Temporal and Spatial Changes of the Agroclimate in Alberta, Canada, from 1901 to 2002

S. S. P. SHEN AND H. YIN

Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, Canada

K. CANNON, A. HOWARD, AND S. CHETNER

Alberta Agriculture, Food and Rural Development, Edmonton, Alberta, Canada

T. R. KARL

National Climatic Data Center, Asheville, North Carolina

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ABSTRACT

This paper analyzes the long-term (1901–2002) temporal trends in the agroclimate of Alberta, Canada, 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 (PCPN), the start of 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), growing degree-days (GDDs), and corn heat units (CHUs). 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. 1) The Alberta PCPN has increased 14% from 1901 to 2002, and the increment is the largest in the north and the northwest of Alberta, then diminishes (or even becomes negative over two small areas) in central and southern Alberta, and finally becomes large again in the southeast corner of the province. 2) No significant long-term trends are found for the SGS, EGS, and LGS. 3) An earlier LSF, a later FFF, and a longer FFP are obvious all over the province. 4) The area with sufficient CHU for corn production, calculated according to the 1973–2002 normal, has extended to the north by about 200–300 km, when compared with the 1913–32 normal, and by about 50–100 km, when compared with the 1943–72 normal; this expansion implies that the potential exists to grow crops and raise livestock in more regions of Alberta than was possible in the past. The annual 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 changes of the agroclimatic parameters imply that Alberta agriculture has benefited from the last century's climate change.

1. Introduction

Alberta is a western province of Canada, bounded by 49°–60°N latitude and 110°–120°W longitude. The Canadian Rockies cut off the southwest corner (Fig. 1). Alberta's area is 0.662 million km^2 and is about 20% larger than that of France. More than one-third of the area is farmland. Environment Canada (1995) reported that Alberta's surface air temperature had gone up and Alberta's winter had become milder. Alberta's daily minimum surface air temperature increased about 1.3°–2.1°C in the period of 1895–1991. The warming climate has been perceived to benefit Alberta agriculture, including the growth of both crops and livestock. Despite these observational results and perceptions, Alberta Agriculture, Food and Rural Development (AAFRD), an Alberta provincial governmental ministry, still needs a quantitative and systematic analysis of the agroclimatic changes in terms of both time and space. Therefore, AAFRD decided to document the details of the Alberta agroclimatic changes and use the information

Corresponding author address: Samuel S. P. Shen, Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, AB T6G 2G1, Canada.
E-mail: shen@ualberta.ca

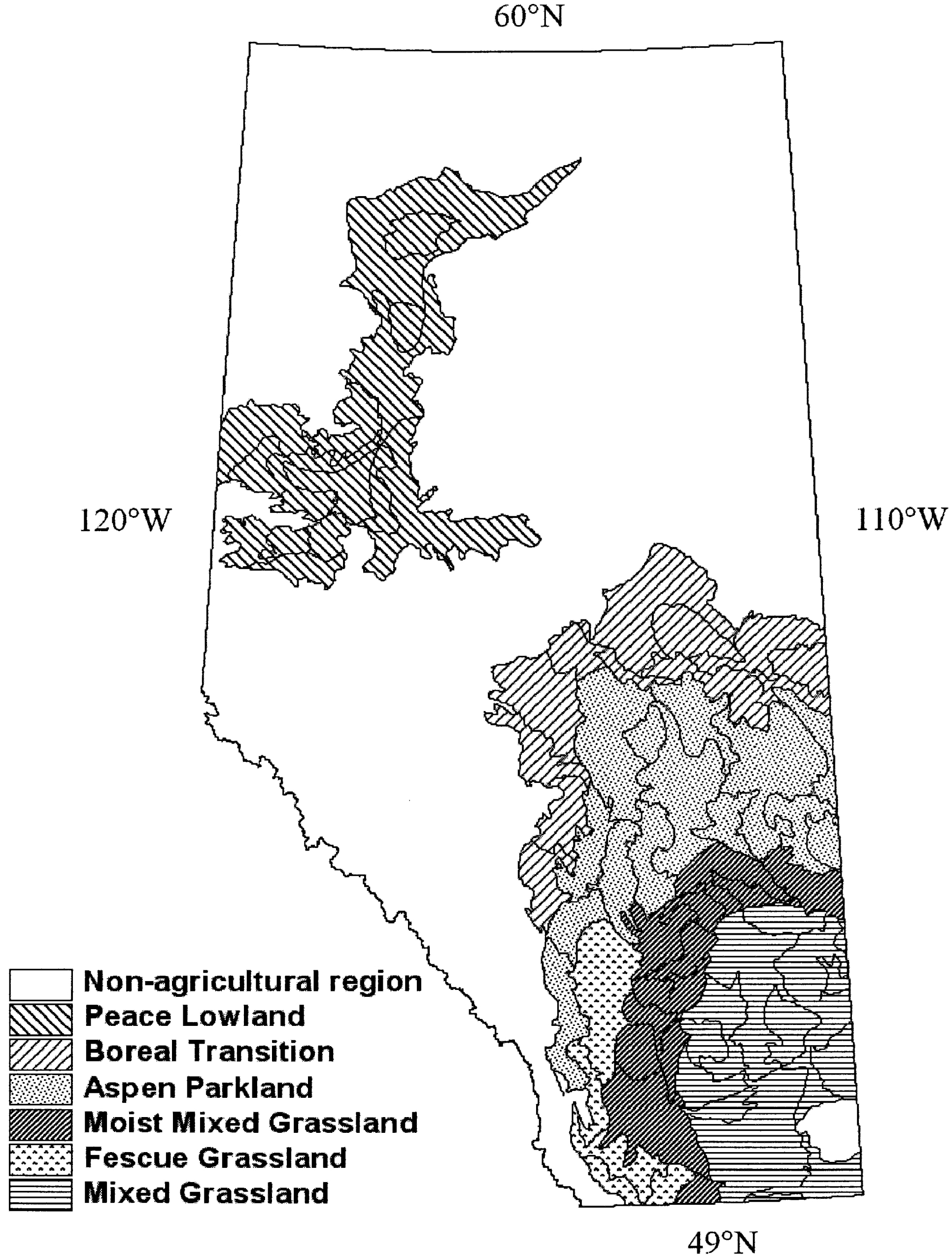

FIG. 1. The province of Alberta and the six ecoregions with extensive agriculture.

to optimally manage the land usage for crops and livestock. The results included in this paper are from the main conclusions of AAFRD's research on agroclimatic change and are important to AAFRD's climate adaptation strategies. Other innovative aspects of this paper are on the following analysis approaches: (a) the variance-retained interpolated daily climate data over ecodistrict polygons were used, in contrast to the data at unevenly distributed stations that were used in other studies (Akinremi et al. 1999; Bootsma 1994; Bootsma et al. 2001; Bonsal et al. 2001); and (b) the area weight was used to calculate the agroclimatic parameters of each ecoregion before the regression analysis.

The agricultural regions, as shown in Fig. 1, are the southeast prairie land and the western Peace River Lowland and have an area of 0.256 million km^2. The rest of Alberta is either covered with forest or its elevation is too high for crop cultivation. Currently, the major Alberta crops are spring wheat, barley, canola, and alfalfa. The most important livestock are beef cattle. Because agriculture affects more people than any other industry or business, the agricultural industry is one of the most important industries 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 AAFRD 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 1 January 1901 to 31 December 2002. Thus, the results in this paper are for the agroclimatic change during this period. The conclusions from this study will provide not only useful information for Albertans for their sustainable agricultural development, but will also provide a method for other people in the world to use to investigate similar problems involving agroclimatic changes.

