Observed Long-Term Trends for Agroclimatic Conditions in Canada

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(Manuscript received 4 May 2009, in final form 21 October 2009)

ABSTRACT
A set of agroclimatic indices representing Canadian climatic conditions for field crop production are analyzed for long-term trends during 1895–2007. The indices are categorized for three crop types: cool season, warm season, and overwintering. Results indicate a significant lengthening of the growing season due to a significantly earlier start and a significantly later end of the growing season. Significant positive trends are also observed for effective growing degree-days and crop heat units at most locations across the country. The occurrence of extremely low temperatures has become less frequent during the nongrowing season, implying a more favorable climate for overwinter survival. In addition, the total numbers of cool days, frost days, and killing-frost days within a growing season have a decreasing trend. This means that crops may also be less vulnerable to cold stress and injury during the growing season. Extreme daily precipitation amounts and 10-day precipitation totals during the growing season have been increasing. Significant trends associated with increased availability of water during the growing season are identified by the standardized precipitation index and seasonal water deficits. The benefit of the increased precipitation may have been offset by an upward trend in evaporative demand; however, this would depend on the amount of growth and productivity resulting from increased actual evapotranspiration.

1. Introduction
Canadian climate records indicate increasingly wetter and warmer conditions throughout the twentieth century (Zhang et al. 2000), although there are regional and seasonal differences. The average increase in annual mean temperatures in southern Canada is 0.9°C since 1895. Winter and spring are warming more than summer and autumn. Daily minimum temperatures are increasing more than daily maximum temperatures, resulting in a significant decrease in the daily temperature range (DTR). The probability distribution of daily temperature is characterized by fewer days of extreme low temperatures during...
winter, spring, and summer, and more days of extreme high temperature during winter and spring (Bonsal et al. 2001). Because of changes in temperature during the latter half of the twentieth century there is now a lower frequency, duration, and intensity of winter cold spells in western Canada; meanwhile, the frequency and duration of warm spells are greater over the majority of the country (Shabbar and Bonsal 2003). An increase in spring temperature, in western Canada in particular, has resulted in earlier snowmelt and consequently earlier spring freshets (Zhang et al. 2001a). The observed trend in upward precipitation is mainly due to increases in the number of small-to-moderate rainfall and snowfall events (Zhang et al. 2000, 2001b).

A more recent analysis (Vincent and Mekis 2006) using a longer time series supports earlier findings (Zhang et al. 2000, 2001a, b). This study shows a trend toward fewer cold nights, cold days, and frost days, and conversely more warm nights, warm days, and summer days across Canada. Results also reveal trends toward more precipitation days and decreases in precipitation intensities and in maximum lengths of dry spells. Peterson et al. (2008) studied changes in extremes across North America, and results indicate a decreasing trend in cold extremes and an increasing trend in warm extremes and precipitation amounts since the 1960s.

These results suggest longer growing seasons in Canada and thus potentially more favorable climate conditions for Canadian agriculture. Rising temperatures in high latitudes have the potential to support a northern expansion of the agriculture region, although most of these lands will remain only marginally suitable for farming because of soil conditions. Bootsma (1994) showed that this was indeed the case in his analysis of long-term trends in some agroclimatic indicators at five climate stations in agricultural locations, and across Canada. In addition, at some locations he found a decreasing trend in aridity, a lengthening of frost-free periods in western Canada with earlier last spring frosts (SF) and later first fall frosts (FF), and an increase in growing degree-days and corn heat units. Still, agricultural production in Canada is subject to significant yield reductions due to climate extremes, as is demonstrated by the 2001/02 drought on the Canadian prairies (Wheaton et al. 2005), which resulted in a 30% reduction of spring wheat yield relative to the 1976–2005 30-yr mean (Qian et al. 2009). Thus, to ensure sustainable agricultural production and food security it is important to understand historical changes and monitor agroclimatic conditions.

The main objective of this work is to develop a set of agroclimatic indices that can be used for near-real-time monitoring of agroclimatic conditions in Canada, and to examine their historical changes. We consider indices that reflect heat accumulations and water conditions during the growing seasons, and other key climatic and weather factors that impact Canadian agricultural production. These indices can be used by program managers, policymakers, and producers to identify risks and opportunities to improve planning and decisions such as crop selection and program administration. To this end, we define indices for each of three types of field crops including warm season, cool season, and overwintering crops that grow in Canada, and analyze their long-term trends.

This study is different from more general climate indices analyses (e.g., Vincent and Mekis 2006; Peterson et al. 2008), as we focus on issues particularly relevant to the Canadian agriculture sector, especially field crops. In his earlier research, Bootsma (1994) examined long-term changes in agroclimatic conditions related to temperature and precipitation in general, but the analyses do not reflect the particular needs of different crops and include a limited number of representative stations. The indices we define here are more specific to the needs of different crop types and are thus of direct relevance to agricultural productivity. In addition, we use climate data from more than 200 stations updated through 2007.

