Alberta Agriculture, Food and Rural Development

Temporal and Spatial Changes of the Agroclimate in Alberta from 1901-2002

By

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Abstract

This paper analyzes the long-term (1901-2002) temporal trends in the agroclimate of Alberta and explores the spatial variations of the agroclimatic resources and the potential crop-growing area in Alberta. Nine agroclimatic parameters are investigated: May-August precipitation, start of growing season, end of growing season, length of growing season, date of last spring frost (LSF), date of first fall frost (FFF), length of frost-free period (FFP), growing degree days, and corn heat units. The temporal trends in the agroclimatic parameters are analyzed by using linear regression. The significance tests of the trends are made by using Kendall's Tau method. The results support the following conclusions. (i) The May-August precipitation has increased all over the province, with larger amplitude in the northern part of the province. (ii) No significant long-term trends are found for the start, end, and length of the growing season. (iii) An earlier LSF, a later FFF, and a longer FFP are obvious all over the province; this trend reduces the risk of frost damages to crops. The change in the LSF and FFF is asymmetric. (iv) The area suitable for corn planting has extended to the north by about 200-300 km compared to the 1910s, and by about 50-100 km compared to the 1940s; this expansion implies that more species of crop can be grown in Alberta than could be previously. The total precipitation follows a similar increasing trend to that of the May-August precipitation and the percentile analysis of precipitation attributes the increase to low-intensity events. The Alberta drought records do not show a discernable trend of drought events, when excluding the extreme dry period from 1999-2002. Therefore, Alberta agriculture has benefited from the last century's climate change.

Contents

1. Introduction

During the last 30 years, Alberta's winter has become milder, and the annual number of warmer-than-normal days has increased. The warming climate has been perceived to benefit Alberta agriculture, including the growth of both crops and cattle. Despite these obvious observational results and perceptions, Alberta Agriculture, Food and Rural Development (AAFRD) still needs a quantitative and systematic analysis of the agroclimatic changes in the aspects of both time and space. Although many results of climate-change assessments are useful to satisfy this need, agroclimatic parameters, such as the corn heat unit and the growing season precipitation, have their own agricultural characteristics and have not been the major concern of provincial or federal meteorological services (Bonsal, 2001; Boostma, 1994; Boostma et al., 2001). Therefore, AAFRD decided to document the details of the Alberta agroclimate changes and use the information to optimally manage the land usage for different species of crops and cattle. The results included in this paper are from the main conclusions from the AAFRD's project on agroclimate change and have never appeared in refereed journals before. Other innovative aspects of this paper are that (a) we used the variance-retained interpolated daily climate data over ecodistrict polygons, in contrast to the data at unevenly distributed stations used in other studies (Bootsma 1994; Zhang et al., 2000), (b) we area-weighted the agroclimatic parameters of each ecoregion before regression analysis, and (c) we found the asymmetry of the agroclimatic change in the spring and fall.

Alberta is a western province of Canada, bounded by 49 and 60 degrees latitude from south and north, and 110 and 120 degrees longitude from east and west, respectively. The Canadian Rockies cuts off the southwest corner (Fig. 1). The major Alberta crops are spring wheat, canola and alfalfa. The most important cattle are cows for both milk and beef. The agricultural regions, as shown in Fig. 1, are in the southeast prairie land and the western Peace Lowland. The rest of Alberta is either covered with forest or its elevation is too high for crop cultivation. Because Agriculture affects more people than any other industry or business, the agricultural industry is the most important industry in Alberta's economy. The sustainable development of agriculture and the agricultural industry is of crucial importance for the long-term economy of Alberta. Adaptation strategies must be in place to cope with the climate change. This paper uses the master dataset produced by

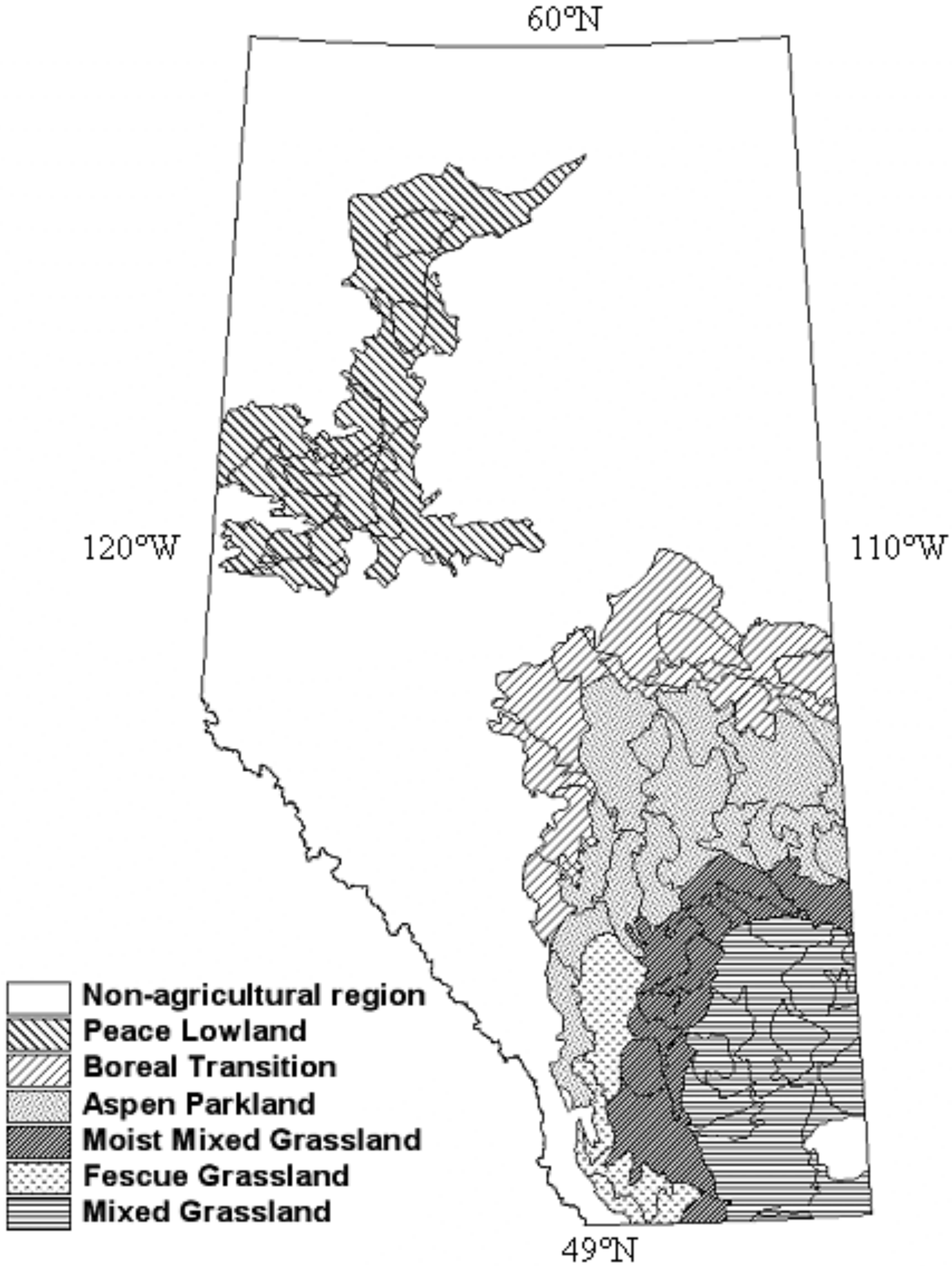

Figure 1. Alberta province and the six ecoregions with extensive agriculture.