The agroclimatic changes in this paper are investigated according to six ecoregions with extensive agriculture, Alberta as a whole, and nine agroclimatic parameters. [The *Agroclimatic Atlas of Alberta, 1971–2000* by Chetner and the Agroclimate Atlas Working Group (2003) and its associated Web site include the information on the ecoregions and 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 (GDDs), and the corn heat units (CHUs). (The acronyms for agroclimatic parameters, polygons, and ecoregions that are used in this paper are summarized in Table 1.)The research on these agroclimate parameters has provided important information to AAFRD, and this paper will present scientific evidence of the following results. 1) Alberta's May–August precipitation increased 14% during the period of 1901–2002; the increment is the largest in the north and the northwest portion of Alberta, then diminishes (or even becomes negative over two small areas) in central and southern Alberta, and finally becomes large again in the southeast corner of the province. 2) No significant long-term trends were found in the SGS, EGS, and LGS. 3) An earlier LSF, a later FFF, and a longer FFP were evident provincewide. 4) The area with sufficient CHU for corn production, calculated from the 1973–2002 normal, has extended to the north by about 200–300 km relative to the 1913–42 normal, and by about 50–100 km relative to the 1943–72 normal; this expansion implies larger areas in Alberta for growing crops and raising livestock than were available in the past. Therefore, the last century's climate change has been beneficial to Alberta agriculture.

TABLE 1. Acronyms of agroclimatic parameters, polygons, and ecoregions (ID is identifier).

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	Calendar day
FFF	First fall frost	Calendar day
FFP	Frost-free period	Days
FG	Fescue grassland	Ecoregion
GDD	Growing degree-day	Degree Celsius
GSP	Growing season precipitation	Millimeter per day
LGS	Length of growing season	Days
LSF	Last spring frost	Calendar day
MG	Mixed grassland	Ecoregion
MMG	Moist mixed grassland	Ecoregion
PL	Peace Lowland	Ecoregion
SGS	Start of growing season	Calendar day
SLC	Soil landscapes of Canada	Polygon ID

This paper focuses on the change of Alberta's agroclimate and does not intend to review the changes in the usual climatic parameters, such as maximum daily temperature and monthly precipitation. The latter have been addressed in many studies, such as those by Bonsal et al. (2001), Environment Canada (1995), Gan (1995), Gullet and Skinner (1992), and Zhang et al. (2000, 2001), and the references therein. However, the parameters under the present investigation are related to those climatic parameters, and, hence, our results are compared with the existing results from climate change studies when applicable. The remainder of this paper is arranged as follows. Section 2 describes the dataset used to derive the agroclimatic parameters. Section 3 presents the definitions of the agroclimatic parameters and the procedures for calculating their trends. Section 4 presents the results for the temporal and spatial changes of the parameters. Section 5 provides conclusions and a discussion.

2. Data

Some soil-quality models, such as the Erosion/Productivity Impact Calculator, need continuous daily climate data at a given resolution as their input. Irregular, and often discontinuous, observations of weather make it necessary to interpolate the point-based weather station data onto a regular grid or over polygons. Realistic simulations crucially depend not only on the climate mean but also on the climate variations. The latter are more important, but are often ignored in many spatial interpolation schemes 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 out and smooth. Precipitation frequency is another problem because 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 developed a hybrid interpolation scheme that uses a reference station to preserve the variance of the interpolated field and still maintain the monthly mean. Using this method and the raw point-based observed weather station data provided by Environment Canada, the U.S. National Climatic Data Center, and Agriculture and Agri-Food Canada, AAFRD produced a master set of daily climate data with different resolutions—1) 10 km $\times$ 10 km regular grid, 2) 6900 townships, 3) 894 soil landscapes of Canada (SLC) polygons, and 4) 149 ecodistrict polygons (EDPs) (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. An updated AAFRD master dataset includes the daily data from 1 January 1901 to 31 December 2002. This paper uses not only the data over EDP and SLC polygons to derive the main results, but also the station data for result checking. The Canadian station data are also checked by comparison with the data from the U.S. National Climatic Data Center's Global Daily Climatology Network dataset.

All of the agroclimatic parameters, except the May–August precipitation, analyzed in this paper were derived from the daily maximum temperature, and daily minimum temperature in the EDP master dataset. This dataset has several advantages. 1) It is the most complete long-term daily dataset for Alberta. 2) It reflects the daily weather variability 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 ecoregions 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. Thus, using the EDP data is convenient to calculate the agroclimatic properties for each ecoregion.

Therefore, this study features the use of the daily interpolated data with complete coverage, as compared with the data used in either the station-based studies or the studies based on interpolated data with too little variance. Of course, caution is always required when using the interpolated data in the data-sparse regions because of the possibility of large errors.

The accuracy of the master dataset was investigated when the interpolation was made. Five stations at Lethbridge, Lacombe, Edmonton, Beaverlodge, and High Level, 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 (for the 1961–97 data): daily maximum temperature of 1.4°–3.2°C, daily minimum temperature of 1.8°–3.2°C, and daily precipitation of 1.8–2.8 mm. Many more cross-validation experiments were made and showed that, for daily temperature and precipitation, the hybrid method had smaller errors than the interpolation methods of a simple nearest-station assignment, inverse-distance-square weighting, and kriging. Fortunately, the errors are not biased toward one side (see Table 2 of Shen et al. 2001), but the size of the precipitation error still needs attention, particularly for the northern regions during the first half of the last century. Figure 2 shows the monthly series of the total number of temperature and precipitation stations in Alberta from January 1901 to December 2002. The seasonal fluctuations are a result of the fact that some stations were operating only in the growing season. Figure 3 shows the distribution of the precipitation stations in four periods: 1901–12, 1913–42, 1943–72, and 1973–2002. Only four stations (Fort Chipewyan, two stations in Fort Vermillion, and Fort McMurray) were north of 56°N before 1912, and they had low elevations and, hence, did not measure the topographic precipitation over the mountain (i.e., Caribou Mountains, Buffalo Hills, Clear Hills, Birch Mountains) and lake (i.e., Lake Athabasca and Lake Claire) regions. Thus, the original 1901–2002 master dataset has a low precipitation bias in the first part of the last century in northern Alberta and, hence, would lead to an unrealistically large trend for the May–August precipitation. To overcome this particular problem and to accurately access the May–August precipitation trend in northern Alberta, the 1961–90 May–August precipitation normals and the daily precipitation anomalies were interpolated separately. The 1961–90 normals were computed for the stations satisfying the following two conditions:

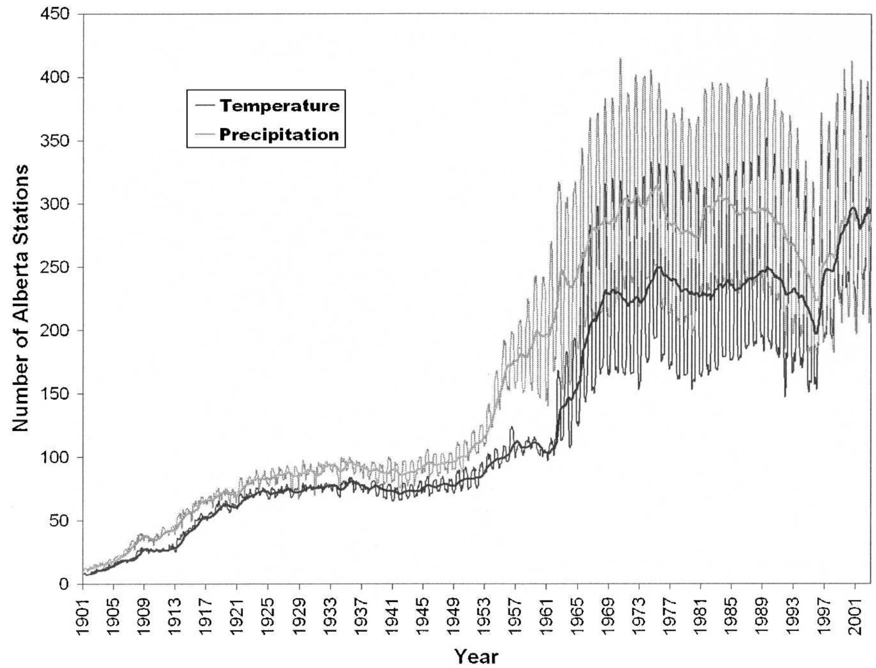

FIG. 2. The monthly number of Alberta stations used in the data interpolation. The smoothed curves are obtained from the 12-point moving averages.

1) having data for at least 98 days among the 123 days (from 1 May to 31 August), and
2) having at least 21 yr that satisfy condition 1.

Two hundred eighteen stations in Alberta during 1961–90 satisfied the above two conditions, and their distribution is shown in Fig. 4. These stations covered Alberta reasonably well, except in some areas in the Canadian Rockies, and, particularly, they covered the mountain and lake regions in the north. The May–August precipitation normals were interpolated onto all of the stations by using the nearest-station assignment method. The daily station anomalies were computed according to these interpolated normals. Then, normals and anomalies were interpolated onto the 10 km × 10 km grid by the nearest-station assignment method and the inverse-distance method, respectively. On each grid, the normal and the daily anomalies were added together, and these sums were further added together for the period from 1 May to 31 August. The EDP May–August precipitation was assigned the average of the values of the grid points inside the polygon. The daily data that are produced from the above interpolation, although good for the May–August precipitation, have much smaller than realistic variance and are not suitable for studies of climate extremes, such as precipitation intensity.

3. Agroclimatic parameters and analysis method

Although most materials contained in this section are available in the literature (e.g., Bootsma et al. 2001; Chetner and the Agroclimate Atlas Working Group 2003; Dzikowski and Heywood 1989), they are briefly summarized here to facilitate a systematic study of Alberta's agroclimatic changes.

a. *Summary of nine agroclimatic parameters*

Alberta is divided into 10 ecoregions, but only 6 have extensive agriculture regions: 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 is the first day of a year for which five consecutive days have a mean temperature above 5°C. The EGS is 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, an abnormally warm week at the end of March started the growing season about a month earlier than normal (not shown in the figures of

FIG. 3. Distributions of the Alberta precipitation stations in the periods of 1901–12, 1913–42, 1943–72, and 1973–2002.

this paper), but a cold event occurred at the beginning of June and put the LSF later than normal. The LGS is the number of days between the SGS and the EGS:

$$\mathrm{LGS} = \mathrm{EGS} - \mathrm{SGS} + 1.$$

The means (standard deviations) of the SGS, EGS, and LGS for the Alberta agricultural region that is the union of the six ecoregions (AR) in 1961–90 are 108 (9.78) (calendar day of a year, i.e., 18 April if not a leap year), 263 (10.80) (calendar day of a year, i.e., 20 Sep-

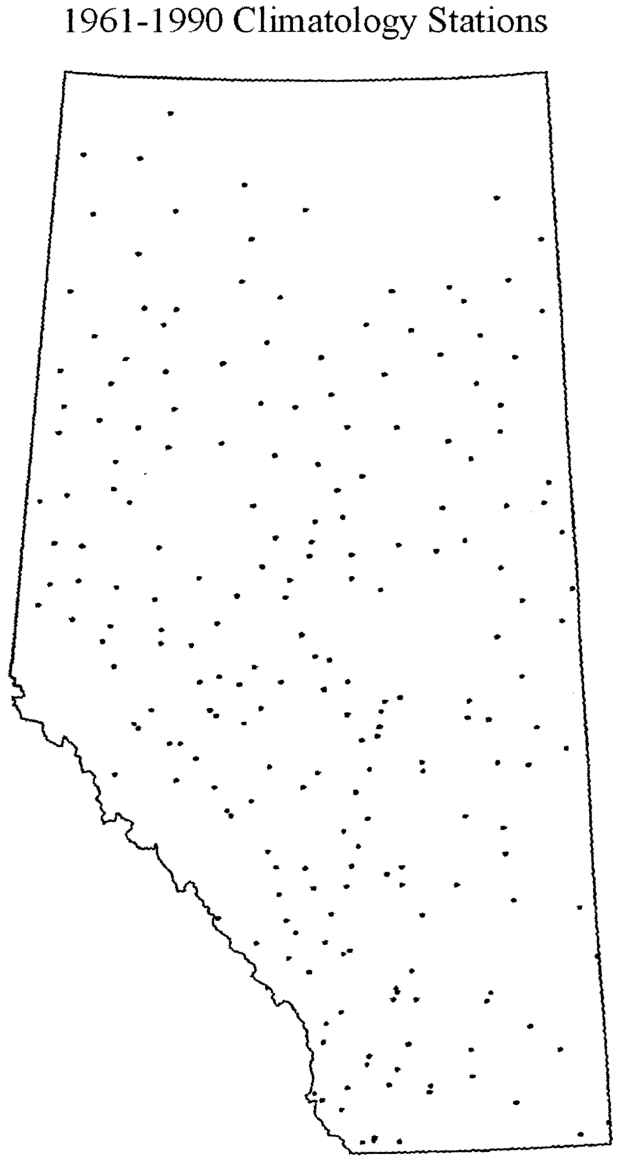

FIG. 4. Distribution of the Alberta precipitation stations whose 1961–90 May–Aug precipitation normals were computed.

tember if not a leap year), and 156 (14.99) (days), respectively.

