Impact of Climatic Warming to the Droughts of Canadian Prairies

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Abstract
Results from applying Kendall's test to 37 stations of temperature and precipitation data, 50 stations of natural streamflow data and 13 stations of evapotranspiration data show that the Prairies have become warmer and somewhat drier in the last four to five decades. The earlier onset of spring snowmelt runoff detected by Burn (1994) further supports this finding. Results on Kendall's test on precipitation, natural streamflow and areal ET indicate that the Prairie may have become drier but the trends detected are less extensive when compared to warming trends. The correlation-distances reveal that temperature data are generally more correlated to each other than precipitation data. The bivariate precipitation versus maximum temperature test failed to detect any link between precipitation and temperature and Kendall's test on the drought duration, severity and magnitude prepared by Bauer and Welsh (1988) for two sites in Saskatchewan also shows no significant trend in the Prairie drought.

1. Introduction
For the past several years, the severity and frequency of extreme events like flooding or prolonged droughts seem to be on the rise in almost all continents. Does an increase in these natural disasters have anything to do with the impact of climatic warming, given that climate change should also bring changes to climate variability? For the Canadian Prairies, in view of its reliance on agriculture, and because of its semi-arid climate, droughts are more of a concern than floods, even though Alberta and Manitoba were flooded recently in 1995 and 1997. The Prairies rely mainly on surface water supply, which essentially is the precipitation minus the evaporation loss. Since both variables are intimately linked to the climate, it is logical to be concern with the external forcings of greenhouse effect on the Prairies' climate, particularly its future drought.

For the Canadian Prairies, the region formed by lines joining Cartwright of Manitoba, Lloydminster of Saskatchewan, and Calgary and Cardston of Alberta, is now known as the Palliser Triangle. In this part of Canada, at least twenty serious droughts had occurred in the nineteenth century, and the worst were in late 1880's and early 1890's. In this century, examples of severe droughts in the Prairies are droughts of the 1936-38, 1961, 1976-77, 1980, 1984-85, and 1988. As recurrent events, we are certain droughts will continue to occur in the Prairies but we do not know if future Prairie droughts will become more severe and or more frequent because of climatic warming, if climatic warming does occur. Under $2XCO_2$, General Circulation models (GCM) projected a global warming due to the greenhouse effects of 1.5 to 4.5 °C, with the most pronounced changes taking place in northern latitudes. GCMs such as GISS (Goddard Institute for Space Studies), GFDL (Geophysical Fluid Dynamics Laboratory), OSU (Oregon State University), and CCC (Canadian Climate Center) unaminously projected a warming over the Canadian Prairies for a 2 x CO_2 scenario, with the largest warming occurring in the winter. GCMs, however, are not consistent in their projections on precipitation and runoff changes in the Prairies. Besides, considerable regional differences have been shown for precipitation and soil moisture (Schlesinger and Mitchell, 1985). It is generally recognized that GCMs' simple land phase hydrology processes and coarse grid resolutions cause their projected hydrologic processes questionable, particularly at regional scales.

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From a study concerning the effects of global warming on the Saskatchewan River basin, Cohen (1991) found no consensus on five GCMs' projected changes in the net basin water supply (GISS84, GISS87, GFDL80, GFDL87, OSU). Despite uncertainties in GCMs' projections, his study indicated a decrease in soil moisture which would result in increased irrigation requirements. Some researchers, however, believe that GCMs generally over-simulated potential evapotranspiration at the expense of soil moisture. Gan (1995) showed that between 1949 and 1989 certain regions of Canada and northeast USA had exhibited significant warming trends in some seasons.

2. Research Methodology

The primary objective of this paper is to analyze the trend of past climatic and hydrologic data, and assess whether the Canadian Prairies has experienced climatic warming in the past several decades, whether it has become drier because of warming, whether there is any direct relationship between its temperature and precipitation, and whether its drought has become worse. To fulfill the objective, the non-parametric Kendall's test for trends (Kendall, 1975) was conducted on temperature, spring snowmelt dates, precipitation, streamflow, potential and actual evapotranspiration, drought duration, magnitude and severity. A bivariate test on precipitation versus maximum temperature was also conducted.