AARD by using an optimal hybrid interpolation method (Griffith, 2002; Shen et al., 2000a,b, 2001). When this research project started, the time span of the dataset was from January 1, 1901 to December 31, 2002. Thus, our results are for the agroclimatic change during this period. The conclusions from this study will provide not only a useful reference for Albertans for their sustainable agricultural development, but also a method for other people in the world to use to investigate similar problems involving agroclimatic changes.

TABLE 1. Glossary of abbreviations

Acronym	Meaning	Unit
ACHU	Accumulated corn heat unit	Dimensionless
AP	Aspen Parkland	Ecoregion
AR	Agricultural Region	Region
BT	Boreal Transition	Ecoregion
CHU	Corn heat unit	Dimensionless
EDP	Ecodistrict polygon	Polygon ID
EGS	End of growing season	Julian day
FFF	First fall frost	Julian day
FFP	Frost free period	Days
FG	Fescue Grassland	Ecoregion
GDD	Growing degree day	Degree Centigrade
GSP	Growing season precipitation	Millimeter/day
LGS	Length of growing season	Days
LSF	Last spring frost	Julian day
MG	Mixed Grassland	Ecoregion
MMG	Moist Mixed Grassland	Ecoregion

The agroclimatic changes in this paper are investigated according to six ecoregions with extensive agriculture, Alberta as a whole, and nine agroclimatic parameters. The nine parameters are the May-August precipitation (PCPN), the start of the growing season (SGS), the end of the growing season (EGS), the length of the growing season (LGS), the date of the last spring frost (LSF), the date of the first fall frost (FFF), the length of the frost-free period (FFP), the growing degree days (GDD), and the corn heat units (CHU). (The acronyms in this paper are summarized in Table 1.) Our research on these agroclimate parameters has provided important information to AARD and this paper will justify the following results. (i) The growing season precipitation has increased all over the province, with larger amplitude in the northern part. (ii) No significant long-term trends have been found for the start, end, and length of the growing season. (iii) An earlier LSF, a later FFF, and a longer FFP now occur in most of the province; this trend reduces the risk of frost damages to crops. The change of LSF and FFF is asymmetric. (iv) The potential growing areas for warm-season crops such as corn have increased and extended to the north by about 200-300 km compared to the 1910s, and by about 50-100 km compared to the 1940s; this expansion implies that a wider variety of crop hybrids are now suitable for a given farmland than were before. Therefore, the last century's climate change has been beneficial for Alberta agriculture.

The remainder of this paper is arranged as follows. Section 2 describes the dataset used to derive the agroclimatic parameters. Section 3 presents their definitions and the calculation procedure for the trends. Section 4 presents the results for the change of the parameters. Section 5 provides our conclusions and a discussion.

2. Data

Some soil-quality models, such as the Erosion/Productivity Impact Calculator, need daily climate data as their input, and these data have to be defined every day at a given resolution. Irregular and often discontinuous observations of weather make it necessary to interpolate the point-based weather station data to regular grid data or data over polygons. Realistic simulations crucially depend on not only the climate mean but also climate variations. As a matter of fact, the latter is more important, but often ignored in many spatial interpolation schemes that are derived from the best fit to the mean. The problem is particularly serious for precipitation because the daily precipitation, such as that in the convective summer storms over the Canadian Prairies, can be spatially localized, while an interpolation method often makes the field spatially spread and smooth. Precipitation frequency is another problem since most interpolation methods yield too many wet days in a month but too little precipitation in a day so that the results do not retain enough temporal variation and hence are temporally too smooth. Shen et al. (2001) overcame the problem and invented a hybrid interpolation scheme that uses a reference station to refine the variance of the interpolated field but maintain the monthly mean. Using this method and the raw point-based observed weather station data provided by Environment Canada, the U.S. National Climate Data Centre, and Agriculture and Agri-Food Canada, AAFRD produced a master set of daily climate data with different resolutions: (i) 10 km by 10 km regular grid, (ii) 6,900 townships, (iii) 894 soil landscape of Canada polygons (SLC), and (iv) 149 ecodistrict polygons (EDP) (Griffith, 2002; Shen et al., 2000a, b, 2001). At these resolutions, every grid or polygon has a uniquely defined value for a climate parameter on each day. This paper uses not only the EDP data to derive the main results, but also the station data for result-checking. The Canadian station data are checked against the data from the US National Climatic Data Center's Global Daily Climatology Network dataset. The latest updated AAFRD master dataset includes the daily data from January 1, 1901 to December 31, 2002.

The accuracy of the master dataset was carefully investigated since it has numerous uses besides the applications to this agroclimate change project. Five stations, ranging from southern to northern Alberta, were selected for cross-validation to assess the interpolation errors (Griffith, 2002; Shen et al., 2001). The root mean square errors, which measure the difference between the interpolated and the true observed values, are in the following range: maximum temperature 1.4 to 3.2°C, minimum temperature 1.8 to 3.2°C, and precipitation 1.8 to 2.8 mm. Many more cross-validation experiments were made and showed that, for the daily temperature and precipitation, the hybrid method had less error than the interpolation methods using simple nearest-station assignment, inverse-distance-square weighting, and kriging.

All the agroclimatic parameters analyzed here, including percentiles of daily precipitation for the analysis of extreme events, were derived from the daily maximum temperature, daily minimum temperature and daily precipitation in the EDP master dataset. Using this dataset has several advantages. (1) This is the most complete long-term daily dataset for Alberta. (2) The dataset can reflect the daily climate variance well;

this capability is important when calculating the agoclimatic elements (such as the SGS and LSF) that are sensitive to the daily climate change. (3) The EDPs are exactly embedded into 10 ecoregiongs divided according to distinctive regional ecological characteristics including climate, physiography, vegetation, soil, water and fauna. Each ecoregion consists of a number of EDPs, ranging from 4 to 38. Therefore, using the EDP data is convenient to calculate the agroclimatic properties for each ecoregion. As a result, this study features the use of completely covered and highly accurate data, compared to the data used in either the station-based studies or the studies based on interpolated data with too little variance.

3. Agroclimatic parameters and analysis method

Although most materials contained in this section are available in literature, they are briefly summarized and sorted here to facilitate a systematic study of Alberta's agroclimatic changes.

a. Summary of nine agroclimatic parameters

Alberta is divided into ten ecoregions, but only six have extensive Agriculture: Peace Lowland (PL), Boreal Transition (BT), Aspen Parkland (AP), Moist Mixed Grassland (MMG), Fescue Grassland (FG) and Mixed Grassland (MG) (Fig. 1). The analyses of the temporal trends in the agroclimatic parameters are conducted mainly on these six ecoregions. The analyzed agroclimatic parameters are summarized as follows.

