University of Alberta

Evaluating Long-term Trends and Variations in Daily and Extreme Precipitation Indices over Western Canada

by

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Abstract

Continuous and long weather records are essential to assess possible long-term, hydrologic/climatic changes at local and regional scales by applying appropriate statistical analysis on daily climate data that may require data quality control, adjustments or gap filling of missing data. In this study, a statistical technique called Markov chain was employed to gap fill missing values of daily precipitation observed at 30 stations in western Canada. The gap filling approach was based on 20 years of selected historical meteorological data. The statistical properties of the daily precipitation data with gap filled values are compared with those of the original data (before gap filling) to ensure that this approach preserves the statistical characteristics of the historical data.

Next, after gap filling precipitation data of those selected stations in western Canada with missing values, ten precipitation indices that represent different precipitation properties were computed from daily data of a total of 30 climate stations, each with at least 50 years of record length (up to 2006). Statistical tests such as the Mann-Whitney-Pettitt statistics and linear regression were used to detect possible change points present and trend magnitudes of these precipitation indices. Results reveal that an increasing trend in the maximum number of consecutive wet days and the annual maximum monthly 5-day precipitation and a decreasing trend in the maximum number of consecutive dry days over majority of the stations of Western Canada. Except for a small area located in southern British Columbia, the annual total precipitation index of many stations had increased but only about 1/3 of these stations show a statistically significant increase in the annual total precipitation index. However, no consistent change was detected in the number of days when precipitation

is equal and greater than 10 mm or 20 mm. Finally, indices of many stations in the Prairie Provinces for the annual monthly maximum 1-day precipitation, precipitation that exceeds the 95 and 99 percentile thresholds, and simple precipitation intensity index (SDII) have decreased but only some of changes are statistically significant. In contrast, no consistent changes in these extreme precipitation indices were detected in BC.

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Chapter 1 Introduction

1.1 Background

Global warming in recent decades is indisputable, and observations show the evidence of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. Under increasing greenhouse gases such as CO_2, methane, nitrous oxide and others, the global temperature has been increasing gradually. Recent analyses of global climate data show that the global mean temperature has risen by about 0.76 ℃ between the late 19th century and early 2000, and continued warming in the first half decade of the 21st century, which has been relatively high at about 0.2 ℃ per decade in the past 30 years (Hansen et al. 2006). While observed temperature warming trends have not been uniform around the globe, larger warming has been observed in the Western than in the Eastern Equatorial Pacific over the past century (Hansen et al. 2006). Given the scale of possible impact of global warming to the cryosphere and hydrosphere globally, many climate scientists across the world are interested in developing tools to reliably predict possible changes of its future climate and its potential impacts. The identification of climate change at local, regional, and continental scales has been the primary focus on recent climate research. Precipitation is a key element of climate. However, precipitation is highly variable spatially and temporally, and so a better knowledge of the amount of precipitation available to us in time and in space, and possible changes to wetter or drier conditions is of practical importance to many sectors socially and economically.

According to IPCC (2007), the observed increase in globally averaged temperatures since the mid-twentieth century, which is very likely due to the observed increase in anthropogenic greenhouse gas concentrations, could result in future precipitation events changing in frequency and intensity. The basic conception of changes in precipitation has been demonstrated by Allen and Ingram (2002). As the Earth warms, higher temperatures lead to higher rates of evaporation and precipitation, and the atmosphere has more capacity to hold more water because the saturation vapor pressure of water vapor increases with an increase in air temperature. Therefore we expect more precipitation likely to fall over shorter intervals of time, thus increasing the frequency of very heavy and extreme precipitation events (An extreme event is defined at each station when daily precipitation exceeds a certain percent of its seasonal or annual mean).

Because of limitations in the spatial and temporal coverage of monitoring networks, and because precipitation is highly variable spatially and temporally, there is substantial uncertainty associated with the trend analysis of precipitation (Huntington, 2006). At present, investigating inter-annual variations and trends in precipitation over the oceans still remains a challenge. According to IPCC (2007), trends of land precipitation at a global scale have been analyzed using data sets, such as the dataset for Precipitation Reconstruction over land by Chen et al. (2002); the Global Precipitation climatology Project by Adler et al. (2003) and the Global Precipitation Climatology Centre dataset of Beck et al. (2005). As suggested in the IPCC Technical Paper VI by Bates et al. (2008), between 30° N and 85° N, precipitation over land had generally increased over the 20th century but for 10° S to 30° N, notable decrease in land precipitation had occurred in the past 30 – 40 years (Figure 1.1). From 10° N to 30° N, the precipitation increased markedly from 1900 to the 1950s, but it declined after about 1970s. This is likely because under increased greenhouse gases, the horizontal transport of water vapour is expected to increase, leading to a drying of the subtropics and parts of the Tropics (Kumar et al., 2004; Neelin et al., 2006), but an increase in precipitation at high latitudes (Emori and Brown, 2005; Held and Soden, 2006). Climate simulations of the 20th-century mean zonal land precipitation generally show an increase at high latitudes and near the Equator, but a decrease in the subtropics of the Northern Hemisphere (Hulme et al., 1998; Held and Soden, 2006; IPCC, 2007). Further, there are reports that globally extreme precipitation events have increased by approximately 0.21% per decade over the last half-century (Alexander et al., 2006; IPCC, 2007)

1.2 Literature Review

Even though long-term changes in climatic means are important, changes in the extremes could have greater direct impact on our daily livelihood. One of the most significant consequences of global warming due to an increase in greenhouse gases would be an increase in the magnitude and frequency of extreme precipitation events. Results simulated by climate models driven with enhanced greenhouse gases have indicated that under a warmer climate, there will be a general increase in extreme precipitation (Cubasch et al., 2001). Climate change indices based on daily precipitation observations have been used to detect changes in extreme precipitations (Peterson et al., 2001).

There are numerous studies of trends analysis in extreme precipitation indices for many regions of the globe. Klein et al. (2003) revealed an increase in the number of extreme wet days from 1946 to 1999 over Europe. Between 1949 and 2007, Rosenberg et al. (2010) found the total annual rainfall over the Pacific Northwest of USA (Spokane, Puget Sound, and Portland) had increased, but there was no evidence of an increase in the extreme precipitation over Spokane and Portland. In Russia, Groisman et al., (2003) suggested a slight increase in heavy precipitation events over the past five decades.

Joshi and Rajeevan (2006) examining trends of extreme rainfall indices for 1901-2000 over India, suggested that most of the extreme rainfall indices have shown significant positive trends over the west coast and northwestern parts of the Peninsula. From 1961 to 2000, the number of rain days in China had decreased throughout most parts of China, but the storm intensity had increased (Zhai et al., 2005). From 1901 to 2002, Ian Smith (2004) found that the mean rainfall of Australia had increased.

Several studies have been conducted to examine the precipitation trends over North America. In the USA, Kunkel et al. (2003) and Groisman et al. (2004) found statistically significant increasing trends in 14% of heavy (upper 5%) and 20% of very heavy (upper 1%) precipitation. Much of this increase occurred during the last three decades of the 20th century and is most apparent over the eastern parts of the country. In Figure 1.2, the % area of the USA, excluding Alaska and Hawaii, with an unusually large amount of total annual precipitation coming from extreme precipitation events (those with more than 5.08 cm of rainfall or snowfall in 24 hours) is displayed. The smooth curve representing the area of USA with an unusually large amount of extreme precipitation averaged over periods of about 10 years shows an obvious upwards trend over the Twentieth Century. From examining precipitation records for 1895–2002 of some West Coast stations of North America, Pryor et al. (2009) only detected a slight upward trend in either the maximum 5-day rainfall or the 95th percentile of daily precipitation.

In Canada, Zhang et al. (2010) showed that annual precipitation total (1950 to 2007) had generally increased over Canada and most of the increasing trends detected are statistically significant and are also coherent over northern Canada. Precipitation in the Arctic had increased significantly in all seasons except summer, which is consistent with climate model projections for future changes in high latitude precipitation. Other than increasing precipitation trends, Qian et al. (2010) also found increasing trends in extreme daily precipitation during the growing season. While, Lucie et al. (2006) suggested a general significant decrease trend for the simple day intensity index over Canada during 1950 to 2003 period.

For western Canada and from 1910 to 2001, Groisman et al. (2005) found an increase in extreme precipitation events in British Columbia south of the 55°N, while Gan (1998) found scattered trends in the precipitation data for the Canadian Prairies. Between 1956 and 1995, rainfall had also increased by about 16%. However, most of this increase is presumably due to the conversion of snowfall to rainfall in spring, coinciding with a warmer and earlier spring (Akinremi et al., 2001).

1.3 Research Objective

The objective of this study is to investigate the long-term trends of various daily and extreme precipitation indices in Western Canada. This study updates and extends the analysis of Bonsal et al. (2001) and Zhang et al. (2001) by using the latest version of the adjusted daily precipitation of Environment Canada (Eva Mekis 2008) for which some adjustment procedures had recently been refined and the datasets extended to 2006 (http://www.cccma.bc.ec.gc.ca/hccd/).

Historical meteorological records often suffer from short periods of records, which was also what had been encountered in this study. On the other hand, meteorological stations with complete, long-term records are usually limited and they are often located far apart from each other, especially in remote and northern areas of Canada. Given that long term, continuous and homogeneous, precipitation data are essential for trend analysis, to achieve the research of this study, a statistical technique involving the Markov chain has been used to extend the records of some selected climate stations of western Canada to at least 50 years.

1.4 Organization

A description of study sites, input datasets and data processing are presented in Chapter 2; detailed statistical analysis of data, such as data gap filling using the Markov chain, cumulative distribution function (CDF), and the Mann-Whitney-Pettit (MWP) test is presented in Chapter 3; results of the MWP tests performed on precipitation indices and possible linkage to the effects of climate change are presented in Chapter 4; and lastly, conclusions and recommendations for future work are presented in Chapter 5.

References

Allen, M. R. and W. J. Ingram, 2002: Constraints on future changes in climate and the hydrologic cycle, *Nature 419*, 224-232.

Akinremi, O. O., Mcginn, S. M, and Cutforth, H. W, 2001: Seasonal and spatial patterns of rainfall trends on the Canadian Prairies. *Journal of Climate 14,* 2177-2182

Adler, R. F., G. J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin, 2003: The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present), *Journal Hydrometeor,* 4, 1147-1167.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P. (eds), 2008: Climate change and water. *Technical Paper of the Intergovernmental Panel on Climate Change.* Geneva: IPCC Secretariat.

Beck. C, Grieser. J and Rudolf. B, 2005: A new monthly precipitation climatology for the global land areas for the period 1951 to 2000. *DWD, Klimastatusbericht 2004,* 181–190.

Bonsal, B.R., X. Zhang, L.A. Vincent and W.D. Hogg, 2001: Characteristics of daily and extreme temperatures over Canada. *Journal of Climate*, 14, 1959–1976.

Chen. M., Xie. P, Janowiak, J. E, 2002: Global land precipitation a 50-yr monthly analysis based on gauge observations. *Journal of Hydrometeorology,* VOL **3**, n. 3, p. 249-266.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. Raper and K. S. Yap. 2001: Projections of future climate change. In: Climate Change 2001: The Scientific Basic. *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge UK and New York USA, 881 pp.

Devine, K.A. and É. Mekis, 2008: Field accuracy of Canadian rain measurements. *Atmosphere-Ocean 46* (2), 213–227.

Emori, S. and S. J. Brown, 2005: Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate. *Geophysical Research Letters 32*, L17706, doi: 10.1029/2005GL023272.

Gan, T.Y., 1998: Hydroclimatic trends and possible climatic warming in the Canadian Prairies, *Water Resources Research*, 34(11), p.3009-3015, AGU.

Groisman, P. Y., B. Sun, R. S. Vose, J. H. Lawrimore, P. H. Whitfield, E. Forland, I. Hanssen-Bauer, M. C. Serreze, V. N. Razuvaev and G. V. Alekseev, 2003: Contemporary climate changes in high latitudes of the Northern Hemisphere: daily resolution. In: Proceeding of the 14th Symposium on Global Change and Climate Variations, 9–13 February 2003, Long Beach, California. *American Meteorology Society* 10 pp.

Groisman, P. Y., Knight, R. W., Easterling, D. R. and Karl, T. R, 2004: Trends in intense precipitation in the climate record. *Journal of Climate* 18, 1326-1350

Groisman P.Ya., Knight R.W., Easterling D.R., Karl T.R., Hegerl G.C. and Razuvaev V.N, 2005: Trends in intense precipitation in the climate record. *Journal of Climate*, 18, 1326–1350.

Hansen, J., Mki. Sato, R. Ruedy, K. Lo, D.W. Lea and M. Medina-Elizade, 2006: *Global Temperature Change Proceedings of the National Academy of Sciences of the United States of America 103*,14288-142923, DOI: 10.1073/pnas.0606291103.

Held, I. M. and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *Journal of Climate*, 19 (21), 5686-5699
Hulme M, Osborn T. J, Johns T. C, 1998: Precipitation Sensitivity to Global Warming: Comparison of Observations with HadCM2 Simulations. *Geophysical Research Letters*, VOL 25, No. 17, pp. 3379-3382,

Huntington. T. G, 2006: Evidence for Intensification of the Global Water Cycle. Review and Synthesis. *Journal of Hydrology* 319, 83–95.

IPCC Fourth Assessment Report, *Intergovernmental Panel on Climate Change*, *2007:* Available from http://www.ipcc.ch/.

Kumar, A., F. Yang, L. Goddard, and S. Schubert, 2004: Differing Trends in the Tropical Surface Temperatures and Precipitation over Land and Oceans. *Journal of Climate* 17, 653-664.

Kunkel, K.E., Easterling, D.R, Redmond, K. and Hubbard, K. 2003: Temporal variations of extreme precipitation events in the United States: 1895-2000. *Geophysical Research Letters* 30: 10.1029/2003GL018052.

Lucie A. Vincent and Éva Mekis. 2006: Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century, *Atmosphere-Ocean*, 44:2, 177-193

L. V. Alexander, X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M. G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre, 2006: Global observed changes in daily climate extremes of temperature and precipitation, *Journal of Geophysical Research*, Vol. 111, D05109, doi: 10.1029/2006JD006290

Neelin, J. D., M. Münnich, H. Su, J. E. Meyerson, and C. Holloway, 2006: Tropical Drying Trends in Global Warming Models and Observations. *Proceedings of the National Academy of Sciences*.

Peterson, T. C., C. Folland, G. Gruza, W. Hogg, A. Mokssit and N. Plummer, 2001: Report on the activities of the working group on climate change detection and related rapporteurs 1998–2001. *Report WCDMP-47, WMOTD 1071*, Geneva, Switzerland, 143 pp.

Pryor, S. C., J. A. Howe, and K. E. Kunkel, 2009: How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *International Journal of Climatology*, 29, 31–45.

Qian, B., Zhang, X., Chen, K., Feng, Y. and O'Brien, T. 2010: Observed long-term trends for agroclimatic conditions in Canada. *Journal of Applied Meteorology and Climatology 49*:604-618. doi:10.1175/2009JAMC2275.1.

Rosenberg, E. A., P. W. Keys, D. B. Booth, D. Hartley, J. Burkey, A. C. Steinemann, and D. P. Lettenmaier, 2010: Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. *Climatic Change,* 102, 319–349.

Smith, Ian. 2004: An assessment of recent trends in Australian rainfall. *Australian Meteorological Magazine*, 2004, Vol 53, No. 3, pp. 163-173.

U. R. Joshi and M. Rajeevan, 2006: Trends in Precipitation Extremes over India. National Climate Centre Research Report No: 3/2006.

Vincent, L. A. and É. Mekis, 2006: Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean* 44 (2), 177-193.

Vincent, L.A. and É. Mekis, , 2009: Discontinuities due to joining precipitation station observation in Canada, *Journal of Applied Meteorology and Climatology*, Vol. 48, No. 1, 156-166.

Zhang, X., R. Brown, L. Vincent, W. Skinner, Y. Feng and E. Mekis, 2010: Canadian climate trends, 1950 ‐ 2007. Canadian Biodiversity: Ecosystem Status and Trends 2010 *Technical Thematic Report Series No. 5*. Published by the Canadian Councils of Resource Ministers

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

Zhai, P., X. Zhang, H. Wan and X. Pan. 2005: Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate* 18, 1096–1108.

