8.3 CHANGES IN DAILY AND EXTREME TEMPERATURE AND PRECIPITATION INDICES RELATED TO DROUGHTS IN CANADA

Eva Mekis and Lucie A. Vincent
Climate Research Branch, Meteorological Service of Canada

1. INTRODUCTION

Weather conditions related to temperature, precipitation, droughts, storms or other aspects of climate, can cause severe damage and large economic and social losses. Assessing changes through temperature and precipitation ground measurements gives us the opportunity to be prepared and adopt strategies to deal with these events. In particular, severe droughts can present serious threat to our society and environment. Over the Canadian Prairies, prolonged droughts have major impacts on agriculture, industry, recreation and aquatic ecosystems. Meteorological droughts often occur when there is below-normal precipitation for an extended period of time with very high temperature which increases evaporation. However, each drought is different and depends on the region affected, its duration and intensity, and the region's capacity to adapt to water shortage.

Earlier work of Vincent and Mekis (2006) reported on trends in daily and extreme temperature and precipitation indices for 1900-2003 and 1950-2003. Trends were generated and analyzed using homogenized data from 210 temperature and 495 precipitation stations across Canada. Results showed increasing trends in warm events and decreasing trends in cold events. For example, the number of frost days has decreased significantly over both time periods. The analysis of daily precipitation indices revealed more days with precipitation, a decrease in daily precipitation intensity and a decrease in the maximum number of consecutive dry days. No consistent change was found in most of the extreme precipitation indices except for a significant increase in the number of days with heavy precipitation.

The present work is also based on homogenized temperature and adjusted precipitation datasets. The study period is extended until 2007 to include the more recent quality controlled climate observations. The objective is to investigate temperature and precipitation indices which are different from the conventional SPI and Palmer Drought Index but can still provide valuable information about droughts in Canada. The trends for five temperature and six precipitation indices are first analyzed over the country. Then the time series are examined for the Canadian Prairies in order to establish if these indices are good indicators of droughts over this region.

**Corresponding author address:* Éva Mekis, Climate Research Division, Environment Canada, 4905 Dufferin Street, Toronto, Ontario, Canada, M3H 5T4;
e-mail: Eva.Mekis@ec.gc.ca

2. DATA

2.1 Temperature Indices

The temperature indices presented in this study are based on daily maximum for 210 stations across the country. Homogeneity problems caused by station relocation and change in observing procedures were addressed using a technique based on regression model with surrounding stations (Vincent et al. 2002). Table 1 presents a list of the five selected temperature indices along with their definition. The annual and summer means of the daily maximum temperatures present the average condition over the year and the season. The warm temperature extremes are described by the number of hot days (days with daily maximum temperature above 30°C), the number of warm days during the summer (days with daily maximum temperature above the 90^{th} percentile) and the number of warm spells during the summer (three consecutive days with daily maximum temperature 5° above normal). The summer is defined as June, July and August. More details about these indices are provided in Vincent and Mekis (2006).

2.2 Precipitation indices

The precipitation indices provided in this study are computed from adjusted daily rain, snow and total precipitation amounts for 461 stations. The precipitation datasets were recently updated to include more recent station's observations, but all observations are still based exclusively on manual observations. The methodology follows the steps described in Mekis and Hogg (1999). Adjustments were applied on daily values for rain and snow separately. For each rain gauge type, corrections to account for wind undercatch, evaporation, and gauge specific wetting loss were implemented. The details of rain gauge corrections are further explained in Devine and Mekis (2008). For snowfall, density corrections based upon coincident ruler and Nipher measurements were applied to all ruler measurements (Mekis and Hopkinson, 2004). Adjustments obtained from homogeneity tests using information from surrounding station were applied for the joining of observations from several stations (Vincent and Mekis, 2008). In Canada, when a station is relocated, a new identification number is often given to the new location and the two station's observations can be combined in order to create a long time series. Great care was as well given to properly account for the trace observation. The list of the precipitation indices included in this study is presented in the second part of Table 1. The annual

Table 1. Number of stations with significant negative, not significant and positive trends for 5 temperature and 6 precipitation indices over 1900-2007 and 1950-2007 respectively. The number in bold indicates that more than 20% of the stations have a significant trend (significant at 5% level).

	Indices	Unit	1900-2007				1950-2007			
			-	ns	+	tot	-	ns	+	tot
Temperature	Annual mean of daily maximum temperature	^oC	0	42	**24**	66	0	92	**67**	159
	Summer mean of daily maximum temperature	^oC	3	69	13	85	0	131	**49**	180
	Number of hot days (Tmax > 30^{o}C)	days	3	48	12	63	2	123	11	136
	Number of summer warm days (Tmax > 90th percentile)	days	11	58	15	84	0	148	31	179
	Number of summer warm spells	#	2	77	9	88	0	167	16	183
Precipitation	Annual total precipitation	mm	2	42	**40**	84	5	184	27	216
	Summer total precipitation	mm	0	108	**32**	140	4	294	20	318
	Days with rain > Trace	days	0	13	**73**	86	3	52	**168**	223
	Days with rain > 10 mm	days	6	50	**30**	86	12	179	32	223
	Maximum number of consequtive dry days	days	**53**	31	0	84	35	176	4	215
	Very wet days (>95th percentile)	days	5	62	**19**	86	13	185	25	223