1) GROWING SEASON

The SGS (start of growing season) is the Julian date of the first of the five consecutive days with a mean temperature above 5°C in a year. The EGS (end of growing season) is the Julian date of the first day in the fall on which the mean temperature is below 5°C. Both SGS and EGS are sensitive to weather outliers in spring and fall, as are the crops. For example, in 1910, there was an abnormally warm week at the end of March that started the growing season about a month earlier than normal, but a cold event occurred at the beginning of June and put the LSF later than normal. The LGS (length of growing season) is the number of days between the SGS and the EGS:

$$LGS = EGS - SGS + 1.$$

The means (standard deviations) of the SGS, EGS, and LGS for the Alberta AR region in 1961-1990 are 108 (9.78) [Julian day], 263 (10.80) [Julian day], and 156 (14.99) [days].

2) FROST-FREE PERIOD

The LSF (last spring frost) day is defined as the last date in a year on or before July 15 when the daily minimum temperature $T_{min} \le 0°C$. The FFF (first fall frost) day is defined as the first date in a year on or after July 16 when $T_{min} \le 0°C$. Similar to SGS and EGS, LSF and FFF are also sensitive to weather outliers, particularly the cold outliers, in late spring and early fall and are good indicators for crops' frost damages. The FFP (frost-free period) is the number of days between the LSF and the FFF:

$$FFP = FFF - LSF + 1.$$

The means (standard deviations) of the LSF, FFF, and FFP for the Alberta AR region in 1961-1990 are 140 (7.36) [Julian day], 257 (8.66) [Julian day], and 118 (11.39) [days]. The LGS is in general longer than FFP. For genetically improved seeds, the growing season may be even longer and can start at the first Julian date of the five consecutive days with a mean temperature above 0°C, rather than 5°C.

3) GROWING DEGREE DAYS

Most of the natural crop species can grow when the daily mean temperature is above 5°C, although the genetic-engineered species can sustain lower temperature and grow even when the daily mean temperature is between 0°C and 5°C. Some people now use values based on 0°C for the growing degree day (GDD). However, because our purpose is to assess the agroclimatic change since 1901, our values for the GDD are still based on 5°C and computed from the mean daily air temperature (T_{mean}) by using the formula

$$\text{Daily GDD} = \begin{cases} T_{mean} - 5.0, & \text{if } T_{mean} > 5.0, \\ 0 \quad , & \text{otherwise,} \end{cases}$$

where $T_{mean} = (T_{\max} + T_{\min})/2.0$. The GDD were cumulated from the SGS to the EGS.

4) CORN HEAT UNIT

Although the GDD measures the heat from solar irradiance on the Earth's surface, the growth of warm-season crops like corn and soybean depends on the daily minimum and maximum temperatures in a more refined way, which is normally measured by the corn heat unit (CHU). Corn growth is slow at a low temperature and becomes fast as the temperature rises until it reaches a threshold temperature at which the growth slows down. The daily CHU is computed from the daily maximum and minimum temperatures. The CHU calculations are treated separately for daytime and nighttime. As well, these calculations assume that no growth occurs at night when temperature is below 4.4°C or during the day when temperature is below 10°C. Moreover, these calculations use 30°C as the threshold temperature of the daytime because warm-season crops develop fastest at 30°C. The night does not have a threshold temperature since the nighttime temperature seldom exceeds 25°C. The daily CHU is the average of the nighttime CHU and the daytime CHU, calculated by using the following formulas:

$$CHU = (CHU_X + CHU_Y)/2,$$

where the nighttime CHU is

$$CHU_X = 1.8(T_{\min} - 4.4),$$

and the daytime CHU is

$$CHU_Y = 3.33(T_{\max} - 10) - 0.084(T_{\max} - 10)^2.$$

In the above, $CHU_X = 0$ if $T_{\min} < 4.4^\circ C$ and $CHU_Y = 0$ if $T_{\max} < 10.0^\circ C$. The accumulated CHU (ACHU) is the accumulation of the daily CHU from the last day of three consecutive days in the spring with mean daily air temperatures greater or equal to 12.8°C, to the first day of the first fall frost, with a minimum temperature less than or equal to -2°C (Bootsma and Brown, 1995). The critical temperature 12.8°C is the value that corresponds closely with the average seeding date for grain corn and also corresponds to the time when sufficient heat has been received to raise the soil temperature to 10°C, which ensures corn germination.

b. Method for data analysis

The above eight temperature-related and other precipitation-related agroclimatic parameters are computed by using the daily temperature and precipitation data for every EDP. The calculated agroclimatic parameters for the EDPs are then averaged for the ecoregions and the entire Alberta province. Since both the EDPs and the ecoregions are irregular polygons and their areas vary, using a simple average is inappropriate. Instead, the area-weighted average is utilized. For an ecoregion with N EDPs, the area-weighted parameter $\overline{R}(t)$ can be calculated by using

$$\overline{R}(t) = \frac{1}{\sum_{i=1}^{N} A_i} \sum_{i=1}^{N} A_i R_i(t),$$

where A_i is the area of the i[th] EDP, and R_i is the value of the parameter R for the same polygon. The ecoregion-averaged data are then employed to create the annual time series of the agroclimatic parameters for the six agricultural ecoregions, the agricultural regions as a whole (i.e., the union of the six ecoregions with extensive agriculture), and the entire province.

After the preparation of the regionally averaged annual time series, the temporal trends of nine agroclimatic parameters are studied by using the linear regression method (See Tables 2 and 3, and Fig. 3). The linear correlation coefficients and significance levels are computed for each agroclimatic parameter with time to detect if significant linear temporal trends exist. Kendall's Tau significance test for a slope to be different from zero is applied here. This non-parametric method does not require the normality assumption of the slope as the t-test does and has been used widely in climate researches (Zhang et al., 2000).

The spatial distributions of three 30-year mean conditions for the agroclimatic parameters in Alberta are plotted. The 30-year periods are 1913-1942, 1943-1972, 1973-2002. Their differences are analyzed to show the changes among the three periods. Also, the spatial distribution of the 102-year trend is studied. The changing and shifting of the agricultural climatic resources and the potential crop-growing areas are analyzed.

4. Results

Table 2 contains the *r* and *s* values for nine different agroclimate parameters and six ecoregions with extensive agriculture, the agricultural region as a whole, and the Alberta region as a whole, where *r* is the correlation coefficient between each agroclimatic parameter and time (unit: year), and *s* is the slope of the temporal trend of each agroclimatic parameter. The agricultural ecoregions are denoted by PL (Peace Lowland), BT (Boreal Transition), AP (Aspen Parkland), MMG (Moist Mixed Grassland), FG (Fescue Grassland), and MG (Mixed Grassland) and are ordered according to their

TABLE 2. Correlation coefficient (*r*) and slope (*s*) of the trend for the nine annual agroclimatic parameters