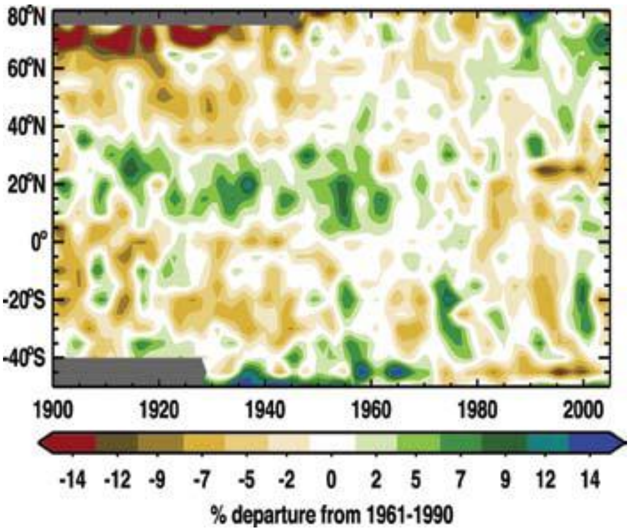


Figure 1.1 Latitude–time section of average annual anomalies for precipitation (%) over land and from 1900 to 2005, relative to the 1961–1990 means. Values are averaged across all longitudes and are smoothed with a filter to remove fluctuations less than about 6 years. The color scale is non-linear and grey areas indicate missing data. (Figure obtained from IPCC technical paper VI)

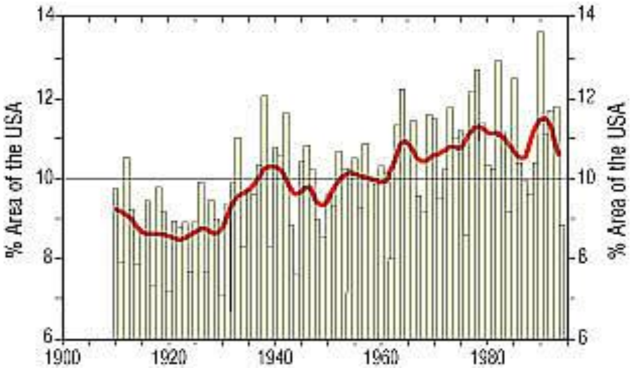


Figure 1.2 The % area of USA, excluding Alaska and Hawaii, with an unusually large amount of total annual precipitation attributed to extreme precipitation events (http://www.greenfacts.org/en/climate-change-ar3/l-3/climate-change-7.htm).

Chapter 2 Study Area and Data Set

The study area is western Canada, which covers a total area of 2,908,433 square kilometers (1,122,952 sq. mi) or approximately 29% of Canada's total land area. From west to east the four provinces of western Canada are British Columbia, Alberta, Saskatchewan and Manitoba. The latter three are collectively known as the Prairie Provinces, while British Columbia is the Pacific Province (Figure 2.1).

Energy and agriculture are Western Canada's dominant revenue. With only 10 million inhabitants, this region is one of the world's largest net exporters of both energy and agricultural commodities per capital. Western Canada covers several major climatic biogeographic and geological zones. In the three Prairie Provinces, mean annual temperatures are the highest in southern Alberta because they are elevated by winter Chinooks, and they decrease moving north and east towards the Hudson Bay. The annual precipitation varies considerably spatially, ranging from less than 300 mm in the semiarid grassland to approximately 700 mm in central Manitoba and more than 1000 mm at high elevations in the Rocky Mountains.

Representative precipitation trends can generally be derived from historical climate records that are accurate with few missing data and of sufficient length, typically more than 50 years long. The following difficulties are often encountered when one attempts to analyze trends in Canadian precipitation data. First, because of its vast land mass and its location in high latitudes, Canada experiences a wide range of climatic regimes. Second, most precipitation is highly variable spatially and temporally (Phillips, 1990). Third, most northern climate observation stations were not set up until the late 1940s and only a limited number of climate stations has been set up in the north. Fourth, the locations, instrumentation, and data collection practices have been changed over time, which give rise to inhomogeneity in climatological records. Therefore, usually reliable trend estimates can only be derived after these inhomogeneity issues are adequately resolved.

In this study, daily rainfall, snowfall and total precipitation data of 30 climate stations selected are based on the first generation Adjusted Precipitation for Canada (APC1) dataset developed in the mid-1990s (Mekis and Hogg, 1999) and subjected to quality control. 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, snowpack densities based on snow ruler measurements were adjusted (Mekis and Hopkinson, 2004). Great care was as well given to properly account for the trace observation (Mekis, 2005).

Information of all meteorological stations selected for this study is shown in Table 2.1. These stations are selected because they are located south of 60 °N, have a record length of more than 50 years, and do not have more than two years of missing data, and missing data do not occur in any of two consecutive years. In addition, the datasets were updated to include data collected between 2004 and 2006, and missing daily data were filled using the Markov chain approach. In this study, A set of ten precipitation indices used for change trend analysis are computed from the adjusted precipitation data. The definitions and procedures of ten precipitation indices analyzed in this study are based on the recommendations by Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) to facilitate the comparison of results obtained in this study with these of other similar studies. A website, http://ccma/seos.uvic.ca/ETCCDMI, dedicated to this effort provides comprehensive descriptions of all of the indices, details of quality control procedures and references to relevant literature (Alexander et al., 2006).

References

Alexander, L. V., X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M. G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre, 2006: Global observed changes in daily climate extremes of temperature and precipitation, *Journal of Geophysical Research*, Vol. 111, D05109, doi: 10.1029/2006JD006290

Devine, K.A. and É. Mekis, 2008: Field accuracy of Canadian rain measurements. *Atmosphere-Ocean* 46 (2), 213–227.

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

Mekis, É And R. Hopkinson, 2004: Derivation of an improved snow water equivalent adjustment factor map for application on snowfall ruler measurements in Canada. 14th *Conference on Applied Climatology,* Seattle, USA. 7-12.

Mekis, É., 2005: J3.7 Adjustments for trace measurements in Canada. 15th Conference on Applied Climatology, Savannah, Georgia, USA, 20-24 June 2005.

Phillips, D.W, 1990: Climates of Canada. *Canadian Government Publishing*, Ottawa, Ontario.

Vincent, L.A. and Mekis, É, 2009: Discontinuities due to joining precipitation station observation in Canada, *Journal of Applied Meteorology and Climatology*, Vol. 48, No. 1, 156-166.

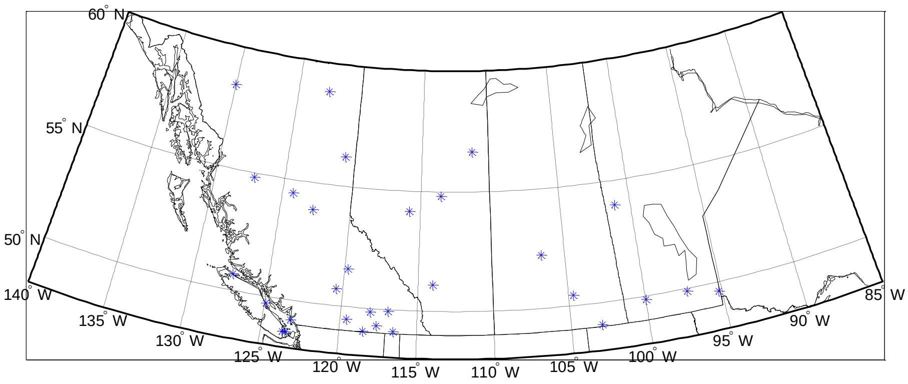


Figure 2.1 Locations of all the selected stations over the study area

Table2.1 A list of meteorological stations of western Canada selected for study

No.	Province	Station No.	Station Name	From	To	Latitude ^{o}N	Longitude ^{o}W
1	BC	1192340	DEASE LAKE	1947	2004	58.42	130.00
2	BC	1026270	PORT HARDY A	1945	2006	50.68	127.37
3	BC	1077500	SMITHERS A	1946	2006	54.82	127.18
4	BC	1021830	COMOX A	1945	2006	49.72	124.9
5	BC	1092970	FORT ST JAMES	1911	2004	54.45	124.25
6	BC	1017230	SHAWNIGAN LAKE	1919	2004	48.65	123.62
7	BC	1018620	VICTORIA INT'L A	1941	2006	48.65	123.43
8	BC	1108447	VANCOUVER INT'L A	1897	2006	49.18	123.17
9	BC	1096450	PRINCE GEORGE A	1918	2006	53.88	122.67
10	BC	1192940	FORT NELSON A	1943	2006	58.83	122.58
11	BC	1183000	FORT ST JOHN A	1941	2006	56.23	120.73
12	BC	1163780	KAMLOOPS A	1897	2006	50.7	120.45
13	BC	1168520	VAVENBY	1929	2004	51.58	119.78
14	BC	1126150	PENTICTON A	1912	2006	49.47	119.60
15	BC	1133270	GRAND FORKS	1941	2004	49.03	118.47
16	BC	1142820	FAUQUIER	1927	2004	49.87	118.07
17	BC	1141455	CASTLEGAR A	1941	2004	49.3	117.63
18	BC	1143900	KASLO	1919	2004	49.92	116.92
19	BC	1142160	CRESTON	1913	2004	49.1	116.52
20	AB	3067372	WHITECOURT A	1945	2006	54.15	115.78
21	AB	3031093	CALGARY INT'L A	1895	2006	51.12	114.02
22	AB	3060321	ATHABASCA 2	1951	2006	54.82	113.53
23	AB	3062693	FORT MCMURRAY A	1924	2006	56.65	111.22
24	SASK	4057120	SASKATOON	1906	2006	52.23	106.62
25	SASK	4016560	REGINA A	1904	2006	50.43	104.67
26	SASK	4012400	ESTEVAN A	1945	2006	49.07	103.00
27	MAN	5052880	THE PAS A	1939	2006	53.97	101.10
28	MAN	5010485	BRANDON CDA	1932	2006	49.87	99.98
29	MAN	5023222	WINNIPEG INT'L A	1895	2006	49.9	97.23
30	MAN	5031320	INDIAN BAY	1941	2005	49.62	95.20

Chapter 3 Research Procedure

This chapter provides details of the research procedure adopted to gap fill missing data of those stations with missing values using the Markov chain and the cumulative distribution function (CDF). After gap filling, statistical properties of the adjusted datasets where analyzed and compared with the original datasets to ensure that statistical properties of the gap filled data are not modified because of gap filling. Other than analyzing the statistical properties of the gap filled data, the Mann-Whitney-Pettit (MWP) test was used to detect possible change points present in the time series of precipitation indices derived from the daily precipitation data.

3.1 Markov Chains

A Markov chain is a statistical technique used for short-term prediction of hydroclimatic data such as precipitation and stream flow. In a discrete time Markov chain, the state of a variable is given at certain discrete time steps. The process starts in one of these states and moves successively from one state to another. Each move is called a step. Suppose in a discrete variable state *S* where $Z_0, Z_1, \ldots, Z_n, \ldots$, are the random variables observed at discrete time steps 0, 1…, *n*…, respectively. A discrete-time Markov chain is a short-term memory system such that the transition from the previous (z_{n-1}) to the present states (z_n) depends only on the previous state, and not on states earlier, e.g., only the immediate past has influence on the present:

$$P\,\{Z_n = z_n | Z_0 = z_0, Z_1 = z_1 \ldots Z_{n-1} = z_{n-1}\} = P\,\{Z_n = z_n | Z_{n-1} = z_{n-1}\} \qquad (3.1)$$

Where $P\,\{Z_n = z_n | Z_{n-1} = z_{n-1}\}$ is the transition probability of the Markov chain. If the transition from state z_{n-1} at time step *(n-1)* to state z_n at time step *n* are represented by *j* and *k*, respectively, then Equation (1) can be re-expressed as

$$p_{jk}(n) = \mathrm{P}\{Z_n = k|Z_{n-1} = j\} \qquad (3.2)$$

A Markov Chain is homogeneous if the transition or conditional probability, $p_{jk}(n)$, is invariant to the shift in the origin, which means that the process is stationary, then $p_{jk}(n)$ is independent of n, and the transition probability can be written as

$$p_{jk} = \mathrm{P}\{Z_n = k|Z_{n-1} = j\}, \text{ for all } n = 1, 2, 3, \ldots \qquad (3.3)$$

The matrix P, formed by placing p_{jk} in row j and column k, for all j and k, is called the transition probability matrix or chain matrix.

We used a first-order Markov chain to fill the data gaps of missing records of the selected meteorological stations. By making the assumption that p_{jk} is invariant to the shift in origin, then by knowing a variable at a given time is sufficient to forecast it at the next time step. The simplest kind of discrete variables is that which has binary values (yes/no), corresponding to only two states it can possibly exist. For the daily precipitation, the two states are their occurrence or non-occurrence. A sequence of daily observations of “precipitation” and “no precipitation” from a meteorological station constitute a time series of that discrete variable.

The Markov chain model for daily precipitation occurrences had been studied extensively. In 1962, Gabriel and Neuman (1962) first found that a first-order Markov chain could provide a satisfactory model for daily precipitation occurrences at Tel Aviv, Israel. There are other models available to simulate precipitation occurrences, e.g., alternating renewal processes between two states (precipitation occurs or does not occur). However, Markov chain models are popularly used models than others. Roldán and Woolhiser (1982) found that they provided better results than an alternating renewal process for five stations in the United States. For most applications a first order (depend only on the previous day) model has been used very often. A Markov Chain model was also used by Bailey (1964), Weiss (1964), as well as Hopkins and Robillard (1964), to describe the occurrence of sequences of wet or dry days. Haan et al. (1976) used a first-order Markov chain with six rainfall states to model both the occurrence and amounts of precipitation. Similarly, Kottegoda et al. (2004) successfully used a first order Markov chain model to predict daily precipitation occurrences and amount in Italy. Deni et al. (2009) also found a first order Markov chain to be most appropriate to model the distribution of wet spells for northwestern and eastern regions of peninsula Malaysia.

In this study, a first-order Markov chain with only two states, wet or dry was used. A day with a total precipitation greater than 0 mm was considered a wet day, represented as state 1, while state 0 represents a dry day with precipitation equal to 0 mm. For example, some records in September 1961 for station Victoria Int'l A (1018620), B.C. are missing. A Markov chain was used to predict the precipitation occurrence for the missing data day. To estimate the transition probability matrix for September 1961, the daily precipitation data for September of 1951 to 1960 and 1962 to 1971 where used to derive the transition probability between wet and dry days for September as showed in Table 3.1.

Table 3.1 Transition probability between Wet and Dry days for September

States	Days	Total Days (day)	Probability	
0→0	278	Dry days	P(D/D)	0.764
0→1	86	364	P(W/D)	0.236
1→0	84	Wet days	P(D/W)	0.356
1→1	152	236	P(W/W)	0.644

0→0 means P (D/D) or a dry day is followed by another dry day, which for

September is 0.764, while 0→1 or P (W/D) for September is estimated to be 0.236. Similarly, the probability of a wet day followed by a wet day, P (W/W), or by a dry day, P (D/W), is 0.644 and 0.356, respectively. Based on Table 3.1, the September transition probability matrix P for this Markov chain is:

$$P = \begin{pmatrix} 0.764 & 0.236 \\ 0.356 & 0.644 \end{pmatrix}$$

In summary, as a first-order Markov chain, the transition probability to a future state depends only on its current state (Wilks, 1995). Therefore the state of a particular day with missing data can be determined based on the previous state and the transition probabilities derived from 20 years' records for the same month in the same station according to the following procedure:

1) The previous day is dry

   Randomly generate a probability P_r, if $P_r \leq$ P (W/D), it is assigned a wet day; if $P_r >$ P (W/D), it is assigned as a dry day.

2) The previous day is wet

   Randomly generate a probability P_r, if $P_r \leq$ P (W/W), it is assigned as a wet day; if $P_r >$ P (W/W), it is assigned as a dry day.

3.2 Cumulative Distribution Function (CDF)

In probability theory, the cumulative distribution function (CDF) describes the probability that a real-valued random variable ***Z*** with a given probability distribution will be found at a value less than or equal to $\boldsymbol{z}$, e.g., $P\ (Z \leq \mathbf{z}) = F_Z\,(\mathbf{z})$. In this study, for each station with some missing data, the CDF is derived based on the closest 20 years of historical precipitation records of the same month. On the basis of the CDF curve derived from precipitation records of the same station, the amount of precipitation on a particular day could be estimated. If the state of the missing data day was determined as a wet day, the precipitation amount (**z**) is estimated from $P_r = F_Z(\mathbf{z})$, which may require linear interpolation between z values associated with two cumulative probabilities that are slightly smaller and larger than P_r, respectively. If it is determined that it will be a dry day, the amount of the precipitation would be set as 0. For instance, based on the September precipitation records of 1951 to 1971 for station (1018620) Victoria Int'l A, B.C, the CDF curve derived is shown in Figure3.1.