and summer total precipitations are characteristics of the water amount available in any given year or season for each location. To determine the frequency of precipitation events, the annual number of days with rain greater than the trace events is computed. The maximum number of consecutive dry days is used to characterize long dry spells every year. To represent extreme wet conditions (potential relief from droughts), the very wet days (number of days with total precipitation above 10 mm) and the number of days with total precipitation above the 95th percentile (from the 1961-1990 average) are included in the study. For the identification of the abnormally dry years, the percent of annual mean precipitation compared to long-term average is also computed.

3. METHODOLOGY

The non-parametric Kendall's test was used to estimate the slope of the trend at any individual station. The 3/5 rule was applied for both temperature and precipitation indices: in any month, if more than 3 consecutive days or more than 5 random days are missing then the month is missing. For each station, the trends were computed for the periods 1950-2007 and 1900-2007 only if more than 80% of the values were present. A single time series was also produced for the Prairies by averaging the stations anomalies (departures from the 1961-1990 average) for each indicator. However, since precipitation amounts can be very large in some areas as compared to others, the percentage anomalies (departures from the 1961-1990 average divided by the 1961-1990 average and multiplied by 100) were used for the annual and summer total precipitation. The Prairies is the region defined between 95° and 115° west and 48° and 55° north. Given these borders, 31 temperature and 45 precipitation stations were used to prepare the Prairies time series.

4. RESULTS

4.1 Trends in temperature indices

The number of stations with significant decreasing, non-significant, and significant increasing trends is given in Table 1 for each index. For 1950-2007, more than 20% of the stations experience significant increase in the annual and summer mean maximum temperature. The temperature increase reaches as much as 2°C at many stations (Fig. 1a and b). While the greatest annual trends occur over the western regions, the summer warming is observed across the country. A few stations show a significant increase in the frequency of hot days (Fig. 1c) while many stations indicate a significant increase in summer warm days (Fig. 1d) over the last 58 years. The number of warm spells during the summer has slightly increased over 1950-2007 however most of the trends are not significant (Fig. 1e).

For 1900-2007, the strongest increasing trends are found in the annual mean maximum temperature (Table 1 and Fig. 2a). The summer mean maximum temperature shows some regional patterns with increase in the Prairies and on the east coast (Fig. 2b). The frequencies of warm events for the 1900-2007 period show a mixture of increasing and decreasing trends with similar regional distribution to the summer temperature (Fig. 2c and 2d). There is no evidence of changes in the number of summer warm spells (Fig. 2e) over the past 108 years. As mentioned in section 3, station data was used only if 80% of the years were available. This condition was met by less than half of the locations used in the 1950-2007 analysis and most of these stations are located in southern Canada.