Region		Pcpn (May-August)	SGS	EGS	LGS	LSF	FFF	FFP	GDD	ACHU
PL	*r*	**0.31****	-0.09	-0.05	0.01	**-0.38****	**0.36****	**0.46****	-0.04	**0.12**†
	s	**1.01**	-0.04	-0.03	0.02	**-0.20**	**0.20**	**0.40**	-0.28	**1.47**
BT	*r*	**0.13***	0.03	-0.01	-0.01	**-0.24****	**0.35****	**0.38****	**0.18****	**0.25****
	s	**0.33**	0.01	0.00	-0.01	**-0.12**	**0.17**	**0.29**	**1.09**	**3.03**
AP	*r*	0.04	0.02	-0.01	-0.03	**-0.23****	**0.32****	**0.37****	**0.23****	**0.26****
	s	0.01	0.02	0.00	-0.02	**-0.11**	**0.16**	**0.27**	**1.49**	**2.99**
MMG	*r*	0.05	0.00	0.00	0.02	**-0.14***	**0.19****	**0.22****	**0.19****	**0.20****
	s	-0.07	-0.02	-0.01	0.01	**-0.07**	**0.08**	**0.14**	**1.56**	**2.53**
FG	*r*	0.08	0.03	-0.07	-0.08	-0.03	0.02	0.06	-0.07	-0.06
	s	0.13	0.01	-0.05	-0.06	-0.02	0.00	0.02	-0.51	-0.20
MG	*r*	0.09	-0.02	-0.02	0.02	-0.04	0.09	0.10	0.09	0.05
	s	0.07	-0.02	-0.03	0.00	-0.02	0.04	0.06	0.75	0.97
AR	*r*	**0.16***	0.00	-0.02	0.00	**-0.25****	**0.33****	**0.36****	**0.11**†	**0.18****
	s	**0.31**	-0.01	-0.01	-0.01	**-0.10**	**0.13**	**0.23**	**0.76**	**2.02**
AB	*r*	**0.36****	-0.02	-0.11	-0.06	**-0.31****	**0.37****	**0.43****	-0.09	0.06
	s	**0.79**	-0.01	-0.05	-0.04	**-0.13**	**0.16**	**0.29**	-0.40	0.62

** Significance level : 0.00<P≤0.01

* Significance level : 0.01<P≤0.05

† Significance level : 0.05<P≤0.10

locations from the northwest to the southeast of Alberta. (See Fig. 1 for the locations of the ecoregions and Table 1 for acronyms.) AR stands for the agricultural region as the union of the six ecoregions, and AB stands for Alberta as the union of the ten ecoregions. When the slope *s* is found to be significant by using Kendall's Tau statistic at the significance level of 10%, then both the *r* and *s* values are shown in bold face in Table 2; otherwise, the *r* and *s* values are in plain text. With different P-values, the significant correlation coefficients are marked by double asterisks when $P \leq 0.01$, by a single asterisk when $0.01 < P \leq 0.05$, and a dagger when $0.05 < P \leq 0.10$.

TABLE 3. The 102-year total changes (*t*) and the percentage changes (*p*) since 1901 of the nine annual agroclimatic parameters (the percentage change is with respect to the linear fitted value in 1901)

Region		Pcpn (May-August)	SGS	EGS	LGS	LSF	FFF	FFP	GDD	ACHU
PL	*t*	**103.0**	-4.1	-3.1	2.0	**-20.4**	**20.4**	**40.8**	-28.6	**149.9**
	P(%)	**60.1**	-3.5	-1.2	1.4	**-13.1**	**8.5**	**48.8**	-2.5	**9.1**
BT	*t*	**33.7**	1.0	0.0	-1.0	**-12.2**	**17.3**	**29.6**	**111.2**	**309.1**
	p(%)	**13.0**	0.9	0.0	-0.6	**-8.0**	**7.1**	**32.3**	**9.7**	**18.5**
AP	*t*	1.0	2.0	0.0	-2.0	**-11.2**	**16.3**	**27.6**	**152.0**	**305.0**
	p(%)	0.4	1.9	0.0	-1.3	**-7.5**	**6.6**	**28.4**	**12.8**	**17.3**
MMG	*t*	-7.1	-2.0	-1.0	1.0	**-7.1**	**8.2**	**14.3**	**159.1**	**258.1**
	p(%)	-3.1	-1.9	-0.4	0.6	**-4.9**	**3.2**	**12.8**	**12.1**	**13.1**
FG	*t*	13.3	1.0	-5.1	-6.1	-2.0	0.0	2.0	-52.0	-20.4
	p(%)	5.4	1.0	-1.9	-3.6	-1.4	0.0	1.8	-4.0	-1.1
MG	*t*	7.1	-2.0	-3.1	0.0	-2.0	4.1	6.1	76.5	98.9
	p(%)	3.9	-2.0	-1.1	0.0	-1.4	1.6	5.0	5.0	4.3
AR	*t*	**31.6**	-1.0	-1.0	-1.0	**-10.2**	**13.3**	**23.5**	**77.5**	**206.0**
	p(%)	**14.3**	-0.9	-0.4	-0.6	**-6.9**	**5.4**	**23.4**	**6.2**	**11.1**
AB	*t*	**80.6**	-1.0	-5.1	-4.1	**-13.3**	**16.3**	**29.6**	-40.8	63.2
	p(%)	**39.8**	-0.9	-1.9	-2.7	**-8.6**	**6.7**	**33.5**	-3.5	3.7

The results showed that the precipitation from May-August, usually included in the growing season defined in Sub-section 3a(1), has a significant positive trend in the northern agricultural region consisting of the PL and BT regions. The magnitude of the increment from 1901 to 2002 is 103.0 mm (60.1%) for the PL and 33.7mm (13.0%) for the BT (see Table 3). The other four agricultural regions in the southern Alberta have no significant trends in the May-August precipitation. Although the May-August precipitation has a significant increment of 31.6 mm (14.3%) when considering the Alberta agricultural region as a whole (i.e., the AR), this significance is attributable to only the two northern ecoregions. The same explanation applies to the significant increment of the May-August precipitation over the entire province; i.e., the positive trend is attributable to the non-agricultural regions and the ecoregions PL and BT. The precipitation results in Tables 2 and 3 agree with the findings of Zhang et al. (2000) who identified the positive precipitation trend in eastern Canada and in the western-most province, British Columbia, and found no significant trends in the Canadian Prairies, especially in southern Alberta and the eastern neighboring province Saskatchewan. The increase of the May-August precipitation is mainly attributable to increasing number of events of low-intensity precipitation, as concluded by Akinremi et al. (1999), Zhang et al. (2001) and Kunkel (2003). Percentile analysis shows no significant increase of the events of 90th, 95th and 99th percentile precipitation from 1901 to 2002 over both the agricultural region (AR) and the entire province (AB). The Alberta drought records from the Alberta Agriculture, Food and Rural Development show no discernable increase signal of drought events or intensity (Shen et al., 2003). Karl and Knight (1998) identified an increase of the 20th century precipitation over the United States and attributed the increase to high-intensity events. Thus, the available results from others and us both demonstrated different patterns of climate change in terms of precipitation between the United States and Canada in the last century.

To further verify these results, we calculated the trend for the May-August precipitation by using a finer resolution. The trend from 1901 to 2002 for every SLC was computed and tested for significance. The contour plot of the trend is shown in Fig. 2(a). The figure shows that the northern half of Alberta had a 60-210 mm significant increase in the May-August precipitation during the 102 years while the southern part of the province had no significant changes, and the heavy agriculture areas AP, MMG and FG even had some decrease. The decrease was due mainly to the severe drought that occurred each year from 1999 to 2002 (Shen et al., 2003).