The paper is organized as follows: section 2 describes the data and the methods. Section 3 provides detailed definitions of the indices. The results of trend analyses are given in section 4, followed by a discussion and conclusions in section 5.

2. Data and methodologies

a. Climate data

This study uses a homogenized temperature dataset and an adjusted precipitation dataset developed at the Climate Research Division of Environment Canada. The homogenized daily temperature dataset consists of daily maximum and minimum temperatures for 210 stations across Canada for the period 1895–2007, where possible. Step changes in monthly temperature data that are caused by changes in station location, instrumentation, observer, and observing program are identified (Vincent 1998) and adjusted (Vincent and Gullett 1999). The monthly adjustment factors are interpolated to daily values to produce adjusted daily temperature data (Vincent et al. 2002). The adjusted precipitation data include daily rainfall and daily snowfall amounts for 495 stations, with data covering the period 1900–2007 [updated from Mekis and Hogg (1999) with more stations and data from recent years]. The adjustment was done on daily rainfall and snowfall separately, to account for wind undercatch, wetting loss, and difference in snow density at different locations. Both
datasets are considered to contain the best available climate data for the study of climate change in Canada, as artifacts caused by changes in data collection are removed to the largest extent possible. These datasets have been used in the identification of trends in Canadian climate (Zhang et al. 2000), in the characterization of extreme precipitation (Zhang et al. 2001b) and extreme temperature (Bonsal et al. 2001), and in indices of climate extremes (Vincent and Mekis 2006; Peterson et al. 2008).

Figure 1 shows the locations of precipitation and temperature stations. Precipitation and temperature measurements are collocated at 147 sites. Only a limited number of locations in the Canadian arctic are analyzed for the entire period of 1895–2007 because most arctic climate station records begin in or after 1948. Missing data still exist in the homogenized daily temperature dataset and the adjusted daily precipitation dataset.

b. Trend analysis

Agroclimatic indices, especially those associated with climate extremes, may not necessarily follow a normal distribution. Therefore, we use a nonparametric Kendall’s tau-based slope estimator (Sen 1968) to compute trends, as this method does not assume a probability distribution for the indices and the results are robust to the effect of outliers in the series. A positive autocorrelation, which often exists in climate data time series, would make the Kendall test unreliable (von Storch 1995; Zhang and Zwiers 2004), thus an iterative procedure is applied to take the effect of lag-1 autocorrelation into account when testing the significance level of a trend. A trend is considered to be statistically significant if it is significant at the 5% level, a procedure originally proposed by Zhang et al. (2000) and refined by Wang and Swail (2001).

Records of meteorological observations in Canada begin in the late nineteenth century but long-term observations are limited to a few sites near the Canada–United States border. Many Canadian stations, especially those in the north, were established in the early 1950s. For this reason, trend analyses are conducted for three time periods, 1895–1950, 1951–2007, and 1895–2007. A trend is calculated if the data meet the following requirements: for periods 1895–1950 and 1951–2007, we require data covering at least a 40-yr period and having at least 30

FIG. 1. Locations of stations. A star marks a station with both temperature and precipitation data, and solid and open circles are for temperature-only and precipitation-only stations, respectively.
values, and for the period 1895–2007, we require data covering at least an 80-yr period and having at least 60 values.

Two types of errors occur with any hypothesis test. The type-I error is to falsely reject the null hypothesis. The occurrence rate of type-I errors is determined by the significance level: the null hypothesis of a statistical test will be rejected by chance at the prescribed significance level when the hypothesis is true. However, when the same test is conducted at a limited number of sites and/or when a series at these sites is correlated, the null hypothesis can be rejected at a rate higher than the specified significance level even if it is true (Livezey and Chen 1983). The type-II error is the failure to reject the null hypothesis while it is false. The rate of occurrence of this error depends on the power of the hypothesis test as well as strength of the signal against the background noise. In the context of this study, it is possible that a significant trend is not identified even if there is one in the series. Because of these errors’ behavior, it is important to assess the overall significance, or field significance, when the null hypothesis is rejected for a certain number of times in a limited-number test. When significant trends have been identified in some stations in this study, we would like to know if the trend is significant or not for the country as a whole, or if we could expect these trends to be identified simply because of chance.

To determine the overall (field) significance of the trend, we use a bootstrap procedure similar to Kiktev et al. (2003) to estimate a threshold percentage at the 5% level for each index at all locations in the trend analysis. The trends are considered to be field significant if the percentage of the locations showing a significant (positive or negative) trend is larger than the threshold percentage obtained by the bootstrap procedure.