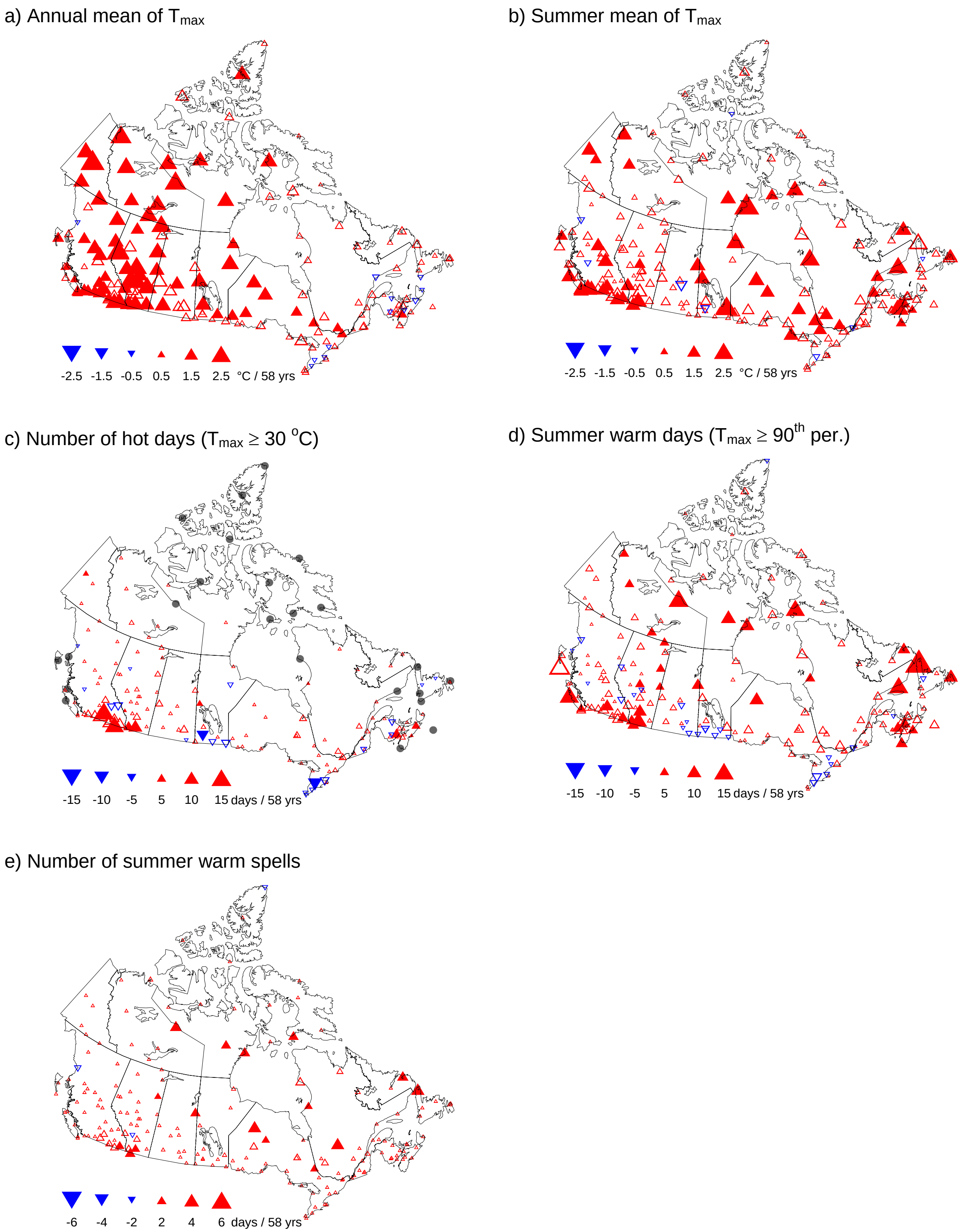

Figure 1. Trends in five temperature indices for 1950-2007. Red and blue upward and downward pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. T_{max} indicates daily maximum temperature. The grey dots indicate the stations for which the condition never occurs.