For the missing data of September, 1961, the precipitation amount for days designated as wet days by the above Markov chain approach are estimated from this CDF, as shown in the 1st day to the 30th day of Table 3.2 given below. Similarly, the missing daily precipitation data for other months are also filled by the Markov chain approach and CDF derived for other months.

Table 3.2 Estimated precipitation depths for 1st to 30st of September 1961 at units of 0.1mm.

Day	1	2	3	4	5	6	7	8	9	10
Depth	15	0	0	3	18	0	0	3	98	0
Day	11	12	13	14	15	16	17	18	19	20
Depth	0	0	0	0	0	0	0	12	20	33
Day	21	22	23	24	25	26	27	28	29	30
Depth	17	24	58	55	24	3	86	3	0	0

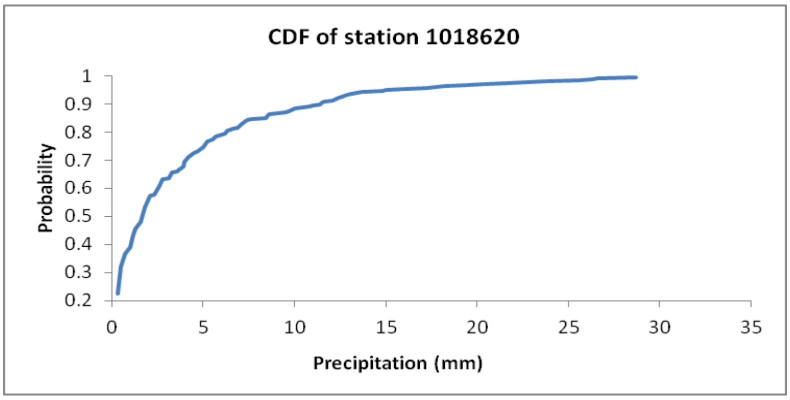


Figure 3.1 CDF of precipitation data of station 1018620 for September derived from observed data of 1951 to 1971.

3.3 Results of Data Gap Filling

To test the feasibility of estimating missing data of a climate station based on a first-order Markov Chain and a CDF curve derived from twenty years of historical data of the same station, results obtained from testing the proposed approach with four other climate stations are presented in Table 3.3. Each station is assumed to have a month of missing data at a time, such as the month shown in Column 2 of Table 3.3, and gap filling the month of missing data is based on the transition probability between wet and dry days (e.g., Table 3.1) and the CDF curve derived from a total of twenty years of historical data shown in Column 3 of Table 3.3. Using the same transition probability and CDF curve for each station, a total of twenty months of missing data were generated for each station (Appendix B:Tables II-1 to 4).

For each climate station, the mean numbers of precipitation days and precipitation depths (mm) obtained from gap filling twenty years of assumed missing precipitation data of a particular month are computed and compared with the observed counterparts to evaluate the proposed gap filling approach. The results shows that mean number of precipitation days and mean precipitation depths of the gap filled data are statistically the same as the observed counterparts, e.g., the null hypothesis H_0 is accepted. For example, for the Victoria Int’l A Station of BC, Station # 1018620 (48°65'N, 123°43'W), the differences in the mean precipitation days and precipitation depths between the observed and the gap filled data are within +/- 5% as shown in Table 3.3. Hypothesis testing on the difference in means was conducted and the results were displayed in column 8 in Table 3.3 as well. For a 2-sided statistical test at a significant level $a = 0.05$, if all the t_0 statistics are within the critical range of –1.96 and 1.96, the null hypothesis cannot be rejected.

Table 3.3 Evaluations of data generation of four stations

Testing Station	Missing Data Date	Period of Records	Monthly Mean Precipitation Days (days)		Daily Mean Precipitation (mm)		Hypothesis Test (t_0)	Change of precipitation
			Original	Generated	Original	Generated		
1133270	Jan.1964#	1954-1974	7.919	8.270	1.564	1.635	0.180	4.6%
3031093	Apr.1997	1986-2006	7.282	7.487	1.016	1.008	-0.262	-0.8%
1018620	Sep.1961	1951-1971	6.103	5.615	1.546	1.472	-0.499	-4.8%
1126150	Dec.1964	1954-1974	10.810	10.560	1.209	1.210	0.284	0.1%

The January data of other years between 1954 and 1974 are also assumed missing, one at a time, so that a total of twenty years of missing data are generated.

Graphically, the CDF of the observed and gap filled data of the four stations match well with each other (Figures 3.2-3.5). On the basis of the summary statistics of Table 3.3, and CDF curves of Figures 3.2-3.5, this proposed approach to gap fill missing data of four climate stations have produced reliable results and it is applied to gap fill all the missing data encountered in this study.

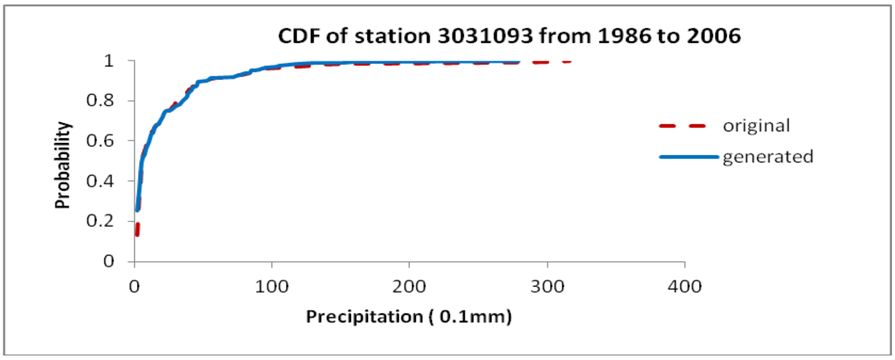


Figure 3.2 CDF curves of original and generated data for station 3031093

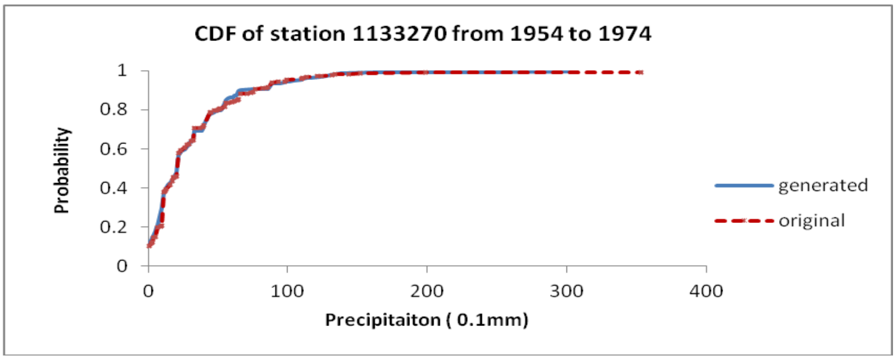


Figure 3.3 CDF curves of original and generated data for station 1133270

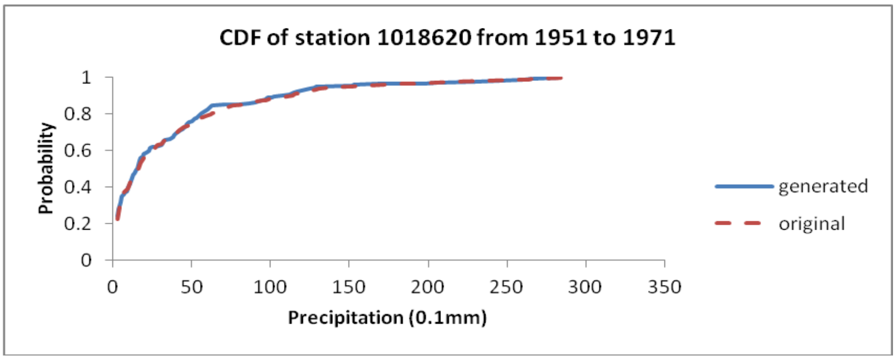


Figure 3.4 CDF curves of original and generated data for station 1018620

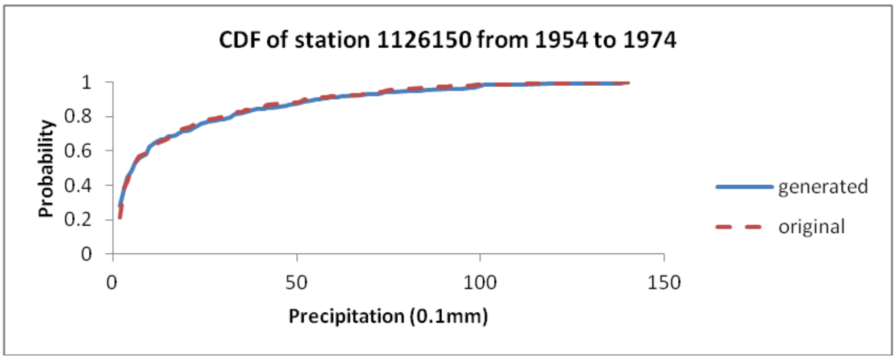


Figure 3.5 CDF curves of original and generated data for station 1126150

3.4 Precipitation Extreme Indices

After filling the missing precipitation data using the above proposed procedure, the following precipitation indices (Table 3.4) were calculated according Equations A1 to A10 (see Appendix A). More information about these indices, such as in terms of precipitation type, frequency, intensity and extremes, etc., is given in the Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) (Alexander et al., 2006).

These precipitation indices selected in this study can be broadly classified into two groups: The first group deals with precipitation depth or intensity, such as PRCPTOT, SDII, R95P, R99P, RX1day and RX5day, while the second group deals with the frequency of exceeding or non-exceeding certain thresholds, such as CDD, CWD, R10mm, and R20mm. By re-expressing precipitation data into a category representing magnitude and another representing frequency, we can gain better insight into often-subtle or hidden features of major climatic regions of Western Canada. These indices are also valuable for assessing the possible impact of climate changes or climate anomalies on regional activities related to agriculture, economy, social development, and other sectors.

Table 3.4 Definitions of ten precipitation indices used in this study

Precipitation indices	Definitions	Units
PRCPTOT	Annual total precipitation in wet days (>=1.0mm)	mm
Rx1day	Monthly maximum 1-day precipitation	mm
Rx5day	Monthly maximum consecutive 5-day precipitation	mm
R95p	Annual total precipitation when daily precipitation >95p	mm
R99p	Annual total precipitation when daily precipitation >99p	mm
SDII	Simple precipitation intensity index (Annual total precipitation/number of wet days)	mm/d
R10mm	Annual count of days when daily precipitation>=10mm	Days
R20mm	Annual count of days when daily precipitation>=20mm	Days
CDD	Max. number of consecutive day days with P<1.0mm	Days
CWD	Max. number of consecutive day days with P>=1.0mm	Days

PRCPTOT, defined as the annual total precipitation in wet days (days with daily precipitation values ≥ 1.0 mm), is probably the most important index reflecting the variations of precipitation over an entire year. Any discussion on changes to precipitation will usually begin with changes of this index at local and regional levels; R95P and R99P are indices for measuring heavy precipitation that exceeds the 95th and the 99th percentile thresholds, respectively. Since some stations do not have data from 1900 to 2006, thresholds are defined using daily precipitation as the 95th and 99th percentile of precipitation on wet days from 1961 to 1990. One index that takes into account the daily mean precipitation during wet days is the SDII defined as the total annual precipitation divided by the number of wet days when precipitation equal or greater than 1.0 mm occur; Very heavy or intense precipitation is measured using the RX1day and RX5day indices, defined as the monthly maximum 1-day or 5-day precipitation, respectively; Among indices that can measure dry conditions is the Consecutive Dry Days Index (CDD), which is the maximum number of consecutive days with daily precipitation ≤ 1.0 mm; In contrast, Consecutive Wet Days Index (CWD) which is the maximum number of consecutive days with precipitation ≥ 1.0 mm, reflects the wet condition; The persistence of intense precipitation can be measured by the total number of annual count of days with daily rainfall exceeding 10mm and 20mm, defined as the R10mm and R20mm indices, respectively.

To examine how gap filling the missing data will affect the above precipitation indices that are of interest to this study, the following precipitation indices are computed ten times for the climate station Kaslo, BC (1143900) with missing data for March, 1994, each time based on a different set of gap filled missing data for the station (see Table 3.5). In general, values of the indices remain approximately the same, except for two cases (2nd and 7th) of R95P and R99P that represent thresholds for the 95th and the 99th percentile exceedance probability.

Table 3.5 Ten sets of precipitation indices derived for March, 1994 for Station 1143900 based on ten sets of gap filled data for that month with missing data.

Index	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
CWD (day)	18	18	18	18	18	18	18	18	18	18
CDD (day)	20	20	20	20	20	20	20	20	20	20
R95p (mm)	140	222	140	140	160	140	220.2	140	140	164.5
R99p (mm)	33.3	78.9	33.3	33.3	33.3	33.3	74.7	33.3	33.3	33.3
SDII (mm/day)	5.5	5.9	5.4	5.4	5.7	5.4	5.9	5.5	5.4	5.6
R10mm (day)	18	21	18	18	22	18	21	19	18	20
R20mm (day)	4	5	4	4	5	4	6	4	4	5
PRCPTOT (mm)	838.1	948.8	873.4	864.5	906.9	874.2	948.7	861.1	873.9	882.4

3.5 Mann-Whitney-Pettit (MWP) Test

The objective of conducting this non-parametric, Mann-Whitney-Pettitt (MWP) test (Pettitt, 1979) on all the precipitation indices is to determine if there is a significant change point or to identify the time (the year) a significant change had occurred in the time series of these precipitation indices. The method of applying MWP to identify the point of significant change in a time series of precipitation data are summarized as follows. (Kiely et al., 1998 and Kiely., 1999).

Assume the length of a time series is T and t is the year of the most likely change point. A time series of T years of precipitation indices can be divided by the year t as two samples represented by $\{X_1, X_2, \ldots X_t\}$ and $\{X_{t+1}, X_{t+2}, \ldots X_T\}$. Next, an index W_t is defined as,

$$W_t = \sum_{j=1}^{T} sgn\ (X_t - X_j) \text{ for any } t \tag{3.4}$$

Where, sgn $(x) = 1$, for $(x)>0$,

sgn $(x) = 0$, for $(x) = 0$

And sgn $(x) = -1$, for $(x) < 0$

If $x = X_i - X_j$, a further index U_t is defined as,

$$U_t = \sum_{i=1}^{t} \sum_{j=1}^{T} sgn\left(X_i - X_j\right) \tag{3.5}$$

A plot of U_t against t for a time series with no change point results in a continually increasing value of $|U_t|$. However, if a change point exists, $|U_t|$ would increase up to this change point and after that it will decline. A plot with many repeated cycles of alternate increasing and decreasing $|U_t|$ demonstrates that the time series has various local change points. In that case, a way to determine the most significant change point still remains an unresolved issue. In this work, the most significant change point t is identified as the point when $|U_t|$ is the maximum. Pettitt (1979) developed the following procedure to determine whether the change point is statistically significant. The probability that a change point is associated with maximal $|U_t|$ can be approximated by,

$$K_T = max_{1 \ll t \ll T} |u_t| \tag{3.6}$$

The probability that a change point being at the year with $|U_t|$ as the maximum is approximately estimated as,

$$p = 1 - exp\left[\frac{-6K_T^2}{T^3 + T^2}\right] \tag{3.7}$$

By this approach, the probability that a change point occurred in any of the selected meteorological stations can be estimated. As an example, the MWP test was applied to the station Kaslo, BC (1143900) with missing data. For this station, *p* (MWP statistic) was computed 10 times for each precipitation index, to test if *p* and the change point (year) will be affected by gap filling the missing data of the station (Table 3.6). We find that both the *p* values and the change points remain almost the same for every index, which is what we expected. This demonstrates that the change point (if present) and the *p* value of the original precipitation data will likely not be affected either by gap filling some missing data or by transforming precipitation data to precipitation indices.

