
1989	25.5	31	89	19	31
1990	26	30.7	90	18.2	29.7
1991	40.9	32.1	91	26.3	30.9
1992	34.6	40.5	92	33.6	39
mean	27.33636	30.20909	AVG	22.14545	29.35455
stds	7.988651	7.192281	STDS	8.472941	7.3964

MDCSPR	MDCWINTNI	billspring	billwintirrig	mdcspirn	mdcwintirrg	
31.1	35.5	50	37.5	40.2		
30.4	39.7	76	49	30.8		
13.7	24.4	62	59	26.1		
10.9	16.6	71	52	38.8		
27.1	29.9	58	64	66.8		
21.7	23.8	63	68	54.1		
10.6	10.8	45	56	26.8		
12.2	18.1	62	56	30.9	20	(83)
12.8	25.8	59.3	65	32.3	55	(84)
37.1	32.8	65	70	50.5	52.1	(87)
32.4	20	74	68	50.9	63.5	(90)
21.81818	25.21818	62.3	58.59091	41.47273	47.65	
10.08968	8.705839	9.414351	9.856009	12.78562	19.05754	

SPRING

	MDC	CD1
1982	31.2	30.8
1983	30.5	31
1984	14	18.3
1985	11.1	17
1986	27.6	31.1
1987	22	28.3
1988	10.7	13.2
1989	12.4	24.3
1990	13	23.8
1991	37.2	41.5
1992	32.4	35.3

WINTER

MDC	CD1
39	36.2
26.2	25
24.6	29.8
26.8	31.5

SPRING

Regression Output		
Constant		-7.66118
Std Err of Y Est		3.918745
R Squared		0.863309
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	1.107851	
Std Err of Coef	0.146942	

WINTER

Regression Output		
Constant		-5.7883
Std Err of Y Est		4.92111
R Squared		0.632932
No. of Observations		4
Degrees of Freedom		2
X Coefficient(s)	1.140842	
Std Err of Coef	0.614335	

Appendix 7: Calculations of MD Cypress yield.

MD CYPRESS YIELD DATA

SPRING

	fallow acr	stubble ac	dryland acr	fallow yld	fallow pro	stubble yl	stubble pr	dryland pr	dryland yld		irrig acr	dryland a	spring acr	irrig yld	irrig pro	dryland pr	spring pro	spring yld
1982	105990	9399	115389	31.76	3366242	23.08	216928.9	3583171	31.05297		1563	115389	116952	40.24	62895.12	3583171	3646066	31.17575
1983	111352	13199	124551	31.43	3499793	21.46	283250.5	3783044	30.37345		1754	124551	126305	38.8	68055.2	3783044	3851099	30.49047
1984	102233	13468	115701	14.81	1514071	5.47	73669.96	1587741	13.72279		2597	115701	118298	26.13	67859.61	1587741	1655600	13.99517
1985	48207	7149	55356	11.16	537990.1	8.85	63268.65	601258.8	10.86167		380	55356	55736	38.79	14740.2	601258.8	615999	11.05208
1986	117376	15781	133157	27.91	3275964	21.17	334083.8	3610048	27.11121		1495	133157	134652	66.81	99880.95	3610048	3709929	27.55198
1987	100430	12275	112705	22.47	2256662	15.75	193331.3	2449993	21.73811		755	112705	113460	54.07	40822.65	2449993	2490816	21.95325
1988	96573	11832	108405	11.07	1069063	6.84	80930.88	1149994	10.60831		796	108405	109201	26.82	21348.72	1149994	1171343	10.72648
1989	99934	12599	112533	12.34	1233186	11.41	143754.6	1376940	12.23588		869	112533	113402	30.93	26878.17	1376940	1403818	12.37913
1990	106875	10675	117550	13.12	1402200	9.77	104294.6	1506495	12.81578		1160	117550	118710	32.32	37491.2	1506495	1543986	13.00637
1991	135314	21947	157261	38.17	5164935	30.6	671578.2	5836514	37.11355		1401	157261	158662	50.45	70680.45	5836514	5907194	37.23131
1992	139487	17056	156543	33.7	4700712	21.62	368750.7	5069463	32.38383		331	156543	156874	50.9	16847.9	5069463	5086311	32.4229
		mean	119013.7						21.81978	mean	1191							
									10.08059									

WINTER	fallow acr	stubble ac	dryland acr	fallow yld	fallow pro	stubble yl	stubble pr	dryland pr	dryland yld	irrig acr	dryland a	wint acr	irrig yld	irrig pro	dryland pr	wint pro	wint yld
1982	1500	20	1520	35.53	53295	33	660	53955	35.49671	NA	1520	NA			53955		
1983	3393	3	3396	39.73	134803.9	25	75	134878.9	39.71699	120	3396	3516	20	2400	134878.9	137278.9	39.04406
1984	4400	130	4530	24.86	109384	8.46	1099.8	110483.8	24.38936	290	4530	4820	55	15950	110483.8	126433.8	26.23108
1985	422	168	590	17.05	7195.1	15.54	2610.72	9805.82	16.62003	NA	590	NA			9805.82		
1986	5416	2290	7706	29.37	159067.9	31.03	71058.7	230126.6	29.8633	NA	7706	NA			230126.6		
1987	5291	2982	8273	28.61	151375.5	15.16	45207.12	196582.6	23.76195	260	8273	8533	52.12	13551.2	196582.6	210133.8	24.62602
1988	9490	4143	13633	13.64	129443.6	4.16	17234.88	146678.5	10.75908	NA	13633	NA			146678.5		
1989	2187	511	2698	18.77	41049.99	15.48	7910.28	48960.27	18.14688	NA	2698	NA			48960.27		
1990	4590	746	5336	26.79	122966.1	19.95	14882.7	137848.8	25.83373	145	5336	5481	63.45	9200.25	137848.8	147049.1	26.82887
1991	3403	788	4191	32.47	110495.4	34.09	26862.92	137358.3	32.7746	NA	4191	NA			137358.3		
1992	1480	157	1637	19.19	28401.2	27.86	4377.16	32778.36	20.02343	NA	1637	NA			32778.36		
			4864.545														