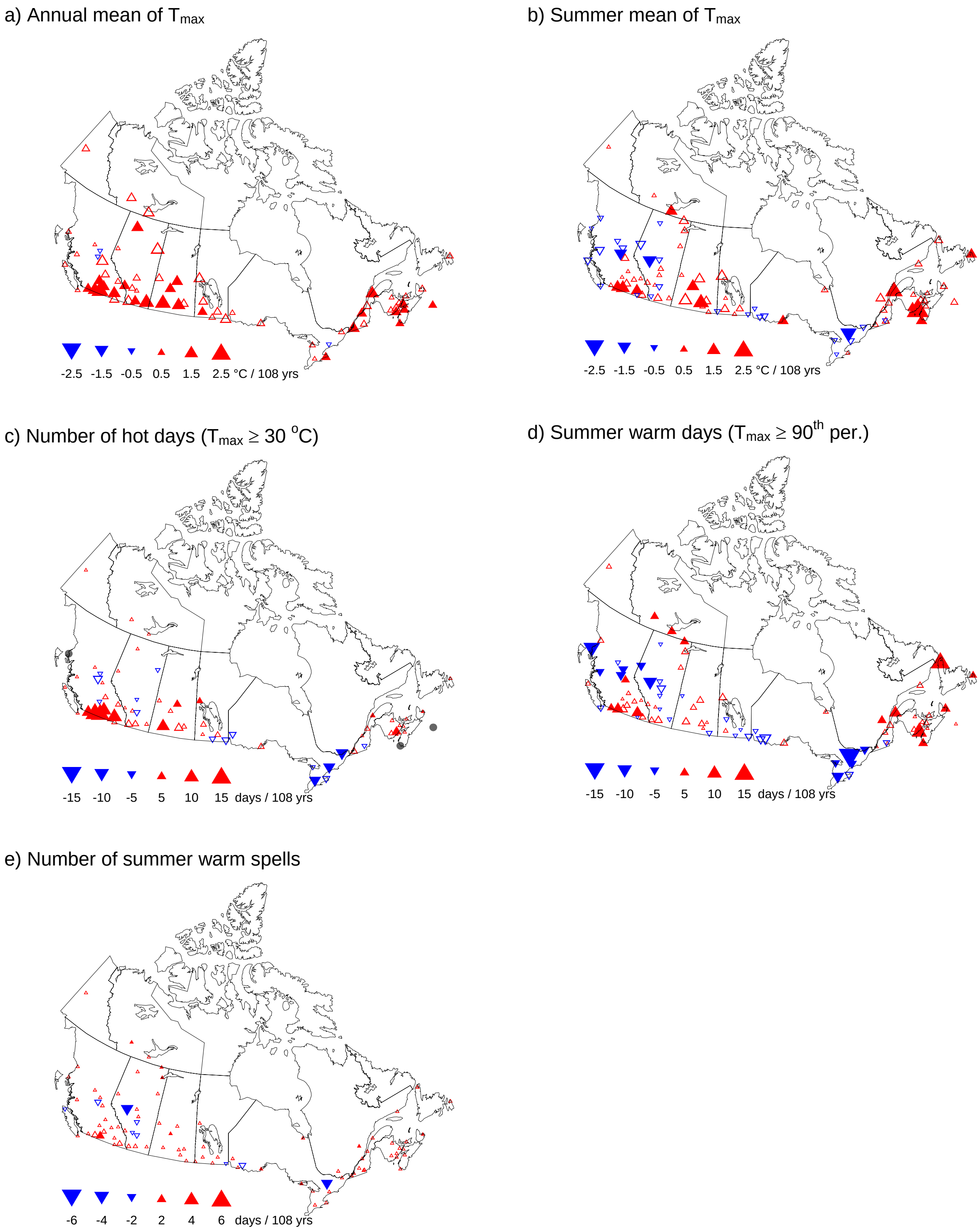

Figure 2. Trends in five temperature indices for 1900-2007. The caption is the same as in Figure 1.

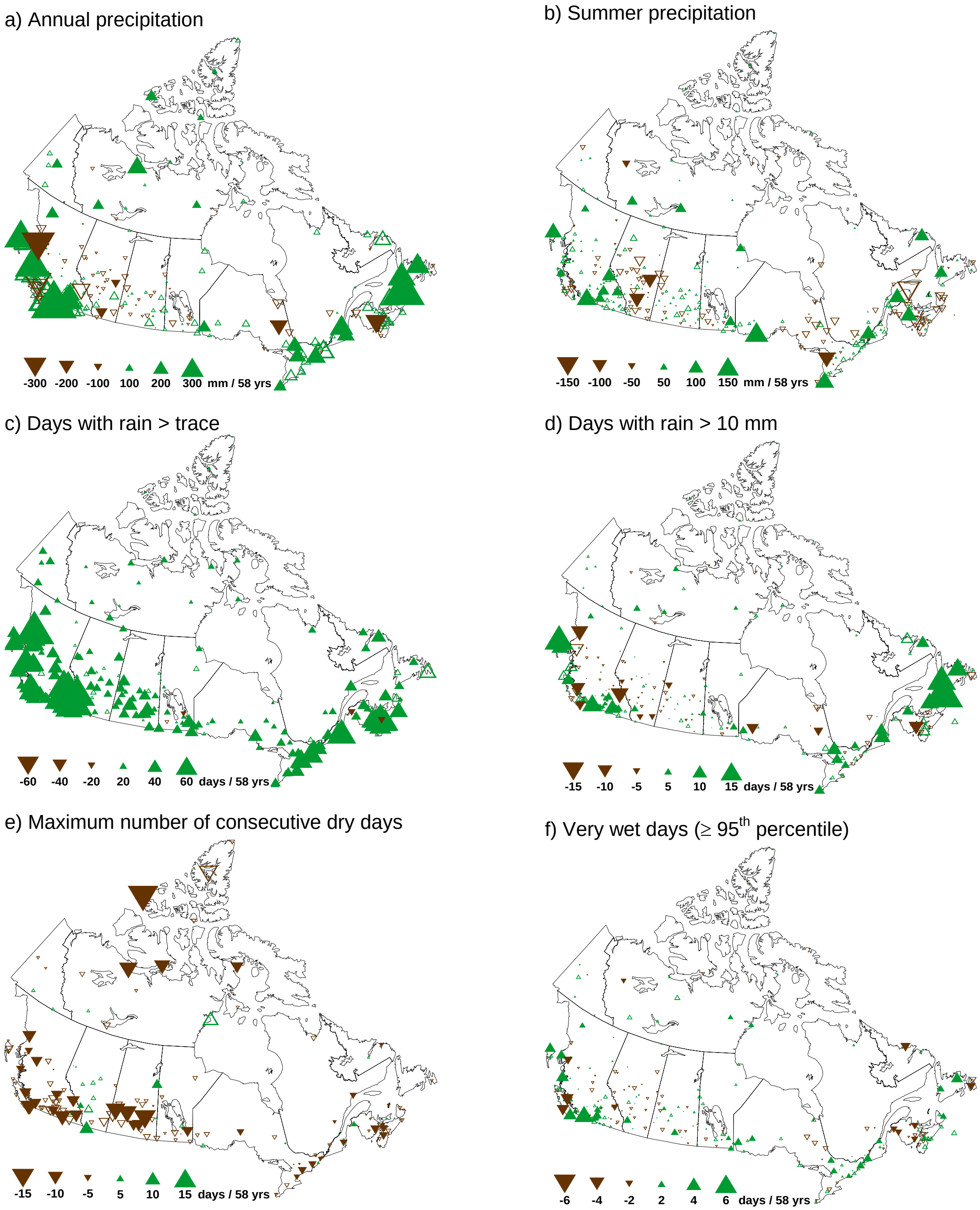

Figure 3. Trends in six precipitation indices for 1950-2007. Brown downward and green upward pointing triangles indicate negative and positive trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