2) Frost-free period

The LSF day is defined as the last date in a year on or before 15 July on which the daily minimum temperature $T_{min} \leq 0°C$. The FFF day is defined as the first date in a year on or after 16 July on which $T_{min} \leq 0°C$. 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 damage. The FFP is the number of days between the LSF and the FFF:

$$\mathrm{FFP} = \mathrm{FFF} - \mathrm{LSF} + 1.$$

The means (standard deviations) of the LSF, FFF, and FFP for the Alberta AR region in 1961–90 are 140 (7.36) (calendar day of a year, i.e., 20 May if not a leap year), 257 (8.66) (calendar day of a year, i.e., 14 September if not a leap year), and 118 (11.39) (days), respectively. The LGS is, in general, longer than the FFP. For genetically improved seeds, the growing season may be even longer and can start on the first calendar 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 genetically engineered species can sustain lower temperatures and grow even when the daily mean temperature is between 0° 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 are computed from the mean daily air temperature (T_{mean}) by using the formula

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

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

4) Corn heat unit

The growth of warm-season crops like corn and soybeans depends on the daily minimum and maximum temperatures in a more refined way than GDD and is normally indicated by the CHU. Corn growth is slow at a low temperature and increases as the temperature rises until it reaches a threshold temperature beyond which the growth again becomes slow. 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 the temperature is below 4.4°C or during the day when the 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 because the nighttime temperature seldom exceeds

25°C. The daily CHU is the average of the nighttime and daytime CHU, calculated by the formulas below:

$$\mathrm{CHU} = (\mathrm{CHU}_X + \mathrm{CHU}_Y)/2,$$

where the nighttime CHU is

$$\mathrm{CHU}_X = 1.8(T_{\min} - 4.4),$$

and the daytime CHU is

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

In the above, $\mathrm{CHU}_X = 0$ if $T_{\min} < 4.4$°C, and $\mathrm{CHU}_Y = 0$ if $T_{\max} < 10.0$°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 after 16 July 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 province of Alberta. Because both the EDPs and the ecoregions are irregular polygons, and their areas vary, the use of a simple average is inappropriate. Instead, the area-weighted average is used. 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 ith EDP, and R_i is the value of the parameter R for this 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 the nine agroclimatic parameters are studied by using the linear regression method. The linear correlation coefficients and significance levels are computed for each agroclimatic parameter to detect if significant linear temporal trends exist. Kendall's tau significance is used to examine the hypothesis that the slope is different from zero. This nonparametric method does not require the normality assumption of the slope, because the Student's t test does and has been used in climate research for trend detection (Daniel 1990; Zhang et al. 2000).

The spatial distributions of three 30-yr mean conditions for the agroclimatic parameters in Alberta are plotted. The 30-yr periods are 1913–42, 1943–72, and 1973–2002. Their differences are analyzed to show the changes among the three periods. Also, the spatial distribution of the 102-yr 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 (units: year), and s is the slope of the temporal trend of each agroclimatic parameter. The agricultural ecoregions are denoted by PL, BT, AP, MMG, FG, and MG, and are ordered according to their locations from the northwest to the southeast of Alberta (see Fig. 1 for the locations of the ecoregions and Table 1 for their acronyms). 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 boldface in Table 2; otherwise, the r and s values are in plain text. With different P values, the significant correlation coefficients are marked by a superscript "b" when $P \leq 0.01$, by a superscript "a" when $0.01 < P \leq 0.05$, and a superscript "c" when $0.05 < P \leq 0.10$.

The results show that the precipitation from May to August, usually included in the growing season defined in section 3a(1), increased 8% (18 mm) during the period of 1901–2002 (Fig. 5a) over the AR, and that this increase is significant at the 10% significance level (see Tables 2 and 3). However, the increment is nonuniform and appears to have a pattern; the increment is the largest in the north and the northwest of Alberta, then the increment diminishes in central and southern Alberta (i.e., the AP and MMG regions), finally, the increment becomes prominent again in the southeast corner of the province (see Fig. 6a). This pattern transition seems to follow that of the 30-yr normals, except in the northeast and the northwest of Alberta (Chetner and the Agroclimate Atlas Working Group 2003; Dzikowski and Heywood 1989). Two small areas in

TABLE 2. Correlation coefficients (r) between the annual agroclimatic parameters and time from 1901 to 2002, and slopes (s) of the trend for the nine annual agroclimatic parameters. 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 boldface.

Region		PCPN (May–Aug)	SGS	EGS	LGS	LSF	FFF	FFP	GDD	ACHU
PL	r	**0.15**[a]	−0.09	−0.05	0.01	**−0.38**[b]	**0.36**[b]	**0.46**[b]	−0.04	**0.12**[c]
	s	**0.52**	−0.04	−0.03	0.01	**−0.20**	**0.20**	**0.40**	−0.28	**1.47**
BT	r	0.06	0.03	−0.01	−0.01	**−0.24**[b]	**0.35**[b]	**0.38**[b]	**0.18**[b]	**0.25**[b]
	s	0.13	0.01	0.00	−0.01	**−0.12**	**0.17**	**0.29**	**1.09**	**3.03**
AP	r	0.05	0.02	−0.01	−0.03	**−0.23**[b]	**0.32**[b]	**0.37**[b]	**0.23**[b]	**0.26**[b]
	s	0.04	0.02	0.00	−0.02	**−0.11**	**0.16**	**0.27**	**1.49**	**2.99**
MMG	r	0.06	0.00	0.00	0.02	**−0.14** [a]	**0.19**[b]	**0.22**[b]	**0.19**[b]	**0.20**[b]
	s	0.00	−0.02	−0.01	0.01	**−0.07**	**0.08**	**0.15**	**1.56**	**2.53**
FG	r	0.07	0.03	−0.07	−0.08	−0.03	0.02	0.06	−0.07	−0.06
	s	0.09	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	0.11	−0.02	−0.03	−0.01	−0.02	0.04	0.06	0.75	0.97
AR	r	**0.12**[c]	0.00	−0.02	0.00	**−0.25**[b]	**0.33**[b]	**0.36**[b]	**0.11**[c]	**0.18**[b]
	s	**0.18**	−0.01	−0.01	0.00	**−0.10**	**0.13**	**0.23**	**0.76**	**2.02**
AB	r	**0.18**[b]	−0.02	−0.11	−0.06	**−0.31**[b]	**0.37**[b]	**0.43**[b]	−0.09	0.06
	s	**0.32**	−0.01	−0.05	−0.04	**−0.13**	**0.16**	**0.29**	−0.40	0.62

[a] Significance level: $0.01 < P \leq 0.05$.
[b] Significance level: $0.00 < P \leq 0.01$.
[c] Significance level: $0.05 < P \leq 0.10$.

central and southern Alberta even experienced a decrease of 30 mm. The PL region's May–August precipitation increased 26% (53 mm) over the period of 1901–2002, and the increment is significant at the 5% significance level. The MMG region experienced zero increment. Thus, the May–August precipitation increase over the agricultural region is attributed to the increase over the northwest and southeast areas. Similar analysis of Fig. 6a implies that the significant increment of the May–August precipitation over the entire province is mainly attributable to the nonagricultural regions in the north and west and the PL ecoregion. 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 of British Columbia, and found no significant trends in the Canadian Prairies, especially in southern Alberta and the eastern-neighboring province of Saskatchewan. The increase of the May–August precipitation is attributable mainly to the increasing number of events of low-intensity precipitation, as Akinremi et al. (1999), Zhang et al. (2001), and Kunkel (2003) concluded. Our percentile analysis also shows no significant increase of the events of the 90th, 95th, and 99th percentile precipitation from 1901 to 2002 over both the AR and all 10 ecoregions of the entire province (AB). (The redundant results are not shown in this paper.) The Alberta drought records show no discernable increase signal of drought events or intensity in the twentieth century (Shen et al. 2003). Karl and Knight (1998) identified an increase in the twentieth-century precipitation over the United States and attributed the increase to high-intensity events. Thus, the available results from others support our finding of different patterns of climate change in terms of precipitation in the United States and Canada during the last century.

The above conclusions were first derived from the daily precipitation data on EDPs. To further verify these results, the same calculation was made by using finer-resolution data, the data on SLC polygons. The May–August precipitation trend from 1901 to 2002 for every SLC polygon was computed and tested for significance. Figure 6a depicts the contour plot of the trend.