Table 3.6 MWP statistic *p* and change points in years ($^{\#}$) found for all precipitation indices computed for station 1143900 based on 10 different cases of gap filling the missing data for March, 1994

	P							
No.	CDD (1952$^{\#}$)	CWD (1952$^{\#}$)	RP95 (1958$^{\#}$)	RP99 (1945$^{\#}$)	R10mm (1953#)	R20mm (1958$^{\#}$)	SDII (1979$^{\#}$)	PRCTOT (1952$^{\#}$)
1	0.966	0.929	0.969	0.802	0.985	0.947	0.925	1.000
2	0.966	0.929	0.979	0.831	0.989	0.952	0.950	1.000
3	0.966	0.929	0.969	0.802	0.985	0.947	0.920	1.000
4	0.966	0.929	0.969	0.802	0.985	0.947	0.922	1.000
5	0.966	0.929	0.972	0.802	0.989	0.952	0.942	1.000
6	0.966	0.929	0.969	0.802	0.985	0.947	0.922	1.000
7	0.966	0.929	0.979	0.831	0.989	0.958	0.950	1.000
8	0.966	0.929	0.972	0.831	0.986	0.947	0.925	1.000
9	0.966	0.929	0.972	0.831	0.985	0.947	0.922	1.000
10	0.966	0.929	0.973	0.831	0.988	0.952	0.932	1.000

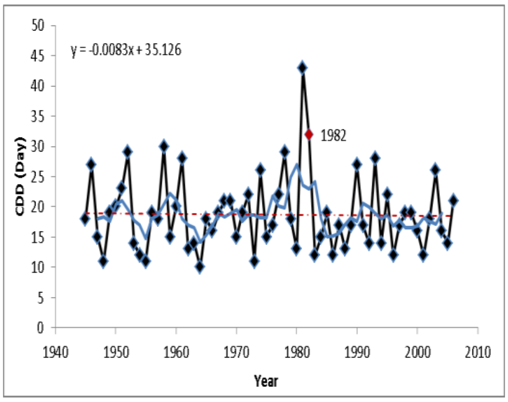
After gap filling the missing data for all 30 stations selected for Western Canada, each station has 50 years or longer data record. Next, the MWP statistic *p* and change points for all the stations are computed. Take the station Port Hardy A, BC (1026270) as an example. Figure 3.6 shows ten indices computed from its daily 1945-2006 precipitation data, with the linear regression fit and the change point (year) identified (Figures for other stations are displayed in Appendix C). For the annual total precipitation index (PRCPTOT), the P value (Mann-Whitney-Pettitt statistic) is 0.894. Prior to the detected change point of 1961, the mean PRCPTOT was 1752.37 mm (pre-1961) but after the change point, PRCPTOT increased to 1940.52 mm (post-1961). This means a nearly 11% increase in the total precipitation after the 1961 change point. Similar upward trends are also found in other indices such as R10mm, R20mm, R95p, R99p, SDII and RX1day, and RX5day. Also, the change points of precipitation indices of Table 3.7 have P values that are statistically significant at 0.05 significant level ($p \geq 0.95$).

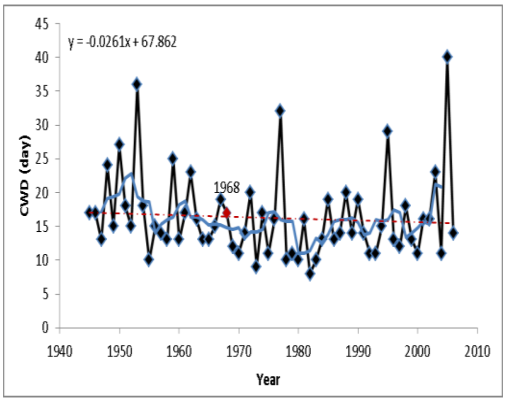
Table 3.7 P values of precipitation indices computed for Station 1026270.

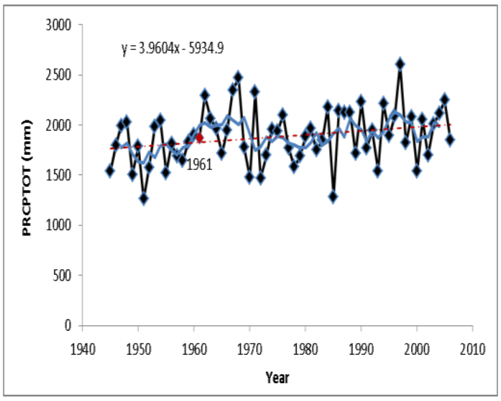
Index	P Value (MWP)	Change Point	% Change of Index after Change Point
R20mm	**0.959**	1985	16%
R95p	**0.964**	1961	57%
R99p	**0.990**	1961	249%
SDII	**0.998**	1961	15%
RX1day	**0.979**	1961	25%
RX5day	**0.993**	1961	26%

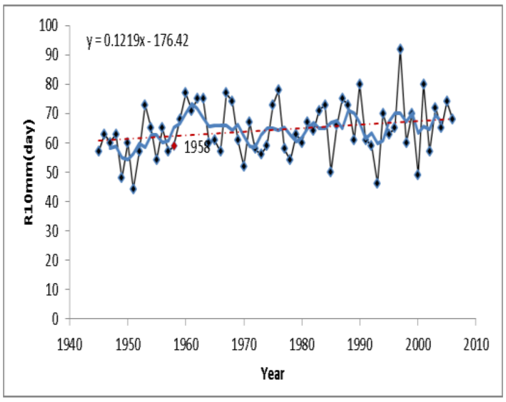
Table 3.7 shows that the increases (percentage) in the mean value of a precipitation index over the two time periods separated by the change point, the pre- versus the post-change point can be very significant, such as the R99p index with a 249% change after the change point. However, indices such as CDD and CWD only show a

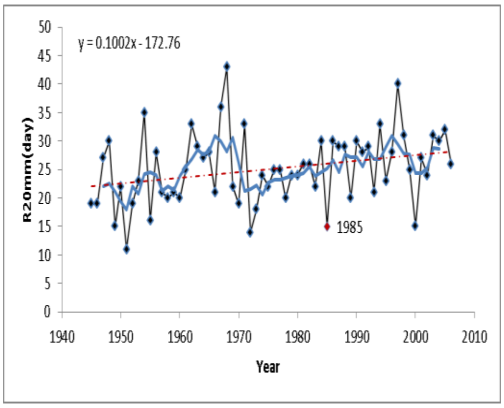
small change from 1945 to 2006 (not shown in Table 3.7) This means that even though precipitation intensity (e.g., Rx1day and Rx5day) and total precipitation volume might have increased over the years, the consecutive numbers of wet or dry had not changed much, which likely implies that changes had been mainly limited to storm intensities and volumes and not much to storm durations.

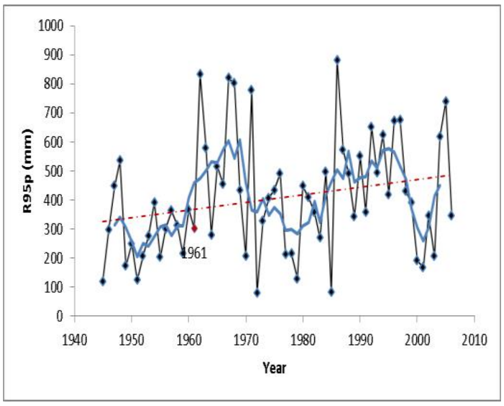












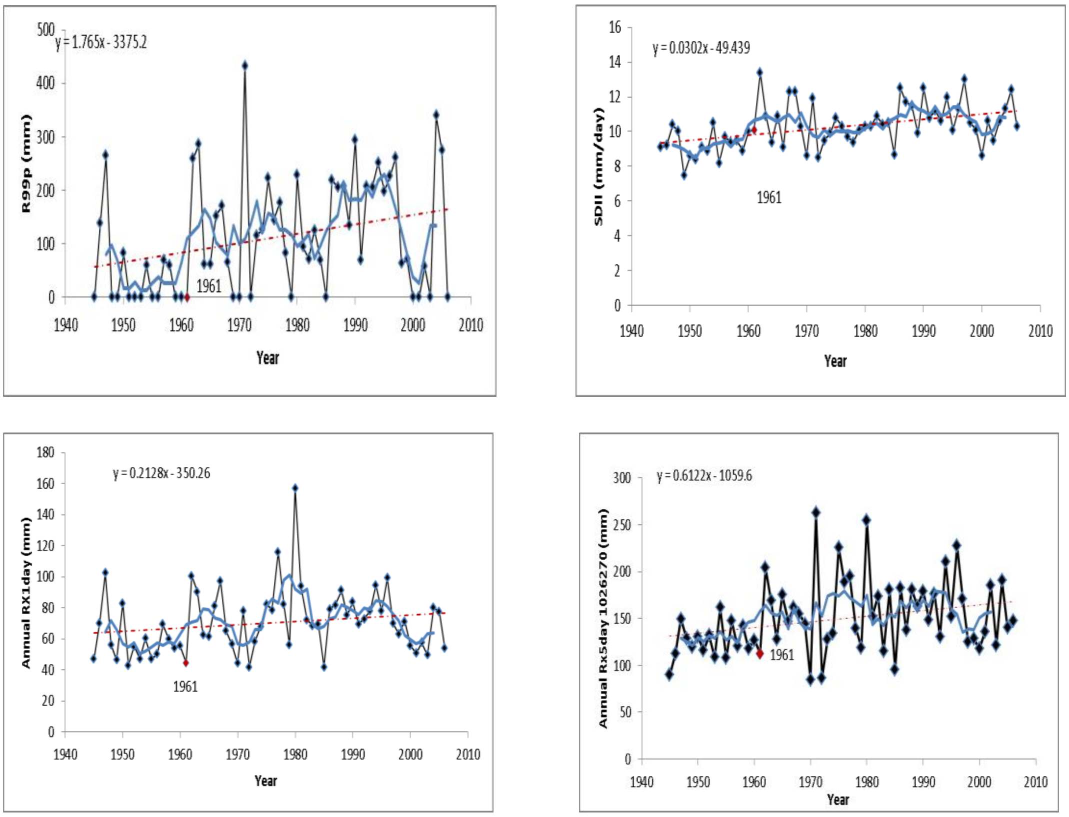


Figure 3.6 Time series plot of 10 precipitation indices with detected change points, the regression line fitted and 5-year moving average for Station 1026270

Tables 3.8 and 3.9 show results of the Mann-Whitney-Pettitt test (P value) and the year when change point was detected for the ten indices considered for all the climate stations selected in this study. P values (MWP statistic) that are statistically significant at 5% significant level (one-sided) are printed as bold in these two tables. Similarly, Tables 3.10 to 3.12 show values of the ten indices before the change point and the percent change after the change point had occurred for each station.

Table 3.8 Mann-Whiney-Pettitt Statistic (P) and Change points identified for PRCPTOT, CDD, CWD, R10mm and R20mm for all stations.

		PRCPTOT		**CDD**		**CWD**		**R10mm**		**R20mm**	
Station Name	Province	P (Mann-Whiney-Pettitt Statistic)	Change point (Year)	P	Change point (Year)	P	Change point (Year)	P	Change point (Year)	P	Change point (Year)
DEASE LAKE	BC	0.927	1960	0.489	1998	0.814	1960	**0.957**	1978	0.470	1960
PORT HARDY A	BC	0.894	1961	0.499	1982	0.888	1968	0.892	1958	**0.959**	**1985**
SMITHERS A	BC	0.553	1955	**0.959**	1963	0.533	1977	0.768	1980	0.768	1996
COMOX A	BC	0.855	1984	0.470	1966	0.515	1971	0.909	1975	0.948	1984
FORT ST JAMES	BC	**0.999***	1946	**0.995**	1946	**0.978**	1954	**0.993**	1946	0.415	1927
SHAWNIGAN LAKE	BC	**0.986**	1946	0.681	1991	0.553	1986	**0.986**	1947	0.857	1930
VICTORIA INT'L A	BC	0.582	1944	0.637	1991	0.620	1973	0.429	1944	0.617	1993
VANCOUVER INT'L A	BC	**0.999**	1957	0.689	1991	0.853	1917	**0.999**	1944	**0.984**	**1958**
PRINCE GEORGE A	BC	**0.999**	1931	**0.991**	1930	**0.973**	1931	**0.997**	1953	0.878	1956
FORT NELSON A	BC	0.616	1954	0.329	1951	0.880	1995	0.850	1954	0.772	1954
FORT ST JOHN A	BC	0.912	1952	0.837	1961	**0.978**	1976	0.751	1950	0.593	1952
KAMLOOPS A	BC	0.518	1927	0.599	1912	0.728	1936	0.627	1951	**0.991**	**1951**
VAVENBY	BC	0.797	1979	0.942	1952	**0.980**	1974	0.698	1959	0.927	1959
PENTICTON A	BC	**0.951**	1976	0.378	1957	0.479	1967	0.805	1970	0.923	1950
GRAND FORKS	BC	**0.936**	1979	0.605	1968	0.849	1989	0.534	1974	0.764	1964
FAUQUIER	BC	**0.999**	1979	**0.993**	1954	**0.999**	1970	**0.999**	1974	0.768	1975
CASTLEGAR A	BC	0.948	1984	0.684	1984	0.647	1980	**0.973**	1983	0.553	1964
KASLO	BC	**0.999**	1952	**0.966**	1952	0.929	1952	**0.985**	1953	0.947	1958
CRESTON	BC	**1.** 00	1957	**0.993**	1974	**0.994**	1957	**0.999**	1952	**0.999**	**1949**
WHITECOURT A	AB	0.877	1968	0.436	1975	**0.972**	1971	0.733	1953	0.803	1996
CALGARY INT'L A	AB	0.483	1903	**0.977**	1941	0.831	1913	0.746	1915	0.884	1914

ATHABASCA 2	AB	0.617	1959	0.883	1996	**0.997**	1977	0.511	1980	0.621	1986
FORT MCMURRAY A	AB	**0.988**	1953	0.910	1954	0.944	1964	0.912	1953	0.554	1997
SASKATOON	SASK	0.686	1975	0.920	1915	0.714	1968	0.938	1956	0.835	1928
REGINA A	SASK	0.722	1940	0.937	1982	0.723	1990	0.587	1976	0.749	1966
ESTEVAN A	SASK	0.436	1990	0.813	1959	0.777	1992	0.766	1978	0.511	1955
THE PAS A	MAN	0.871	1962	0.700	1966	0.514	1956	0.907	1962	0.412	1992
BRANDON CDA	MAN	0.887	1975	0.480	1982	0.759	1977	0.705	1975	**0.986**	**1977**
WINNIPEG INT'L A	MAN	0.426	1940	0.494	1946	0.757	1910	0.394	1970	0.526	1930
INDIAN BAY	MAN	0.540	1998	0.592	1966	**0.988**	1960	0.766	1971	0.838	1993

*Bolded P values are statistically significant at 5% significant level.

Table 3.9 Mann-Whiney-Pettitt Statistic (P) and Change points identified for R95, R99P, SDII, R1x day and R5x day for all stations.