In addition to finding whether there is trend or not in temperature and precipitation data, the magnitude of trend β is also estimated (see Figure 2). For temperature data, β_k is expressed in $^{o}C\ year^{-1}$. To ensure that trends detected are most likely caused not by anthropogenic changes at the measuring stations but by natural and CO_2-induced variations of climate, only stations that were found to be homogeneous from a screening test conducted by Gullet et al. (1991) were chosen for this study.

3.0 Discussion of Results

The data tested for trends were temperature, precipitation, streamflow, drought (in terms of duration, magnitude and severity), and evapotranspiration. The significance levels used for two-sided hypothesis tests are $\alpha = 0.05$ and $\alpha = 0.10$, but the discussion of results is primarily based on the $\alpha = 0.05$.

3.1 Temperature

From Kendall's test on 37 stations of maximum temperature data (14 in Alberta, 14 in Saskatchewan, 8 in Manitoba, and 1 in Ontario), it is found that for the past 40 years (1949-1989) the Canadian Prairies have experienced warming (Figure 1), especially during January, March, April, and June. In March and June, over 60 % of the stations exhibited significant warming at $\alpha = 0.05$ (Table 1). Between September and December, the Canadian Prairies did experience cooling (results not shown) but not sufficiently to become significant at $\alpha = 0.05$. On a whole, the warming and cooling trends of the minimum temperature series are similar to that of the maximum temperature. As expected, the average temperature series (Table 1) also gives similar patterns and timing for the warming and cooling trends.

From the differences between average quarterly temperature of two 15-year periods (1959-1973 and 1974-1988), Hengeveld (1991) found similar trends in the Prairies in winter and spring. The number of stations showing trends are extensive enough for us to conclude that temperature trends in certain months are signals, not noise. The warming detected is likely an indication of a broadscale response to a systematic forcing mechanism, which in this case should be the greenhouse effect.

3.2 Precipitation

Tests of monthly precipitation data (Table 1) show that in the past 40 years, between November and February, 8% to 18% of the stations experienced a significant decrease of precipitation, and only one case of significant increase at $\alpha = 0.10$. However, unlike temperature data, these trends are scattered without any obvious pattern. It is unclear whether the scattered precipitation trends detected are noise or signals, given that intuitively warming should increase precipitation and vice versa, if other climatic factors remain unchanged. It seems that the high spatial variability of precipitation and the effects of other factors complicate the attempt to directly link the effects of warming on droughts.

Ripley (1986) found declining trends between 1910-1970 in the summer precipitation of three sites in Saskatchewan. Ripley, however, cautioned that it is too early to conclude whether this decrease in precipitation is a result of the greenhouse effect or only part of the natural climatic fluctuations. Given that GISS projects annual increases in precipitation, GFDL projects decreases in precipitation, and OSU projects both scenarios (Cohen, 1991), we should definitely take a cautious approach on any GCM projected precipitation.

3.3 Bivariate Test on Precipitation Versus Maximum Temperature

As an attempt to link warmer climate to more severe droughts, the Maronna and Yohai's (1978) bivariate test for detecting changes in the mean of an independent series $\{y_i\}$, the precipitation, relative to a second correlated series $\{x_i\}$, the maximum temperature, was conducted. This test depends on the assumptions that $\{x_i, y_i\}$ is an independent sequence of two-dimensional, bivariate normal, random vectors of size n, and the sequence is stationary, except it may have a possible shift in the mean of $\{y_i\}$. To ensure normality, the precipitation data were transformed to the normal domain using a 3-parameter, log-normal, quantile transformation procedure. In the process of transformation, problems finding realistic parameters were encountered in some stations and so these stations were discarded.

