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Changes in the hydrological character of rainfall on the Canadian prairies

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Abstract:

Many studies have examined trends in the amount and phase of precipitation on the Canadian prairies over the period of record but without considering the unusual hydrology and hydrography of the region. On the Canadian prairies, runoff is primarily due to spring snowmelt over frozen soils but can also be caused by intense rainfall from summer thunderstorms. The fraction of spring snowmelt forming runoff is strongly influenced by the rate of melt and the presence of ice layers near the surface in frozen soils or at the base of the snowpack, all of which can be influenced by rainfall in the spring and late fall. Precipitation intensities sufficient to cause runoff are generally due to small, intense convective storms, which are prevalent during the summer months. Historical records of the fraction of monthly precipitation falling as rain, obtained from the Historical Adjusted Climate Database for Canada (HACDC), were found to display statistically significant increasing trends over the periods 1901–2000 and 1951–2000 at many locations on the Canadian prairies. The fraction of stations showing significant trends, and the importance of the trends, were strongly dependent on the month of the year.

Single-day summer rainfalls are believed to be primarily convective in the Canadian prairies. Historical records obtained from HACDC indicate that the hydrological importance of single-day summer rainfalls has not increased and has shown significant decreases at many locations over the periods 1901–2000 and 1951–2000. Conversely, the hydrological importance of summer multiple-day rain events has not decreased and has significantly increased at many locations over the periods analysed.

Multiscaling analyses of summer rainfall events demonstrated that the temporal uniformity of rainfall on the Canadian prairies has increased over the periods 1901–2000 and 1951–2000. Analyses of the ratios of rainfall over multiple days demonstrate significant trends over the same periods, confirming the general tendency to temporal uniformity over scales between 1 and 32 days. Longer rain events strongly suggest greater spatial extents for storms and therefore the potential for increasing tendencies to promote basin-scale rainfall–runoff events such as seen in 2011 in the region.

KEY WORDS rainfall; hydrology; trend; prairie

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INTRODUCTION

Many researchers have examined the historical record for the presence of significant trends in precipitation in the Canadian prairies and other regions (Akinremi *et al.*, 1999; Stone *et al.*, 2000; Zhang *et al.*, 2001; Vincent and Mekis, 2006). The existence of significant trends demonstrates the non-stationarity of the climate and serves as a guide to the downscaling of future climate simulations.

The hydrography of the Canadian prairies is unusual in that many of the major rivers rise in the Rocky Mountains and their foothills and, in most years, are little affected by inflows from the prairie agricultural and grassland pasture regions. Smaller streams are affected by local runoff, which is only produced from snowmelt or rainfall over frozen soils, intense rainfall rates in summer or long-term heavy rainfall in spring and summer, but the records of these streams are scarce, short and rarely complete. Therefore, analysis of the rainfall variables capable of causing runoff can ultimately contribute to methods for estimating trends in the flows of Canadian prairie streams.

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Some common climatological variables used to detect the effects of climate change are described by Mekis and Vincent (2005) and Peterson *et al.* (2001). The joint CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) defines 27 core indices of climate change, which can be accessed on its website at http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml. The ETCCDI precipitation variables are monthly maximum 1-day precipitation, monthly maximum consecutive 5-day precipitation, simple precipitation intensity index, annual count of days when precipitation is $\geq$10 mm, annual count of days when precipitation is $\geq$20 mm, annual count of days when precipitation is greater than or equal to a defined value, maximum number of consecutive days with rainfall is $\geq$1 mm, annual total precipitation in wet days, annual total precipitation when rainfall >95th percentile and annual total precipitation when rainfall is >99th percentile. The percentiles are of precipitation on wet days in the 1961–1990 period.

The use of standardized indices for detecting climate change is understandable and often desirable, but the standardized precipitation variables used do not necessarily correlate with important hydrological events in specific hydroclimatic regions. This is particularly true for the Canadian prairies where, because of the region's dry, cold climate and unusual hydrography, surface runoff events are comparatively rare and are caused by very specific types of events.

Although snowfall generally constitutes about a third of annual precipitation on the Canadian prairies, the spring melt of the winter snow accumulation typically causes the majority of annual runoff in prairie basins because of the restricted infiltration rates of frozen soils, large spatial extent and synchronicity of snowmelt and low spring evaporation rates. Figure 1, which plots the monthly fractions of annual peak runoff events for small streams in the Canadian prairies, demonstrates that more than two-thirds of the annual peaks occur during March and April and are due to the spring freshet. Similarly, more than two-thirds of the annual flow volume of the selected sites also occurred during the months of March and April.

The phase of precipitation in the spring and fall influences runoff from the spring snowmelt freshet in two ways. In the spring, atmospheric conditions associated with rain falling on a snowpack typically include a saturated atmosphere at above freezing temperatures. These conditions can accelerate melt by transferring kinetic energy, conductive heat, turbulent sensible and/or turbulent latent heat to the snowpack. The latent heat contribution from condensation on the snowpack is normally the largest contribution (Marks *et al*., 1998). Rain on snow can also contribute direct runoff by rapid movement through the snowpack (Singh *et al*., 1997). Increases in fall rainfall may also contribute to enhanced spring runoff by reducing the infiltration of subsequent snowmelt water into frozen soils through the formation of impermeable ice layers at the soil–snow interface (Gray *et al*., 2001). All other factors being equal, trends that increase the rain fraction of spring and fall precipitation, will tend to cause increased runoff in the spring freshet. Fang and Pomeroy (2007) demonstrated this in a climate change simulation using physically based hydrological model of a small prairie stream that included energy balance snowmelt and infiltration to frozen soil algorithms. The modest warming (2.6 °C) and wetting (11%) predicted by an ensemble of selected scenarios by 2050 for south-west Saskatchewan led to a 24% increase in spring runoff. The impact of the phase change of precipitation in fall and spring from snowfall to rainfall was a major factor in this increase in prairie snowmelt runoff.

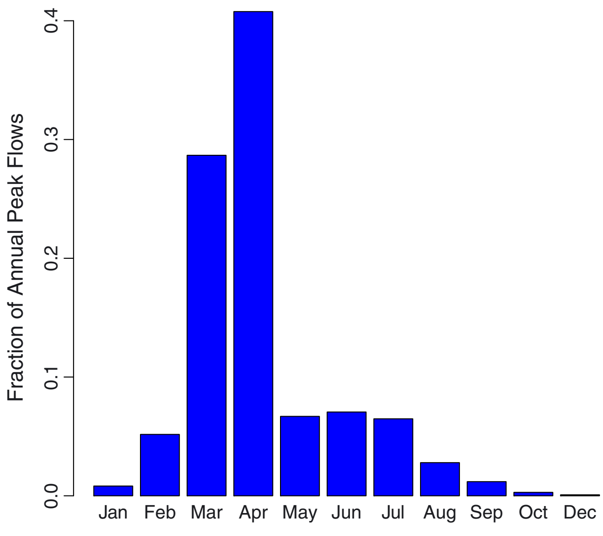

Figure 1. Monthly fractions of annual peak flows for all 89 unregulated prairie streams having gross basin areas smaller than 1000 km², over the period 1919–2009. Data from the Water Survey of Canada, available at http://www.ec.gc.ca/rhc-wsc/

On the Canadian prairies, summer rainfall is rarely capable of causing runoff as infiltration rates generally exceed rainfall rates and evapotranspiration rapidly depletes soil moisture so that soils are unsaturated for most of the summer and saturation overland flow is unusual. Very exceptionally, large frontal rainfall systems have persisted for a long period, and then saturation overland flow does occur, one example being the Souris River floods of 2011. Thunderstorms, which occur frequently during the summer months, can produce very intense rainfall rates over small areas, which can exceed the soil's ability to infiltrate water, causing infiltration excess (Hortonian) runoff. Rainfall intensities on the Canadian prairies can be quite high and spatially variable as a result (Dyck and Gray, 1979). The small spatial extent of thunderstorms means that they are generally not able to generate enough runoff to cause changes in the discharge of Canadian prairie rivers.

Raddatz and Kern (1984) classified Canadian prairie precipitation types by their approximate horizontal scales, including thunderclouds (1 km), fronts and squall lines (10–100 km) and synoptic cyclones (1000 km). Thunderstorms are entirely convective in nature, whereas larger scale events may be non-convective or may contain regions of convection embedded within non-convective frontal system rainfall. Raddatz and Hanesiak (2008) examined more than 1000 24-h rainfalls greater than 10 mm on the Canadian prairies over the period 2000–2004 and found that 79% were wholly or partially convective.

Thunderstorms tend to be small and fast moving, and although the area affected by each storm may be small, they can be very frequent (Gray, 1970). Raddatz (2000), in examining prairie summer rainfalls for the years 1997–1999, determined that some water vapour from regional evapotranspiration was recycled and was responsible for 24–35% of the total rainfall, the remainder being advected into the region. The prevalence of precipitation recycling is consistent with small-scale convective storms.

The post-glacial hydrography of the Canadian prairies may also allow storms whose rainfall rates are smaller than the rate of infiltration to cause runoff. Rather than having a conventional drainage system derived from fluvial erosion, many of the Canadian prairies drains internally to small topographic depressions left by glacial ice; wetlands have formed in many of these depressions (Stichling and Blackwell, 1957). In many cases, the wetlands are situated on nearly impermeable glacial till, which restricts deep percolation of water (Woo and Rowsell, 1993), and runoff from these wetlands only occurs when their water storage exceeds their depressional storage capacity (Fang *et al*., 2010). Once a wetland is full, all further direct rainfall to the wetland, less open water evaporation, will overflow becoming surface runoff, regardless of the rainfall rate.