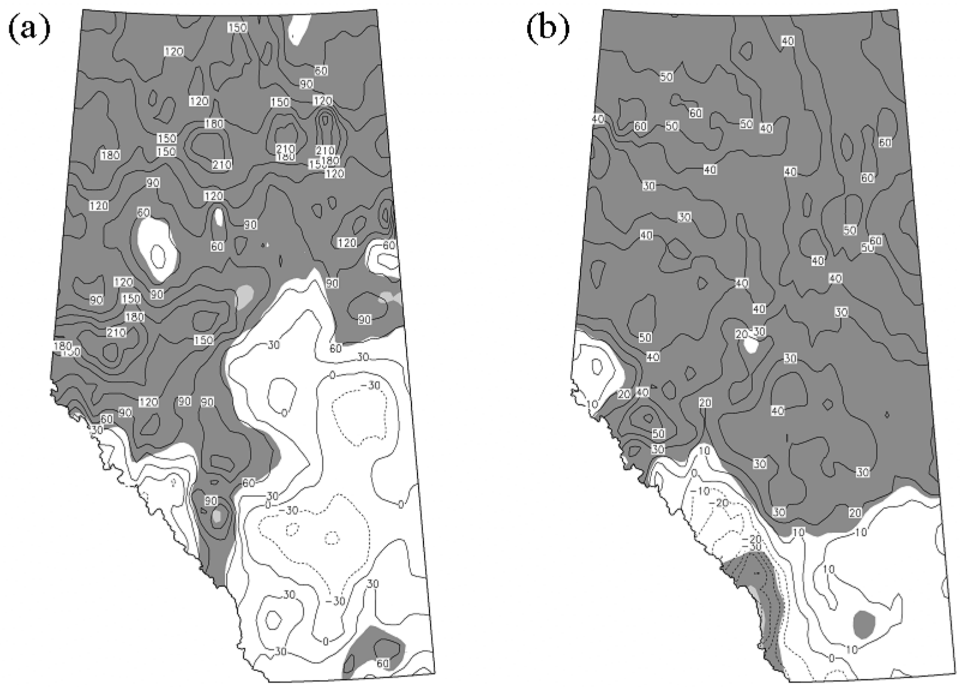

Figure 2. Spatial distribution of the temporal trends from linear regression. (a) May-August precipitation (unit: mm/102yr), (b) FFP (unit: day/102yr). The shaded regions are where significant trends exist at 5% significance level.

The values of SGS, EGS, and LGS do not show significant changes from 1901 to 2002, possibly because the climate warming is caused mainly by the higher minimum temperature, particularly in the winter, and the increase of the mean temperature in the spring and fall is small. For this reason, one may infer that the agroclimatic parameters crucially depending on daily minimum temperature should have changed significantly. Our data analysis supports this inference. Our numerical results have demonstrated a significantly earlier LSF, a later FFF, and a longer FFP in the four northern agricultural regions: PL, BT, AP and MMG. The linear regression slopes become smaller from the north to the south, indicating a larger change in the north and a smaller change in the south, as is clearly shown in Fig. 2(b). This figure shows that the FFP has increased over the entire province from 1901 to 2002, except in the Rocky Mountain areas. This exception is most likely resulted from the lack of in situ observational data for the high-elevation areas. Moreover, these areas have no agriculture. According to the linear regression from 1901 to 2002, the LSF in the ecoregion PL was 20 days earlier in 2002 compared to 1901, 12 days earlier in the ecoregion BT, 11 days earlier in the ecoregion AP, 7 days earlier in the ecoregion MMG, 10 days earlier in the entire agricultural region AR, and 13 days earlier in the entire province AB. The FFF was 20 days later in PL, 17 days later in BT, 16 days later in AP, 8 days later in MMG, 13 days later in AR, and 16 days later in AB. This trend of an earlier LSF and later FFF resulted in an increase in the FFP of 41, 30, 28, 14 days in the PL, BT, AP, MMG, respectively, 24 days in the entire agricultural region, and 30 days in the entire Alberta province (the spatial distribution of the trends is in Fig. 2 (b)). The earlier LSF implies that consecutive warm days in the spring are occurring earlier and reducing the frost risk for spring crops. The delay of consecutive cold days in the fall ensures less damage from frost for the growing plants. The percentage change of the FFF from 1901 to 2002 is the largest over PL (8.5%) (see Table 3). It is interesting to note that the changes in the LSF and FFF are asymmetric. The absolute value of the FFF slope is larger than that for the LSF. This is because the Alberta winter arrived much later in the 1980s and 1990s than it did previously, but the Alberta winter did not end that much earlier in the spring.

The GDD and ACHU are two types of easy-to-use energy terms in agroclimatology that relate plant growth to temperature. The more energy available, the more likely the plant will reach maturity, and the more hybrids of plant can be grown in an area. Table 3 shows significant positive trends in the GDD in three ecoregions (BT, AP and MMG) and in the ACHU in four ecoregions (PL, BT, AP and MMG). The largest percentage change in the GDD is over AP (12.8%), and in the CHU is over BT (18.5%). Normally, the northern part has larger changes than the south, but why did the GDD not have a significant trend over PL? The possible reason is the GDD being defined by using the daily mean temperature. A more refined heat definition, such as the CHU, using both the daily minimum and maximum temperatures, should give a more agriculturally realistic assessment of the change of plant-available heat energy.

Fig. 3 shows the annual time series of the six agroclimatic parameters with significant linear trends in the entire agricultural area AR. The 11-year running means are also shown. The positive trend of the May-August precipitation is resulted from the steady increase of precipitation after the 1920s. The variance of the temporal precipitation change over time decreased during the last 30 years. To check the moist supply for the entire crop-growing period, we also calculated the total growing season precipitation (GSP) in the unit of [mm/day]. The GSP follows similar trend as the May-August precipitation and their correlation is 0.90. (The GSP figures are not shown in this paper.) The shift of the LSF to the earlier date before 1940s and between 1970s and 1980s, together with the shift of the FFF to the later date in the same periods accounts for the increase of the FFP in the corresponding period. This increase of the FFP indicates lower risks for and damage to crops in Alberta. This result is consistent with the findings of Zhang et al. (2000), who showed that a mean temperature warming of 0.9°C in southern Canada (south of 60°N) resulted from the increases in temperature prior to the 1940s and after the 1970s. This result also agrees with that of Folland et al. (2001) who found that most of the increase of the temperature occurred in two periods, from about 1910 to 1945 and since 1976. This warming trend is also demonstrated by the increase of the GDD and ACHU before the 1940s, while during the 1970s-1980s, the increasing trends of the GDD and ACHU were not substantial because of the increase of the variance of these two parameters. The LSF usually occurred in May during the 1960s. However, in 1969, the minimum temperature fell below zero almost all over the province on around June 13, which resulted in an exceptional late LSF in that year (see Fig. 3(b)). Another exceptional case involves the FFF in 1918. Observations from the northern and central part of the province indicated a below-zero minimum temperature on around July 24, which was almost one month earlier than usual and caused the earlier FFF in that year. From July 21-23 in 1992 (see Fig. 3(c)), the minimum temperature decreased to below zero over most of the province, resulting in a small value of FFF in 1992. Other extremes were also checked and compared with the station observations. Most of these extremes were due to the natural variance, while the results before 1910s may be inaccurate because of too few observations.