The null hypothesis H_0 for Maronna and Yohai's test is that all $\{x_i, y_i\}$ pairs have the same bivariate normal distribution, $N(\mu_x,\mu_y,\sigma_x^2,\sigma_y^2,\rho_{xy})$. The alternative hypothesis H_1, is that for some $0 < i_0 < n$ and $d \neq 0$, the distribution of $\{x_i, y_i\}$ is $N(\mu_x,\mu_y,\sigma_x^2,\sigma_y^2,\rho_{xy})$ for $i < i_0$ and is $N(\mu_x,\mu_y+d,\sigma_x^2,\sigma_y^2,\rho_{xy})$ for $i > i_0$. Both precipitation $\{y_i\}$ and maximum temperature $\{x_i\}$ are monthly data taken from a single site. The assumption of independence is satisfied since data are tested on a seasonal basis. The test might indicate whether there is a shift in the mean of precipitation relative to temperature, e.g., when $d \neq 0$.

The bivariate test results in Table 1 give no clear cut indication of a shift in the mean precipitation relative to temperature, even though on a whole there are more negative trends than positive trends. The numbers of tests that are significant in all months are few, irrespective of whether the second variable (temperature) shows strong trend patterns or not. Diaz (1986), likewise found no systematic relationship between changes in mean temperature and precipitation in northern North America and contiguous United States respectively. The assumption of stationarity may not be satisfied when the second variable, which in this case is temperature, has a trend; but apparently this does not matter because the trends detected are insufficient for us to conclude whether there is a direct link between warmer temperature and a decrease in precipitation, as concluded in Section 3.2.

3.4 Trend Magnitudes of Maximum Temperature, Precipitation and Streamflow

Trend Magnitudes β of maximum temperature in ^{o}C/year, precipitation in mm/year and streamflow in m^3/sec/year are estimated by the slope estimator of Equation 1. Since months are always heterogeneous, only trend magnitudes of individual months, not the annual values, are reported here. Histograms and boxplots of trend magnitudes given in Figure 2 reveal that majority of the temperature trend magnitudes are positive; and the positive values are also generally larger than the negative values. Therefore there are many more stations with positive temperature trends than negative trends (see Table 1).

In contrast to temperature, precipitation trend magnitudes estimated are primarily negative though such trends are relatively modest when compared to the temperature counterparts. In terms of variability, the boxplots also show that, other than the May and June precipitation, β at the 25th and β at the 75th percentiles do not differ much. However, the largest and the smallest β can be different from each other, particularly for maximum temperature in January and precipitation in June.

The histogram plot shows that about two-third of streamflow trend magnitudes are negative while one-third are positive. Similar results are found in the boxplots for March to October. Furthermore, boxplots show that most trend magnitudes are small but there are also quite a few outliers, which are predominantly negative (lines plotted below the boxes). These outliers likely represent droughts (minor or major) that occurred in the last several decades.

3.5 Spring snowmelt Dates

Burn (1994) used Kendall's test to estimate trends of the timing of the spring snowmelt runoff in the west-central Canada, which includes the Prairies, the northeastern and the northwestern forests. Out of 84 natural rivers (flow not affected by regulation), he found that 25 (30%) and 37 (44%) exhibited a trend of earlier spring runoff event at 5% ($\alpha = 0.05$) and 10% ($\alpha = 0.10$) significance levels respectively. Burn concluded that a greater number of rivers exhibited earlier spring runoff because of the impact of climatic change than because of chance occurrence. Burn's finding agrees with the general positive trends found in temperature data since warmer temperature, particularly during winter, bring in higher rainfall to snowfall ratios, decrease snowpack, and trigger earlier spring melt. The earlier onset of spring melt could lead to a longer period of low flows during summer and fall and a further drawdown of fall moisture reserves.