3. Agroclimatic indices

Different types of crops require different climates to optimize growth and yield. Three important cardinal temperatures (Soule 1985) are used to characterize agricultural crop responses to ambient air temperature. The minimum and maximum cardinal temperatures (CT_{min} and CT_{max}) specify the temperature range for growth, and the optimum temperature (T_{opt}) is the temperature at which the crop growth is at the maximum rate. Field crops in Canada may be categorized into three types, namely cool season crops, warm season crops, and overwintering crops, according to their cardinal temperatures. Cool season crops require a relatively low temperature. They include those commonly found in Canada such as spring wheat, barley, canola, oat, and rye. In contrast, warm season crops such as corn, soybean, and sweet potato need a relatively warm temperature condition. Warm season crops grow during summer only in the agricultural regions of southern Canada. Overwintering crops are mainly biennial and perennial field crops such as herbaceous plants (winter wheat, alfalfa, timothy, strawberry, etc.) and woody fruit trees (apple, apricot, cherry, chestnut, grape, peach, pear, pecan, plum, etc.). They normally grow and develop during the warm growing season and become dormant during the cold nongrowing season.

Climate indices have been widely used to monitor climate change (e.g., Peterson et al. 2008; Alexander et al. 2006; Vincent and Mekis 2006). Many of these climate indices are not designed to address the specific needs of a particular sector and are not necessarily relevant to agricultural production. For example, percentile-based temperature indices reflect how far away temperature on a day is from climatology of the date. As a result, information important for crop growth such as annual cycle is absent from such indices. It is thus not possible to know, from such indices, if heat accumulations in the growing season become more or less favorable for crop production. In this study, we define growing seasons based on the cardinal temperatures of each crop type to more accurately assess the suitability of the climate. Crop-type-relevant growing seasons can also be very useful in planting decisions such as crop selection, and therefore, applicable to climate change adaptation strategies. In addition, we also include other indices, such as cool spells and heat waves, to characterize extreme events that may need to be considered in the assessment of agricultural production risks. We categorize cardinal temperatures for different field crops from the literature, as listed in Table 1.

<table>
<thead>
<tr>
<th>Type of field crops (common species growing in Canada)</th>
<th>CT_{min} (°C)</th>
<th>T_{opt} (°C)</th>
<th>CT_{max} (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool season crops (wheat, barley, canola, rye, oat, pea, potato, etc.)</td>
<td>5.0</td>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Warm season crops (corn, soybean, sweet potato, etc.)</td>
<td>10.0</td>
<td>30.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Overwintering crops (biennial or perennial herbaceous crops and fruit trees)</td>
<td>5.0</td>
<td>25.0</td>
<td>35.0</td>
</tr>
</tbody>
</table>

a. Growing season and number of frost-free days

The initiation and termination of growth for different crop types occur at different temperatures. As a result,
we define the growing season start (GSS) and end (GSE) dates for three types of crops according to their cardinal temperatures. Once the growing season is defined for a particular crop type, other indices related to heat and water conditions are computed in accordance with the growing season. We define a growing season as starting from the day (GSS) when the weighted mean air temperature has reached  

\[
X_n = \frac{X_{n-2} + 4X_{n-1} + 6X_n + 4X_{n+1} + X_{n+2}}{16},
\]

where \(X_n\) is the smoothed average temperature for day \(n\) and \(X_t\) (where \(t = n - 2, n - 1, n, n + 1,\) and \(n + 2\)) is the daily mean air temperature on day \(t\). This definition for growing season was adopted from Bootsma (1994), but we use relevant \(CT_{min}\), as reported in the literature, for the crop types rather than a fixed threshold temperature of 5.5°C, which is suitable for the perennial grass crop.

The ending date of a growing season for cool season crops, such as spring wheat and other small grain cereals, which are commonly planted in spring in Canada, is defined differently from other crops. These crops mature during summer when air temperatures reach their seasonally highest values (Porter and Gawith 1999). The cool season crop’s growing season ends when the crop reaches its maturity. Extremely high temperatures can speed up the maturity process for cool season crops (Angadi et al. 2000), although some crops may still grow slowly at the \(CT_{max}\). Therefore, GSE for cool season crops is 31 August, or the day when the weighted mean daily maximum air temperature reached \(CT_{max}\) (30°C), for five consecutive days in August, whichever is earlier. Equation (1) was applied to calculate this weighted mean except that daily mean temperature in (1) was replaced by daily maximum temperature. We compared the calculated GSS and GSE with documented phenological data including seeding, maturity, and harvest dates (Nuttonson 1955, 1957, 1958) at some locations and found reasonably good agreement between them. For example, a \(t\) test showed no significant difference between the 1941–70 mean GSE for cool season crops and the documented maturity dates of spring wheat at 10 locations on the prairies. Though the \(t\) test may not be a very effective test to identify a significant difference in the mean, we believe the cardinal temperature–based growing season reflects the actual crop phenological period well.