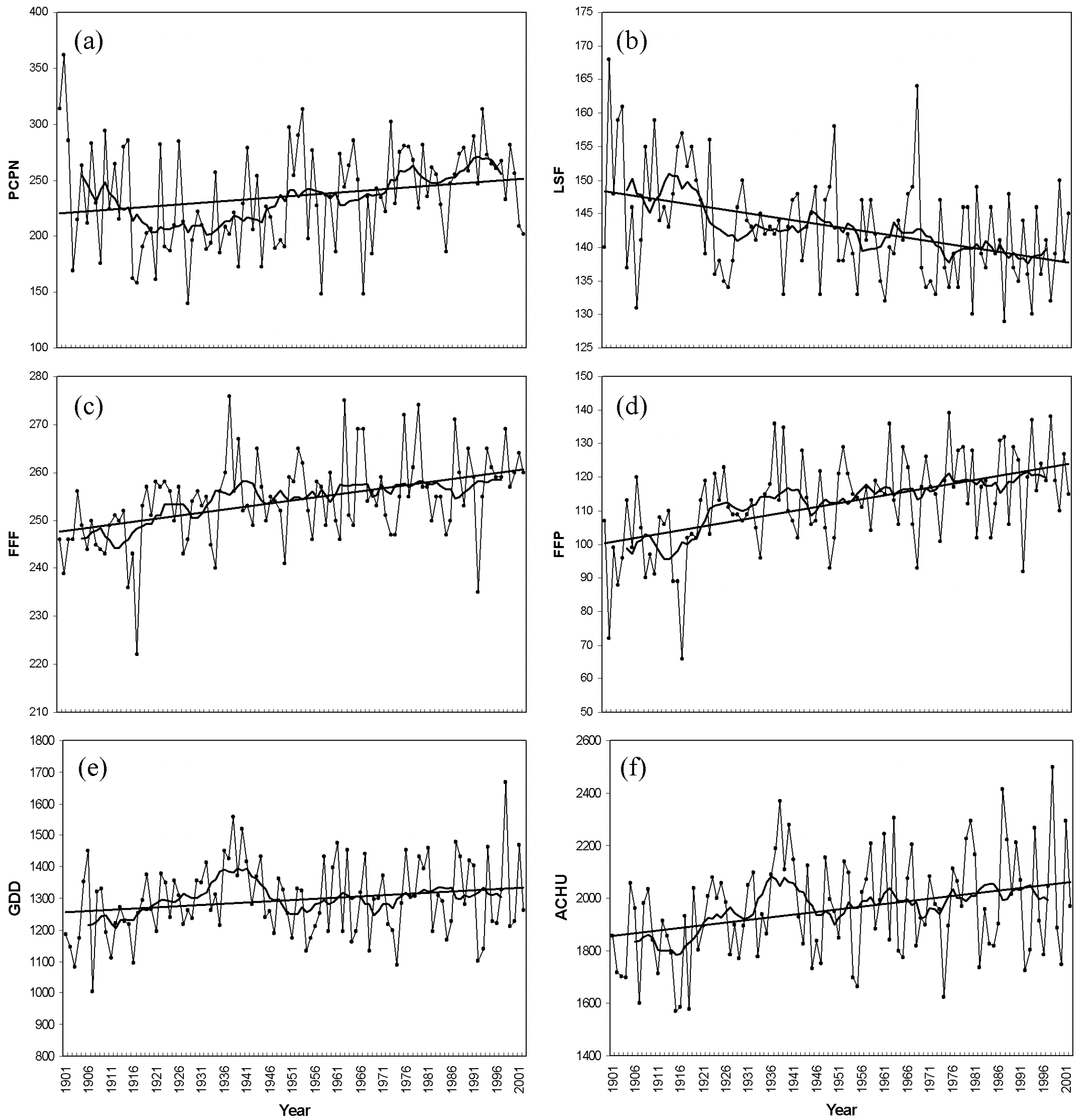

Figure 3. Annual time series (thin curve with dots), 11-year running mean (thick curve), and linear regression line (straight line). (a) May-August precipitation [unit: mm], (b) LSF [unit: day], (c) FFF [unit: day], (d) FFP [unit: day], (e) accumulated GDD in the growing season, and (f) ACHU.

Alberta has relatively large geographical variability across the province. From the Sub-arctic region in the north to the Prairie Grassland in the south, from the high elevation mountains in the west to the flat areas in the east, the Alberta climate varies