		R95		**R99P**		**SDII**		**Rx1day**		**Rx5day**	
Station Name	Province	P (Mann-Whiney-Pettitt Statistic)	Change point (Year)	P	Change point (Year)	P	Change point (Year)	P	Change point (Year)	P	Change point (Year)
DEASE LAKE	BC	**0.950**[*]	1979	0.945	1979	**0.997**	1978	**0.956**	1979	**0.975**	1978
PORT HARDY A	BC	**0.964**	1961	**0.990**	1961	**0.998**	1961	**0.979**	1961	**0.993**	1961
SMITHERS A	BC	0.632	1966	0.460	1966	0.609	1955	0.399	1956	0.417	1975
COMOX A	BC	0.912	1975	0.524	1975	0.808	1975	0.491	1969	0.288	1998
FORT ST JAMES	BC	**0.987**	1932	0.670	1934	**0.994**	1929	0.889	1952	0.911	1947
SHAWNIGAN LAKE	BC	0.889	1946	0.699	1971	**0.976**	1946	0.711	1933	0.905	1966
VICTORIA INT'L A	BC	0.513	1993	0.516	1946	**0.979**	1973	0.751	1985	0.833	1993
VANCOUVER INT'L A	BC	0.947	1958	**0.972**	1953	**0.998**	1970	**0.988**	1953	0.934	1978
PRINCE GEORGE A	BC	0.797	1953	0.799	1966	0.928	1956	0.784	1966	0.349	1956
FORT NELSON A	BC	0.463	1954	0.239	1960	**0.993**	1974	0.939	1954	0.438	1954

FORT ST JOHN A	BC	0.823	1952	0.863	1953	0.928	1970	**0.961**	1953	0.944	1953
KAMLOOPS A	BC	0.870	1952	**0.965**	1954	**0.985**	1951	0.949	1954	**0.994**	1927
VAVENBY	BC	0.921	1959	0.876	1959	**0.979**	1959	0.810	1934	0.932	1981
PENTICTON A	BC	0.788	1953	**0.957**	1950	**0.977**	1975	0.912	1958	0.945	1951
GRAND FORKS	BC	0.514	1971	0.538	1987	0.514	1974	0.317	1984	0.820	1989
FAUQUIER	BC	**0.981**	1975	0.550	1981	**0.997**	1954	0.672	1941	0.675	1984
CASTLEGAR A	BC	0.471	1963	0.790	1959	0.792	1963	0.838	1959	0.865	1993
KASLO	BC	**0.969**	1958	0.802	1945	0.925	1979	0.709	1985	0.709	1985
CRESTON	BC	**0.999**	1949	**0.994**	1950	**0.996**	1949	**0.997**	1950	**0.998**	1949
WHITECOURT A	AB	0.874	1996	0.715	1996	0.842	1951	0.942	1991	0.787	1990
CALGARY INT'L A	AB	0.777	1914	0.840	1956	**0.981**	1915	0.369	1909	0.529	1906
ATHABASCA 2	AB	0.563	1984	0.349	1964	0.621	1955	0.393	1977	0.467	1968
FORT MCMURRAY A	AB	0.602	1997	0.612	1981	0.925	1997	0.640	1962	0.670	1955
SASKATOON	SASK	0.765	1928	0.935	1975	**0.999**	1945	0.761	1971	0.493	1946
REGINA A	SASK	0.693	1965	0.659	1923	0.737	1928	0.807	1923	0.554	1977
ESTEVAN A	SASK	0.532	1975	0.275	1965	0.474	1955	0.556	1975	0.436	1990
THE PAS A	MAN	0.511	1962	0.665	1982	**0.952**	1992	0.624	1992	0.624	1981
BRANDON CDA	MAN	0.783	1977	0.465	1937	0.843	1977	0.256	1937	0.515	1961
WINNIPEG INT'L A	MAN	0.635	1914	0.932	1961	0.856	1931	0.844	1961	0.624	1937
INDIAN BAY	MAN	0.840	1993	0.506	1974	0.289	1950	0.722	1951	0.848	1980

*Bolded P values are statistically significant at 5% significant level.

Table 3.10 Comparison of Annual PRCPTOT, CDD, CWD between the two periods for each station

Station No.	Annual PRCPTOT			CDD			CWD		
	Period before and after Change Point	Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point
DEASE LAKE	1947-60[$]-2004	391.44	17.92%	1947-98[$]-2004	23.6	-16.96%	1947-60[$]-2004	5.286	22.97%
PORT HARDY A	1945-61-2006	1752.37	10.74%	1945-82-2006	19.553	-11.14%	1945-68-2006	17.625	-12.27%
SMITHERS A	1946-55-2006	498.15	8.15%	1946-63-2006	24.556	-16.56%	1946-77-2006	6.719	1.11%
COMOX A	1945-84-2006	1254.84	-9.20%	1945-66-2006	24.409	12.56%	1945-71-2006	10.963	-8.52%
FORT ST JAMES	1911-46-2004	394.01	22.53%	1911-46-2004	26.114	-17.77%	1911-54-2004	5.250	13.90%
SHAWNIGAN LAKE	1919-46-2004	1094.74	16.69%	1919-91-2004	31.890	-20.88%	1919-86-2004	12.015	-13.07%
VICTORIA INT'L A	1941-44-2006	667.20	37.23%	1941-91-2006	31.804	-14.06%	1941-73-2006	10.667	-17.33%
VANCOUVER INT'L A	1897-57-2006	1074.59	12.85%	1897-91-2006	28.632	-18.74%	1897-17-2006	9.429	21.67%
PRINCE GEORGE A	1918-31-2006	442.37	43.31%	1918-30-2006	29.923	-38.35%	1918-31-2006	5.214	45.24%
FORT NELSON A	1943-54-2006	435.08	10.67%	1943-51-2006	21.444	18.87%	1943-95-2006	6.075	-20.69%
FORT ST JOHN A	1941-52-2006	407.17	25.63%	1941-61-2006	30.048	-12.66%	1941-76-2006	6.361	-15.11%
KAMLOOPS A	1897-27-2006	295.13	-6.45%	1897-12-2006	37.750	-15.34%	1897-36-2006	4.150	11.19%
VAVENBY	1929-79-2006	432.85	2.65%	1929-52-2004	23.708	-12.64%	1929-74-2004	5.326	15.78%
PENTICTON A	1912-76-2006	304.45	12.86%	1912-57-2006	31.956	-6.81%	1912-67-2006	4.821	3.17%
GRAND FORKS	1941-79-2004	453.12	15.15%	1941-68-2004	25.889	9.62%	1941-89-2004	6.245	12.09%
FAUQUIER	1927-79-2004	562.16	36.05%	1927-54-2004	26.750	-20.15%	1927-70-2004	6.585	48.22%
CASTLEGAR A	1941-84-2004	772.26	-8.66%	1941-84-2004	25.023	12.47%	1941-80-2004	8.150	6.85%
KASLO	1919-52-2004	695.31	21.47%	1919-52-2004	22.941	-18.77%	1919-52-2004	8.029	14.96%
CRESTON	1913-57-2004	472.84	31.34%	1913-74-2004	29.475	-22.52%	1913-57-2004	6.822	19.14%
WHITECOURT A	1945-68-2006	530.77	11.67%	1945-75-2006	24.839	5.62%	1945-71-2006	5.556	31.14%
CALGARY INT'L A	1895-03-2006	555.11	-20.82%	1895-41-2006	36.468	-15.96%	1895-13-2006	6.684	-19.24%

ATHABASCA 2	1951-59-2006	453.77	14.17%	1951-96-2006	25.565	37.69%	1951-77-2006	5.222	34.70%
FORT MCMURRAY A	1924-53-2006	412.75	16.09%	1924-54-2006	29.032	-15.54%	1924-64-2006	4.780	14.05%
SASKATOON	1904-40-2006	400.28	-7.29%	1906-15-2006	47.200	-39.26%	1906-68-2006	4.667	8.83%
REGINA A	1904-40-2006	393.62	7.82%	1904-82-2006	32.962	-19.73%	1904-90-2006	4.425	18.64%
ESTEVAN A	1943-54-2006	458.51	7.55%	1945-59-2006	26.733	21.61%	1945-92-2006	4.604	14.80%
THE PAS A	1939-62-2006	451.49	10.39%	1939-66-2006	27.630	-11.81%	1939-56-2006	5.353	-9.52%
BRANDON CDA	1932-75-2006	538.99	-9.97%	1932-82-2006	30.098	-14.72%	1932-77-2006	5.043	-12.49%
WINNIPEG INT'L A	1895-40-2006	547.36	3.97%	1895-46-2006	24.269	-4.68%	1895-10-2006	5.313	-13.14%
INDIAN BAY	1941-98-2005	647.90	13.50%	1941-66-2005	21.192	9.26%	1941-60-2005	4.650	24.73%

$ 60 means 1960

Table 3.11 Comparison of R10mm, R20mm, R95p between the two periods for each station

Station No.	R10mm			R20mm			R95p		
	Period before and after Change Point	Mean Value Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point
DEASE LAKE	1947-78$-2004	7.613	26.98%	1947-60-2004	1.154	40.59%	1947-79-2004	81.881	33.46%
PORT HARDY A	1945-58-2006	58.929	11.89%	1945-85-2006	23.800	16.39%	1945-61-2006	286.788	56.64%
SMITHERS A	1946-80-2006	12.829	-14.55%	1946-96-2006	2.902	-48.31%	1946-66-2006	135.467	-15.56%
COMOX A	1945-75-2006	43.710	-12.32%	1945-84-2006	15.925	-19.51%	1945-75-2006	306.248	-24.28%
FORT ST JAMES	1911-46-2004	7.543	33.47%	1911-27-2004	0.813	56.21%	1911-32-2004	51.171	76.00%
SHAWNIGAN LAKE	1919-47-2004	35.069	19.01%	1919-30-2004	11.500	43.71%	1919-46-2004	229.686	33.81%
VICTORIA INT'L A	1941-44-2006	21.000	35.25%	1941-93-2006	8.208	22.78%	1941-93-2006	200.732	25.24%
VANCOUVER INT'L A	1897-44-2006	36.200	16.85%	1897-58-2006	10.300	29.13%	1897-58-2006	197.769	24.67%
PRINCE GEORGE A	1918-53-2006	12.900	23.26%	1918-56-2006	1.641	41.38%	1918-53-2006	99.781	24.27%

FORT NELSON A	1943-54-2006	8.417	41.89%	1943-54-2006	2.333	47.53%	1943-54-2006	93.725	26.52%
FORT ST JOHN A	1941-50-2006	9.500	35.53%	1941-52-2006	2.333	49.21%	1941-52-2006	74.933	72.23%
KAMLOOPS A	1897-51-2006	5.727	-12.70%	1897-51-2006	1.200	-58.33%	1932-77-2006	68.711	-10.34%
VAVENBY	1929-59-2004	9.194	-12.50%	1929-59-2004	1.516	-50.17%	1929-59-2004	105.639	-25.15%
PENTICTON A	1912-70-2006	6.069	16.23%	1912-50-2006	1.263	-41.67%	1912-53-2006	76.812	-14.40%
GRAND FORKS	1941-74-2004	9.091	12.84%	1941-64-2004	1.652	-27.66%	1941-71-2004	88.733	14.71%
FAUQUIER	1927-74-2004	14.204	34.74%	1927-75-2004	2.408	27.44%	1927-75-2004	109.098	33.16%
CASTLEGAR A	1941-83-2004	24.190	-14.50%	1941-64-2004	3.304	24.01%	1941-63-2004	124.082	15.17%
KASLO	1919-53-2004	20.057	21.03%	1919-58-2004	3.625	30.73%	1919-58-2004	134.680	28.58%
CRESTON	1913-52-2004	11.154	39.22%	1913-49-2004	1.167	88.27%	1913-49-2004	70.822	68.69%
WHITECOURT A	1945-53-2006	11.556	30.95%	1945-96-2006	4.827	-37.85%	1945-96-2006	141.863	-41.47%
CALGARY INT'L A	1895-15-2006	14.143	-17.64%	1895-14-2006	4.900	-33.45%	1895-14-2006	168.430	-32.29%
ATHABASCA 2	1951-80-2006	13.800	-7.47%	1951-86-2006	3.778	-15.29%	1951-84-2006	138.003	-16.96%
FORT MCMURRAY A	1932-77-2006	10.370	22.04%	1924-97-2006	2.824	-40.99%	1924-97-2006	118.527	-39.72%
SASKATOON	1906-56-2006	10.431	-14.68%	1906-28-2006	3.783	-28.49%	1906-28-2006	140.009	-22.70%
REGINA A	1904-76-2006	10.795	-12.30%	1904-66-2006	3.556	-19.84%	1904-65-2006	123.895	-14.53%
ESTEVAN A	1945-78-2006	13.529	-13.15%	1945-55-2006	5.000	-21.18%	1945-55-2006	145.436	-20.90%
THE PAS A	1039-62-2006	11.174	16.74%	1939-92-2006	3.472	13.30%	1939-62-2006	108.561	18.30%
BRANDON CDA	1932-75-2006	15.455	-7.74%	1932-77-2006	5.457	-33.01%	1932-77-2006	143.676	-25.57%
WINNIPEG INT'L A	1895-70-2006	16.513	-5.29%	1895-30-2006	5.722	-9.63%	1895-14-2006	176.250	-19.18%
INDIAN BAY	1941-71-2006	20.065	-9.85%	1941-93-2005	5.717	34.10%	1941-93-2005	161.602	42.62%

$ 78 means 1978

Table 3.12 Comparison of R99p, SDII, Annual Rx1day and Annual Rx5day between the two periods for each station

Station No.	R99p			SDII			Annual Rx1day			Annual Rx5day		
	Period before and after Change Point	Mean Value Before change point (mm)	%Change after change point	Period before and after Change Point	Mean Value Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point	Period before and after Change Point	Before change point (mm)	%Change after change point
DEASE LAKE	1947-79[$]-2004	22.188	47.28%	1947-78-2004	4.061	9.71%	1947-78-2004	24.261	14.69%	1947-78-2004	40.397	18.67%
PORT HARDY A	1945-61-2006	39.700	249.17%	1945-61-2006	9.265	14.99%	1945-61-2006	59.200	24.93%	1945-61-2006	125.681	25.99%
SMITHERS A	1946-66-2006	44.871	-26.95%	1946-55-2004	4.558	7.24%	1946-55-2004	30.000	7.43%	1946-55-2004	57.740	-6.78%
COMOX A	1945-75-2006	99.852	-27.60%	1945-75-2006	9.329	-5.91%	1945-75-2006	61.021	-6.80%	1945-75-2006	123.440	-2.14%
FORT ST JAMES	1911-34-2004	19.839	71.71%	1911-29-2004	4.261	13.30%	1911-29-2004	22.736	15.09%	1911-29-2004	38.184	17.29%
SHAWNIGAN LAKE	1919-71-2004	70.347	62.35%	1919-46-2004	8.384	10.74%	1919-46-2004	52.013	20.53%	1919-46-2004	124.408	15.59%
VICTORIA INT'L A	1941-46-2006	22.367	180.24%	1941-73-2006	7.009	9.38%	1941-73-2006	46.732	17.74%	1941-73-2006	93.227	25.18%
VANCOUVER INT'L A	1897-53-2006	50.165	51.24%	1897-70-2006	8.101	9.55%	1897-70-2006	43.307	17.75%	1897-70-2006	96.044	12.99%
PRINCE GEORGE A	1918-66-2006	34.600	-29.44%	1918-56-2006	5.013	3.85%	1918-56-2006	29.417	-12.76%	1918-56-2006	50.503	3.79%
FORT NELSON A	1943-60-2006	46.428	-16.05%	1943-74-2006	4.772	13.56%	1943-74-2006	12.731	175.42%	1943-74-2006	53.991	14.86%
FORT ST JOHN A	1941-53-2006	8.908	324.59%	1941-70-2006	5.227	9.37%	1941-70-2006	26.525	42.58%	1941-70-2006	45.983	39.30%
KAMLOOPS A	1897-54-2006	30.007	-46.28%	1897-51-2006	4.476	7.35%	1897-51-2006	23.211	-9.78%	1897-51-2006	39.697	-16.89%
VAVENBY	1929-59-2004	44.565	-44.87%	1929-59-2004	4.696	-8.52%	1929-59-2004	15.133	60.44%	1929-59-2004	37.342	18.87%
PENTICTON A	1912-50-2006	35.818	-41.69%	1912-63-2006	4.186	7.06%	1912-63-2006	24.711	-13.68%	1912-63-2006	37.450	-11.67%
GRAND FORKS	1941-87-2004	28.115	-13.65%	1943-74-2004	4.618	2.33%	1943-74-2004	24.489	-6.12%	1943-74-2004	41.437	16.69%
FAUQUIER	1927-81-2004	31.655	53.38%	1927-54-2004	5.839	-8.82%	1927-54-2004	32.167	-13.57%	1927-54-2004	50.200	11.96%
CASTLEGAR A	1941-59-2004	21.178	89.84%	1941-63-2004	6.068	4.21%	1941-63-2004	29.084	12.07%	1941-63-2004	59.338	19.61%
KASLO	1919-45-2004	31.815	69.41%	1919-79-2004	5.855	6.47%	1919-79-2004	31.794	13.33%	1919-79-2004	31.794	13.33%
CRESTON	1913-50-2004	20.881	105.55%	1913-49-2004	4.881	8.78%	1913-49-2004	24.281	24.40%	1913-49-2004	44.905	25.39%
WHITECOURT A	1945-96-2005	43.969	-86.99%	1945-51-2006	5.000	17.63%	1945-51-2006	46.794	-25.70%	1945-51-2006	75.448	-19.07%

CALGARY INT'L A	1895-56-2006	67.469	-41.88%	1895-15-2006	6.829	-16.99%	1895-15-2006	46.243	-13.19%	1895-15-2006	83.110	-21.08%
ATHABASCA 2	1951-64-2006	28.429	45.64%	1951-55-2006	6.320	-13.10%	1951-55-2006	41.965	-3.31%	1951-55-2006	67.112	8.85%
FORT MCMURRAY A	1924-81-2006	47.134	-33.52%	1924-97-2006	5.150	-19.96%	1924-97-2006	39.453	-8.86%	1924-97-2006	54.974	8.49%
SASKATOON	1906-75-2006	39.437	-46.97%	1906-45-2006	5.848	-14.16%	1906-45-2006	38.314	-5.27%	1906-45-2006	57.943	-6.97%
REGINA A	1904-23-2006	64.140	-34.84%	1904-28-2006	6.208	-11.92%	1904-28-2006	47.061	-15.04%	1904-28-2006	62.410	-5.91%
ESTEVAN A	1945-65-2006	43.505	-23.96%	1945-55-2006	6.300	-5.42%	1945-55-2006	44.343	-10.43%	1945-55-2006	61.516	11.11%
THE PAS A	1939-82-2006	35.663	41.90%	1939-92-2006	5.428	9.67%	1939-92-2006	36.900	16.62%	1939-92-2006	71.519	8.48%
BRANDON CDA	1932-37-2006	89.367	-52.42%	1932-77-2006	6.876	-7.12%	1932-77-2006	59.960	-19.91%	1932-77-2006	78.352	-13.47%
WINNIPEG INT'L A	1895-61-2006	29.996	66.80%	1895-31-2006	6.846	-5.95%	1895-31-2006	47.974	5.43%	1895-31-2006	71.519	3.32%
INDIAN BAY	1941-74-2005	59.212	-12.96%	1941-50-2005	6.900	-3.62%	1941-50-2005	53.764	-10.99%	1941-50-2005	71.495	20.93%

$ 79 means 1979

References

A.N. Pettitt. 1979: A non-parametric approach to the change point problem *Applied Statistics*, Vol. 28, No. 2 pp. 126–135

Gabriel, K.R and Neumann, J., 1962: A Markov chain model for daily rainfall occurrence. Quarterly *Journal of the Royal Meteorological Society* 88, 90–95.