Producers traditionally determine the actual length of a growing season and the suitable dates for planting and harvesting field crops by the number of frost-free days (FFD), the date of the last spring frost, and the date of the first fall frost, respectively. A day with minimum temperature greater than 0°C is considered a frost-free day, as frost often occurs when daily minimum temperature is below 0°C. Severe damage can occur when the daily minimum temperature is below -2°C, even for cool season crops; thus a day with such a temperature is defined as a killing-frost day. The number of days free from killing frosts (FFD -2), the date of the last spring killing frost (SF -2), and the date of the first fall killing frost (FF -2) are adopted in this study. These two temperature thresholds (0°C for frost and -2°C for killing frost) are also used in Bootsma (1994).

### b. Extremely low and high temperatures

Extremely low or high temperatures affect crops differently throughout their phenological development and during growing and nongrowing seasons. Within a growing season, temperature can still be below \(CT_{min}\). Lower temperature can suppress growth and sometimes kill the crops, especially when crops are already well developed after planting. Temperatures higher than \(CT_{max}\) may also suppress growth. We consider days with temperatures below \(CT_{min}\) or above \(CT_{max}\) during the growing season as cool spells or heat waves, respectively. We define cool spells and heat waves for the three types of crops separately, corresponding to their respective cardinal temperatures. Cool spells and heat waves are identified for the entire growing season and their severity is characterized by five indices. These indices include the total number (TE) of cool spells or heat waves, the mean length (ML), maximum length (XL), and mean temperature (MT) during the cool spells and heat waves, and the most extreme temperature (LT), the lowest recorded for cool spells and the highest recorded for heat waves, respectively. Traditionally a growing season is defined by fixed calendar days for practical purposes (i.e., 1 April–31 August for cool season crops, 1 April–30 September for overwintering crops, and 1 May–30 September for warm season crops). These definitions are also used to compare with the temperature-based crop growing season from GSS to GSE.

Ice-freeze damage to crops during the nongrowing season is the most important factor determining the suitable distribution of overwintering agricultural field crops (Chen et al. 1993). Based on plant physiological status, these crops must undergo a dormant period and two nondormant periods during their overwintering stages. In late fall, they experience a natural hardening process involving acclimation to the cold and a series of phytochemical and biochemical changes to increase their hardiness over the winter and enhance their ability to...
survive during the ice-freeze period. In early spring, they experience a dehardening process of physiological preparation for new growth in the coming growing season. Plant hardiness is significantly different between dormant and nondormant periods; therefore we define critical killing temperatures for these crops separately in Table 2, based on Coleman (1992), Embree (1984), Krueger (1983), and Parker (1963). Potential ice-freeze damage is measured using the number of days with daily minimum temperature lower than the critical killing temperatures for each group of overwintering crops during three time intervals, identified in Table 2.

c. EGDD and CHU

Growing degree-days (GDD) are computed by summing daily mean temperature values above CT\textsubscript{min} (5°C for cool season and overwintering crops and 10°C for warm season crops) from GSS to GSE according to the following formula:

\[
\text{GDD} = \frac{T_{\text{max}} + T_{\text{min}}}{2} - CT_{\text{min}}, \quad \text{and} \\
\text{GDD} = 0, \quad \text{if} \quad \frac{T_{\text{max}} + T_{\text{min}}}{2} < CT_{\text{min}},
\]

where \(T_{\text{max}}\) and \(T_{\text{min}}\) are daily maximum and minimum air temperatures, respectively. To reflect the influence of day length on the crop maturity process at high latitudes, we also compute the effective growing degree-days (EGDD) by applying a day-length factor (DLF) to GDD (Bootsma et al. 2005a).