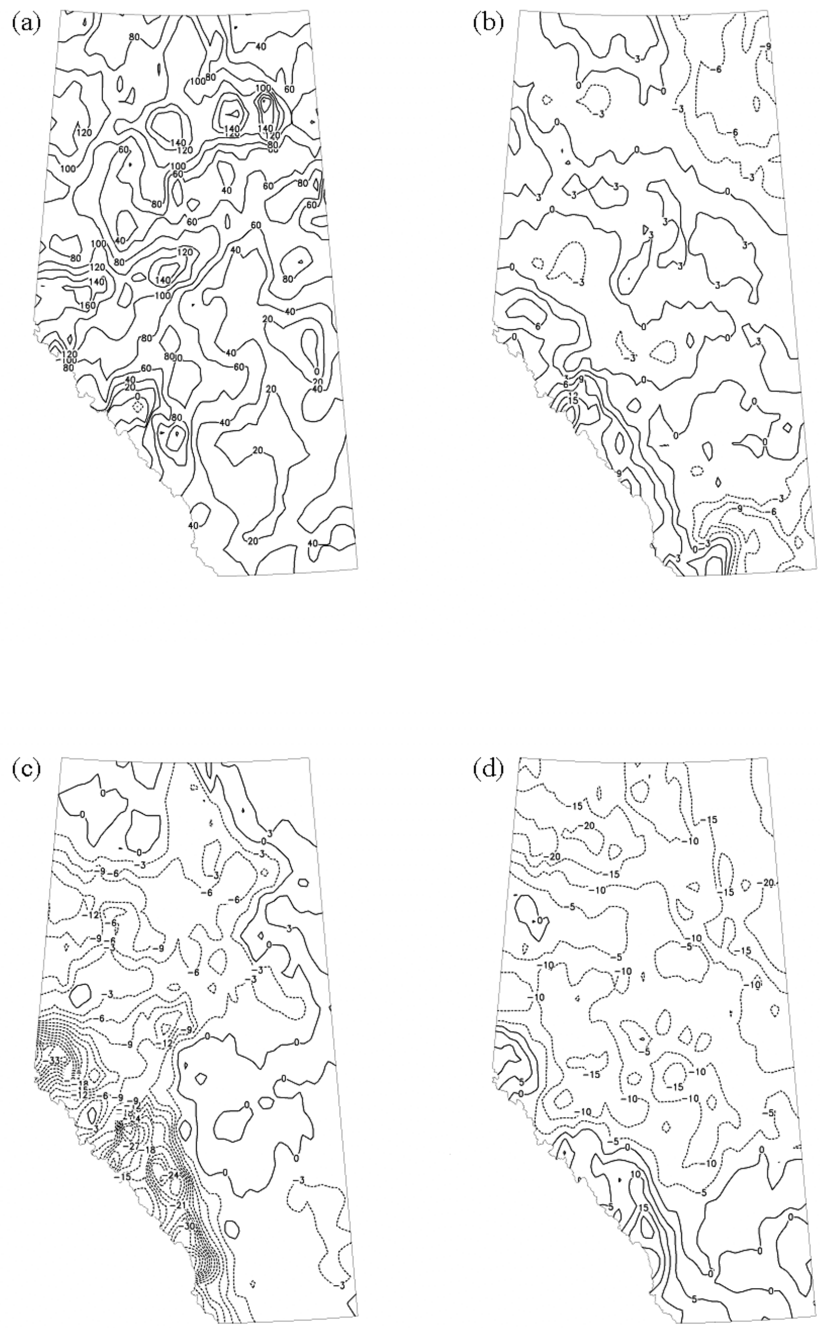

Figure 4. The difference of the recent 30-year normal (1973-2002) minus the 1913-1942 normal for six agroclimatic parameters. (a) May-August precipitation [Unit: mm], (b) SGS [unit: day], (c) EGS [unit: day], (d) LSF [unit: day], (e) FFF [unit: day], and (f) ACHU.

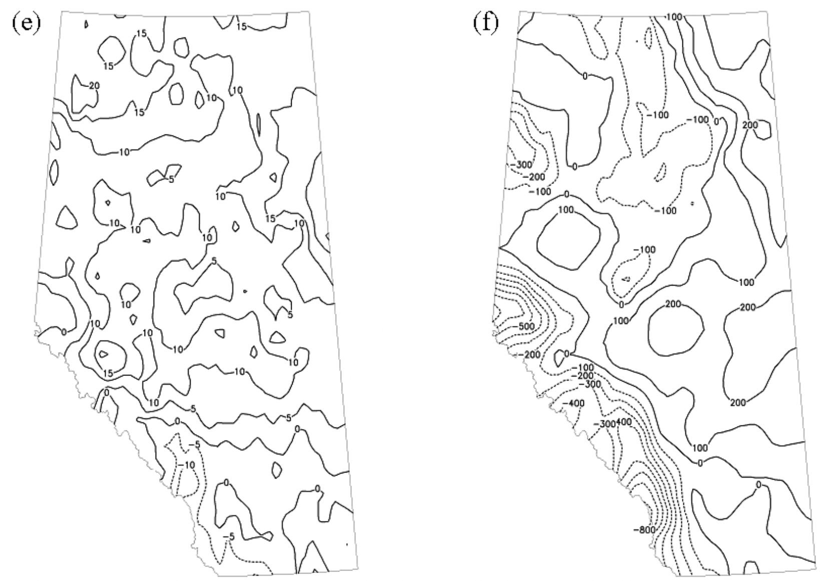

Figure 4. Continued

from region to region. The climate change over time in Alberta also differs from place to place. Fig. 4 shows the difference between the recent 30-year normal (1973-2002) and the 30-year normal of 60 years earlier (1913-1942) for six agroclimatic parameters. The results in this figure are based on the SLC data. The information given in the plots for the Canadian Rockies and the northern-most areas of Alberta is not as reliable as that of the remaining regions because of very sparse station observations. Fig. 4(a) indicates an increase in the May-August precipitation of 40-120 mm over PL and BT. The change over other agriculture areas is about 20-60 mm. In general, the northern part of the province had a larger increase in precipitation than southern Alberta. The changes in the start, end, and length of the growing season were also not uniform. Fig. 4(b) shows the change in the SGS and appears to support a northwest-southeast-oriented pattern. The most remarkable change occurred over the southeast corner of Alberta where the SGS is 3-9 days earlier now than it was 60 years ago. Part of the PL and BT ecoregions has an even later SGS but only by at most three days. This finding may be inaccurate due to the SGS being defined by using the daily mean temperature. The EGS in the PL region (Fig. 4(c)) was noticeably earlier (3-9 days) than it was 60 years ago. The southeast corner also has an earlier EGS, but the difference is small. As a result, the LGS (not shown in the figure) became 3-9 days longer than it was 60 years ago in the southeast corner of the province and 0-3 days longer in part of the BT and AP, while in the PL region, the LGS was shorter by 3-12 days. Although the SGS, EGS and LGS do not have a long-term linear trend from 1901 to 2002, the 30-year climatology has experienced some changes during the last 60 years. An earlier LSF (Fig. 4(d)), a later FFF (Fig. 4(e)) and a longer FFP (not shown in the figure) occurred all over the Alberta except in the southeast corner. The change shows a north-south gradient pattern. In the northern agricultural regions, the LSF was earlier by 10-15 days, and the FFF was later by about 10 days from 1973-2002 compared to 60 years ago. As a result, the FFP was longer by about 20 days in most of the agricultural regions, but in the southeast corner, the FFP did not significantly change. The ACHU (Fig. 4(f)) has increased most over the BT and AP ecoregions by an amount of 100-200, yet, almost no increase occurred in southern Alberta, and a decrease occurred in part of the PL ecoregion. The GDD's 30-year normal (not shown in the figure) has a similar spatial pattern to that of the ACHU.

The comparison of the 1973-2002 normal and the 1943-1972 normal is given in Fig. 5. The difference in the May-August precipitation (not shown) has a similar pattern to that shown in Fig. 4(a), but the magnitude is smaller. The SGS (Fig. 5 (a)) was earlier by 3-6 days in almost the entire province, with the greatest difference in the southeast corner and in part of the PL region. The EGS (Fig. 5(b)) occurred later in the Alberta agriculture region by 0-6 days. The EGS was late by 6 days in part of the PL region. The earlier SGS and later EGS resulted in a longer LGS (not shown) in all the agricultural regions in Alberta by 5-10 days. The LSF, FFF and FFP (not shown) have a similar pattern to those in the Fig. 3 but with smaller magnitudes. A larger area of increased ACHU (Fig. 5(d)) has been found compared to that in Fig. 4(f).

The change of the GDD and ACHU in the agricultural regions is important for the farmers, who can now optimally select crop hybrids for a given farmland. For instance, corn hybrids grown for silage in Prairies usually require 2,000 to 2,100 ACHU. Thus, knowing when corn can be grown in the AP ecoregion is important. Fig. 6 shows the regions of the ACHU greater than or equal to 2,000 for the 1913-1942 normal, 1943-1972 normal, and 1973-2002 normal. The area suitable for corn planting has now extended to