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 of 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

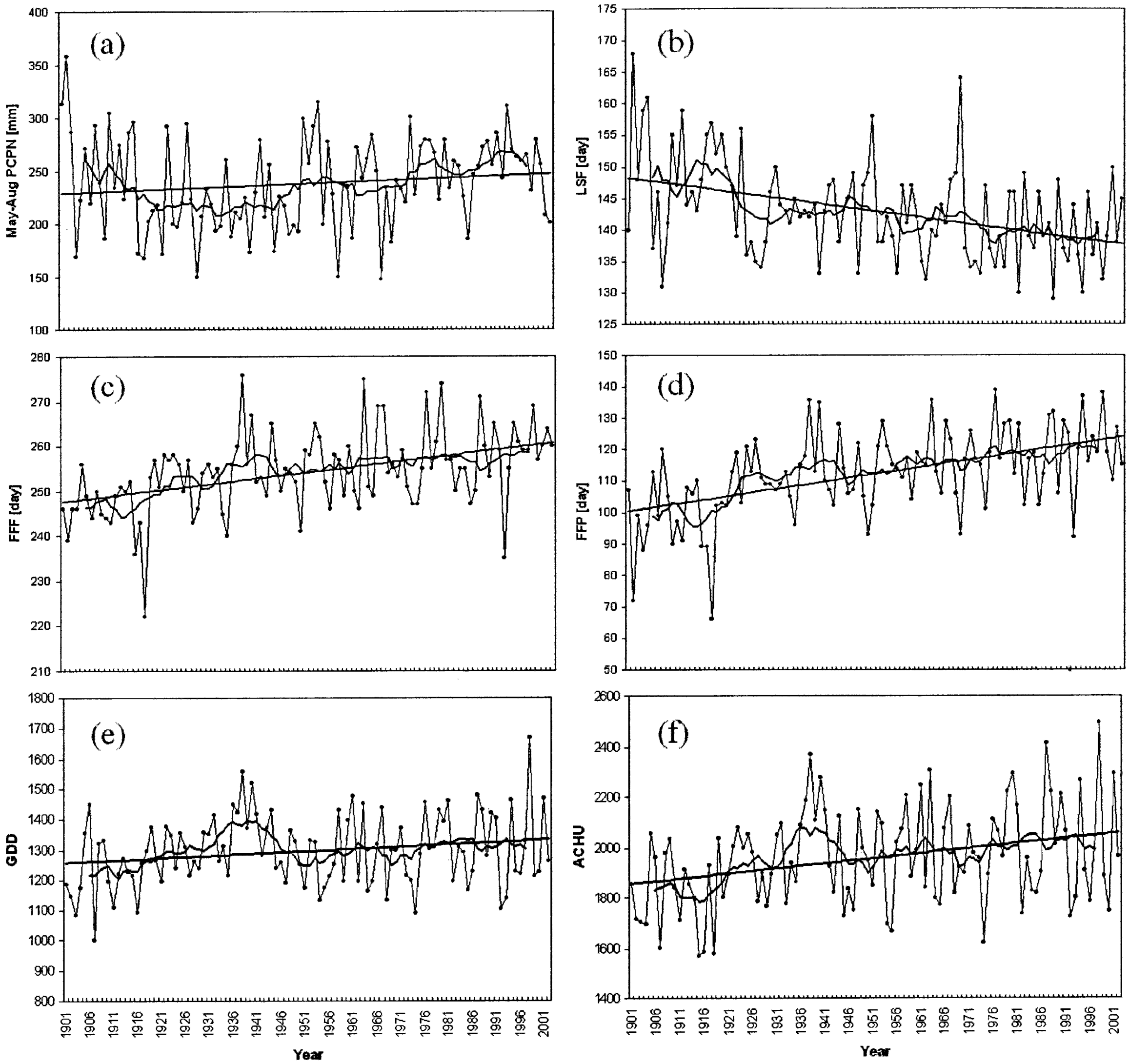

FIG. 5. Annual time series (thin curve with dots), 11-yr running mean (thick curve), and linear regression line (straight line): (a) May–Aug precipitation (units: mm), (b) LSF (units: day), (c) FFF (units: day), (d) FFP (units: day), (e) accumulated GDD in the growing season, and (f) ACHU.

clearly shown in Fig. 6b. This figure shows that the FFP has increased over the entire province from 1901 to 2002. According to the linear regression from 1901 to 2002, the LSF in the PL ecoregion was 20 days earlier in 2002 relative to that in 1901, 12 days earlier in the BT ecoregion, 11 days earlier in the AP ecoregion, 7 days earlier in the MMG ecoregion, 10 days earlier in AR, and 13 days earlier in 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, and 14 days in the PL, BT, AP, and MMG ecoregions, respectively, 24 days in the AR, and 30 days in the AB (the spatial distribution of the trends is shown in Fig. 6b). The earlier LSF implies that consecutive warm days in the spring occur earlier and, hence, allow spring melts to occur earlier too. These conditions raise soil temperature earlier for seed germination and, thus, reduce the frost risk for spring crops. The delay of consecutive cold days in the fall improves the chances for crops to mature to a higher-quality yield. The percentage change of the FFF from 1901 to 2002 is the largest over PL (8.5%) (see Table 3). The absolute value of the FFF slope is comparable to that of the LSF for most ecoregions. However, our provincial average suggests a slightly larger FFF increment than a LSF decrease, and the difference between the FFF increase and the LSF de-

TABLE 3. The total changes (t) and the percentage changes (p) from 1901 to 2002 of the nine annual agroclimatic parameters (the percentage change is with respect to the linear fitted value in 1901).

Region		PCPN (May–Aug)	SGS	EGS	LGS	LSF	FFF	FFP	GDD	ACHU
PL	t	**53.0**	−4.1	−3.1	1.0	**−20.4**	**20.4**	**40.8**	−28.6	**149.9**
	p (%)	**25.5**	−3.5	−1.2	0.7	**−13.1**	**8.5**	**48.8**	−2.5	**9.1**
BT	t	13.3	1.0	0.0	−1.0	**−12.2**	**17.3**	**29.6**	**111.2**	**309.1**
	p (%)	4.8	0.9	0.0	−0.6	**−8.0**	**7.1**	**32.3**	**9.7**	**18.5**
AP	t	4.1	2.0	0.0	−2.0	**−11.2**	**16.3**	**27.6**	**152.0**	**305.0**
	p (%)	1.6	1.9	0.0	−1.3	**−7.5**	**6.6**	**28.4**	**12.8**	**17.3**
MMG	t	0.0	−2.0	−1.0	1.0	**−7.1**	**8.2**	**15.3**	**159.1**	**258.1**
	p (%)	0.0	−1.9	−0.4	0.6	**−4.9**	**3.2**	**13.7**	**12.1**	**13.1**
FG	t	9.2	1.0	−5.1	−6.1	−2.0	0.0	2.0	−52.0	−20.4
	p (%)	3.7	1.0	−1.9	−3.6	−1.4	0.0	1.8	−4.0	−1.1
MG	t	11.2	−2.0	−3.1	−1.1	−2.0	4.1	6.1	76.5	98.9
	p (%)	6.3	−2.0	−1.1	−0.6	−1.4	1.6	5.0	5.0	4.3
AR	t	**18.4**	−1.0	−1.0	0.0	**−10.2**	**13.3**	**23.5**	**77.5**	**206.0**
	p (%)	**8.0**	−0.9	−0.4	0.0	**−6.9**	**5.4**	**23.4**	**6.2**	**11.1**
AB	t	**32.6**	−1.0	−5.1	−4.1	**−13.3**	**16.3**	**29.6**	−40.8	63.2
	p (%)	**13.6**	−0.9	−1.9	−2.7	**−8.6**	**6.7**	**33.5**	−3.5	3.7

crease is 3 days (see Tables 2 and 3). It was noticed that Bonsal et al. (2001) found a slightly larger decrease of LSF than the increase of FFF for most of Canada, based upon an analysis of data from 210 high-quality stations in the periods of 1900–98 and 1951–98. Because of the spatial inhomogeneity of the LSF and FFF changes discerned in Table 3, the difference between the conclusions of Bonsal et al. (2001) and our research is insignificant considering the noise level of the current data. Nonetheless, this difference will be worth investigating further when more accurate datasets become available.