Crop heat units (CHU) are also called corn heat units as this indicator has been widely used to rate the suitability of a climate for corn and soybean production in Canada (Major et al. 1976; Chapman and Brown 1978; Bootsma et al. 1992, 1999; Brown and Bootsma 1993). Daily CHU accumulations are computed according to the following equations (Brown 1975; Bootsma 1994):

\[
Y_{\text{max}} = 3.33(T_{\text{max}} - 10.0) - 0.084(T_{\text{max}} - 10.0)^2,
\]

where \(Y_{\text{max}} = 0\) if \(T_{\text{max}} < 10.0°C\).

\[
Y_{\text{min}} = \begin{cases} 
9 \frac{(T_{\text{min}} - 4.4)}{5}, & \text{if } T_{\text{min}} < 4.4°C, \\
0, & \text{else}
\end{cases}
\]

\[
\text{CHU} = \frac{(Y_{\text{max}} + Y_{\text{min}})}{2}.
\]

Daily CHU was accumulated from GSS to GSE for warm season crops. To be comparable with results from other studies (e.g., Bootsma 1994), CHU was also computed for a time period from 1 May to FF.

d. Extreme precipitation and precipitation deficit

The impacts of extreme precipitation on crop growth and development vary depending on the phenological stage and the sensitivity of crops to excessive precipitation. Extreme precipitation can also affect crop planting and harvest, and cause soil erosion, nutrient leaching, and the spread of plant and soil pests and diseases (Arnold et al. 1995; Flanagan and Livingston 1995). The maximum 1-day precipitation (PID) and consecutive 10-day precipitation total (P10D) during the growing season were employed to represent extreme precipitation.

The standardized precipitation index (SPI; McKee et al. 1993) is used to reflect dryness or wetness during the growing season. Primarily a meteorological drought index based on precipitation, SPI is commonly calculated for 3-, 6-, 9-, 12-, 24-, or 48-month periods. In calculating the SPI, the observed precipitation values during the 3-, 6-, 9-, 12-, 24-, or 48-month period are first fitted to a gamma distribution. The gamma distribution is then transformed to the standard normal distribution, which gives a value of SPI for the time scale used.

As SPI only involves precipitation, we use the seasonal water deficit (SWD) to measure soil moisture in the rooting zone to reflect the combined effects of temperature and precipitation. The influence of temperature is represented by potential evapotranspiration (PE), which is estimated from daily maximum and minimum temperatures and solar radiation at the top of the atmosphere using the methods of Baier and Robertson (1965) and Baier (1971). SWD is the accumulated difference between potential evapotranspiration and precipitation.
Table 3. Percentage (%) of the locations showing positive (+) or negative (−) trends significant at the 5% level in growing season–related indices. Trend that is field significant at the 5% level is boldface. Subscripts c, o, and w represent cool season, overwintering, and warm season crops, respectively. GSS is the same as GSS, and thus is omitted in the table. The subscript −2 indicates killing frost, and N is the number of stations that have sufficient data for trend analyses.

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<tbody>
<tr>
<td></td>
<td>N</td>
<td>+</td>
<td>−</td>
<td>N</td>
</tr>
<tr>
<td>GSS</td>
<td>71</td>
<td>0.0</td>
<td>1.4</td>
<td>196</td>
</tr>
<tr>
<td>GSL</td>
<td>68</td>
<td>1.5</td>
<td>2.9</td>
<td>196</td>
</tr>
<tr>
<td>SF</td>
<td>68</td>
<td>4.4</td>
<td>7.4</td>
<td>208</td>
</tr>
<tr>
<td>FFD</td>
<td>68</td>
<td>13.2</td>
<td>4.4</td>
<td>208</td>
</tr>
<tr>
<td>FSE</td>
<td>68</td>
<td>29.9</td>
<td>5.9</td>
<td>208</td>
</tr>
</tbody>
</table>

(PE − P) during the growing season. Note that a positive SPI indicates a wet condition while a positive SWD value suggests a lack of water availability.

4. Results

This section presents trend analyses results. We focus on trends for the period 1895–2007 rather than the two subperiods because 1) a trend over a longer period is less affected by multidecadal variability of the climate system, 2) a trend is easier to detect with a larger sample (Zhang and Zwiers 2004; Zhang et al. 2004), and 3) the spatial coverage of climate stations in the agricultural region is reasonably good. Trends for the two subperiods 1895–1950 and 1951–2007 are also provided for comparison. They are often consistent with those for the longer period, especially in the case of the subperiod 1951–2007.