Three types of prairie rainfall are of great hydrological interest and were selected for analysis: (1) short duration (typically convective) rain storms, (2) accumulations of rainfall over multiple days and (3) rainfall occurring during the fall and spring, usually over frozen, partially thawed or saturated soils. The purpose of this research is to determine how the distribution of Canadian prairie rainfall has changed over the period of record in ways that can readily affect the region's hydrological response by studying changes in trends in precipitation variables, which can most directly influence prairie hydrology.

Because there are multiple runoff-generating mechanisms that can interact in many different ways, the importance of a trend in a given variable is difficult to assess without the use of a physically based model of prairie hydrology. The intent of this research is to determine the locations where there are statistically significant trends in the forcing variables that are linked to prairie runoff. Those variables showing significant trends at large fractions of the stations tested are therefore identified as being the most important to investigate further for their significance in influencing trends in prairie runoff.

DATA SETS

All data were obtained from the Historical Adjusted Climate Database for Canada (HACDC). Monthly data can be downloaded directly from the website at ec.gc.ca/dccha-ahccd. Daily values must be obtained by e-mailing the researchers who produced the data. These data originate from meteorological stations operated by the Meteorological Service of Canada to World Meteorological Organization standards as they developed over time. These values were then adjusted for the effects of measurement errors as described by Mekis and Vincent (2011). Thus, they represent the best-quality historical data that can be obtained for Canada and are as free from bias because of changes in collection methodology as possible. Sub-daily data do not exist in the data set.

The sites selected for analysis lie within the Canadian prairie ecozone as described by Marshall *et al*. (1996). The outline of the Canadian prairie ecozone is plotted on all maps in this paper. Two periods were selected for analyses. The interval 1901–2000 provides a long record, but only very small numbers of sites on the Canadian prairies have complete records over this period, even with the joining of records performed by Mekis and Vincent (2011). The interval 1951–2000 allows the analysis of many more stations, over a shorter period.

Precipitation variables

Any significant trends in the fall and spring rainfall may be due to trends in the overall monthly precipitation and/or trends in the phase of the precipitation. Accordingly, the fraction of monthly precipitation falling as rain was examined for the selected stations over the period of analysis. The rainfall fraction was determined by dividing the total monthly rainfall by the total monthly precipitation. The locations of the 11 sites, which had values over the period 1901–2000, and of the 38 sites having values over the period 1951–2000 are plotted in Figure 2.

As described previously, sub-daily rainfall data are not available in the HACDC database, and therefore, single-day rainfalls were selected as indexes of convective storms. Although empirical relationships (such as intensity–duration–frequency curves) and scaling theory can define the relationship between daily and shorter duration rainfall intensities, they cannot determine how these relations have changed over time. Therefore, the actual changes in

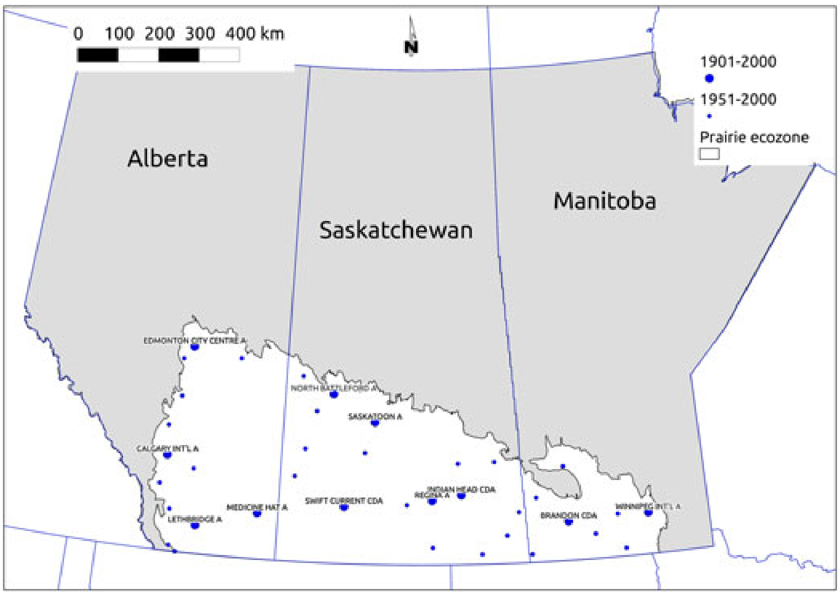

Figure 2. Locations of Historical Adjusted Climate Database for Canada sites of monthly rainfall and total precipitation used in the analyses. The location of the prairie ecozone is also displayed. Projection is UTM13

convective events at sub-daily time scales are not detectable from these daily datasets.

Single-day rainfall events were identified within the HACDC daily rainfall by locating those daily rainfall values, which were preceded and followed by days with zero rainfall, and therefore, the identification of trends in the single-day rainfall events is sensitive to changes in the recording of zero-rainfall events. Because of differences in their construction, the set of daily rainfall sites selected for analysis was not the same as the set of monthly precipitation sites, although the regions covered were broadly similar, as shown by the locations of seven sites, which had values over the period 1901–2000, and of the 24 sites having values over the period 1951–2000 plotted in Figure 3.

In Canadian precipitation records, trace precipitation events are those that are deemed to be too small to measure accurately. The HACDC data sets have been corrected for trace rainfall by replacing the trace values with calculated rainfall values, which are identified in the record as having been trace events (Mekis and Vincent, 2011). Although trace events are by definition non-zero, the probability distribution of rainfall values between zero and the threshold of measurement is believed to be evenly distributed (Mekis and Vincent, 2011), and therefore, some trace events may actually be zero-rainfall events.

According to Mekis and Hogg (1999) and Mekis (2005), the frequencies of trace precipitation events have increased over time in the records of Canadian precipitation stations because of changes in instrumentation and data collection procedures. As trends in the frequency of trace events may lead to spurious trends in single-day rain events, the single-day rainfall events were identified by using zero rainfall and by using the time-varying value of the trace events as thresholds to identify single-day rainfall events. The use of zero as rainfall threshold may underestimate the number of single-day events, and this bias will be more pronounced at later dates. The use of the trace value of rainfall may overestimate the number of single-day rain events, but the bias should not vary over time. The differences between the numbers of trends detected by the two methods are an index of the importance of trends in the trace values.

Multiple-day rain events were determined in the same manner as single-day rain events. In addition to the annual maximum total rain falling during multiple-day events, the length of rain events and the temporal distribution of rain are also examined.

TREND ANALYSIS METHODOLOGY

The existence of autocorrelation in a time series can affect statistical tests of trends (Hamed and Rao, 1998; Yue *et al*., 2002). Plots of the autocorrelation function (ACF) *versus* lag for daily precipitation at Canadian prairie locations typically demonstrate a very small, but persistent, degree of autocorrelation over many days, as is evident in the example of Indian Head, SK, rainfalls shown in Figure 4. The frequency distribution of daily rainfalls for Indian Head, plotted as a histogram in Figure 5, shows that the vast majority of days have no rainfall as would be expected in a semi-arid to sub-humid climate. The ACF for daily rainfalls in excess of 1 mm for Indian Head is shown in Figure 6; note the much smaller autocorrelation than that found for all events in Figure 4. As only non-zero values were analysed for the existence of trends, autocorrelation in the data sets is not generally considered to be important, and the daily rainfall and monthly precipitation data were not subjected to any form of pre-whitening.

In Figures 4 and 6, the dashed lines represent the 95% confidence interval for uncorrelated values. The autocorrelation length, which is the number of annual values exceeding the uncorrelated confidence intervals, is therefore an index of the degree of autocorrelation in a time series and was

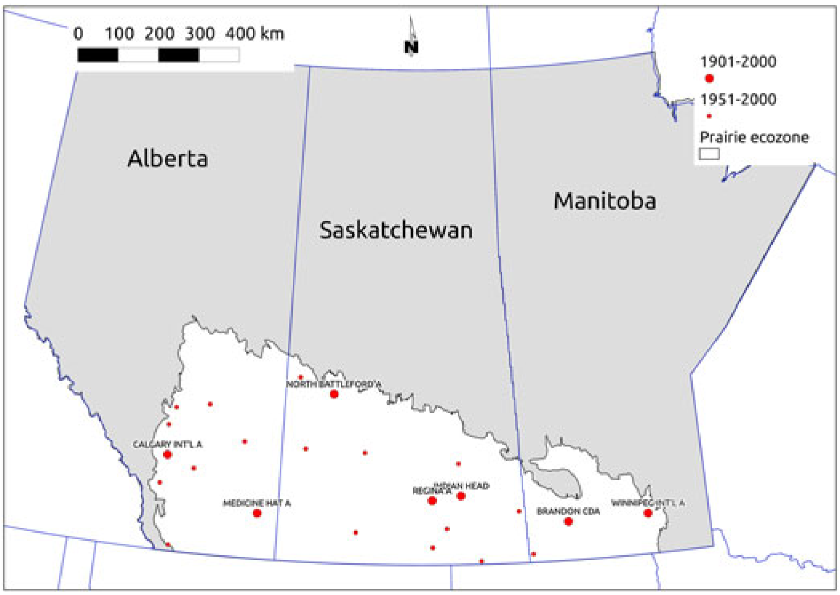

Figure 3. Locations of Historical Adjusted Climate Database for Canada sites of daily rainfall used in the analyses. The location of the prairie ecozone is also displayed. Projection is UTM13