3.6 Natural Streamflow

As an attempt to resolve part of the uncertainty of precipitation data, trends from streamflow and evapotranspiration data were also analyzed. About 50 streamflow stations (depending on the month) of Water Survey Canada were selected for Kendall's test. To avoid the anthropogenic effects of streamflow regulation, only stations that recorded natural flows were chosen for the study. Given that many such stations in Canada stop recording streamflow during winter because of extremely low flow under river freeze-up conditions, the analysis was conducted on non-winter months only, i.e., March to October (see Table 3). Other than a few exceptions, the test periods chosen for these stations are mostly between late 1940's, or early 1950's to 1993, or 40 years in length.

Kendall's test shows that negative trends are much more extensive than positive trends, which happened mostly in March only (14%). The most severe negative trends happened mainly in May (22%) and June (18%), while less than 10% exhibited negative trends in the remaining months analyzed (Table 3). The positive trends detected in March can be attributed to an earlier onset of spring melt caused by climatic warming while relatively more extensive negative trends detected in May and June may be partly attributed to drier climate. On a whole, it seems that the Canadian Prairies has experienced less streamflow for the last four decades but the drier condition found may not be extensive enough for us to conclude that climatic warming has exacerbated the Prairie drought. Compared to the contradicting results between GISS, which simulated a substantial increase in runoff in the Rockies and GFDL, which simulated lower runoff (Cohen, 1991), it is more likely that runoff has decreased in the last several decades but generally only at a modest level.

3.7 Potential and Areal (Actual) Evapotranspiration

Since warmer temperature generally means greater demand for agricultural water and more evapotranspiration (ET), trends for the monthly areal and potential ET for 13 locations in Alberta were estimated (Table 3). The record length of monthly ET estimates tested vary from 34 years to over 80 years. All the ET estimates were computed by the Alberta Environmental Protection using the Complimentary Relationship Areal Evapotranspiration (CRAE) model (see Eq. 1) developed by Morton (1983). In Eq. 1, PET = Potential ET, AET = Areal or actual ET and WET = Wet environment ET. Details on computing the 3 terms of CRAE, using monthly variables like sunshine, dew point temperature or relative humidity, and mean air temperature, etc., are given in Morton (1983).

$$PET + AET = 2\ WET \qquad (1)$$

As expected, due to the warming trends of March to June, many of the test sites (54% to 77%) exhibited positive trends in the potential ET in these few months. However, according to Morton's CRAE model, the areal or actual

ET exhibited opposite trends (negative), particularly for April, May, July and August (over 70%). This contradicts the results of a drought analysis in the Saskatchewan study by Williams et al. (1988) who concluded that ET will increase because of elevated temperature.

The plausible reason that a greater potential for ET caused by a warmer climate could end up in a generally less actual ET is that the Prairies has been getting drier because precipitation has decreased and so there is less moisture available for ET to take place. Albeit negative trends detected in precipitation are scattered in patterns, and that of streamflow are also not extensive, the additional results of potential and areal ET seem to further support the conjecture that the Prairies has become drier in the past four to five decades. The range of annual mean potential and areal ET estimated from CRAE for the 13 locations in Alberta are (789.8mm, 1131.5mm) and (308.2mm, 416.3mm) respectively. With an annual areal ET of about 350mm and annual precipitation of about 450mm, it is obvious that ET plays a major role on the water budgets of Alberta and the rest of the Prairies. However, again the evidence gathered from trend analysis on historical data has not provided sufficient evidence for us to conclude that warmer climate will lead to more severe droughts in the Prairies.

3.8 Trends of Drought Duration, Magnitude and Severity

From the negative trends detected in natural streamflow, scattered trends in precipitation, and trends in areal ET, it seems that the Canadian Prairie has become drier. Implicitly that can be interpreted as the Prairie drought has become worse, since drought is a relative term. The bivariate test of Section 3.3, however, does not show a link between warmer temperature and a decrease in precipitation. To objectively identify if drought in the Prairie has really got worse because of warming, trends in the time series representing meteorological drought for two sub-regions of South Saskatchewan River, one located near Saskatoon and one around Lake Diefenbaker were estimated. These two sites are chosen because the South Saskatchewan River Basin has been prone to drought and around these two sites, there has been significant warming and negative precipitation trends detected, and the onset of spring snowmelt runoff has also been earlier (Section 3.5).