The GDD and ACHU are two types of easy-to-use energy terms in agroclimatology that relate plant growth to temperature. The more energy that is available, the more likely the plant will be to reach maturity, and the more hybrids of the plant that can be grown in an area. Table 2 shows significant positive trends (at the 1% significance level) in the GDD and ACHU in three ecoregions (BT, AP, and MMG), and the increments over the period of 1901–2002 are around or greater than 10%. The largest percentage change in the GDD is over AP (13%), and in the CHU is over BT (19%). These increases are consistent with the increment of the plant hardiness subzone index for most of Alberta and make growing more varieties of crop species possible (McKenney et al. 2001).

Figure 5 shows the annual time series of the six agroclimatic parameters with significant linear trends in the AR. The 11-yr running means are also shown. The positive trend of the May–August precipitation is a result of the steady increase of precipitation after the 1920s. The variance of the temporal precipitation change over time decreased during 1973–2002. To check the moisture supply as a result of precipitation for the entire crop-growing period, the total growing season precipitation (GSP) (millimeters per day) was calculated. The GSP follows a 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 an earlier date before the 1940s and between the1970s and 1980s, together with the shift of the FFF to a later date in the same periods, cause the increase of the FFP in the corresponding period. This increase indicates lower risks for frost damage to crops in Alberta, if crops are planted at the normal time. 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 manifested in Alberta by a rapid increase of the GDD and ACHU from 1901 to the 1940s, but the increase rate is smaller after the 1970s. The LSF usually occurred in May during the decade of the 1960s. However, in 1969, the minimum temperature fell below zero almost all over the province on around 13 June, and this resulted in an exceptionally late LSF in that year (see Fig. 5b). Another exceptional case involves the FFF in 1918. Observations from the northern and central part of Alberta indicated a below-zero minimum temperature on around 24 July, which was almost 1 month earlier than usual and caused the earlier FFF in that year. From 21 to 23 July 1992 (see Fig. 5c), the minimum temperature

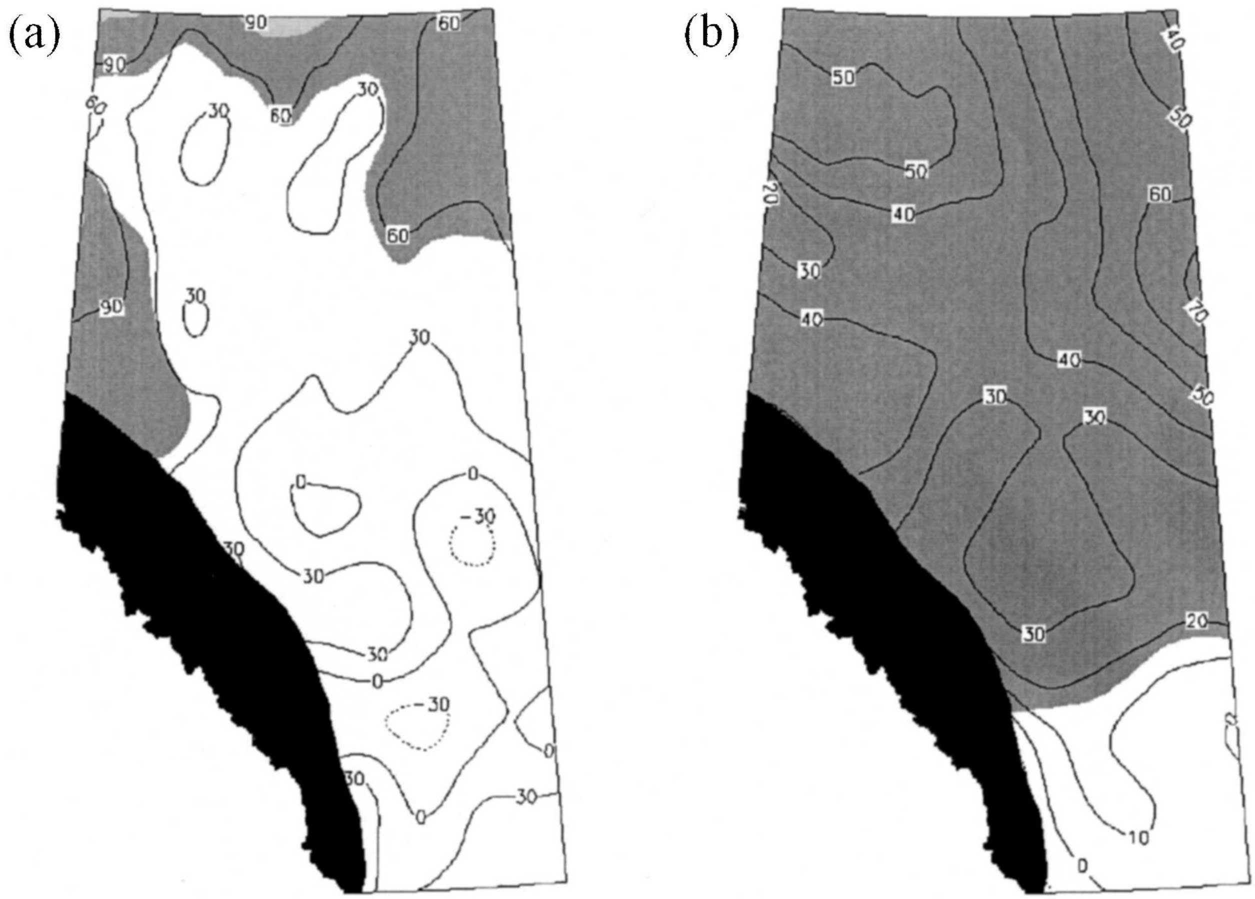

FIG. 6. Spatial distribution of the temporal trends from linear regression: (a) May–Aug precipitation [units: mm (102 yr)$^{-1}$], (b) FFP [units: day (102 yr)$^{-1}$]. The shaded regions are where significant trends exist at the 5% significance level. The Rocky Mountain areas are blacked out because of insufficient station data and large gradients of trends, and, hence, the possibility of very large errors.

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 a result of the natural variance, while the results before the1910s may be inaccurate because of too few observations.