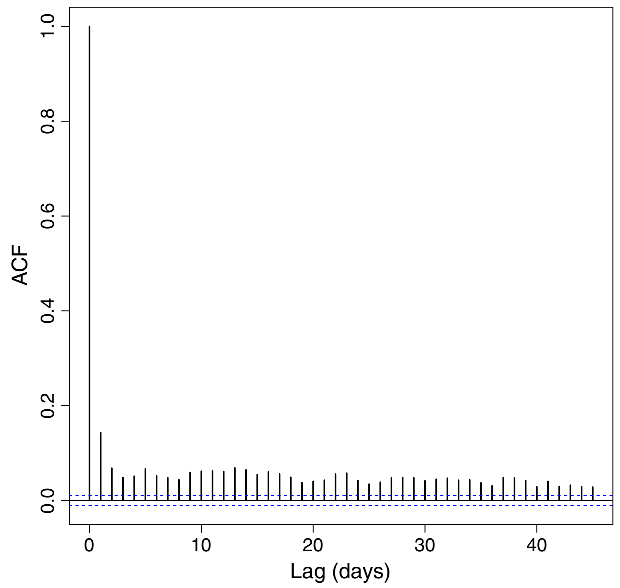

Figure 4. Autocorrelation function (ACF) of daily rainfalls for Indian Head, SK, *versus* lag (days) over the period 1901–2000. The dashed lines represent the 95% confidence interval for uncorrelated values

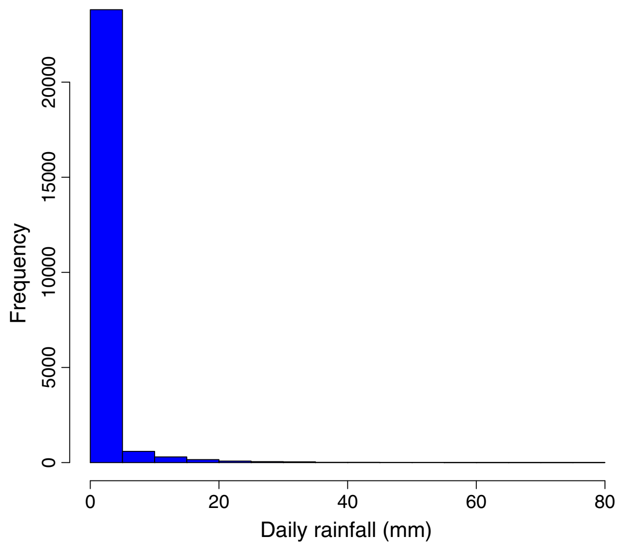

Figure 5. Histogram of daily rainfalls for Indian Head, SK, over the period 1901–2000

computed for all annual variables, such as annual maxima. In all cases, the mean value of the autocorrelation length for each variable was less than 1 year, and therefore, the annual values were not pre-whitened either.

Trend detection methods

Mann–Kendall tests were used to test for the existence of trends in the monthly precipitation variables and some of the daily rainfall variables. The Mann–Kendall test is well known and has been shown to work well with skewed data (Mehmet, 2003). Other daily rainfall variables were tested with using the Generalized Extreme Value (GEV) and the Generalized Pareto Distribution (GPD). All analyses were conducted using the open-source statistical program R (Ihaka and Gentleman, 2007).

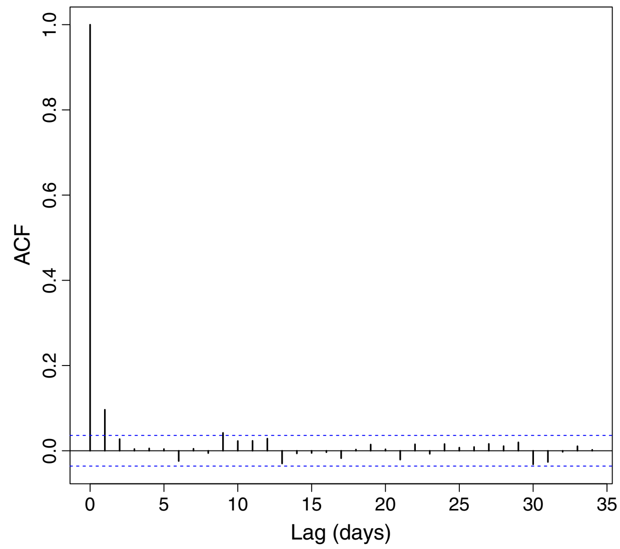

Figure 6. Autocorrelation function (ACF) of daily rainfalls exceeding 1 mm for Indian Head, SK, *versus* lag (days) over the period 1901–2000. The dashed lines represent the 95% confidence interval for uncorrelated values

GEV tests of annual maxima. A set of annual maxima can be treated as a single distribution of values, which is typically highly skewed. The GEV distribution combines the Gumbel, Frechet and Weibull distributions (the Type I, II and III extreme value distributions) and has been shown to accurately fit annual precipitation maxima for all of Canada (Adamowski, 1996). The GEV is defined as (Coles, 2001)

$$G(z) = GEV(\mu, \sigma, \xi) = \exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}, \tag{1}$$

where μ is the location parameter, σ the scale parameter and ξ the shape parameter.

The Gumbell, Frechet and Weibull distributions correspond to $\xi = 0$, $\xi > 0$ and $\xi < 0$, respectively. If the distribution is non-stationary, then its parameters will vary over time as

$$G(z) = GEV(\mu(t), \sigma(t), \xi(t)) \tag{2}$$

where $\mu(t)$, $\sigma(t)$ and $\xi(t)$ are time-varying values of the location, scale and shape parameters, respectively.

As there are three parameters, it is possible that one or more of the parameters will vary with the remainder being stationary as in

$$G(z) = GEV(\mu, \sigma(t), \xi(t)) \tag{3}$$

The ability of a given model to reproduce the distribution of measured values is defined by the model's likelihood function, which is the probability of the observed variable as a function of a probability density function (Coles, 2001). The greater the magnitude of the likelihood, the smaller will be the root mean square error of the fitted distribution. As the negative logarithm of the likelihood (NLLH) is generally used, the model having the smaller NLLH better describes the measured values. A Chi-squared test can determine if the difference between NLLH values is significant at a specified level, the null hypothesis being that there is no difference between the models (Coles, 2001). If one of the models has no trends in its parameters, and the other model parameter(s) include trend(s), then rejection of the null hypothesis implies the existence of trend(s) in the modelled parameters. All of the GEV tests in this research were based entirely on the existence of trends in the location parameter, which is the most powerful change detection method, according to Zhang *et al*. (2004). Significant trends designated as being positive show increases in the extreme values, whereas significant trends designated as being negative show decreases in the extreme values, over the period tested.

GPD tests of single-day rainfall. As the GEV only fits extreme values, it omits the majority of any probability distribution. This is especially true for the GPD, which well described the single-day rainfall events identified at the prairie stations, as this distribution is dominated by small values. The cumulative distribution function (F) of the GPD is defined as (Coles, 2001)

$$F(z) = GPD(\mu, \sigma, \xi) = 1 - \left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi} \quad (4)$$

where μ is the location parameter, σ the scale parameter and ξ the shape parameter (for $\xi \neq 0$).

As with the GEV model, a Chi-squared test is used to detect if values of the parameters incorporating a trend result in a better fit to the empirical data than does a model having constant values in its parameters. The function gpd.fit in the R package 'ismev' (which is derived from Coles (2001)) used for this analysis tests the scale and shape parameters for the existence of statistically significant trends, the location parameter being assumed to be constant. Therefore, a statistically significant trend in either of these parameters is regarded as constituting a significant trend in the GPD. In practice, all significant trends found were in the scale parameters.

As the GPD is defined for values exceeding a threshold, the selection of a threshold value is important. Coles (2001) recommends plots of the GPD parameters against threshold value to determine ranges where the threshold results in a stable distribution. Unfortunately, the use of large (>10 mm) thresholds required to satisfy this condition excludes the majority of single-day rainfall values. As all stations showed agreement between the summer single-day rainfalls exceeding 1 mm and fitted GPD values significant according to a Chi-square test at the 5% level, a 1-mm threshold was used for all GPD tests.

Significant trends designated as being positive show increases in the values of the distribution, whereas significant trends designated as being negative show decreases in the values of the distribution, over the period tested.

Precipitation phase

Mann–Kendall tests were carried out on the rainfall fractions (rainfall as a fraction of total precipitation depth) for the months of September–May, inclusive. The summer months were ignored as their rainfall is typically very close to 100% of the precipitation. The results of the tests are summarized in Table I. In addition to the results of the Mann–Kendall tests, mean values of slopes from least-squares fitted linear models of the rainfall fraction *versus* time are also listed.