a. Growing season and FFD

Trends related to the characteristics of growing seasons are tabulated in Table 3. As the Julian day or the day of year is used to mark the GSS, GSE, SF, and FF, a negative trend in GSS and SF indicates an advance or an earlier start to the growing season and the frost-free period while a positive trend for GSE and FF indicates a later end of the growing season and the frost-free period. The magnitude of trends varies from one location to another, but the trends suggest a lengthening of growing seasons for all three crop types. To provide an overall picture of the trends over the country, we list the median value along with the 80% range (i.e., the lower and the upper 10 percentiles, in brackets) of the estimated trends at all available locations. The start of the growing season has a negative trend of −6.4 (from −14.6 to 0.0) for overwintering and cool season crops and −5.6 (from −11.8 to 0.0) days century\(^{-1}\) for warm season crops, respectively, during 1895–2007. There is also a positive trend in the date of the growing season end for the warm season and overwintering crops, but no change for cool season crops. A positive trend of GSE is observed by the magnitude of 2.4 (−4.3–10.3) and 2.6 (−4.4–11.1) days century\(^{-1}\) for warm season crops and overwintering crops, respectively. The absolute value of trends for growing season start was larger than that for growing season end, consistent with stronger warming in spring than in autumn (Zhang et al. 2000). The earlier start and/or the later end of the growing season resulted in a lengthening in the growing seasons by 6.1 (0.0–15.2), 8.2 (−5.3–16.7), and 10.4 (−1.4–23.0) days century\(^{-1}\) for cool season, warm season, and overwintering crops, respectively. There are higher percentages of stations showing a significant trend for 1951–2007 than for 1895–1950, also consistent with stronger warming in the second half of the twentieth century (Zhang et al. 2000).

The spatial distribution of the trends is quite homogeneous. We display in Fig. 2, as examples, the spatial distribution of trends of GSS, GSE, and growing season length (GSL) for overwintering crops for 1895–2007. The spatial distributions of the trends for other crops and for the two subperiods are similar, although not included herein. A negative trend in GSS is observed for more than 90% of stations, and it is statistically significant at the 5% level at more than 50% of the stations analyzed. Stations with a significant trend are mainly located in eastern Canada and southern British Columbia (BC), Canada; this is perhaps related to less temperature variability in the regions. A positive trend in GSE is observed in almost two-thirds of stations, and it is statistically significant at 20% of the stations. There are two stations showing a negative trend in the northwest prairies. The advance toward an earlier growing season start and a tendency toward a later growing season end have resulted in a lengthening of the growing season. Positive growing season trends are found at more than 80% stations, and are statistically significant at about one-third of the stations. Again, stations with a significant trend are mainly located in eastern Canada and southern BC. Trends in GSS, GSE, and GSL are all field significant according to the field significance test, meaning that there have been significant changes in the growing season in Canada. Note, however, that trends in the main agriculture region, the Canadian prairies, are less significant,
suggesting that it is perhaps still too early to take advantage of generally longer growing seasons in the region because of a highly variable climate.

In general, the frost-free and killing-frost-free periods have lengthening trends (Table 3). For example, significant negative trends in SF and SF$_{2}$ are detected at half of the stations for the 1895–2007 period (Table 3), and none of the stations show a significant positive trend, clearly indicating that the last spring frost is occurring at a significantly earlier date. The magnitude of the trends is $-11.1$ (from $-23.1$ to $0.0$) and $-9.9$ (from $-22.7$ to $0.0$) days century$^{-1}$ for SF and SF$_{2}$, respectively. The occurrence of the first fall frost (FF and FF$_{2}$; Table 3) has become significantly later, and a significant positive trend is found at more than 40% of the stations. Across the country, the trend has a magnitude of 9.4 (0.0–21.9) and 8.5 (0.0–19.3) days century$^{-1}$ in FF and FF$_{2}$, respectively. These are clear indications of a later start of the frost season. A later start and earlier end have resulted in a longer frost-free period. In fact, a significant lengthening in FFD and FFD$_{2}$ is found at more than 60% of the stations. The trends have a magnitude of 19.7 (1.2–43.5) and 19.3 (0.0–41.3) days century$^{-1}$ for FFD and FFD$_{2}$, respectively (i.e., the frost-free period has become approximately 20 days longer since the beginning of the twentieth century). The trends in frost-free periods are all field significant at the 5% level. They are stronger in the 1951–2007 than 1895–1950 series, in accordance with a larger temperature increase in the second half of the twentieth century. Over the space, almost all the stations show a negative sign in SF and SF$_{2}$, and a positive sign in FF, FF$_{2}$, FFD, and FFD$_{2}$. Stations with significant trends are also more or less evenly distributed. These suggest that the trends in frost-related indicators are quite homogeneous across the country. In Fig. 3, we show trends in SF, FF, and FFD during 1895–2007 as examples.

b. Extreme temperatures

Field crop production in Canada is affected more by extended cool spells in the growing season and extremely low temperatures during wintertime compared to extremely high temperatures in summer: Heat waves with daily maximum temperature over 35°C are rarely observed in most years at many locations. Heat waves with daily maximum temperatures above 30°C during the growing season of cool season crops have only very weak trends (not shown). Therefore, in this study we are not much concerned about heat waves but focus our analyses on cool spells.