Three components of drought -- duration (number of months), magnitude (average water deficiency in mm/month) and severity (cumulative water deficiency in mm) -- were tested for trend using Kendall's test. The time series of these three drought components of the two test sites for the 1912 to 1987 period were prepared by Bauer and Welsh (1988) who adopted the following criteria to define a meteorological drought: (1) A drought was deemed to have begun in the first of three successive months with a precipitation deficit provided that in at least one of the three months the deficit was greater than the mean monthly deficit (which is the sum of all the deficits for the given months over the period of record divided by the number of deficits) for that month; (2) A drought was deemed to have ended in the month prior to the month in which the cumulative total of deficits and surpluses from the beginning of the drought became positive or in the last month with a deficit prior to a period when at least two of three months had a surplus.

No significant trend at $\alpha = 0.05$ or $\alpha = 0.10$ was detected from any of the three drought components in both test sites. Conversely, the duration and severity of drought in the Lake Diefenbaker area have even become less severe though the change has not been significant statistically (see Table 4). Also, with only scattered trends being detected in the precipitation, it seems unnecessary to extend the test to other sites in the Prairie. The Prairie might have become warmer and drier in the last four to five decades, but there is yet solid evidence to conclude that climatic warming, if occurred, has caused the Prairie drought to become more severe. Apparently Williams et al. (1988)'s conclusion, that the frequency of drought could increase by a factor of 3 to 10, or would be more severe and longer, may be premature.

To ensure further economic growth in the Prairie provinces, a dependable, long-term water supply system is indispensable. Given that future droughts may happen more frequently and by larger scales because of climatic warming, it will be wise to implement some water resource strategies, and fine-tune our actions as the impact of climatic change unfolds.

4.0 Summary and Conclusions

Results of Kendall's test applied to the maximum, minimum and average temperature data of 37 stations in the Prairies, and to the potential ET in 13 sites in Alberta generally show that the Prairies has become warmer in the last four to five decades. The earlier onset of spring snowmelt runoff detected by Burn (1994) further supports this finding. Results on Kendall's test on precipitation, natural streamflow and areal ET indicate that the Prairie may have become drier but the trends detected are less extensive. The correlation-distances reveal that temperature data are generally correlated to each other while precipitation data are not. The bivariate precipitation versus maximum temperature test failed to detect any link between precipitation and temperature and Kendall's test on the drought duration, severity and magnitude prepared by Bauer and Welsh (1988) for two sites in Saskatchewan also shows no significant trend in the Prairie drought.

It is fairly obvious that the temperature trends detected in this study is partly due to human activities but it is difficult to separate the anthropogenic component from that due to climate variability. It is even harder to do the same to trends detected in other variables tested in this study. To understand the occurrence and evolution of the Prairie drought, we should identify and separate dominant, deterministic components of the Prairie drought from high frequency variations. Drought-producing mechanisms are intimately linked to the general hemispheric circulation, which in turn are affected by the land/atmosphere interactions, and on an interannual time scale, by the coupling of the atmosphere/ ocean/land/cryosphere system. It has been suggested that the Prairie drought may be related to North Pacific Ocean SST (Ripley, 1988) and North Pacific and North Atlantic SST (Rasmussen, 1988). Given that decadal-scale, severe summer droughts over the Prairies or the Great Plains are rare, even during the 1930's, Rasmussen also suggested looking for biennial variability in the Prairie climate elements, such as that of QBO (Quasi-biennial oscillation). So far ENSO has been associated to winter-time temperature field in western Canada, flood and drought in central Canada (Gingras and Adamozski, 1995), and streamflow patterns in the U.S. (Kahya and Dracup, 1993). Ripley (1988) suggested further exploring the effects of ENSO over the Rocky Mountains which contain the headwaters of major rivers in the Prairies. Another possible approach may be to identify the low frequency components of climate variability and relate them to drought, since drought is part of climate variability and has manifested long-term memory.