Hopkins, J.W., and P. Robillard. 1964: Some statistics of daily rainfall occurrence for the Canadian Prairie Provinces. *Journal of Applied Meteorology*, vol. 3, Issue 5, pp.600-602.

Haan, C. T., D. M. Allen, and J. O. Street. 1976: A Markov chain model of daily rainfall. *Water Resources*. 2(3), 443--449.

Kiely, G., J.D. Albertson and M.B. Parlange. 1998: Recent trends in diurnal variation of precipitation at Valentia on the west coast of Ireland. *Journal of Hydrology*, 207 (1998), pp. 270–279

Kiely., G., 1999: Climate change in Ireland from precipitation and streamlow observations *Advance Water Recourses*, 23 (1999), pp. 141–151

L. V. Alexander, X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M. G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D. B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J. L. Vazquez-Aguirre, 2006: Global observed changes in daily climate extremes of temperature and precipitation, *Journal of Geophysical Research*, Vol. 111, D05109, doi: 10.1029/2006JD006290

N.T. Kottegoda, L. Natale, E. Raiteri, 2004: Some considerations of periodicity and persistence in daily rainfalls. *Journal of Hydrology* 296:23–37

N.T. Bailey. 1964: The Elements of Stochastic Processes with Application to the Natural Sciences. *Wiley, London* (1964)

Roldán, J., and D. A. Woolhiser, 1982: Stochastic daily precipitation models. 1. A comparison of occurrence processes. *Water Resources Reviews,* 18, 1451–1459.

Sayang Mohd Deni, Abdul Aziz Jemain and Kamarulzaman Ibrahim, 2009: Fitting optimum order of Markov chain models for daily rainfall occurrences in Peninsular Malaysia *Theoretical & Applied Climatology*, Vol. 97 Issue 1/2, p109-121, 13p

Wilks, D. S., 1995: An Introduction. International Geophysics Series, Statistical Methods in the *Atmospheric Sciences* Vol. 59, Academic Press, 467 pp

Weiss. L. L. 1964: ‘Sequences of wet and *dry* days described by a Markov Chain Probability model’, *Monthly Weather Review, 92,* 160.

Chapter 4   Discussions of Results

4.1 Trends in Annual Total Precipitation

We will begin our discussion on changes to the precipitation of western Canada in terms of PRCPTOT, which is one of ten precipitation indices examined in this study. As showed in Tables 3.7 and 3.9, and in Figure 4.1, positive trends in PRCPTOT occurred mostly over the northwestern area, and the average % increase in the annual total precipitation for the post change-point period (2^{nd} period) was about 10-15% of the average annual precipitation of the pre change-point period. On a whole, about 70% of the stations show positive trends in PRCPTOT and about 1/3 of the positive trends are significant statistically. The remaining stations that show negative trends are mainly located in the southeastern part of Western Canada. Our results concur with those of Zhang et al. (2001) who also found precipitation totals of Canada to generally exhibit increasing trends. Figure 4.2 shows that about 2/3 of change points (years) detected on the basis of the MWP statistic occurred somewhere between 1940s and 1970s. However, some decreasing trends detected for southeastern stations occurred much earlier, e.g., in the 1920-30s. Table 4.1 shows that trend magnitudes of PRCPTOT range from 0.34 to 4.36 mm per year for all stations that had experienced significant changes.

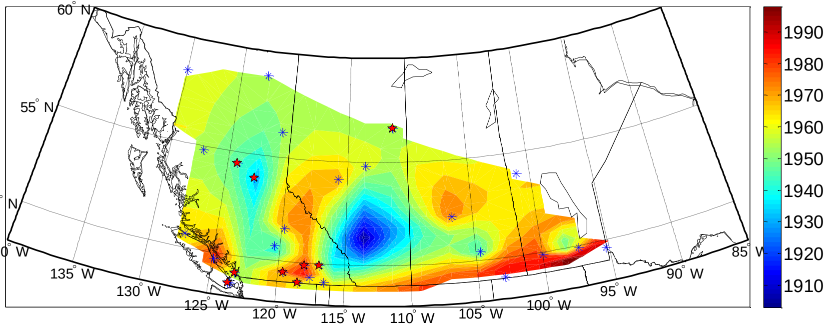


Figure 4.1 Spatial distribution of the calander year at which the change point of PRCPTOT was detected.

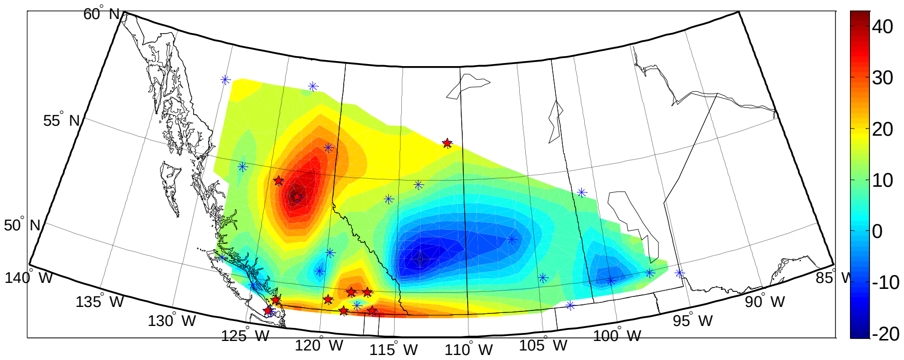


Figure 4.2 Spatial distribution of the percent (%) change in PRCPTOT after the change point was detected over the average PRCPTOT prior to the detected change point.

Table 4.1 Trend magnitudes (mm/yr) of PRCPTOT for stations that experienced statistically significant change to PRCPTOT at α = 0.05.

Station	3062693	1096450	1108447	1091970	1126150	1142160	1142820	1143900
Trend Magnitude	0.3498	1.5895	1.8543	1.261	0.4508	2.6439	4.3598	2.7922

4.2 Changes in Precipitation Frequency Indices

Observed decreasing trends of the Consecutive Dry Days Index (CDD) detected for most of the stations examined further reinforce trends obtained for PRCPTOT, that Western Canada had generally become wetter in the Twentieth Century (Figure 4.4). Only a few stations located in central Alberta, south border of Saskatchewan and Manitoba showed increasing trends in CDD. Our results agree with that of Lucie et al. (2006) who also found a general reduction in the number of consecutive dry days over Canada. The change-point (year) detected generally occurred between 1940s and 1970s, but some occurred as late as 1990s (Figure 4.3). In contrast, their majority of trends detected for the Consecutive Wet Days Index (CWD) over western Canada are increasing trends, which is consistent with the decreasing trends detected for the CDD index. Only a few decreasing trends have been detected for CWD in the west and north of BC, as well as some stations located in southeastern of Manitoba (Figure 4.6).

Results of trend magnitudes (days/year) for stations with statistically significant changes to CDD and CWD at α = 0.05 significant level are shown in Tables 4.2 and 4.3. For CDD, the trend magnitudes range from -0.05 to -0.108 days per year, while for CWD, the trend magnitudes are ranged between 0.0024 and 0.08 days per year.

The annual count number of days with daily precipitation equal or exceeding 10 mm (R10mm) had generally decreased in the southern parts (somewhere between 50 °N to 53 °N) of the Prairie Provinces such as Alberta, Saskatchewan and Manitoba. However, in central to northwestern of Alberta and in northern BC (north of 53 °N), both R10mm and R20mm indices had shown fairly great increasing trends, as well as some stations located in the south border of BC and Alberta. In between these two regions are a mixture of modest increasing and decreasing trends (Figures 4.8 and 4.10). Most of the statistically significant change points (year) occurred around 1950s and 1970s for both R10mm and R20mm indices as shown in Figures 4.7 and 4.9.

Results of trend magnitudes (days/year) for stations with statistically significant changes to R10mm and R20mm at α = 0.05 significant level are shown in Tables 4.4 and 4.5. There are more stations with a significant change to R10mm than to R20mm. For R10mm, the trend magnitudes range from 0.03 to 0.11 days per year, with one station has the negative trend magnitude as -0.0419 days per year. Only a few stations showed a significant change to R20mm with a mixture of positive and negative trends, ranging from -0.0075 to 0.11 days per year.

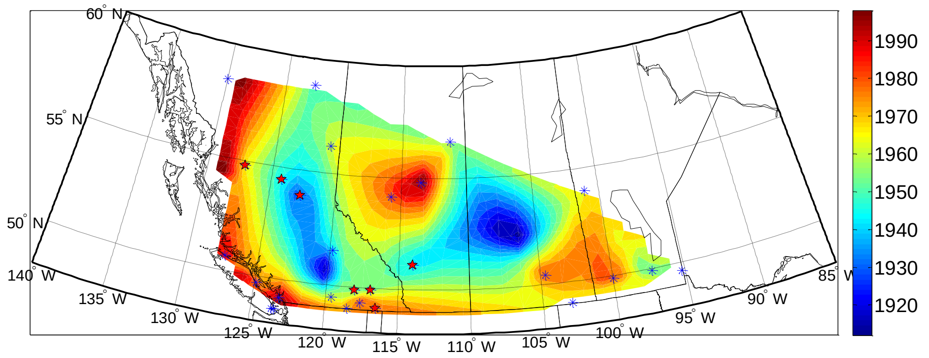


Figure 4.3 Spatial distribution of the calander year at which the change point of CDD was detected.

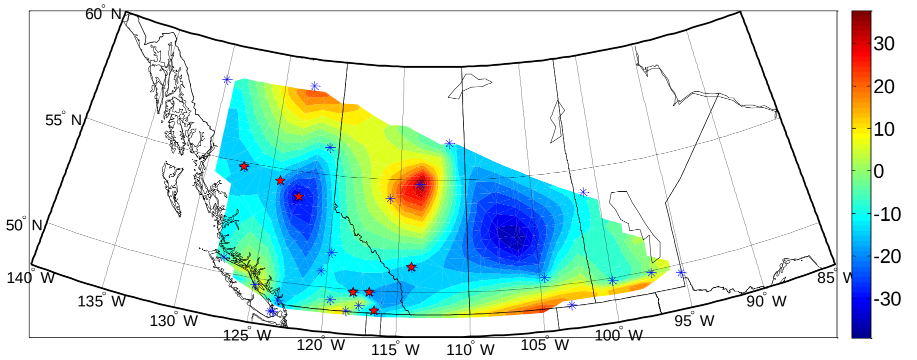


Figure 4.4 Spatial distribution of the percent (%) change in CDD after the change point was detected over the average CDD prior to the detected change point.

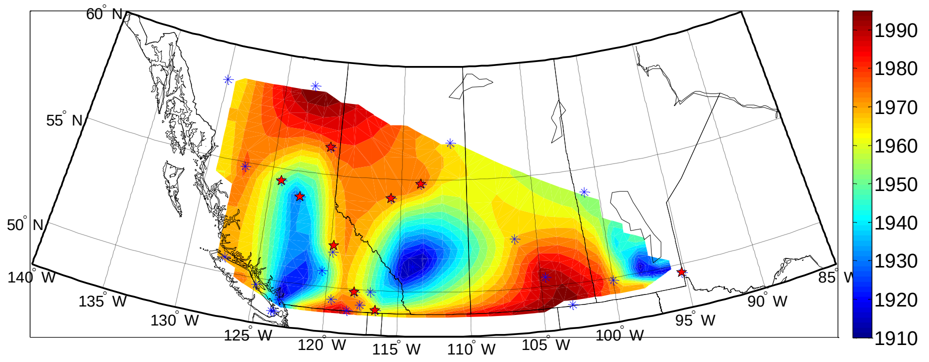


Figure 4.5 Spatial distribution of the calander year at which the change point of CWD was detected.

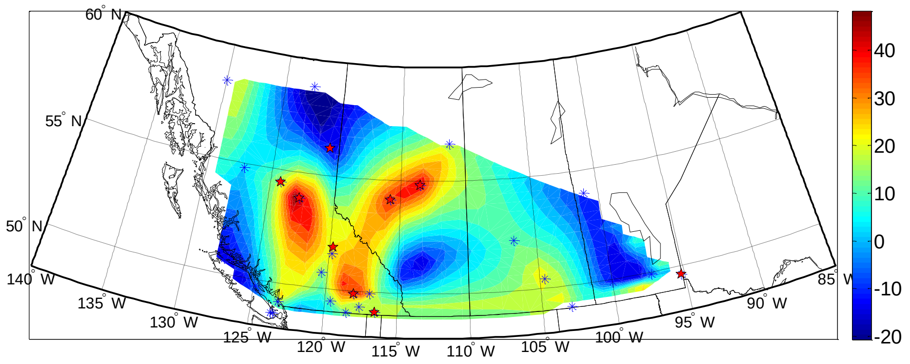


Figure 4.6 Spatial distribution of the percent (%) change in CWD after the change point was detected over the average CWD prior to the detected change point.

Table 4.2 Trend magnitudes (days/yr) of CDD for stations that experienced statistically significant change to CDD at α = 0.05.

Station	3031093	1096450	1092970	1177500	1142820	1143900	1142160
Trend Magnitude of CDD (Days/year)	-0.0726	-0.0767	-0.0557	-0.0703	-0.1087	-0.0543	-0.0815

Table 4.3 Trend magnitudes (days/yr) of CWD for stations that experienced statistically significant change to CWD at α = 0.05.

Station	3060321	1096450	1183000	1092970	1142160	1142820	1165820	3067372	3031320
Trend magnitude of CWD (Days/yr)	0.0515	0.0203	-0.0105	0.0091	0.0256	0.0867	0.0142	0.0382	0.0024

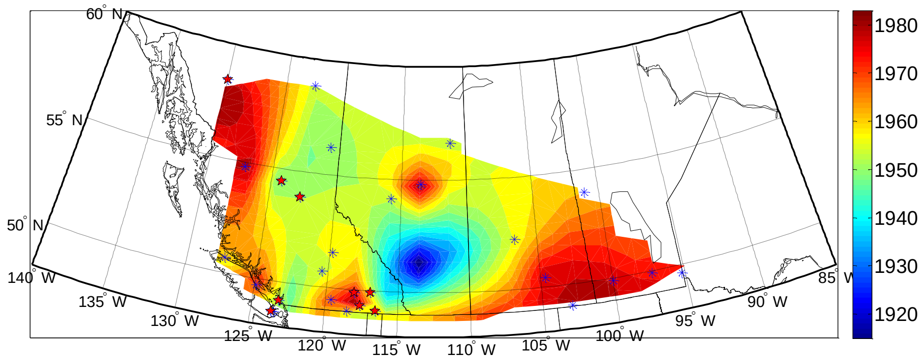


Figure 4.7 Spatial distribution of the calander year at which the change point of R10mm was detected.