Since the growing seasons have extended in both ends and temperature trends are not uniform in different seasons (Zhang et al. 2000), it is necessary to evaluate the risk for agricultural crops encountering cool spells. We
summarize trends in cool spell–related indices in Table 4. For cool season crops, the number of cool spells decreases at some locations, but the length of cool spells has become longer and the temperature within cool spells lower. The results are similar for overwintering crops. For warm season crops, the number of cool spells has also decreased, with approximately 20% of the stations showing a significant decreasing trend over 1895–2007. However, temperatures during the cool spells have also increased, contrary to the findings for cool season and overwintering crops.

Significant trends in cool spell–related indices are mainly located in the far west and in the east, with only a small fraction in the main agriculture region. Figures 4a–c display trends in the number of cool spells, mean length of cool spells, and mean temperature for cool spells during the warm crop growing season for the 1895–2007 period. Results for other crops are similar.

The number of days with killing temperatures for woody deciduous fruit trees has significantly decreased across the country during 1895–2007 for three phases of the nongrowing season, namely, dormant (December, January, and February), early spring (March), and late fall (October and November). Significant decreasing trends are found at more than 50% of the stations during the dormant period and early spring, and a significant positive trend is not found at a single station (not shown). The decreasing trend in the number of killing-temperature days for woody fruit trees is fairly evenly distributed.

Table 4. As in Table 3, but for cool spell–related indices.

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Fig. 3. As in Fig. 2, but for trends in the (a) date of SF, (b) date of FF, (c) number of FFD, and (d) number of FFD during 1895–2007.
across the country during the dormant period and early spring, though a considerable number (17%) of stations show a positive albeit not statistically significant trend during late fall (Fig. 5). Similar distributions are observed for herbaceous overwintering crops. The median magnitudes of the trends during 1895–2007 are \(-1.4\) (from \(-4.0\) to 0.0), \(-6.0\) (from \(-13.7\) to \(-0.7\)), and \(-4.4\) (from \(-8.4\) to 0.0) days century\(^{-1}\) for woody fruit trees, and are \(-2.2\) (from \(-6.8\) to 0.0), \(-7.4\) (from \(-14.0\) to \(-1.8\)), and \(-3.8\) (from \(-8.0\) to 0.0) days century\(^{-1}\) for herbaceous overwintering crops, in the late fall, dormant period, and early spring, respectively. The magnitude of the trends during 1951–2007 is often larger than that for 1895–2007.

The number of frost days, number of killing-frost days, and number of cool days (i.e., daily minimum temperature lower than 5°C) within the overwintering crops’ growing season all have a significant negative trend for 1895–2007 (not shown). Results for other cool season and warm season crops’ growing seasons are similar. These clearly indicate that crops may have been becoming less vulnerable to cold damage in the early period of the growing season because of a temperature increase.

c. EGDD and CHU

Because of lengthening in the growing seasons and the increase in the growing season temperatures, trends in GDD, EGDD, and CHU are overwhelmingly positive and significant (Table 5). The highest percentages of stations with significant trends are observed for these indices. As growing degree-days are most often used to evaluate heat conditions for cool season and overwintering crops and crop heat units are more suitable for warm season crops, the following analyses are focused on EGDD for overwintering crops and CHU for warm season crops.

A significant increase in EGDD for overwintering crops is found at 64.5% of the stations during 1895–2007. The percentages of stations with significantly positive trends for two subperiods are just slightly smaller. The median magnitude of the trends is 153.2 (53.0–282.5) degree-days century\(^{-1}\) across the country for 1895–2007. Significant positive CHU trends are also found at most of the stations during the 1895–2007 period, with a median magnitude of the trends at 228.1 (77.0–395.3) units century\(^{-1}\) for the period. The trends in both EGDD and CHU are spatially homogeneous, as stations with significant trends are quite evenly distributed across the country (Fig. 6).

Trends in EGDD and CHU may be attributed to the extended length of the growing season and the increase of temperature within the growing season. To reveal the factor that may have played a major role in the trends, accumulated values for the traditionally fixed time frames of growing seasons are calculated from 1 April to
30 September for EGDD of overwintering crops, and from 1 May to the first fall frost for CHU of warm season crops. The percentages of the locations where a significant positive trend is detected for these two indices are larger than those for the corresponding two indices accumulated during the crop cardinal temperature–based growing season (Table 5). The trends are consistent across the country (Fig. 6). The median magnitudes of the trend are 134.3 (49.9–230.1) degree-days century\(^{-1}\) for EGDD and 296.5 (117.4–539.3) units century\(^{-1}\) for CHU during 1895–2007, respectively. This slightly larger median trend of CHU for the fixed growing season for warm season crops may be associated with an unrealistically early growing season start (1 May) in many locations across the country. These results confirm the need for agroclimatic indices defined with temperature-based growing seasons since the actual growing season varies widely across the country under diverse climates. They indicate that the temperature increase during the growing season played a more important role in the increase of EGDD and CHU than the increase in the length of the growing season.