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Table 1 Results of trend analyses using Kendall's test on 37 climatic stations of monthly temperature and precipitation data; and results of bivariate test on 26 climatic stations of precipitation versus maximum temperature of the Canadian Prairies.

		November		December		January		February		March		April		May		June	
Climatic Variable	Types of Trend# / α-level	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
Maximum Temperature	0.10	0	0	0	0	29	0	0	0	31	0	23	0	15	0	24	0
	0.05	0	0	0	0	22	0	0	0	23	0	10	0	7	0	22	0
Minimum Temperature	0.10	0	1	0	0	29	0	5	0	35	0	17	0	17	0	15	0
	0.05	0	0	0	0	19	0	0	0	33	0	8	0	15	0	12	0
Average Temperature	0.10	0	0	0	0	29	0	3	0	35	0	18	0	15	0	25	0
	0.05	0	0	0	0	24	0	0	0	31	0	11	0	6	0	20	0
Precipitation	0.10	1	7	0	3	0	7	0	9	0	1	0	2	1	0	0	5
	0.05	0	3	0	2	0	5	0	7	0	0	0	0	0	0	0	3
Precipitation versus Maximum Temperature	0.10	1	5	1	0	1	4	2	3	2	1	1	0	1	3	0	4
	0.05	1	2	0	0	1	1	1	1	1	1	0	0	0	2	0	3

Table 2 Estimated correlation distances (km) in the north-south and east-west directions for monthly maximum temperature and precipitation of 28 stations in Alberta and Saskatchewan.

	North-South Direction				East-West Direction			
	January	April	July	October	January	April	July	October
Maximum Temperature	2200	1700	410	1800	3600	1930	630	1270
Precipitation	100	100	#	120	230	220	100	280

No realistic correlation distance (the distance in km at which the cross-correlation coefficient is equal to 0.5) was obtained.

Table 3 Results of trend analyses using Kendall's test on 51 stations of monthly streamflow located mostly in the Canadian Prairies, and 13 stations of potential and areal evapotranspiration located in Alberta.

	Streamflow				Potential Evapotranspiration				Areal Evapotranspiration			
α-level	0.10		0.05		0.10		0.05		0.10		0.05	
Types of Trend#	+	-	+	-	+	-	+	-	+	-	+	-
March	9	2	7	0	9	0	8	0	3	0	2	0
April	2	7	0	4	12	0	10	0	0	10	0	10
May	2	20	1	11	7	0	7	0	0	10	0	9
June	0	13	0	9	10	0	9	0	2	6	2	6
July	1	5	0	4	5	0	4	0	1	8	0	8
August	0	5	0	3	5	0	5	0	0	9	0	8
September	2	4	1	4	4	0	3	0	0	7	0	6
October	0	5	0	4	5	0	4	0	0	6	0	6

+ = Positive trend, - = Negative trend

Table 4 Kendall's statistics obtained for two sub-regions of South Saskatchewan River regions (around Saskatoon and Lake Diefenbaker) show no significant trend in drought duration (months), magnitude (mm/month) and severity (mm).

	Kendall's statistics normalized to the Normal (0,1) domain*		
	Drought duration	Drought Magnitude	Drought Severity
Saskatoon	-0.20	0.98	0.50
Lake Diefenbaker	-1.31	-0.06	-1.31

* For a two-sided test, trends are considered significant if the absolute values of the Kendall's statistics are equal or greater than 1.645 at $\alpha = 0.10$ and 1.96 at $\alpha = 0.05$ respectively.