The patterns of significant trends were similar during the two periods evaluated with the greatest numbers of stations showing significant trends in precipitation phase during the months of December–March, although the actual monthly fraction of precipitation falling as rain during December, January and February was very small. It is probable that the most important precipitation phase change fractions occur in the months of November (1901–2000), March (1901–2000 and 1951–2000) and April (1951–2000) when the fraction of stations affected by trends is large, the monthly precipitation is comprised

Table I. Summary of Mann–Kendall tests of precipitation phase over the periods 1901–2000 (11 stations tested) and 1951–2000 (38 stations tested)

	1901–2000			1951–2000		
Month	Mean monthly percentage of precipitation falling as rain	Number of sites having a significant trend	Slope of linear model (%/year)	Mean monthly percentage of precipitation falling as rain	Number of sites having a significant trend	Slope of linear model (%/year)
Jan	3	11	0.02	3	7	0.01
Feb	4	11	0.09	5	10	0.08
Mar	13	11	0.10	13	24	0.21
Apr	55	1	0.28	53	16	0.36
May	93	0	N/A	93	3	0.04
Sep	94	0	N/A	95	2	0.16
Oct	67	0	N/A	65	4	0.28
Nov	17	5	0.05	15	1	0.38
Dec	5	11	0.03	4	8	0.00

All significant trends were positive, indicating and increasing fraction of the precipitation falling as rain. All tests used a 5% level of significance.

of both rain and snow and the slopes of the linear models are large. By these criteria, it appears that the month of April was more important in the second half of the 20th century, than the century as a whole, with the opposite being true of November. Because 38 time series were tested at a 5% level of significance, over the interval 1951–2000, two series could be expected to show significant trends by chance.

The hydrological importance of rainfall events depends very much on the state of the winter snowcover. As deep winter snowpacks have a higher liquid water retention capacity than do shallow packs, they will tend to resist the formation of ice lenses. Similarly, the contribution of spring rain atmospheric conditions to melt (because of its latent, sensible, conductive and kinetic energy inputs) will also be affected by the depth and temperature of the snowpack. Determination of the relative hydrological importance of the trends in monthly rainfall will require further research using physically based hydrological models.

The existence of significant trends in the phase of precipitation is generally consistent with Akinremi *et al.* (1999) who found inverse relationships between the trends for annual rainfall and snowfall totals at many locations over the periods 1921–1960 and 1961–1995. The trends are also consistent with the trends (both significant and not significant at the 5% level) evident in temperature variables (increasing numbers of warm days and warm nights, decreasing numbers of cold days and cold nights) and precipitation variables (increasing days with rain, decreasing annual snowfall and snowfall to precipitation ratio) reported by Vincent and Mekis (2006) at locations in the Canadian prairies over the intervals 1900–2003 and 1950–2004.

Single-day rainfalls

It is assumed that single-day rainfall, that is, rainfall occurring during 1 day with zero rainfall on the preceding and following days, is an index of the occurrence of small-scale convective rain events because of localized thunder-clouds. Averaged over all of the stations, single-day rainfall accounted for 24% of the summer (June–July–August) total rainfall. Conversely, rainfalls lasting multiple days are caused by large-scale systems and/or by repeated small-scale convective events.

As described previously, single-day rainfall events were identified by (1) using zero rainfall as a threshold and (2) using the trace rainfall as a threshold. The two sets of events are designated here as zero-threshold and trace-threshold single-day rainfall events. All analyses were conducted over the months of June–August as these months contain the majority of convective storms and to avoiding biassing the data set by including additional rain because of the change in precipitation phase in the fall and spring. The term ‘threshold’ refers to that used to determine the existence of rainfall on the days adjacent to the single-day rainfall.

Annual maximum single-day rainfall. The annual maxima of rain falling in single-day rainfall events were analysed for significant trends in the GEV distribution. The data were tested over both periods using both methods for determining the single-day rain events. The results of the tests, mapped in Figures 7 and 8, show little evidence for significant trends.

No significant trends were found in the single-day rain events determined using zero-rainfall thresholds. Only a single site was found to show a significant trend for the trace-threshold events over 1901–2000 (Indian Head, SK) and 1951–2000 periods (Stettler, AB). The two significant trends are negative in that they indicated that the annual maximum single-day rainfall had decreased over the period of record. However, as a 5% level of significance was used, and more than 20 sites were tested over the 1951–2000 period, a single significant trend would be expected to occur by chance.

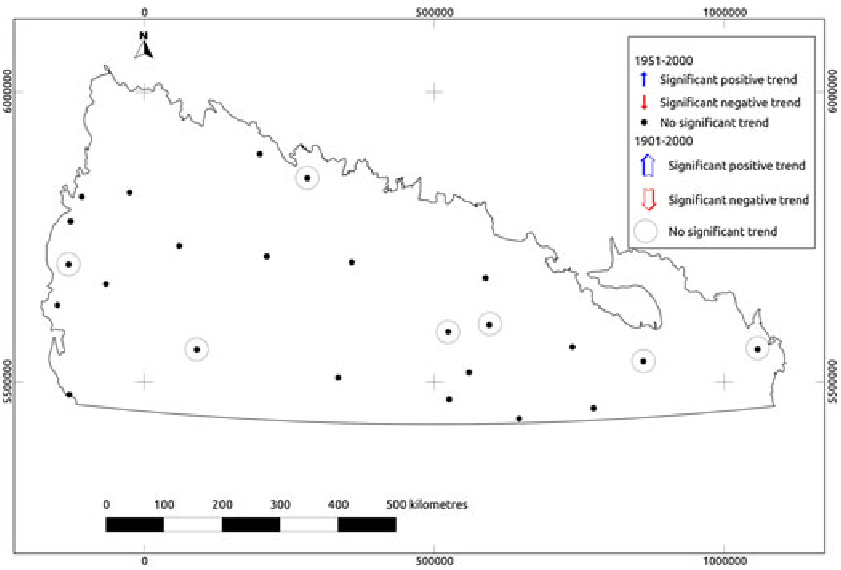

Figure 7. Map of sites within the Canadian prairie ecozone having significant trends in the generalized extreme value of annual maximum single-day summer rainfall determined using zero-value thresholds. Projection is UTM13

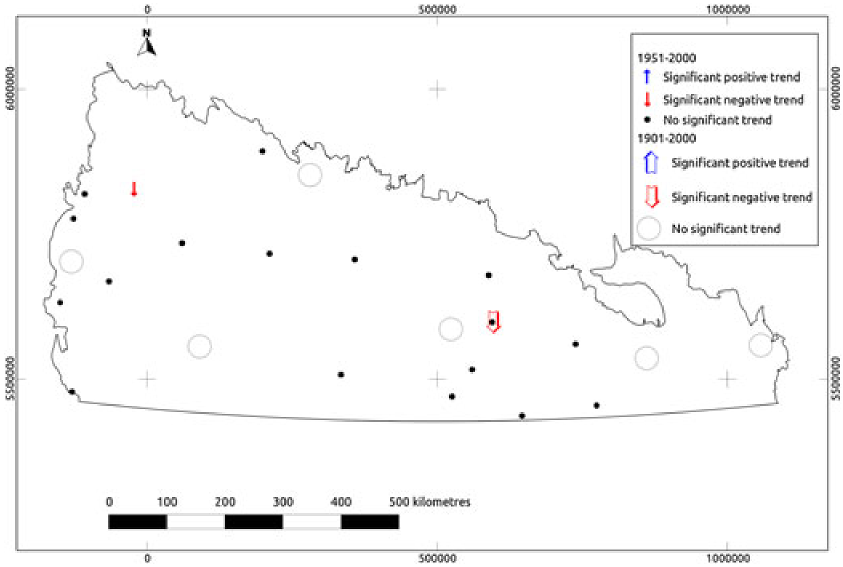

Figure 8. Map of sites within the Canadian prairie ecozone having significant trends in the generalized extreme value of annual maximum single-day summer rainfall determined using trace-value thresholds. Projection is UTM13

Frequency distribution of single-day rainfalls. The results of the GPD tests of single-day rain events are mapped in Figures 9 and 10. As with the GEV tests, the results of the GPD tests are broadly similar for both methods of determining the single-day rain events. As with the GEV test, only a single site (Indian Head, SK) showed a significant trend over the period 1901–2000, although it was shown by both thresholding methods. Compared with the GEV tests, more stations showed significant GPD trends over the periods 1951–2000. The difference between the numbers of significant trends in the GEV and GPD tests is believed to be because of the GPD test being influenced by the many small values of single-day rainfall. To examine this, Figure 11 plots the quantiles of the fitted GPDs on the basis of the values of the distribution parameters in 1901 and 2000 at a single station; Saskatoon. The change in the fitted distribution over the period affects many of the distribution, not simply the largest values.