Alberta has relatively large geographical variability across the province. From the subarctic region in the north to the prairie grassland in the south, and from the high elevation mountains in the west to the flat areas in the east, the Alberta climate varies considerably from region to region. The climate change over time in Alberta also differs from place to place. Figure 7 shows the difference between the recent 30-yr normal (1973–2002) and the 30-yr normal of 60 yr earlier (1913–42) for six agroclimatic parameters (see Fig. 3 for station distributions during the two periods). The results in this figure are based on the data over the SLC polygons. The information given in the plots over the northernmost areas of Alberta is not as reliable as that for the agricultural regions because of very sparse station observations. Figure 7a indicates an increase in the May–August precipitation of 40–60 mm over the PL and BT. The change over other agriculture areas is about 20–60 mm. In general, the western part of the province had a larger increase in precipitation than the eastern part, which is typically drier. The black area over the Canadian Rockies indicates an inaccurate conclusion area as a result of insufficient data coverage. The changes in the SGS, EGS, and LGS were also nonuniform. Figure 7b 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 yr ago. The EGS in the PL region (Fig. 7c) was noticeably earlier (3–9 days) than it was 60 yr 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 yr ago in

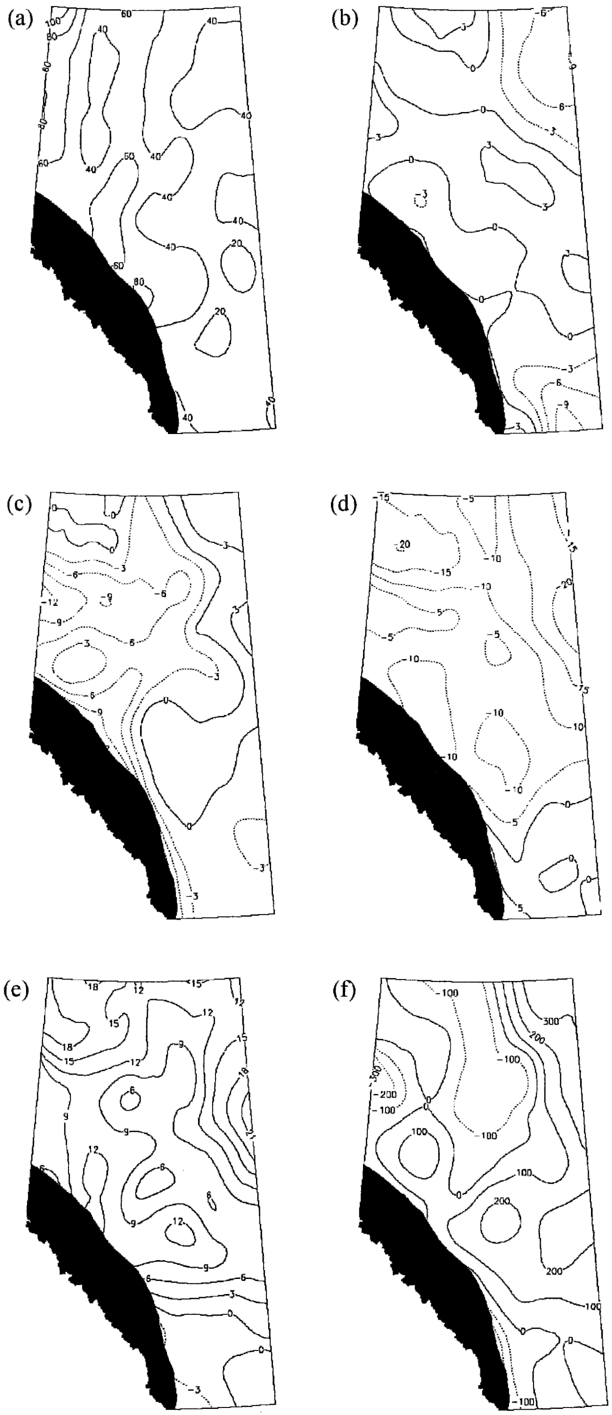

FIG. 7. The difference of the recent 30-yr normal (1973–2002) minus the 1913–42 normal for six agroclimatic parameters. (a) May–Aug precipitation (units: mm), (b) SGS (units: day), (c) EGS (units: day), (d) LSF (units: day), (e) FFF (units: day), and (f) ACHU. The Rocky Mountain areas are blacked because of insufficient data.

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, Alberta's climate experienced some changes during the last 60 yr. An earlier LSF (Fig. 7d), a later FFF (Fig. 7e), and a longer FFP (not shown in the figure) occurred in most of Alberta, excluding 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 to 2002 relative to that of 60 yr 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. 7f) increased most over the BT and AP ecoregions by an amount of 100–200 units, yet almost no increase occurred in southern Alberta, and a decrease occurred in part of the PL ecoregion. The GDD's 30-yr normal (not shown in the figure) has a similar spatial pattern to that of the ACHU.

The 1973–2002 and 1943–72 normals are compared in Fig. 8 (see Figs. 3c and 3d) for the station distributions). The difference in the May–August precipitation (not shown) has a similar pattern to that shown in Fig. 7a, but the magnitude is smaller. The SGS (Fig. 8a) 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. On average, the EGS (Fig. 8b) occurred 0–6 days later in the Alberta agriculture region. 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 of the agricultural regions in Alberta by 5–10 days. The LSF, FFF, and FFP (not shown) have a similar pattern to those in Fig. 7, but with smaller magnitudes. A larger area of increased ACHU (Fig. 8d) has been found comparable to that shown in Fig. 7f).

The increase in GDD and ACHU over the agricultural regions is an important climatic development for farmers, who have more options to select crop hybrids based on factors such as agronomic parameters for a given farmland. For instance, corn hybrids grown for silage on the Prairies usually require 2000–2100 ACHU, while grain hybrids require 2200–2400 ACHU to mature. Knowing where ACHUs are above these thresholds is important to the corn and feed industry. Figure 9 shows the regions of the ACHU greater than or equal to 2000 for the 1913–42, 1943–72, and 1973–2002 normals (see Figs. 3b–d for the station distributions). The area suitable for planting corn according to the 1973–2002 normal has extended to the north by about 200–300 km relative to the 1913–42 normal,

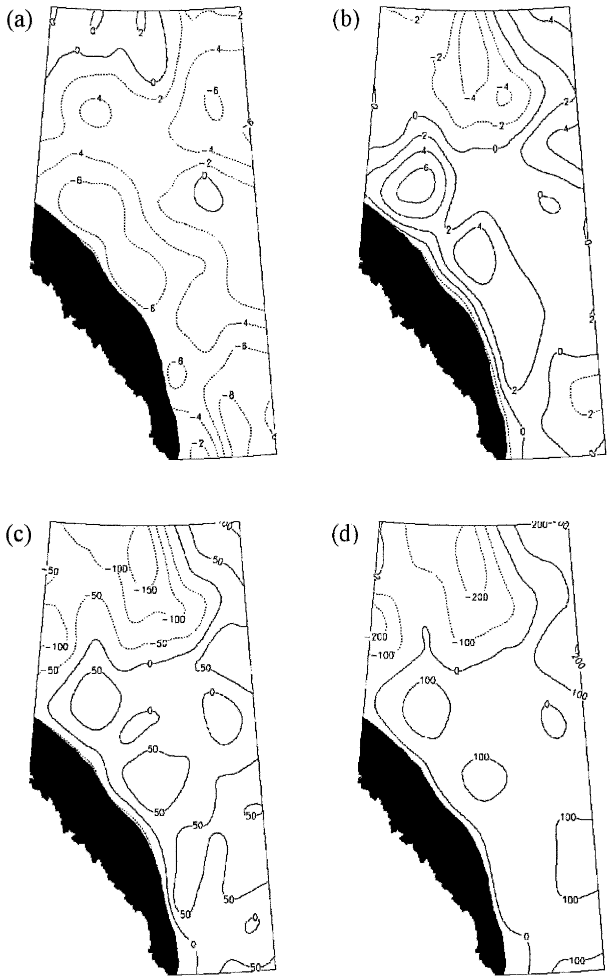

FIG. 8. The difference of the recent 30-yr normal (1973–2002) minus the 1943–72 normal for four agroclimatic parameters. (a) SGS (units: day), (b) EGS (units: day), (c) GDD, and (d) ACHU. The Rocky Mountain areas are blacked out because of insufficient data.