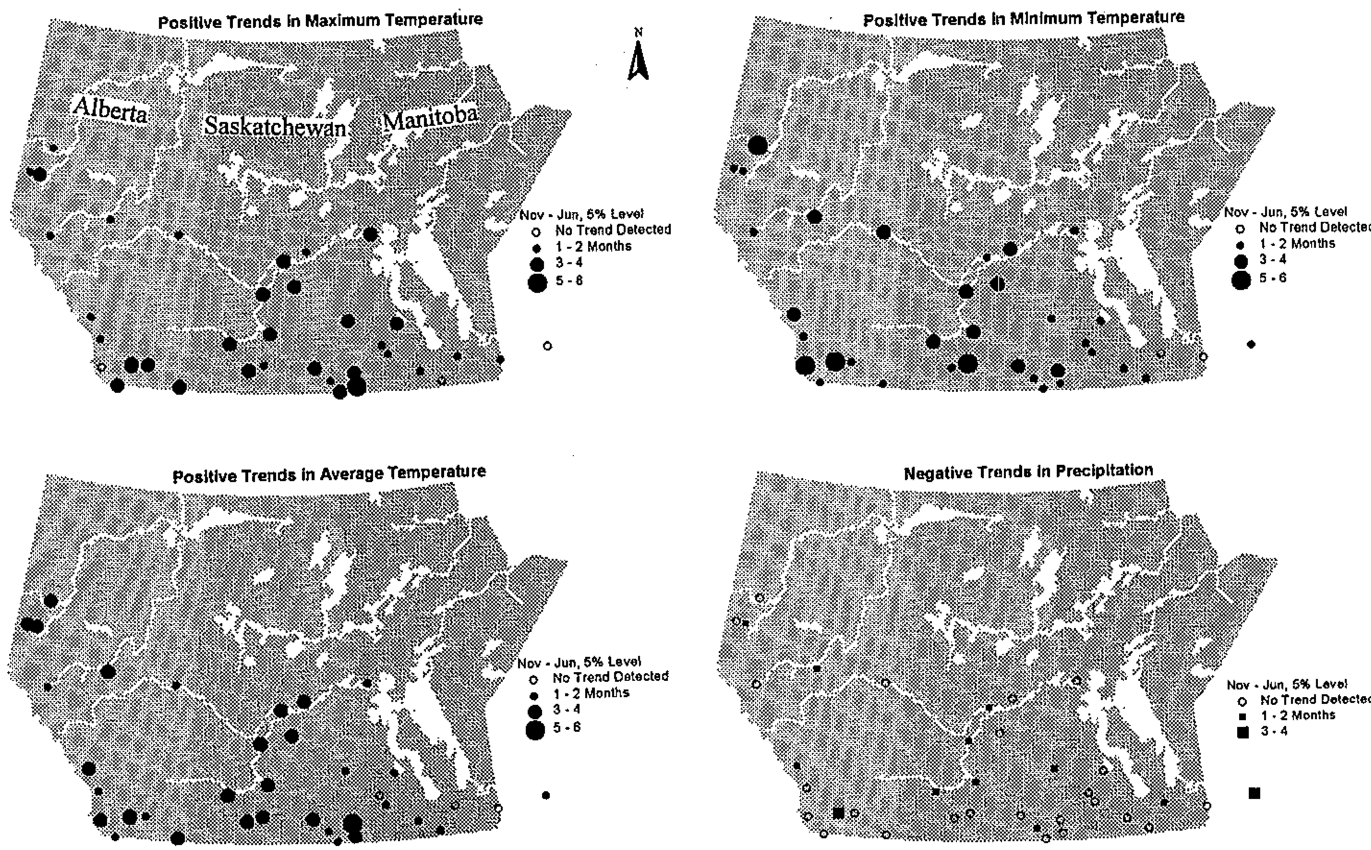

Figure 1 The number of months (out of 8) for each of the 37 stations that show significant trends based on the univariate Kendall test applied with a two-sided test ($\alpha = 0.05$). Virtually all the maximum, minimum, and average monthly temperature data in the Canadian Prairies tested with significant trends are positive trends while the significant trends of precipitation data are negative trends.