Effects of changes in phase on rainfall trends. As discussed previously, the GPD and GEV tests were restricted to the months of June–August to prevent non-convective single-day rainfalls in the fall and spring from influencing the detection of trends in convective rainfalls. If non-summer single-day rainfalls are included, then the number of statistically significant GPD trends in data sets may be increased. For example, including the non-summer events, the number of statistically significant trends for trace-threshold single-day rain events from 1 to 3 increased, out of the seven stations tested over the period 1901–2000, using a threshold of 1 mm. This effect disappears (i.e. there are no increases in the number of significant trends) when large thresholds (10 mm) are

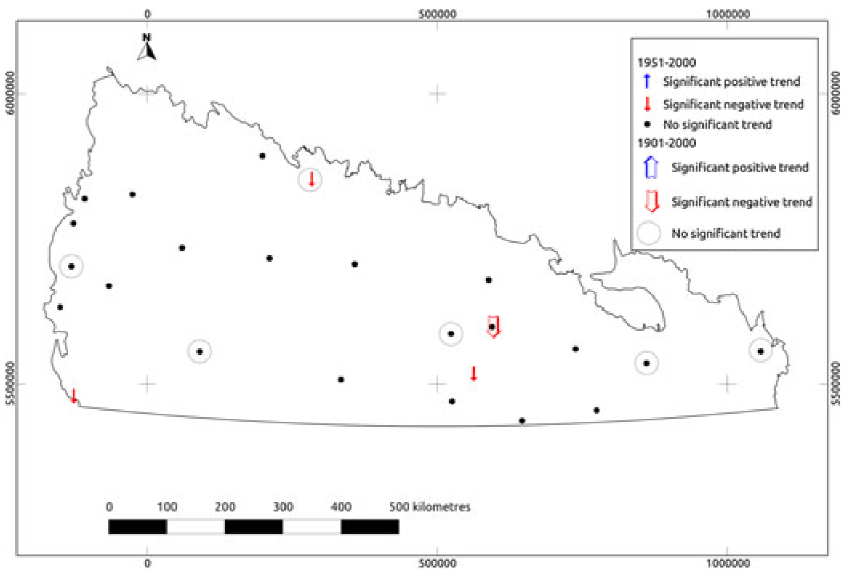

Figure 9. Map of sites within the Canadian prairie ecozone having significant trends in the generalized Pareto distribution of single-day summer rainfall determined using zero-value thresholds. Projection is UTM13

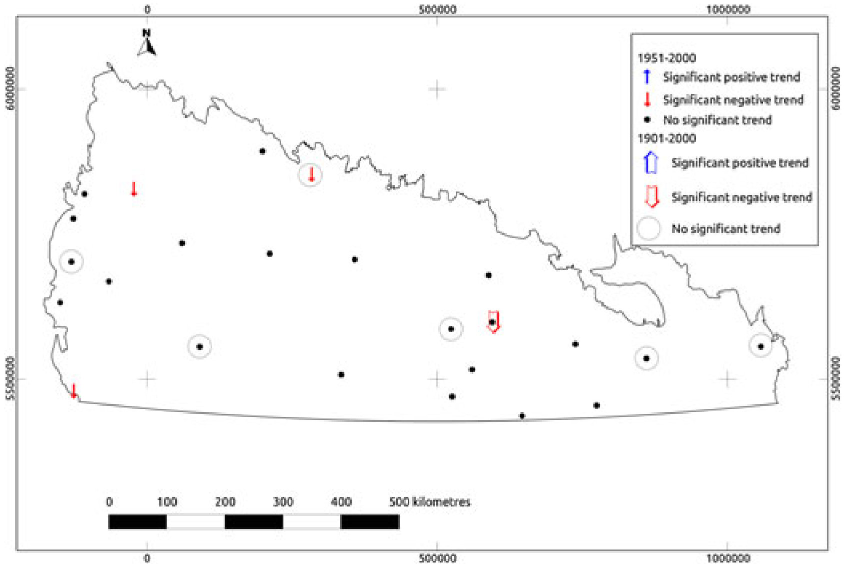

Figure 10. Map of sites within the Canadian prairie ecozone having significant trends in the generalized Pareto distribution of single-day summer rainfall determined using trace-value thresholds. Projection is UTM13

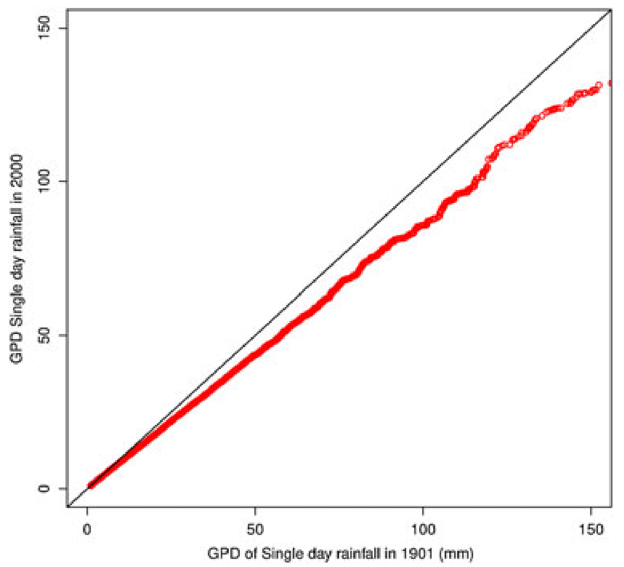

Figure 11. Quantile–quantile plot of values computed from generalized Pareto distributions (GPD) fitted to single-day rainfalls for Saskatoon, SK, in 1901 and 2000

used, or when GEV tests are performed, presumably because heavy single-day rain events require convection, which is very rare during the fall, winter and spring.

Summer single-day fraction of total precipitation. The fraction of summer rainfall, which occurred in single-day events, was calculated as an index of the overall importance of single-day events and, by extension, of convective storms. Figure 12 indicates that over the period 1901–2000, the majority (five out of seven) of the stations tested showed trends that were significant at the 5% level, all of which indicated that single-day rainfall events accounted for decreasing fractions of annual rainfall. These stations were scattered throughout the prairie region and included both semi-arid and sub-humid locations. Over the period 1951–2000, the evidence of trends is weaker, with only 7 of 24 stations showing trends, with 6 being negative and 1 (Brandon, MB) being positive. Only a single station (Indian Head, SK) showed trends over both time intervals.

Multiple-day rainfalls

Multiple-day rain events were defined as being contiguous rainfalls, with non-zero rainfall occurring each day. As the differences between the statistics of the single-day rainfalls defined by the two thresholding methods were demonstrated to be small, zero-rainfall thresholds were used for all analyses of multiple-day rainfalls.

Length of rainfall event. Although the GPD appears to define rain cluster lengths well, it was not used for trend analyses as the length values are integers and, as they vary over a fairly narrow range, were highly constrained. Instead, Mann–Kendall tests were conducted on the maximum annual lengths of multiple-day rain events. The results of the tests are plotted in Figure 13. Over the period 1901–2000, the maximum rain event lengths showed significant trends for a majority (four out of seven) of stations. All of the significant trends were positive. These tended to be in the sub-humid climate locations and did not occur in the semi-arid Palliser Triangle in the south-west centre of the Canadian prairies. Over the period 1951–2000, only 8 of 24 stations showed any significant trends. The only station showing significant trends over both periods was Indian Head, SK.

Event rainfall totals. The quantity of rain occurring in multiple-day events was tested for the existence of trends. The GEV tests of annual extremes, plotted in Figure 14, show no significant trends over the period 1901–2000, but 5 of 24 stations, in the sub-humid northwestern portion of the Canadian prairies, showed positive trends over the period 1951–2000.

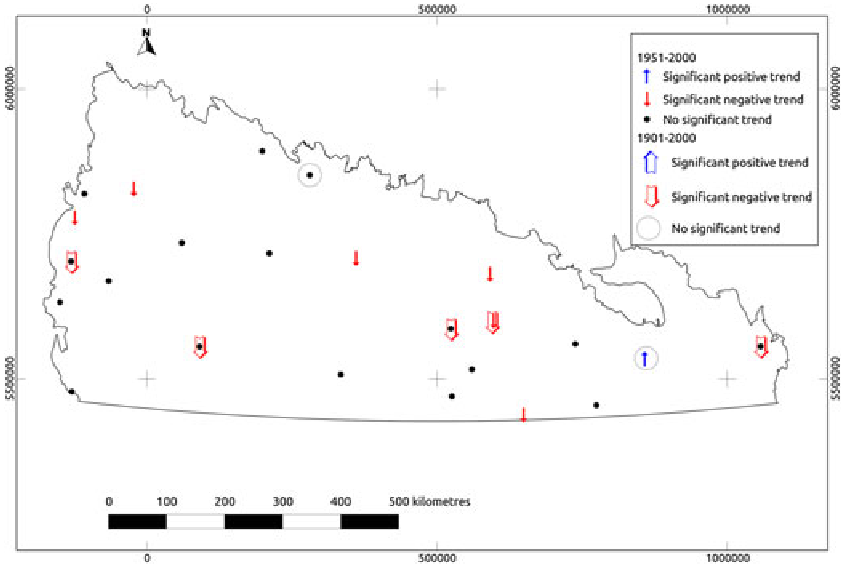

Figure 12. Map of sites within the Canadian prairie ecozone having significant trends, according to Mann–Kendall tests, in the fraction of summer rainfall due to single-day events. Projection is UTM13