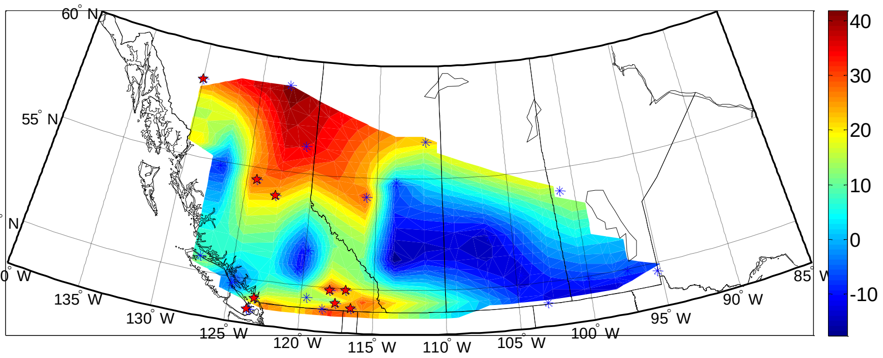


Figure 4.8 Spatial distribution of the percent (%) change in R10mm after the change point was detected over the average R10mm prior to the detected change point.

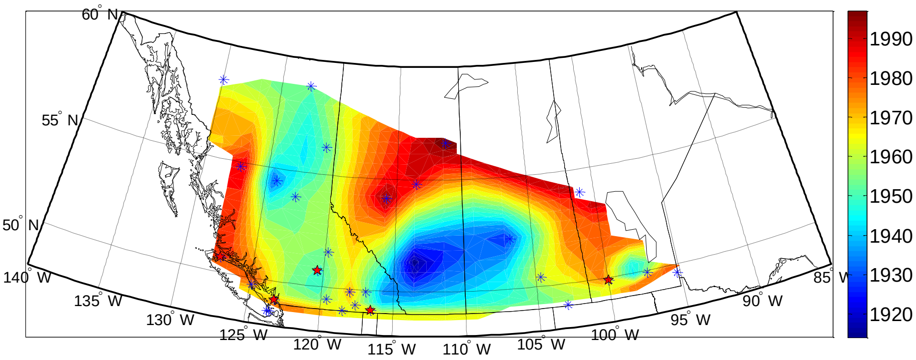


Figure 4.9 Spatial distribution of the calander year at which the change point of R20mm was detected.

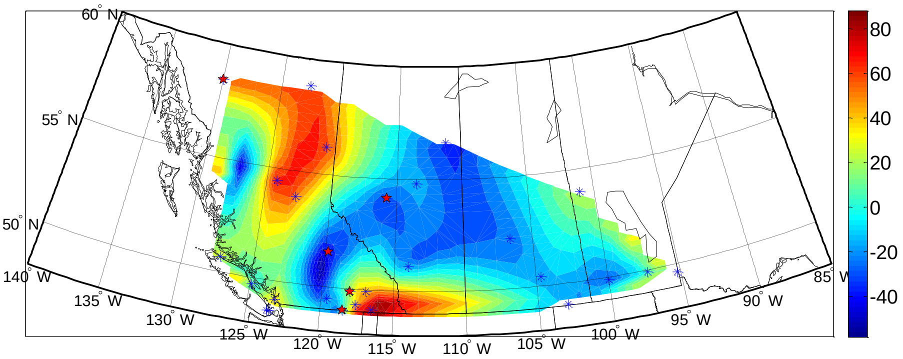


Figure 4.10 Spatial distribution of the percent (%) change in R20mm after the change point was detected over the average R20mm prior to the detected change point.

Table 4.4 Trend magnitudes (days/yr) of R10mm for stations that experienced statistically significant change to R10mm at α = 0.05.

Station	1096450	1108447	1092970	1141455	1142160	1192340	1017230	1142820	1143900
Trend Magnitude	0.0525	0.0861	0.0346	-0.0419	0.067	0.0416	0.085	0.1074	0.0632

Table 4.5 Trend magnitudes (days/yr) of R20mm for stations that experienced statistically significant change to R20mm at α = 0.05.

Station	1026270	1108447	1142160	1163780	5010485
Trend Magnitude	0.1002	0.0374	0.0171	-0.0075	-0.0234

4.3 Changes in Precipitation Depth and Intensity Indices

The annual total precipitation for extreme precipitation events that exceeded the 95% (R95p) and the 99% (R99p) thresholds generally showed decreasing trends in all three Prairie Provinces (Alberta, Saskatchewan and Manitoba) after the change point was detected, which happened between 1950 to 1970 for both indices (Figure 4.11and 4.13). Several stations in southeastern BC also show decreasing trends in R99p after the detection of change points. However, increasing trends were mostly detected for R99p in other parts of BC especially stations located in northern BC and majority stations for R95p located in BC. Overall, the R95p index tends showed higher trend magnitudes than that of R99p over Western Canada (Figures 4.12 and 4.14).

Even though many stations in the Prairie Provinces show negative changes to R95p, stations that show statistically significant changes in R95p are mostly stations showing increasing trends, which are estimated to be about 0.04 to 2.64 mm per year (Table 4.6). On the other hand, for the five stations with a statistically significant change to R99p (Table 4.7), a mixture of positive and negative trends that range from -0.15 to 1.765 mm per year are estimated.

On the basis of results obtained for the Rx1day index (Figure 4.18), the monthly maximum 1-day precipitation of all stations located in the three Prairie Provinces had decreased after the detection of change points. Some negative change had also occurred in southern BC but only positive changes have been detected over northern BC. On the basis of the MWP statistic (Table 3.8), the change point detected for the Rx1day index generally lie somewhere between 1950s and 1970s (Figure 4.17), and generally the index shows positive change. The trend magnitudes for stations with statistically significant changes are ranging from 0.0527 to 0.612 mm per year. For the RX5day index which represents the maximum 5-day precipitation amount (a potential indicator of flood producing events), even though majority of the stations in western Canada show positive change (Figure 4.20), some stations (between 50 °N to 53 °N in Prairie Provinces) also show negative change. The trend magnitudes for stations experiencing statistically significant changes range from about -0.0757 to 0.6122 mm per year.

In terms of simple precipitation intensity represented by the SDII index, most climate stations located in the three Prairie Provinces had experienced a negative change except some stations located in North West part of Alberta, and the majority of stations located in BC mostly showed positive change (Figure 4.16). Likely due to the shadowing effect of the Canadian Rockies, there is usually a strong contrast between the precipitation of BC (in terms of frequency and intensity) of the Pacific than that of the Prairie Provinces. In addition, changes to the SDII index are generally significant statistically (P value > 0.95), particularly for stations located in BC (Table 3.14). The change-point (year) detected generally occurred between 1940s and 1970s, but some occurred as early as 1930s (Figure 4.15). These results pertaining to precipitation changes based on the SDII index will have important implications to the future reliability of water resources for municipal water supply, agricultural economy (Riha *et al*., 1996), ecological sustainability and possibly increase of flood risk (Arnell *et al*., 1997).

Table 4.8 shows the trend magnitude (mm/day/yr) of SDII for stations with statistically significant changes to SDII. For most of these are positive trends of magnitude ranging from 0.034 to 0.042 mm/day/yr. There are a few negative trends with magnitudes ranging between -0.0127 and -0.004 mm/day/yr.

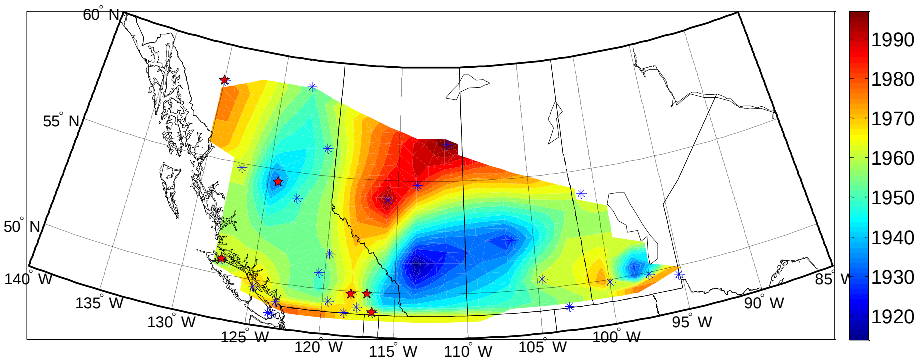


Figure 4.11 Spatial distribution of the calander year at which the change point of R95p was detected.

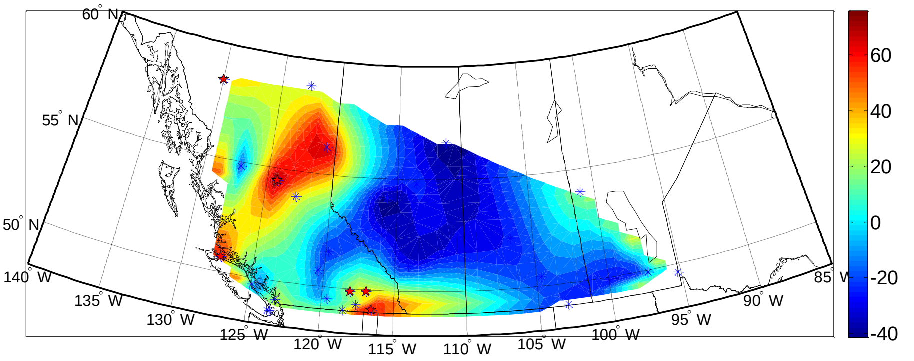


Figure 4.12 Spatial distribution of the percent (%) change in R95p after the change point was detected over the average R95p prior to the detected change point.

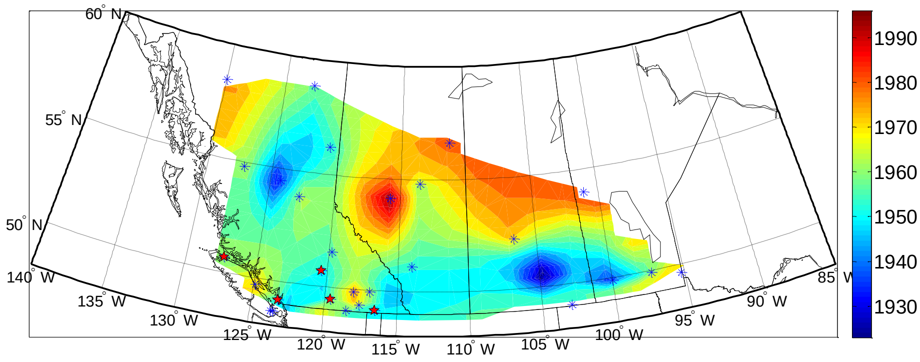


Figure 4.13 Spatial distribution of the calander year at which the change point of R99p was detected.

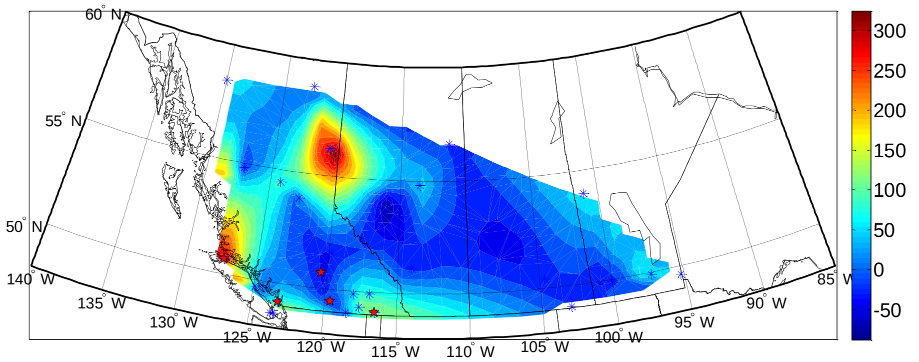


Figure 4.14 Spatial distribution of the percent (%) change in R99p after the change point was detected over the average R99p prior to the detected change point.

Table 4.6 Trend magnitudes (mm/yr) of R95p for stations that experienced statistically significant change to R95p at α = 0.05.

Station	1026270	1192340	1142820	1143900	1192970	1142160
Trend Magnitude	2.6359	0.6151	0.5973	0.734	0.4177	0.7308

Table 4.7 Trend magnitudes (mm/yr) of R99p for stations that experienced statistically significant change to R99p at α = 0.05.

Station	1026270	1163780	1108447	1126150	1142160
Trend Magnitude	1.765	-0.1507	0.2548	-0.085	0.3091

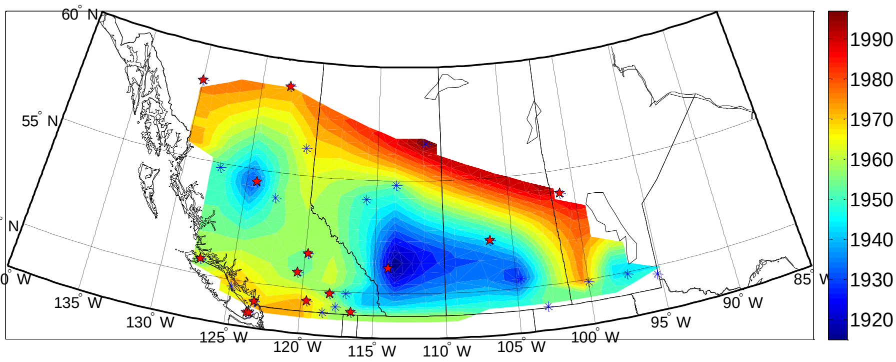


Figure 4.15 Spatial distribution of the calander year at which the change point of SDII was detected.

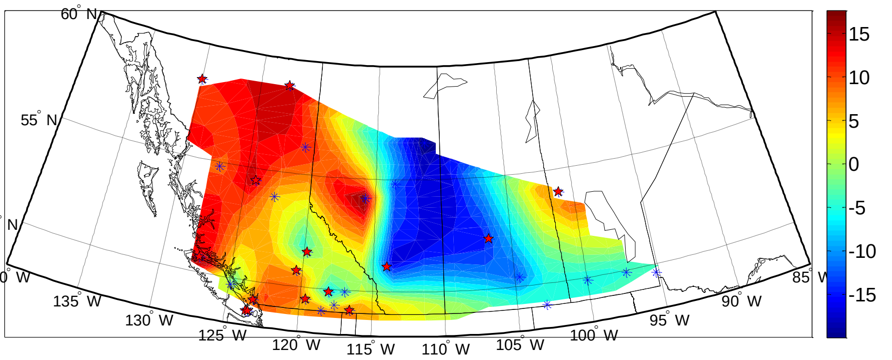


Figure 4.16 Spatial distribution of the percent (%) change in SDII after the change point was detected over the average SDII prior to the detected change point.

Table 4.8 Trend magnitudes (mm/day/yr) of SDII for stations that experienced statistically significant change to SDII at α = 0.05.

Station	1018620	1026270	1192940	4057120	1108447	1092970	1126150
Trend Magnitude	0.0188	0.0302	0.0413	-0.0127	0.0082	0.0034	0.0035
Station	1142160	1163780	1192340	1017230	1165820	1142820	5052880
Trend Magnitude	0.0037	-0.004	0.009	0.0117	-0.0052	-0.0079	0.0106

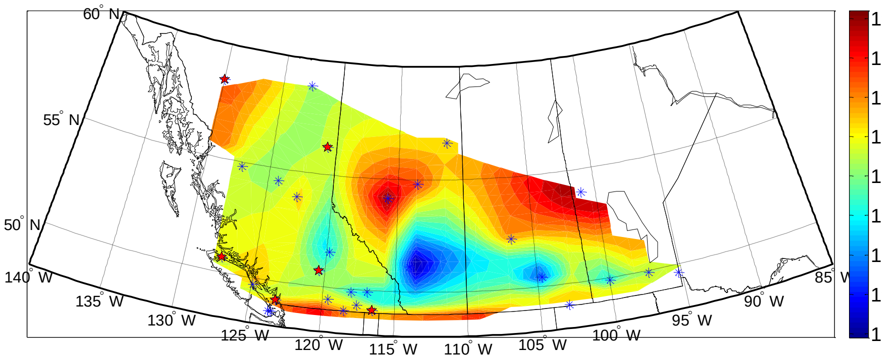


Figure 4.17 Spatial distribution of the calander year at which the change point of Annual Rx1day was detected.