d. Extreme precipitation and precipitation availability during the growing season

Maximum daily precipitation during the growing season shows a significant trend at some stations (Table 6), consistent with the findings of Zhang et al. (2001b). Trends in the maximum 10-day precipitation totals are

FIG. 5. As in Fig. 2, but for trends in numbers of days with killing temperatures in (a) dormant period (December–February; \(\leq -30^\circ\text{C}\)), (b) early spring (March; \(\leq -10^\circ\text{C}\)), and (c) late fall (October–November; \(\leq -10^\circ\text{C}\)) for woody deciduous fruit trees.
field significant for 1895–2007, with the majority of stations showing a positive trend. Stations with significant trends are scattered across the country (Fig. 7). The trend in P10D is not field significant for the two subperiods. This suggest that while there might be a significant increase in P10D since 1895, the significance is generally weak.

The trend in the standardized precipitation index for 1895–2007 is field significant (Table 7), and almost all significant trends are positive. Stations with significant positive trends are mainly located in the west and in the east. Only a few stations with significant positive trends are located in the prairie ecozone of Alberta and Saskatchewan, Canada (Fig. 8). In fact, some stations, especially in the prairie ecozone of Alberta and Saskatchewan, show a decreasing trend. Results for the subperiod 1951–2007 are similar, though the percentage of stations with a significant trend is smaller. These suggest that precipitation remains a major limiting factor for field crop production in that region where moisture stress is currently a major yield-limiting factor (Qian et al. 2009).

The seasonal water deficit shows a trend that is also field significant for 1895–2007, with the majority of stations showing a positive trend. Stations with significant trends are scattered across the country (Fig. 7). The trend in P10D is not field significant for the two subperiods. This suggest that while there might be a significant increase in P10D since 1895, the significance is generally weak.

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The seasonal water deficit shows a trend that is also field significant for 1895–2007. The majority of the significant trends is negative, although, the percentage of stations with significant trends is smaller than that in SPI. This suggests that the increase in precipitation is in

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Table 6. As in Table 3, but for extreme precipitation–related indices. P1D and P10D are calculated for different periods, as in EGDD and CHU in Table 5.

FIG. 6. As in Fig. 2, but for trends in (a) EGDD for overwintering crops accumulated from GSS to GSE, (b) CHU for warm season crops accumulated from GSS to GSE, (c) EGDD accumulated for the fixed growing season for overwintering crops (1 Apr–30 Sep), and (d) CHU accumulated from 1 May to FF for warm season crops during 1895–2007.
part offset by an increase in temperature that demands more water for evaporation. But for the two shorter subperiods, trends in SWD are not very clear, as there is only a small percentage of stations showing a significant trend, and there are more stations with a significant positive trend than negative trend. This suggests that water conditions in most regions across the country have been improving since 1895, though this is not the case for the prairie ecozone where positive trends (albeit not statistically significant at the 5% level) in SWD are dominant.

5. Conclusions and discussion

Using the best available daily temperature and precipitation data for climate trend analysis in Canada, we have computed agroclimatic indices representing extreme weather, heat, and water conditions during the growing season for cool season, warm season, and overwintering crops across the country. We find a significant increasing trend in the length of the growing season and in the associated available heat. The winter temperature is less damaging and the frost-free periods are longer. We also find trends in precipitation-related indices that indicate more availability of water, though the trend in the main agriculture region is less significant.

Our results will be useful in further developing a climate monitoring system specific to the Canadian agriculture sector, which is currently underway. Growers and policymakers may use such information of historical changes to develop climate adaptation strategies such as crop selections. For example, an increasing trend in heat accumulations may be more favorable for corn and soybean production but less favorable for barley production (Bootsma et al. 2005b). Crops demanding a high

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Fig. 7. As in Fig. 2, but for trends for P1D and P10D during the growing season from GSS to GSE and the fixed period (1 Apr–30 Sep) for overwintering crops during 1895–2007.
amount of CHU may be suited to more locations in Canada, especially in the northern areas of existing agricultural regions. A balance should be reached by taking advantage of the increases in growing season length and heat accumulations and managing the risks associated with seasonal water deficits.

Acknowledgments. We are indebted to Andy Bootsma, Reinder De Jong, Sam Gameda, Denise Neilsen, and Nathaniel Newlands at Agriculture and Agri-Food Canada for their helpful communications on definitions of agroclimatic indices. We are also grateful to Enric Aguilar for his helpful comments on an earlier version of the manuscript. Editor Julie Winkler and three anonymous reviewers provided considerable suggestions that helped to improve this paper.

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