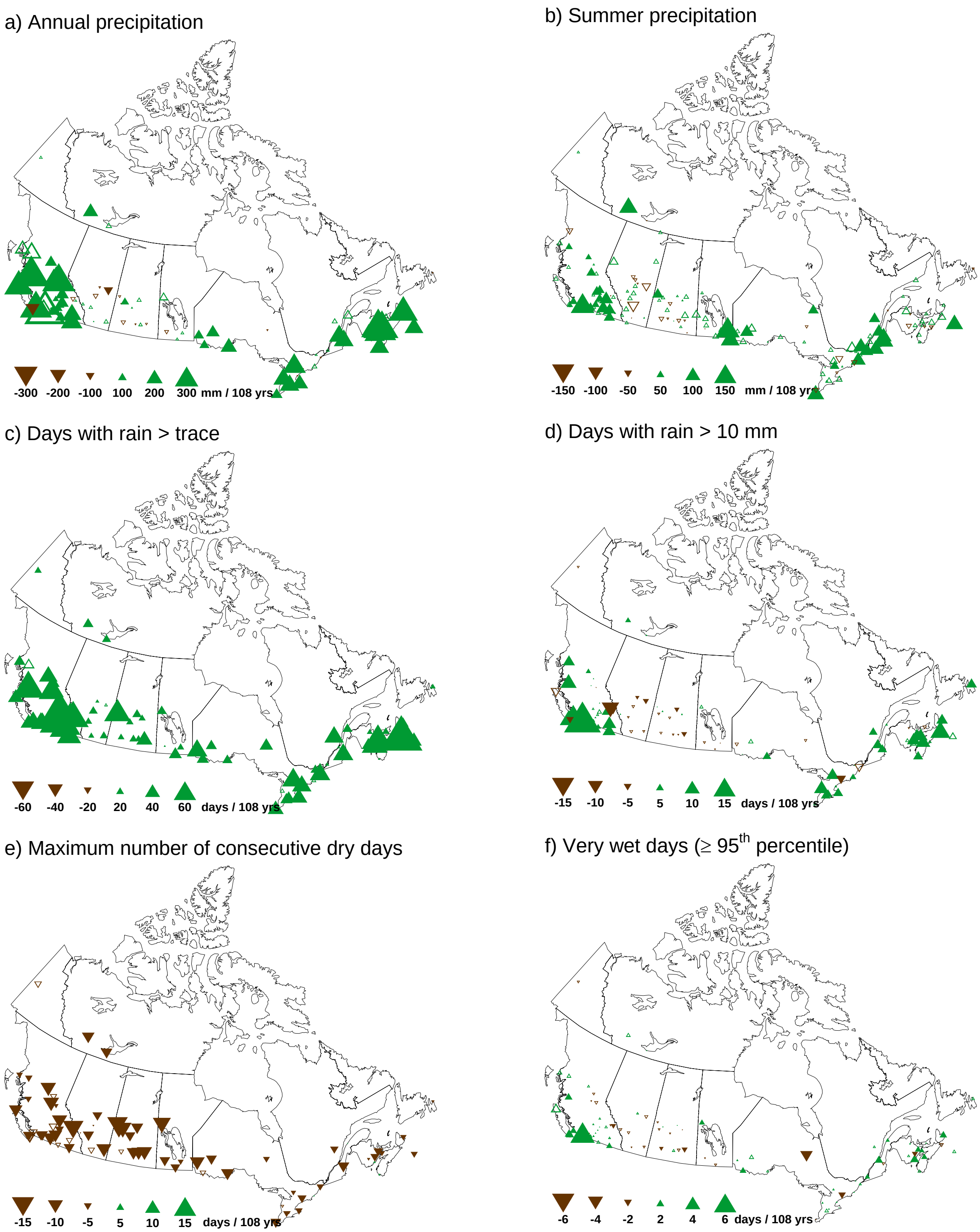

Figure 4. Trends in six precipitation indices for 1900-2007. Brown downward and green upward pointing triangles indicate negative and positive trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

4.2 Trends in precipitation indices

Trend results for both periods are summarized in the second part of Table 1. For 1950-2007, a mixture of positive and negative trends is detected in the annual precipitation (Fig. 3a). Since the trends in the actual annual total amount were obtained, the largest changes are observed on the coastal regions. The annual precipitation increase reaches as much as 300 mm at many stations. The summer trends show regional patterns (Fig. 3b). The number of days with rain has extensively increased through the whole country (Fig. 3c), more than 75% of the stations show a significant trend (Table 1). The days with rain greater than 10 mm (Fig. 3d) and the very wet days (Fig. 3f) do not show such a uniform pattern. Therefore the increase frequency of rain events occurred in the smaller range of precipitation events and not in the extremes. The maximum number of consecutive dry days is directly connected to the days with rain events, since there are more days with rain, the dry spells are shorter (Fig. 3e).