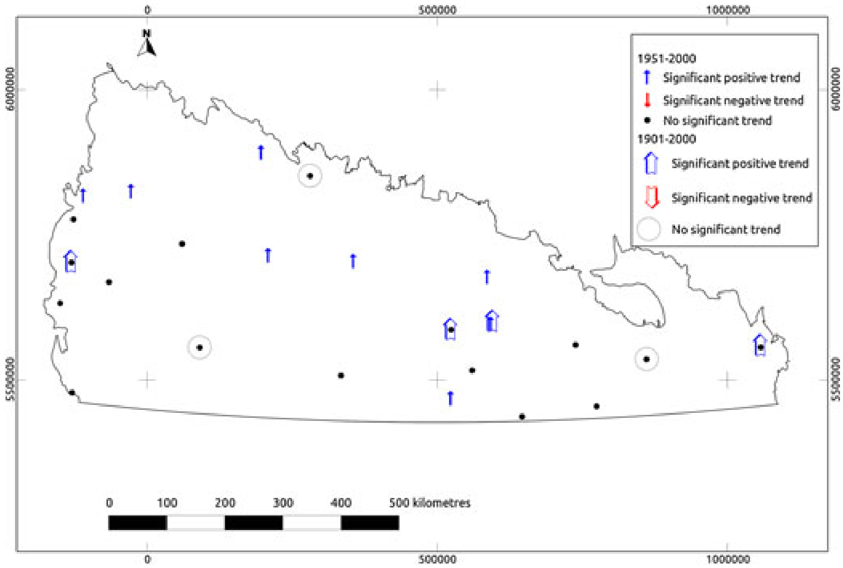

Figure 13. Map of sites within the Canadian prairie ecozone having significant trends, according to Mann–Kendall tests, in the maximum annual length of summer multiple-day rainfall events. Projection is UTM13

Generalized Pareto Distribution tests were conducted on the multiple-day rainfall totals. As with the single-day rainfalls, the numbers of stations showing significant trends were much greater for the GPD trends than the GEV trends, presumably because the GPD test included more of the frequency distribution than did the GEV test. Figure 15 plots the GPD test results, 11 out of 24 stations showing significant positive trends over the period 1951–2000. Over the period 1901–2000, 5 out of 7 stations showed significant positive trends, all of which also had significant trends over 1951–2000. These stations were scattered throughout the Canadian prairies.

MULTIFRACTAL ANALYSIS

Although the previous analyses demonstrated the existence of statistically significant trends in many rainfall variables, they do not define the variability of the time series over many temporal scales, which is necessary for downscaling. Previous research has demonstrated the existence of multiscaling in rainfall time series at many locations (Gaume *et al*., 2007) (Garcia-Marin *et al*., 2008), which is useful for downscaling a time series while reproducing the scaling behaviour of all moments of the original time series.

Significant temporal trends have been shown to exist in the multifractality of precipitation (Royer *et al*., 2008) and Canadian prairie snowfall (Shook and Pomeroy, 2010). The existence of trends in Canadian prairie rainfall is of interest to explain the trends in the temporal variability of rainfall noted previously. Also, evidence of nonstationarity in the multiscaling of Canadian prairie rainfall will influence the selection of methods for downscaling of future climate simulations.

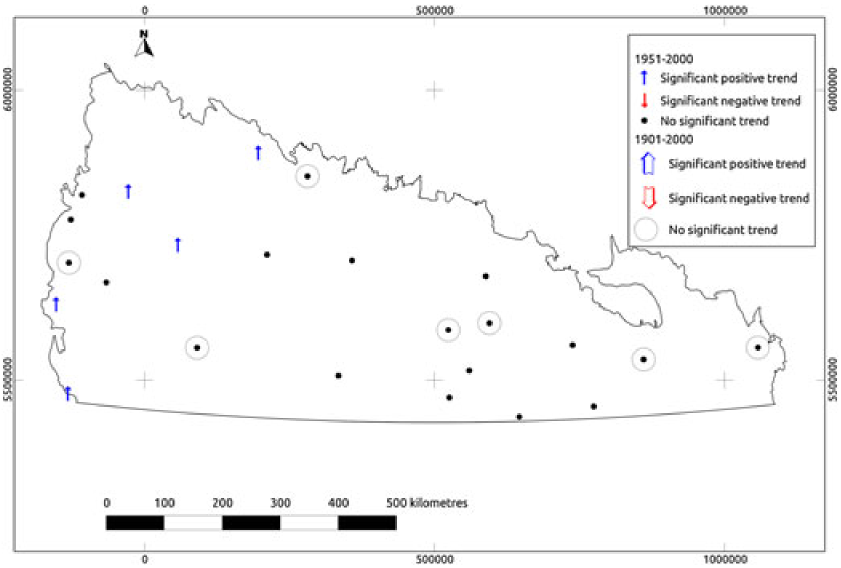

Figure 14. Map of sites within the Canadian prairie ecozone having significant trends in the generalized extreme value of annual maximum multiple-day summer rainfall accumulations. Projection is UTM13

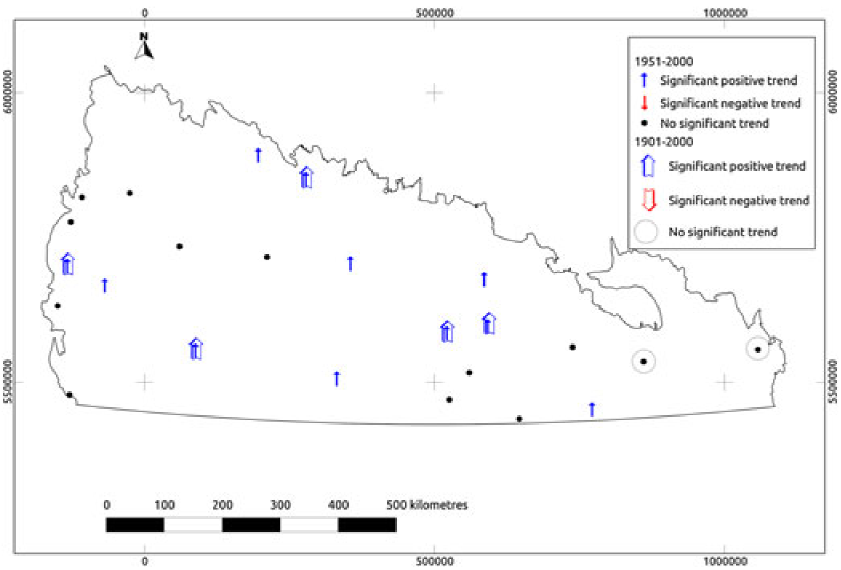

Figure 15. Map of sites within the Canadian prairie ecozone having significant trends in the generalized Pareto distribution of multiple-day summer rainfall accumulations. Projection is UTM13

The power spectra of all of the daily rainfall data sets analysed display scaling over intervals between 1 day and 1 month with parameters virtually identical to those determined by Shook and Pomeroy (2010) for prairie daily snowfall quantities. As discussed previously, sub-daily rainfall data were not available from HACDC. Had these been available, it would have been possible to determine if the scaling relationships could be extended to finer temporal scales.

All scaling analyses in this research were based on periods between 1 day and 1 month. The methodology used is described more fully in Shook and Pomeroy (2010) but is summarized here. The magnitude of the scaling present in a time series can be defined by the behaviour of the moment scaling function, $K(q)$, which is related to the normalized value of the time series $\varepsilon(t)$ by (Olsson, 1995).

$$\left\langle \varepsilon_{\lambda}^{q} \right\rangle \approx \lambda^{K(q)} \tag{5}$$

where q is the moment and λ is the scale factor (ratio of scale of interest to size of entire data set).

The symbols $\langle\rangle$ refer to the process of ensemble averaging, where the results of the calculations are averaged over all values of $\varepsilon(t)$.

A nonlinear relationship between $K(q)$ and q, which is indicative of multifractality, can be quantified by the universal multifractal relationship between the constants α and $C1$ (Seuront *et al.*, 1999):

$$K(q) = \frac{C1}{\alpha - 1}(q^{\alpha} - q), \text{ for } \alpha \neq 1, q \geq 0 \tag{6}$$

The constants α and $C1$ are indices of the inhomogeneity of a dataset, and because $C1$ is in the numerator and α is in the denominator of Equation 6, the constants act in opposite directions. Small values of α and/or large values of *C1* are indicative of tendencies to large fluctuations in the data; large values of α and/or small values of *C1* are indicative of greater temporal homogeneity (Finn *et al.*, 2001). Therefore, the existence of significant trends in either or both of the universal multifractal parameters indicates changes over time in the mutliscaling of a dataset and trends in its temporal homogeneity.

Each time series was divided into 25 subsections, and the values of α and *C1* were computed for each of the subsections. The results of Mann–Kendall tests on the magnitudes of the parameters are mapped in Figure 16. Because significant trends in either of the parameters indicate a change in the multiscaling of a dataset, the parameter trends were combined to simplify the map. Significant trends designated as being positive are due to increases in α and/or to decreases in *C1*.

Over the period 1901–2000, 5 out of 7 stations showed significant trends in α and/or in *C1*. Over the period 1951–2000, 11 out of 24 sites showed significant trends in the parameters. These stations are well distributed across the Canadian prairies. In all cases, the trends indicated an increase in the value of α or a decrease in the value of *C1*, indicating that the data were becoming more temporally uniform. Shook and Pomeroy (2010) show examples of the change in temporal distribution of snowfall caused by changes in the values of the dataset's multiscaling parameters.

Measured cascade multipliers

Multifractal data sets are often constructed through the multifractal cascade process (Gaume *et al.*, 2007). The process, as described in Shook and Pomeroy (2010), consists of repeatedly dividing a conserved quantity, such as rainfall, into smaller units of space and/or time through repetitive multiplication by a factor that is randomly generated according to some distribution. By inverting the process, the naturally occurring cascade multipliers can be determined.

Each multiplicative cascade divides a rainfall total into two (usually unequal) pieces. For example, given the rainfall over 8 days, the total is divided into two 4-day total rainfalls. Each 4-day rainfall is then subdivided unevenly into two 2-day rainfalls. Each 2-day rainfall is subdivided unevenly into two 1-day rainfalls.