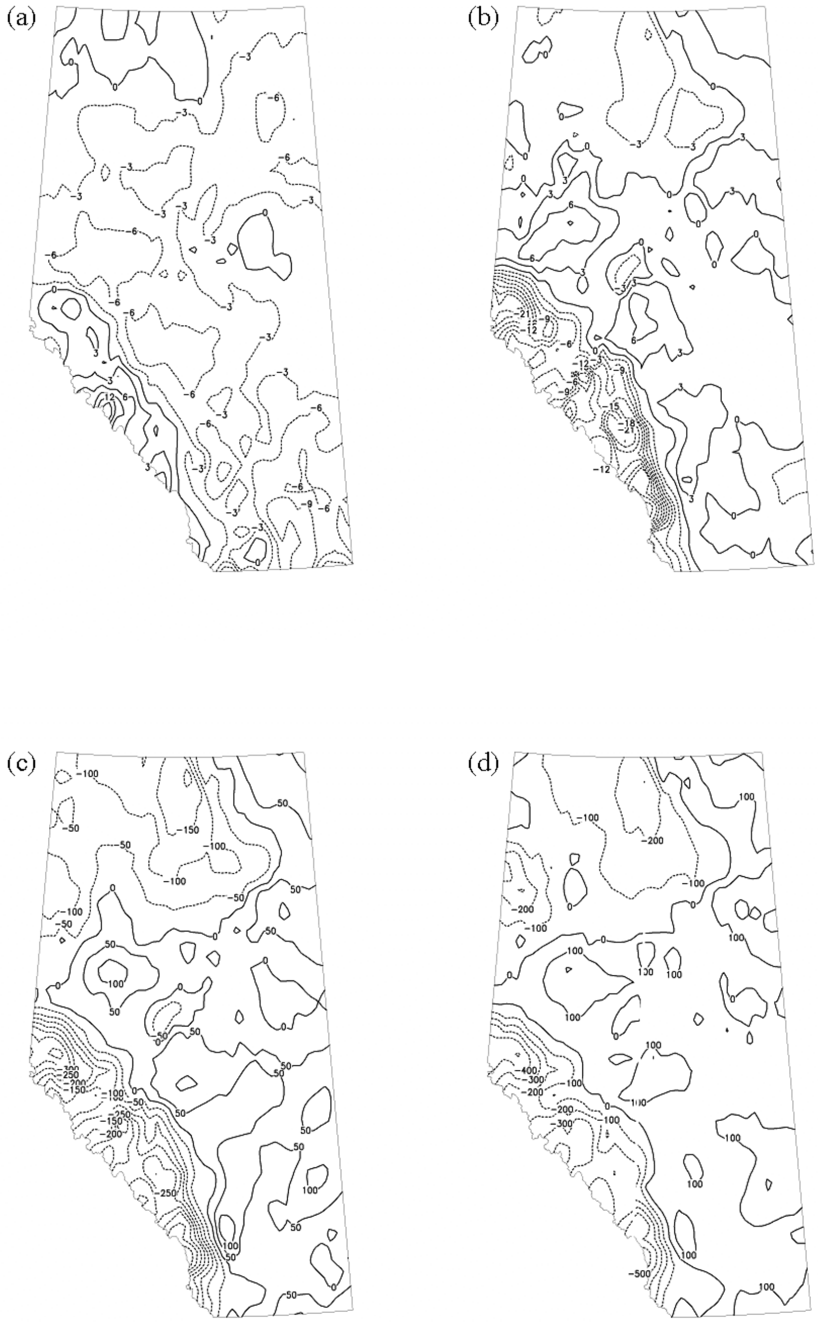

Figure 5. The difference of the recent 30-year normal (1973-2002) minus the 1943-1972 normal for four agroclimatic parameters. (a) SGS [unit: day], (b) EGS [unit: day], (c) GDD, and (d) ACHU.

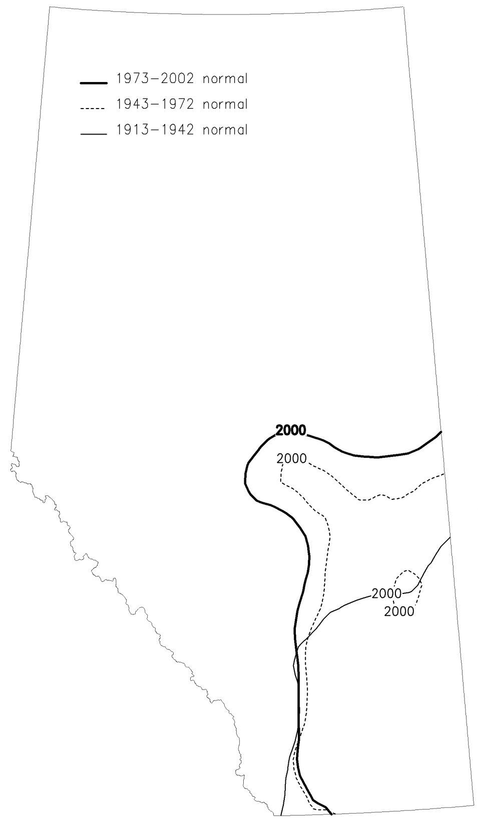

Figure 6. The areas with ACHU ≥ 2,000 for the 1913-1942 normal, 1943-1972 normal and 1973-2002 normal.

the north by about 200-300km compared to the1913-1942 normal, and by about 50-100 km compared to the 1943-1972 normal. This finding indicates that with the warming trend in the climate, the potential growing areas for some warm-season crops such as corn have increased.

5. Conclusions and discussion

A linear trend analysis has been performed on nine agroclimatic parameters in Alberta during the period 1901- 2002 by using highly accurate interpolated daily climate data. The spatial distributions of the changes in the agroclimatic parameters in three time periods (1913-1942, 1943-1972 and 1973-2002) have been investigated. The results have shown an increase in the growing season precipitation all over the province, with a larger amplitude in the northern part of the province.

An earlier LSF, a later FFF and a longer FFP occurred in most of the province. Long-term significant trends in these parameters exist in almost the entire province except in the southeast corner. The asymmetric change of the LSF and the FFF is indicated by the larger slope of the FFF compared to that of the LSF. This finding implies that the postponing of the FFF in the winter is larger than the shift of the LSF to an earlier date in the spring.

However, no significant long-term trends have been found for the start, end, and length of the growing season. This finding might be inaccurate because of the growing season being defined by using the criterion of the daily mean temperature greater than 5^{o}C. If the criterion is changed to the daily mean greater than 0^{o}C or changed to the daily minimum temperature, the conclusions may be different. However, by comparing the 1973-2002 and 1943-1972 normals, an earlier SGS, a later EGS and a longer LGS were detected with the magnitudes of 3-6 days, 0-6 days, and 5-10 days, respectively.

The warming trend in Alberta's climate has also been demonstrated by the increase of the GDD and ACHU in most of the agricultural regions in Alberta. The area suitable for corn planting has extended to the north by about 200-300km since the 1910s, and by about 50-100 km since the 1940s. This extension implies that Alberta farmers now have a larger variety of crops to choose from than were available previously.

A warming trend exists in Alberta, and this trend will affect crop-management decisions such as those involving the seeding date and crop-variety choices. The warming trend is spatially varying. The analysis of regional or local changes of climate is important for decision-making by the agricultural sector. Of course, the possible impact of climate change on agriculture is far more complicated than what the nine agroclimatic parameters can address here. For example, in addition to the change in the mean conditions of the climate, extreme climatic events and the processes of moist variation on land-surface can also cause significant damage to agriculture. The percentile analyses of others and ours on daily precipitation have indicated that the increase of annual and growing season precipitations in Alberta is attributed to low intensity events. Therefore, although we have no hesitation in concluding that the warming climate and increased precipitation benefit Alberta agriculture, more quantitative studies of the agroclimatic parameters based on many important factors, such as soil moisture, relative humidity and evaportranspiration, should be made in the future.

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