For 1900-2007, the changes are more pronounced than for the 1950-2007 period. The annual precipitation significantly increased at nearly half of the locations; the greatest increases are once again observed on the coastal regions (Fig. 4a). The summer precipitation has also increased at more than 20% of the stations (Table 1 and Fig. 4b). The days with rain events increased at all locations, significant trends were found at 85% of the locations (Fig. 4c). Consequently, decreasing trends were observed in the maximum number of consecutive dry days at all locations (Fig. 4e). The number of days with rain greater than 10 mm has also increased at many locations (Fig. 4d). More than 20% of stations indicate significant increase in the number of very wet days during the past 108 years (Table 1 and Fig. 4f).

4.3 Temperature and precipitation indices over the Prairies

Some studies have examined the droughts characteristics over the Canadian Prairies (Roberts et al. 2006), the atmospheric circulation patterns associated with the Prairies droughts (Bonsal and Wheaton 2005), and have done a historical comparison of the 2001/2002 Prairies droughts (Bonsal and Regier 2007). In the current study, the Prairies time series were prepared for each index to establish if these indices are good indicators of droughts over the region. Some well known Prairies droughts have been identified for the following years: 1936-1937, 1961, 1984-1985, 1988 and 2001-2002 (Bonsal and Regier 2007).

Figure 5 presents the Prairies time series for the five temperature indices. For the annual mean maximum temperature, the series shows that 1988 was more than 2°C above normal. The summer mean maximum temperature indicates that 1936, 1937, 1961, 1984, 1988 were more than 1°C above normal (1961 being more than 3°C above normal). The number of hot days and the summer warm days show similar results: more than 5 days above normal for 1936, 1937, 1984, 1988 and 2001 and about 15 days above normal for 1961. There was at least one more warm spell during 1936, 1937, 1984, 1988 and 2002 and at least 4 more spells in 1961 compared to the 1961-1990 average. Therefore the four summer temperature indices are probably better indicators of droughts in the Prairies. Table 2 shows significant increase of 1.2°C in the annual mean of maximum temperature for 1900-2007 and 1.6°C for 1950-2007. The Prairies time series for the six precipitation indices are given in Figure 6. The annual precipitation shows considerably drier than normal for the 1930's 1961, 1988 and 2001 while the summer precipitation show drier than normal for the 1930's, 1961 and 1984. The days with rain and the maximum number of consecutive dry days indicate an almost steady increase and decrease over the past 108 years respectively. The results for the number of days with rain above 10 mm and of very wet days show similar results: fewer days than normal with extreme precipitation was detected for the 1930's, 1961, and 2001. Significant changes were found in the number of days with rain (25.1 more days for 1900-2007 and 22.0 more days for 1950-2007) (Table 2), for the maximum number of consecutive dry days (10.7 and 5.3 fewer

Table 2. Prairies trends for the 1900-2007 and 1950-2007 periods. The numbers in bold indicate trends significant at the 5% level. The * indicates that the station percentage anomalies were used in the computation of the Prairies series

	Indices	Unit	1900-2007	1950-2007
Temperature	Annual mean of daily maximum temperature	°C	**1.2**	**1.6**
	Summer mean of daily maximum temperature	°C	0.9	0.7
	Number of hot days (Tmax > 30°C)	days	3.5	1.5
	Number of summer warm days (Tmax > 90th percentile)	days	2.0	1.6
	Number of summer warm spells	#	0.3	0.4
Precipitation	Annual total precipitation*	%	8.0	5.3
	Summer total precipitation*	%	1.3	5.9
	Days with rain > Trace	days	**25.1**	**22.0**
	Days with rain > 10 mm	days	-0.3	0.6
	Maximum number of consequtive dry days	days	**-10.7**	**-5.3**
	Very wet days (>95th percentile)	days	**-0.6**	0.3