An advantage of testing the cascade multipliers over checking ratios for conventional lengths of time (1, 2, 5, 7, 10 days) is that the multipliers test the variability of rainfall over all scales. The presence of significant trends in the frequency distributions of the multipliers at varying temporal scales demonstrates how downscaling of rainfall quantities such as intensity and duration has changed over time.

The natural cascade multipliers were computed using the following steps:

(1) Divide the rainfall time series into sequential 2-day periods;
(2) Compute the mean rainfall for each 2-day period;
(3) Omit all 2-day rainfall values equal to 0;
(4) Calculate the ratio of the first day's rainfall to the 2-day total; and
(5) Repeat the steps 1–4 for longer (i.e. 4, 8, 16 days) periods.

Cascade multiplier values of 0 or 1 indicate that all of the rain in the longer period is concentrated in the first half or second half of the period. Conversely, a cascade value of 0.5 indicates that the rainfall is evenly divided between each half period.

The frequency distributions of cascade multipliers typically resemble the example histogram plotted in Figure 17 from the Saskatoon observations, the values of

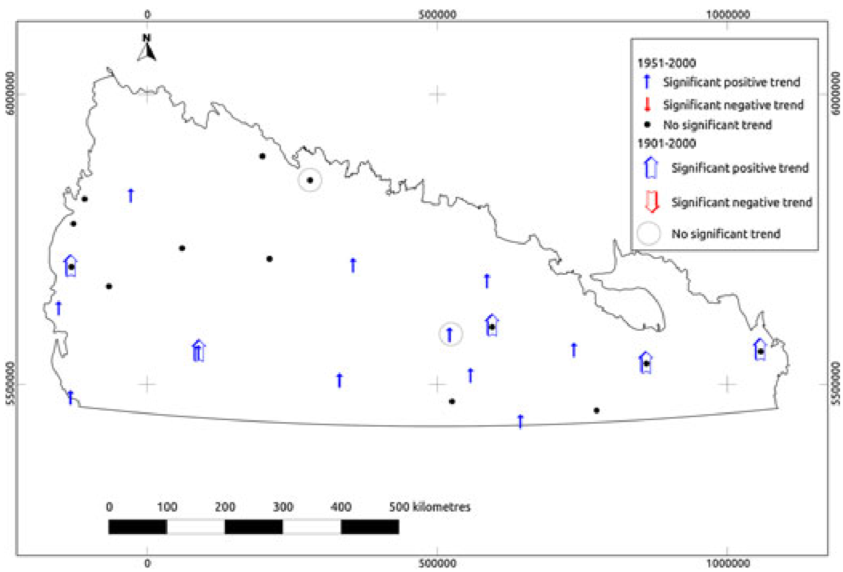

Figure 16. Map of sites within the Canadian prairie ecozone having significant trends in the universal multifractal parameters, according to Mann–Kendall tests, for summer daily rainfalls. Significant positive trends indicate increased uniformity in the temporal distribution of rainfall because of a significant increase in the value of α and/or a significant decrease in the value of *C1*. Projection is UTM13

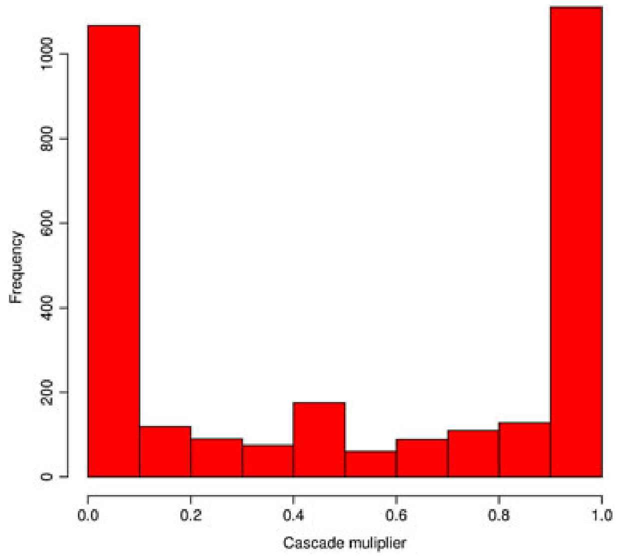

Figure 17. Histogram of multipliers for 2-day to 1-day rainfall totals. Data for Saskatoon, SK, for the period 1901–2000

0 or 1 being the most frequent and similar in distribution. At all levels, for all stations over their periods of record, the null hypothesis of uniform distribution of the non-zero/one values could not be rejected by Chi-squared tests at the 5% level. Thus, the 0/1 frequency of cascade multipliers defines their overall distribution and can be used to test for the existence of trends.

Because the cascade multiplier repeatedly divides periods in half, the method works best when the number of days is an even power of 2. As the intent was to analyse rainfall scaling for periods of up to 1 month, periods of 96 days = 3 × 32 (i.e. 2^5) days were selected. Days 148–243 (May 28 to August 31 for non-leap years) were selected for analyses as this period is unlikely to be affected by the observed changes in the phase of precipitation.

Mean and standard deviations of the 0/1 fractions were determined over all stations for all five periods and are listed in Table II. The 0/1 fractions show marked differences over the five periods, indicating the time scales over which rain events vary. In particular, the low mean value for the 8-day to 4-day cascade indicates that 4-day dry spells, or rain events, are relatively uncommon unless they are part of a longer-term event. By contrast, the large mean value for the 2-day to 1-day cascades indicates that single-day rainfall events are relatively common, compared with 2-day rainfalls.

Table II. Means and standard deviations of cascade ratio 0/1 fractions over the period 1901–2000

Period (day/s)	Mean	Standard deviation
2–1	0.65	0.08
4–2	0.36	0.10
8–4	0.12	0.07
16–8	0.34	0.06
32–16	0.33	0.05

Seven stations were tested.

Trends in cascade multipliers. The fraction of the cascade multipliers equal to 1 or 0 was determined for sub-ranges of the 100-year and 50-year periods, as was done for the multifractal parameters. Mann–Kendall tests were performed on the 1–0 fractions, and the percentages of stations showing positive (increasing 0–1 fractions), negative (decreasing 0–1 fractions) or no trends were tabulated for each stage of the cascades, as shown in Table III.

Over the period 1901–2000, only small fractions of the stations displayed significant trends, all of which were negative. Over the period 1951–2000, greater fractions of the stations showed significant trends, both positive and negative, with the negative trends predominating. The number of stations showing significant trends appears to vary only slightly with the time scale.

The existence of significant trends in the cascade multipliers, as well as in the values of α and *C1*, is an indication of non-stationarity in the downscaling of rainfall in the Canadian prairies over the periods analysed. Because the significant trends are both positive and negative, more detailed investigation will be required to determine the effects on a given time series of the trends at each time scale. However, the greater number of negative trends indicates an overall tendency for summer rainfall to be distributed more evenly over temporal scales between 1 and 32 days, over the periods tested.

Table III. Significant trends in multiple-day cascade ratio 0/1 fraction

		Numbers of stations showing trend significant at 5% level				
Period and number of stations	Trend	2–1 day	4–2 days	8–4 days	16–8 days	32–16 days
1901–2000 7 stations	Positive	0	0	0	0	0
	Negative	1	1	1	2	2
	None	6	6	6	5	5
1951–2000 24 stations	Positive	3	1	4	3	4
	Negative	8	13	11	11	10
	None	13	10	9	10	10

All tests were performed using the Mann–Kendall test at a 5% level of significance.

SUMMARY AND CONCLUSIONS

The trends for spring and autumn precipitation to fall as rain rather than snow over the periods 1901–2000 and 1951–2000 are consistent with the trends noted by Vincent *et al*. (2007) of increasingly warm mean surface temperatures during the winter and spring, although their study was conducted over the period 1955–2005 and is not directly comparable. Vincent and Mekis (2006) found significant trends of decreasing snowfall fractions of annual precipitation at several locations in the Canadian prairies over the interval 1950–2003.

Enhanced spring runoff has the potential to fundamentally change the response of Canadian Prairie river basins to subsequent rainfall by filling storage such as that in ponds and wetlands, over very large regions. In most years, these have represented a significant unfilled depressional storage capacity that limits the contributing area for streamflow generation. When this storage is filled, the hydrological connectivity of these basins increases, and the contributing area for runoff also increases resulting in much higher streamflow (Fang *et al*. 2010; Pomeroy *et al*., 2010).

Over the period 1951–2000, the fraction of summer rain falling as single-day events has been decreasing at many locations (one site showed a significant increasing trend, and many showed no trend). Significant decreasing trends were also found at the majority of sites over 1901–2000. The annual extreme single-day rainfalls either showed no significant trend or significant decreasing trends, depending on the period examined and the method of analysis. The GPD of single-day rain events exceeding 1 mm also showed either no significant trends or significant decreasing trends. Many of the decreasing trends in single-day extreme rainfall were found in the sub-humid western, northern and eastern fringes of the Canadian prairies.

Thus, over the periods 1901–2000 and 1950–2000, the importance of summer single-day storms for producing runoff in the Canadian prairies does not appear to have increased and appears to have declined at some locations. The increase in trace values over time in the HACDC rainfall record did not greatly affect these results.

The summer multiple-day rain events showed significant trends to increasing annual maximum accumulation at a few locations over the period 1951–2000, although no significant trends were evident over 1901–2000. More sites showed significant positive trends in their GPD over both periods, indicating that smaller events are more affected by the changes in the nature of rainfall than are the annual maxima. Many sites also showed significant trends; all of which were positive in the maximum length of summer rain events over the period 1901–2000 and 1951–2000.