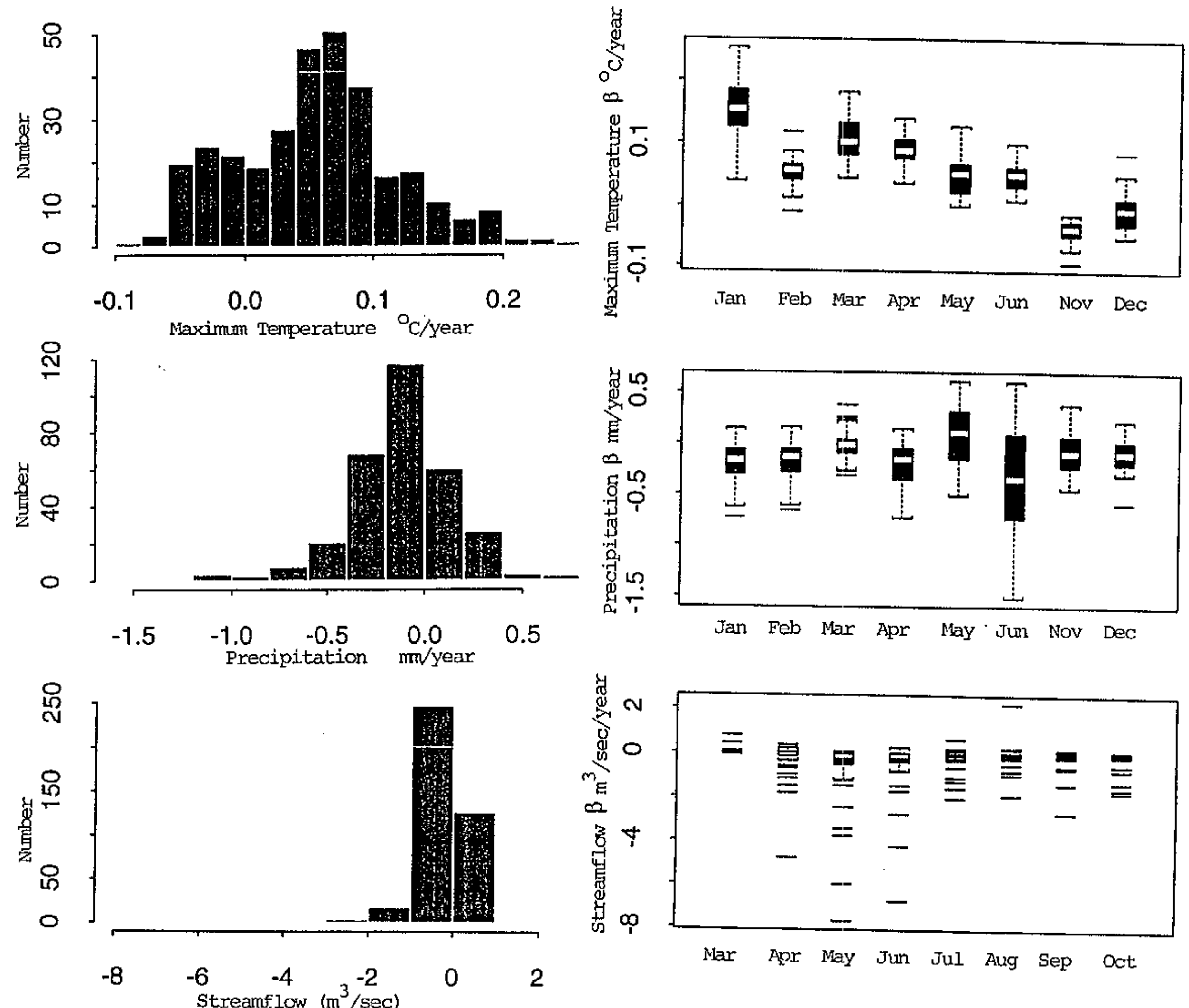

Figure 2 Histograms that show the overall distribution, and boxplots that show the monthly distributions (which include outliers) of the trend magnitude β obtained for the Prairies' maximum temperature (β in °C/yr), precipitation (β in mm/yr), and streamflow data (β in m^3/sec/yr).