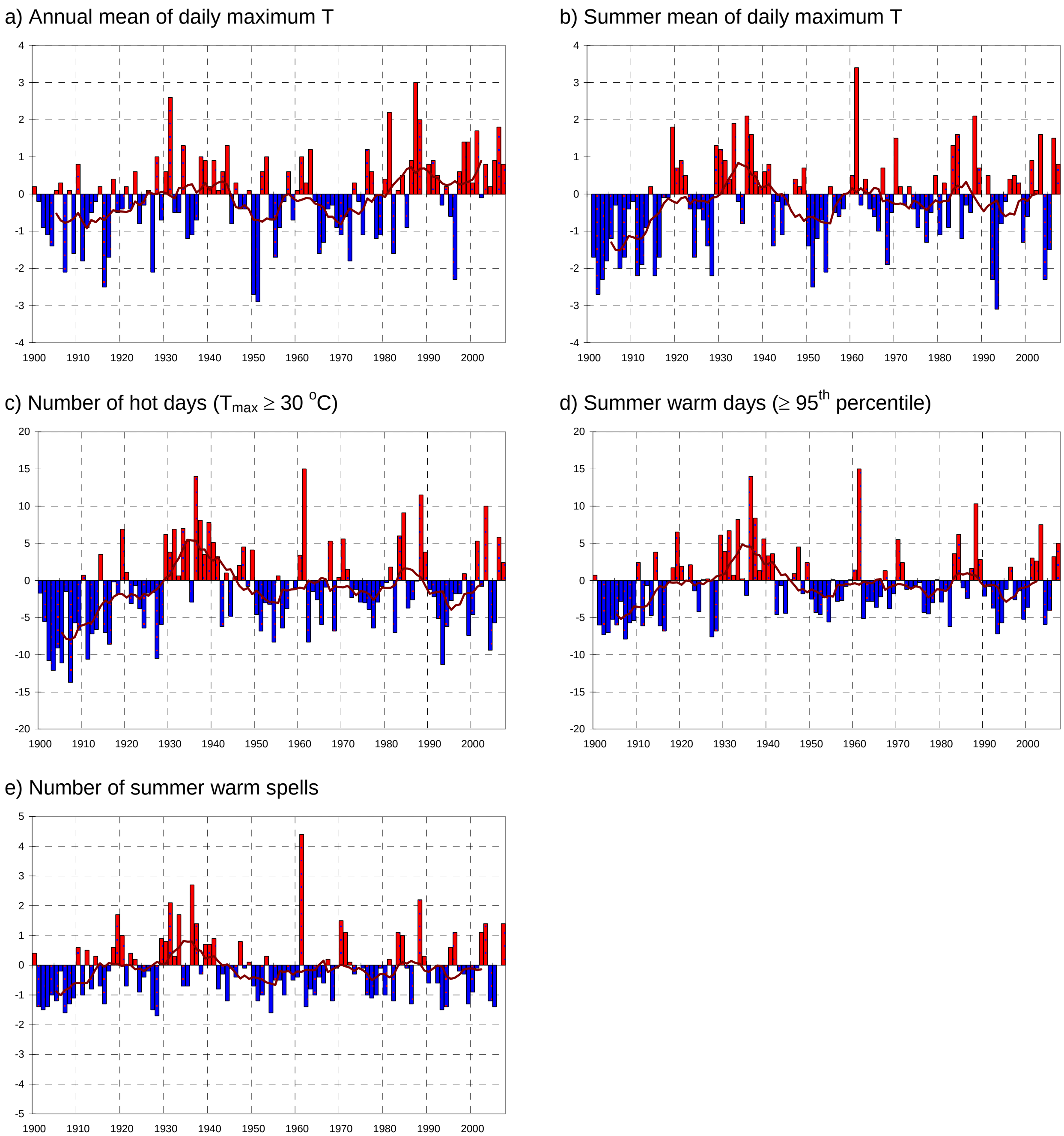

Figure 5. Prairie temperature time series for 1900-2007 computed from the station anomalies. The dark red line represents the 11-year running mean.