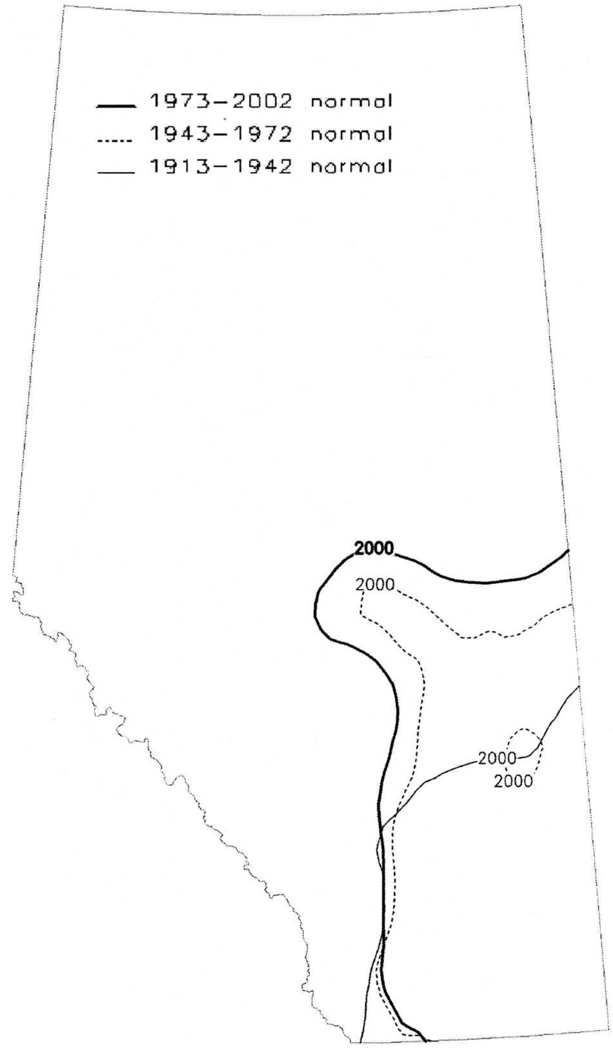

FIG. 9. The areas with ACHU ≥ 2000 for the 1913–42, 1943–72, and 1973–2002 normals.

and by about 50–100 km relative to the 1943–72 normal. This finding indicates that with the increasing heat units in the growing season, the potential growing areas for some warm-season crops, such as corn, have increased.

5. Conclusions and discussion

By using the interpolated data of daily maximum temperature, daily minimum temperature, and daily precipitation over the EDP and SLC polygons and using area-weighted averages and linear regression, the temporal and spatial changes of nine agroclimatic parameters in Alberta during the period of 1901–2002 have been analyzed. The temporal changes are represented by linear trends. The significance levels of the linear trends are determined by Kendall's tau method. The spatial changes are represented by the climate differences during the three time periods (1913–42, 1943–72, and 1973–2002). Our numerical results support the following conclusions. The May–August precipitation had increased over Alberta from 1901 to 2002, but the increase is nonuniform. The largest and most significant increment (at the 5% significance level) was in northern and northwestern Alberta, ranging from 30 to 90 mm. The increment was not significant in other areas of Alberta. The increment diminished to zero or was even negative in central and southern Alberta, and it became large again (reaching 30 mm) in Alberta's southeast corner. This spatial pattern of precipitation change and the increase of the surface air temperature made central and southern Alberta vulnerable to the impact of drought toward the end of the last century (and the years to come if the pattern and trend continue). In deriving the above conclusions on precipitation, the errors attributed to the changes of rain gauges and coding practices were not considered. The wind undercatch and wetting loss before 1970s may contribute to 2%–4% of underestimation of the precipitation in the earlier part of the last century (Zhang et al. 2000, 2001).

An earlier LSF, a later FFF, and a longer FFP now occur in most of Alberta. Significant long-term trends in these parameters exist in almost the entire province except in the southeastern tip of Alberta. The significant extension of FFP over 30 days in northern and central Alberta can greatly reduce the frost risks to crops and bring economic benefits to Alberta agricultural producers. The FFP extension occurred in concurrence with the rise of the plant hardiness index, which depends on minimum temperature, by one or two zones over Alberta (McKenney et al. 2001). However, no significant long-term trends have been found for the SGS, EGS, and LGS based on the definition of the daily mean temperature greater than 5°C for five consecutive days. The conclusion may vary if the definition is changed to the daily mean that is greater than 0°C or the daily minimum temperature, according to some new types of seeds or new types of crops. Nonetheless, by comparing the 1973–2002 and 1943–72 normals, an earlier SGS, a later EGS, and a longer LGS over the Alberta agricultural region were detected with the magnitudes of 3–6, 0–6, and 5–10 days, respectively. The LGS extension can benefit both crop yield and quality, and other agricultural production activities on a farm.

The warming trend in Alberta's climate has been demonstrated by the increase of the GDD and ACHU in most of the agricultural regions in Alberta. The area with sufficient CHU for corn production has extended to the north by about 200–300 km 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 varies spatially. 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 weather events and the processes of moisture variation on the land surface can also cause significant damage to agriculture. Our own and other's percentile analyses on daily precipitation have indicated that the increase of annual and growing season precipitation in Alberta is attributed to low-intensity events. Therefore, although there is no hesitation for us to conclude that the warming climate and increased precipitation benefit agriculture in Alberta, 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.

In addition, the data analysis method needs to be further improved. The errors in both the station data and the interpolated data need to be assessed more carefully despite the initial estimate of the interpolation errors by cross validation (Shen et al. 2001). Because of the oversmoothness of the interpolation results, the method used here that interpolates the climate normals and climate anomalies separately for the May–August precipitation total cannot be applied to either precipitation intensity studies or frost conditions. An interpolation method needs to be developed to take care of both topographic elevation and climatic variance for temperature and precipitation.

Last, the linear trend analysis can be subjected to further scrutiny. Although trends of increase or decrease are clearly demonstrated in Figs. 5b, c, d, and f, and less clear trends are in Figs. 5a and e, the small correlations shown in Table 2 imply that a small portion of the variance is explained by the linear regression. Regression with higher-order polynomials or a finite Fourier series may be more meaningful in climate change analysis (Vinnikov et al. 2002). It is also worth exploring the application of the trend-detection method derived from the empirical mode decomposition method that was developed recently to analyze the data from nonlinear and nonstationary processes (Huang et al. 2003).

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