Thus, over the periods 1901–2000 and 1950–2000, the importance of summer multiple-day storms for producing runoff in the Canadian prairies does not appear to have decreased and appears to have increased at many locations. In combination with greater spring and fall rainfall fraction causing a hypothesized increase in spring runoff filling prairie wetlands with snowmelt, the increasingly important multiple-day rainfall events may be able to contribute to prairie runoff.

There are significant trends in the multifractal parameters α and $C1$ for many sites; all of which indicate increasing temporal uniformity of summer rainfall. As the multifractal analyses include both single-day and multiple-day events, they are affected by the changes in the fraction of rain occurring in single-day events.

Over the period 1951–2000, significant trends, both positive and negative, were found in the rainfall cascade 0/1 ratios, although the negative trends, which indicate greater uniformity of rainfall, outnumber positive trends. Over the period 1901–2000, there were few significant trends, but all were negative in direction.

The results of the analyses of the multifractal cascades are consistent with the results of the analyses of the multifractal constants and show an overall tendency to increasing uniformity of summer rainfall over all scales between 1 and 32 days. In practical terms, this indicates that the rainfall was less likely to be concentrated in short duration events, separated by rain-free intervals, over the periods tested. These results are also consistent with the significant trends to longer duration of annual maximum multiple-day summer rainfall and the decreasing fraction of summer rain falling in single-day events, found at many locations.

Further research will be required to determine the effects of the observed trends in precipitation variables on the hydrology of the Canadian prairies. However, the trends to increasing precipitation uniformity may imply that frontal precipitation events, rather than small-scale convective storms have increased over the periods of records. If the trends continue in the future, and are accompanied by increased spring runoff because of significant trends in precipitation phase during the fall and spring, the multiple-day rain events may be capable of producing large areas of runoff generation in Canadian prairie basins, which will change the hydrological character of the region. The large scale and highly destructive Canadian prairie flooding of 2011 was entirely consistent with this mechanism.

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REFERENCES

Adamowski K. 1996. Regional rainfall distribution for Canada. *Atmospheric Research* **42**(1–4): 75–88. DOI: 10.1016/0169–8095(95)00054–2.

Akinremi OO, McGinn SM, Cutforth HW. 1999. Precipitation trends on the Canadian prairies. *Journal of Climate* **12**: 2996–3003.

Coles S. 2001. An Introduction to Statistical Modeling of Extreme Values. Springer-Verlag: London. ISBN: 1852334592.

Dyck GE, Gray DM. 1979. Prairie rainfall characteristics. In Summer Meeting of ASAE and CSAE. American Society of Agricultural Engineers: Winnipeg, Manitoba; 13.

Fang X, Pomeroy JW. 2007. Snowmelt runoff sensitivity analysis to drought on the Canadian prairies. *Hydrological Processes* **2609**: 2594–2609. DOI: 10.1002/hyp.

Fang X, Pomeroy JW, Westbrook CJ, Guo X, Minke AG, Brown T. 2010. Prediction of snowmelt derived streamflow in a wetland dominated prairie basin. *Hydrology and Earth System Sciences* **14**(6): 991–1006. DOI: 10.5194/hess-14-991-2010.

Finn D, Lamb B, Leclerc MY, Lovejoy S, Pecknold S, Schertzer D. 2001. Multifractal analysis of line-source plume concentration fluctuations in surface-layer flows. *Journal of Applied Meteorology* **40**: 229–245.

Garcia-Marin AP, Jiminez-Hornero FJ, Ayuso-Munoz JL, Rabanales C, Mendel EG. 2008. Universal multifractal description of an hourly rainfall time series from a location in southern Spain. *Atmosfera* **21**(4): 347–355.

Gaume E, Mouhous N, Andrieu H. 2007. Rainfall stochastic disaggregation models: Calibration and validation of a multiplicative cascade model. *Advances in Water Resources* **30**(5): 1301–1319. DOI: 10.1016/j.advwatres.2006.11.007.

Gray D. 1970. Handbook on the Principles of Hydrology: With Special Emphasis Directed to Canadian Conditions in the Discussions, Applications, and Presentation of Data. Water Information Center: Huntingdon, New York. ISBN: 0-912394-07-2.

Gray DM, Toth B, Zhao L, Pomeroy JW, Granger RJ. 2001. Estimating areal snowmelt infiltration into frozen soils. *Hydrological Processes* **15**(16): 3095–3111. DOI: 10.1002/hyp.320.

Hamed KH, Rao AR. 1998. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* **204**: 182–196.

Ihaka R, Gentleman R. 2007. R: a language for data analysis and graphics. *Journal of Computational and Graphical Statistics* **5**(3): 299–314.

Marks D, Kimball J, Tingey D, Link T. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest Flood. *Hydrological Processes* **12**: 1569–1587.

Marshall IB, Smith CA, Selby CJ. 1996. A national framework for monitoring and reporting on environmental sustainability in Canada. *Environmental Monitoring and Assessment* **39**: 25–38.

Mehmet BON. 2003. The power of statistical tests for trend detection. *Turkish Journal of Environmental Science* **27**: 247–251.

Mekis É, Hogg WD. 1999. Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere-Ocean* **37**(1): 53–85.

Mekis É. 2005. Adjustments for trace measurements in Canada. In Proc. 15th Conference on Applied Climatology. Am. Meteorol. Soc: Savannah, GA.

Mekis É, Vincent LA. 2005. Precipitation and temperature related climate indices for Canada. *American Meteorological Society 16th Conference on Climate Variability and Change*.

Mekis É, Vincent LA. 2011. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. *Atmosphere-Ocean* **49**(2): 163–177.

Olsson J. 1995. Limits and characteristics of the multifractal behavior of a high-resolution rainfall time series. *Nonlinear Processes in Geophysics* **2**: 23–29.

Peterson TC, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N. 2001. Report on the activities of the working group on climate change detection and related Rapporteurs 1998–2001. Report WCDMP-47, WMO-TD 1071, World Meteorological Organization, Geneva, Switzerland.

Pomeroy J, Fang X, Westbrook C, Minke A, Guo X, Brown T. 2010. Prairie hydrological model study final report. Centre for hydrology report no. 7. Centre for Hydrology, University of Saskatchewan, Saskatoon. 127 p. http://www.usask.ca/hydrology/reports/CHRpt07_PHMS-Final-Report_Jan10.pdf

Raddatz RL. 2000. Summer rainfall recycling for an agricultural region of the Canadian prairies. *Canadian Journal of Soil Science* (March 1999), **80**: 367–373.

Raddatz RL, Hanesiak JM. 2008. Significant summer rainfall in the Canadian prairie Provinces: modes and mechanisms 2000 – 2004. *International Journal of Climatology* **28**(February): 1607–1613. DOI: 10.1002/joc.

Raddatz RL, Kern J. 1984. An assessment of the near real-time rainfall network on Canada's Eastern prairies. *Atmospheric Environment* **22**(4): 474–483.

Royer J, Biaou A, Chauvin F, Schertzer D, Lovejoy S. 2008. Multifractal analysis of the evolution of simulated precipitation over France in a climate scenario. *Comptes Rendus Geosciences* **340**(7): 431–440. DOI: 10.1016/j.crte.2008.05.002.

Seuront L, Schmitt F, Lagadeuc Y, Schertzer D, Lovejoy S. 1999. Universal multifractal analysis as a tool to characterize multiscale intermittent patterns: Example of phytoplankton distribution in turbulent coastal waters. *J. Plankton Res* **21**(5): 877–922.

Shook KR, Pomeroy JW. 2010. Hydrological effects of the temporal variability of the multiscaling of snowfall on the Canadian prairies. *Hydrology and Earth System Sciences* **14**(7): 1195–1203.

Singh P, Spitzbart G, Hubl H, Weinmeister HW. 1997. Hydrological response of snowpack under rain-on-snow events: a field study. *Journal of Hydrology* **202**(1–4): 1–20.

Stichling W, Blackwell SR. 1957. Drainage area as a hydrologic factor on the Canadian prairies, in *IUGG Proceedings, Volume 111*.

Stone D, Weaver A, Zwiers F. 2000. Trends in Canadian precipitation intensity. *Atmosphere-Ocean* **38**(2): 321–347.

Vincent LA, Mekis É. 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Science And Technology* **44**(2): 177–193.

Vincent LA, van Wijngaarden WA, Hopkinson R. 2007. Surface temperature and humidity trends in Canada for 1953–2005. *Journal of Climate* **20**: 5100–5113.

Woo M-K, Rowsell RD. 1993. Hydrology of a prairie slough. *Journal of Hydrology* **146**: 175–207.

Yue S, Pilon P, Phinney B, Cavadias G. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes* **16**(9): 1807–1829. DOI: 10.1002/hyp.1095.

Zhang X, Hogg W, Mekis É. 2001. Spatial and temporal characteristics of heavy precipitation events over Canada. *Journal of Climate* **14**: 1923–1936.

Zhang X, Zwiers FW, Li G. 2004. Monte Carlo experiments on the detection of trends in extreme values. *Journal of Climate* **17**(10): 1945–1952, DOI: 10.1175/1520–0442(2004)017 < 1945:MCEOTD 2.0.CO;2.