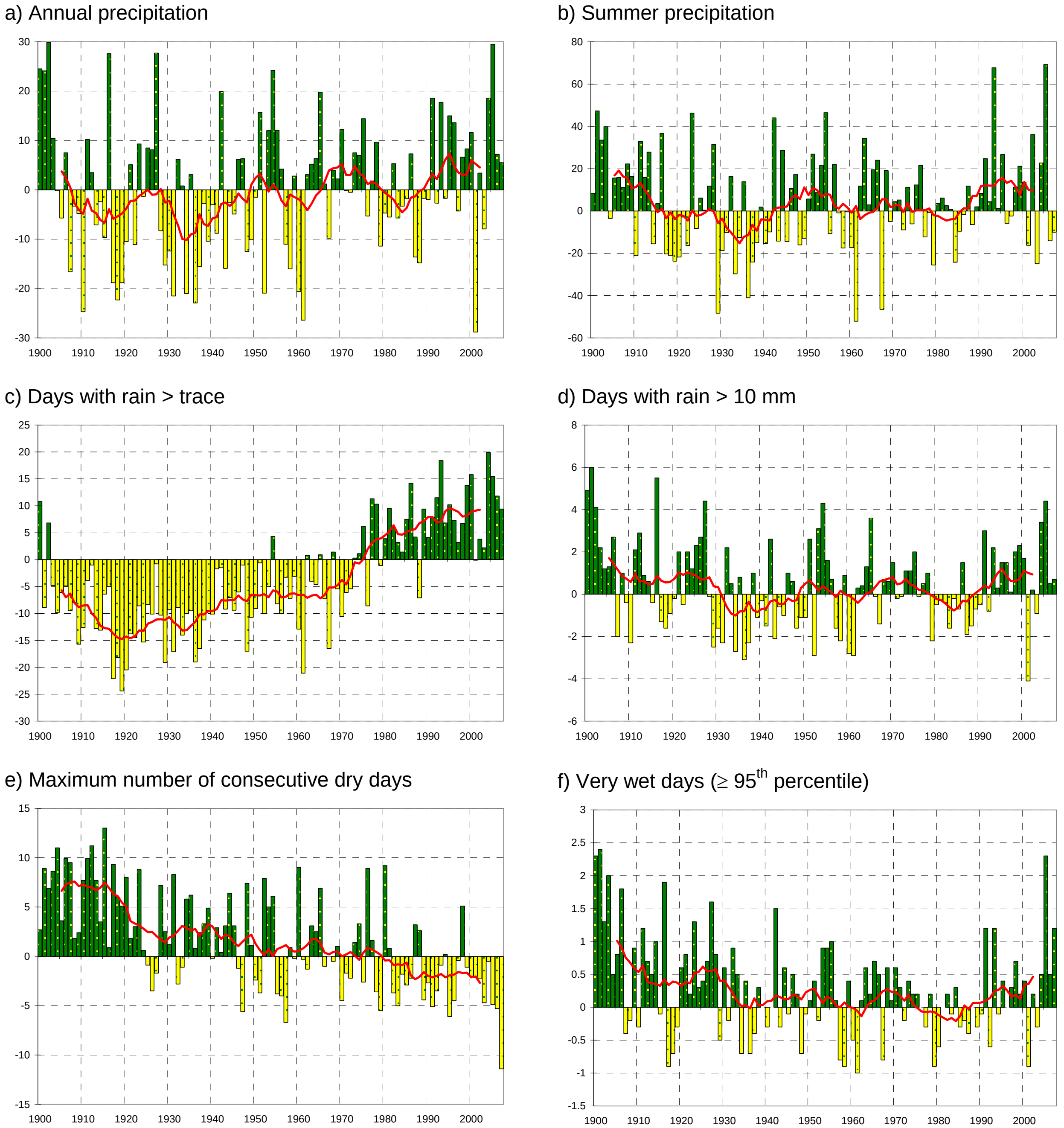

Figure 6. Prairie precipitation time series for 1900-2007 computed from a) and b) percentage station anomalies and c) – f) station anomalies. The dark red line represents the 11-year running mean.

days for 1900-2007 and 1950-2007 respectively) and for the very wet days (0.6 fewer days for 1900-2007).

The Prairies-wide mean of the percent of average annual precipitation indicator (North American Drought Monitor, 2008) was also computed (Fig. 7). The time-series displays very clearly the worst droughts occurring in the 1930's ("dirty '30s" or "dustbowl horrors"), the beginning of 1960's, 1988 and even the lack of water from 2001 to 2003 (in the current study, the year is defined from January until December and the agricultural year definition was not used). When the water shortage information at the beginning of the 2000's (Fig. 7) is combined with the consistently warm conditions (Fig. 5a), the severity of the 2001/2002 drought event has become clear. From historical perspectives, the water shortage before 1960 is more pronounced than for the past 50 years (Fig. 7).

5. CONCLUSION

This study examined the trends and variations of several possible temperature and precipitation indices related droughts over Canada. Prairies time series were also prepared to identify the major known drought events and to help understanding the relevance of some temperature and precipitation indices in drought occurrence assessment.

For temperature, the most significant change was found in the annual mean of daily maximum temperature where significant increases were found for both 1900-2007 and 1950-2007 intervals. In the summer series, significant changes were found in the more recent period. There is little evidence of changes in the number of hot days, summer warm days and summer warm spells. The summer mean of daily maximum temperature, the number of hot days and summer warm days seem to be good indicators of droughts in the Prairies.

For precipitation, significant increasing trends were found for days with rain across the country for both periods. Since the frequency of days with rain greater than 10 mm did not change in the same scale, it is concluded that the increase in rain occurs in the smaller range of precipitation events. More stations displayed significant changes during the 108 years. Both the annual and summer precipitation displayed increasing trends through the whole country with the exception of the Prairies.

For the Prairie precipitation series, even if the days with rain significantly increased, the extremes did not change and significant decrease of 0.6 days was found in the very wet days for the last 108 years. The annual and summer precipitation, and the days with rain and very wet days seem to be good indicators of droughts in the Canadian Prairies. The best single drought indicator was the percent of average precipitation, where all the major historical Prairie drought events could be detected.

6. REFERENCES

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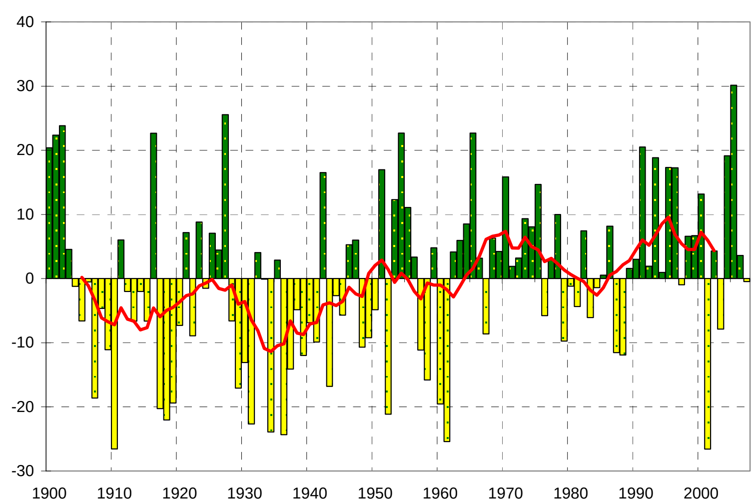

Figure 7. Percent of average precipitation for the Prairies calculated over the 1900-2007 base period.