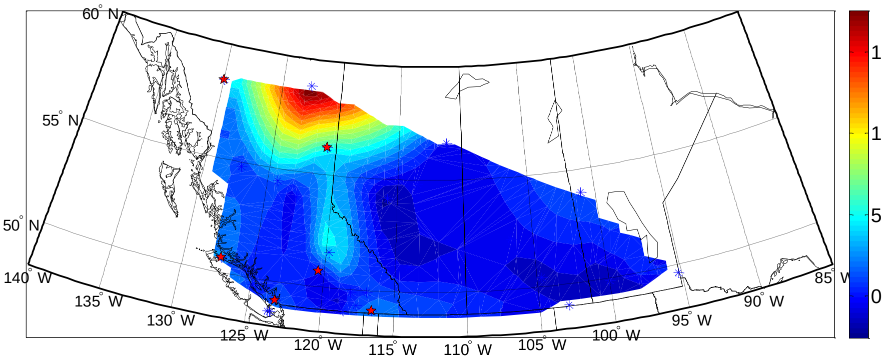


Figure 4.18 Spatial distribution of the percent (%) change in the Annual Rx1day after the change point was detected over the average Annual Rx1day prior to the detected change point.

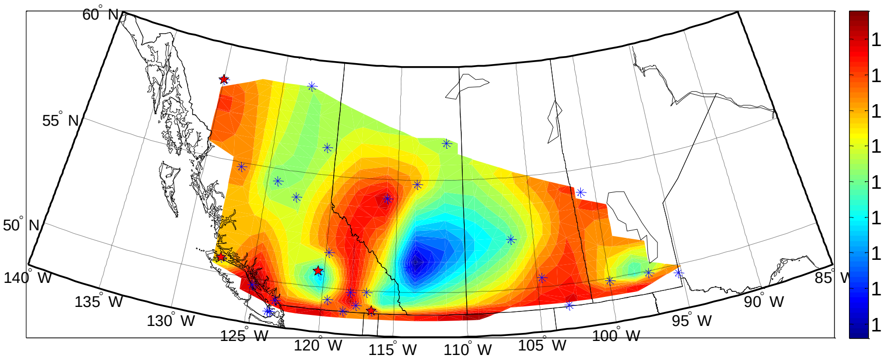


Figure 4.19 Spatial distribution of the calander year at which the change point of Annual Rx5day was detected.

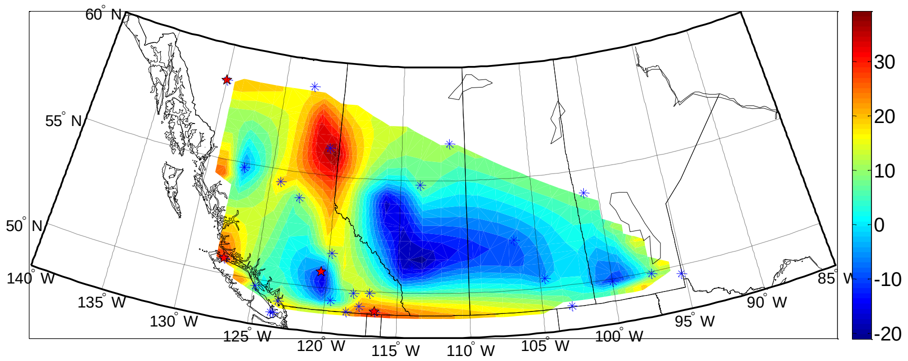


Figure 4.20 Spatial distribution of the percent (%) change in the annual Rx5day after the change point was detected over the annual Rx5day prior to the detected change point.

Table 4.9 Trend magnitudes (mm/yr) of annual Rx1day for stations that experienced statistically significant change to annual Rx1day at α = 0.05.

Station	1026270	1108447	1142160	1183000	1192340	1026270
Trend Magnitude	0.2128	0.0914	0.0703	0.0527	0.0976	0.6122

Table 4.10 Trend magnitudes (mm/yr) of annual Rx5day for stations that experienced statistically significant change to annual Rx5day at α = 0.05.

Station	1163780	1026270	1192340	1142160
Trend Magnitude	-0.0757	0.6122	0.1675	0.1624

4.4 Correlation Between DTR and Precipitation Indices

From the above results on change points and trends of ten precipitation indices analyzed for 30 climate stations distributed across western Canada, precipitation of western Canada had undergone changes in the 20th and the early 21th century, even though only some of these changes had been significant statistically at α = 0.05. Could these detected precipitation changes be related to the fact that mother Earth has been experiencing unprecedented climate warming on a global scale? Based on recent observations and climate model simulations, global warming which IPCC (Intergovernmental Panel of Climate Change) and many scientists of the climate community attribute to an unprecedented increase in atmospheric concentration of greenhouse gases, will lead to glacier retreat, decrease of Arctic sea ice, snow cover, permafrost degradation, changes to precipitation, and many other possible changes at global scale. For example, some recent climate model studies projected that precipitation in high latitude regions of North America is expected to increase in the mid 21st Century (e.g., Råisånen, 2009; Lawrence and Slater, 2009), and some climate model studies conducted to simulate the effects of increased greenhouse gases suggest an increase in the mean precipitation and frequency of heavy precipitation (Bony et al., 1995; Meehl et al., 2000).

Several preliminary tests were conducted in this study to relate certain temperature indices to precipitation indices, such as diurnal temperature range (DTR), monthly maximum value of daily maximum temperature (TX_x) and minimum temperature (TN_x), monthly minimum value of daily maximum temperature (TX_n) and minimum temperature (TN_n), number of summer days (SU) and number of icing days (ID). However, only results based on the annual DTR is presented in this report. Lets Tx_{ij} and Tn_{ij} be the daily maximum and minimum temperature respectively on day i and in period j. If I represent the number of days in j, then:

$$DTR_j = \frac{\sum_{i=1}^{I}(T_{x_{ij}} - T_{n_{ij}})}{I} \tag{4.1}$$

As showed in Table 4.11, DTR tends to be more negatively than positively correlated to precipitation indices and many of these correlations are statistically significant at 5% significant level. By analyzing the global mean surface air temperature, Easterling et al. (1997) showed that its increase is due, at least in part, to differential changes in daily maximum and minimum temperatures (the daily minimum temperature increasing at a higher rate or decreasing at a lower rate than the daily maximum) resulting in a narrowing of the Diurnal Temperature Range (DTR). On the other hand, more precipitation is generally expected from a warmer than a colder atmosphere given the former can accommodate more atmospheric water vapour. Therefore, we expect generally a negative correlation between DTR and precipitation indices given that a warmer climate means a narrowing of the DTR but an overall increase in precipitation. Our results are also supported by the findings of Dai et. al (1997), and Madden and Williams (1978), who suggested that annual mean DTR has a strong negative correlation with precipitation. Trenberth and Shea (2005) showed that significant large-scale correlations between observed monthly mean temperature and precipitation for North America and Europe have been expanded globally.

Table 4.11 Correlations between DTR and precipitation indices for each station with significant changes

Station	CDD	CWD	PRCPTOT	R10mm	R20mm	R95p	R99p	Rx1day	Rx5day	SDII
1018620	0.202	0.006	**-0.442***	**-0.416**	**-0.260**	**-0.281**	-0.011	-0.026	-0.157	**-0.249**
1026270	0.189	-0.162	**-0.357**	**-0.349**	-0.244	-0.171	-0.099	-0.148	-0.192	-0.191
1077500	0.340	0.176	-0.010	0.038	**0.313**	0.218	**0.437**	**0.385**	**0.355**	0.180
1092970	**0.448**	-0.116	**-0.526**	**-0.393**	-0.142	**-0.301**	-0.174	**-0.247**	**-0.274**	**-0.110**
1096450	**0.456**	**-0.209**	**-0.570**	**-0.442**	-0.174	**-0.250**	-0.031	-0.017	-0.167	-0.139
1141455	**0.346**	-0.028	**-0.355**	**-0.356**	-0.234	**-0.322**	-0.048	0.020	-0.018	-0.235
1142160	**0.290**	-0.185	**-0.514**	**-0.426**	**-0.222**	**-0.303**	-0.073	-0.108	-0.171	**-0.277**
1143900	0.094	-0.007	-0.130	-0.186	-0.085	-0.120	0.058	0.066	0.066	-0.129
1163780	0.122	-0.070	-0.253	-0.185	0.002	-0.166	-0.049	-0.159	-0.140	-0.106
1168520	**0.412**	**-0.363**	**-0.520**	**-0.478**	-0.057	**-0.311**	-0.107	-0.102	-0.229	**-0.292**
1183000	0.129	-0.100	**-0.333**	**-0.316**	**-0.281**	**-0.264**	-0.147	-0.061	-0.207	**-0.349**
1192340	0.105	0.478	**0.038**	0.160	0.454	0.055	0.323	0.126	0.237	0.441
1192940	-0.003	-0.002	**-0.279**	**-0.259**	0.018	-0.197	-0.242	-0.196	-0.146	-0.184
3031093	**0.256**	-0.073	**-0.483**	**-0.399**	**-0.265**	**-0.284**	**-0.186**	**-0.243**	**-0.199**	**-0.231**
3062693	**0.218**	-0.076	**-0.293**	**-0.272**	**-0.280**	-0.216	-0.032	0.068	-0.040	**-0.225**
4057120	0.123	-0.095	**-0.315**	-0.178	-0.044	-0.109	-0.072	-0.165	-0.174	-0.050
5010485	**0.370**	-0.194	**-0.496**	**-0.462**	**-0.398**	**-0.351**	-0.142	-0.093	**-0.338**	**-0.299**
5052880	0.120	0.984	0.255	0.469	0.150	0.144	0.555	0.316	0.979	0.585

*Bolded values are statistically significant at 5% significant level.

References:

A.N. Pettitt. 1979: A non-parametric approach to the change point problem *Applied Statistics*, Vol. 28, No. 2 pp. 126–135

Bony S, Duvel JP and LeTreut H. 1995. Observed dependence of the water vapour and clear-sky greenhouse effect on sea surface temperature. *Climate Dynamics,* 11 307–320.

Dai, A., I.Y. Fung, and A.D. Del Genio, 1997: Surface observed global land precipitation variations during 1900-1988. *Journal of Climate*, 10, 2943-2962, doi: 10.1175/1520-0442.

Easterling, D. R., Briony Horton, Philip D. Jones, Thomas C. Peterson, Thomas R. Karl, David E. Parker, M. James Salinger, Vyacheslav Razuvayev, Neil Plummer, Paul Jamason and Christopher K. Folland. 1997: Maximum and minimum temperature trends for the globe. *Science* Vol. 277, No. 5324 pp. 364–367.

Lawrence, D. M., and A.G. Slater. 2009: The contribution of snow condition trends to future ground climate. *Climate Dynamics,* 10.1007/s00382-009-0537-4

Lucie A. Vincent and Éva Mekis. 2006: Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century, *Atmosphere-Ocean,* 44:2, 177-193

Madden, R. A., and J. Williams. 1978: The correlation between temperature and precipitation in the United States and Europe, *Monthly Weather Review 106*, 142– 147

Meehl GA, Zwiers F, Evans J, Knutson T, Mearns L, Whetton P. 2000: Trends in Extreme weather and climate events: Issues related to modelling extremes in projections of future climate change, *Bulletin of the American Meteorological Society 81(3),* 427–436.

N.W. Arnell., N. Reynard, R. King, C. Proudhomme and J. Branson. 1997: Effects of climate change on river flows and groundwater recharge: guidelines for resource assessment. *Environment Agency Technical Report,* W82, Bristol.

P. M. Heikkinen, M. L. Räisänen and R. H. Johnson. 2009: Geochemical Characterisation of Seepage and Drainage Water Quality from Two Sulphide Mine Tailings Impoundments: Acid Mine Drainage versus Neutral Mine Drainage *Mine Water and the Environment* Volume 28, Number 1, 30-49, DOI: 10.1007/s10230-008-0056-2

Riha, S., D.S. Wilks and P. Simonets, 1996: Impact of temperature and precipitation variability on crop model predictions. *Climatic Change 32*, 293-311

Trenberth, K. and Shea, D. 2005: Relationships between precipitation and surface temperature. *Geophysical Research Letters* 32(14): doi: 10.1029/2005GL022760. issn: 0094-8276.

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

Chapter 5 Summary and Conclusions

The objective of this study was to investigate the long-term trends of various daily and extreme precipitation indices of climate stations in Western Canada with at least 50 or more years of data. To conduct this study, missing data of the selected climate stations were first gap filled by the Markov chain approach. In general, data of climate stations with missing values, after being gap-filled by this approach, retained their statistical properties and so the Markov chain is a useful tool in filling gaps in precipitation data. In other words, the daily precipitation data with gap-filled values preserve the statistical characteristic of the historical records. The Markov chain has also being successfully applied to gap fill other types of data with missing values. For example, Carmelia et al. (2012) used Markov chain with multiple imputation (MI) to replace missing CO_2 fluxes, Hui et al. (2003) Markov chain with MI to replace missing eddy covariance measurements data, and Remund and Page (2002) used a form of Markov chain to replace missing short- and long-wave radiation data.

Ten precipitation indices were first computed from daily precipitation data for stations with missing data and possible changes to these indices of 30 stations were analyzed. Most of climate stations analyzed for West Canada showed decreasing trends in the number of consecutive dry days (CDD) index. In contrast, increasing trends were detected for the number of consecutive wet days (CWD) over majority of the climate stations analyzed in this study. The majority of western Canada has been getting wetter since the middle of the 20th Century. However, less consistent change has been found in the extreme precipitation indices, R10mm and R20mm, which respectively represent the number of days when precipitation equal or exceed 10mm or 20mm (R10mm/R20mm).

For the monthly maximum 1-day precipitation index, Rx1day, the annual total precipitation when daily precipitation exceeds 95 or 99 % threshold index, R95p/R99p, and the precipitation intensity index, SDII, decreasing trends seem to have dominated the Prairie Provinces (Alberta, Saskatchewan and Manitoba). However, a mixture of decreasing and increasing trends were detected in British Columbia (BC) for R95p/R99p and mostly positive trends were observed for SDII.

In terms of the monthly maximum consecutive 5-day precipitation index, Rx5day, predominantly increasing trends have been observed across western Canada. In terms of PRCPTOP, the annual total precipitation during wet days, other than for a small area in southern BC, most stations across Western Canada showed increasing trends. Finally, based on many negative correlations found between DTR (diurnal temperature range) and precipitation indices, it seems that western Canada has become wetter since the middle of the 20th century likely because of a warming climate attributed to the greenhouse effects of increasing atmospheric concentration of greenhouse gases. Further research is needed to obtain a better understanding of regional and seasonal changes to precipitation in relation to other climatic factors, especially temperature, and how such changes will potentially impact the water resources, agricultural economy, and the environment of western Canada.

References

Carmelia M. Dragomir, Wim Klaassen, Mirela Voiculescu, Lucian P. Georgescu and Sander van der Laan, 2012: Estimating Annual CO_2 Flux for Lutjewad Station Using Three Different Gap-Filling Techniques. *Scientific World Journal*, 2012: 842893. doi: 10.1100/2012/842893

Dafeng Hui, Shiqiang Wan, Bo Su, Gabriel Katul, Russell Monson, Yiqi Luo, 2003: Gap-filling missing data in eddy covariance measurements using multiple imputation (MI) for annual estimations. *Agricultural and Forest Meteorology* 121 (2004) 93-111

Jan Remund and John Page, 2002: Advanced parameters WP 5.2b: Chain of algorithms: short- and longwave radiation with associated temperature prediction resources.

Appendix

A: Precipitation Index Algorithms

Let RR_{ij} be the daily precipitation amount on day *i* in period *j*. *I* is number of days in period *j*.

$$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}$$

Rx1day= max (RR_{ij})

R10mm: Count the number of days where $RR_{ij} \geq 10\ mm$

R20mm: Count the number of days where $RR_{ij} \geq 20\ mm$

CDD: Count the largest number of consecutive days where $RR_{ij} < 1\ mm$

CWD: Count the largest number of consecutive days where $RR_{ij} \geq 1\ mm$

Let RR_{kj} be the daily precipitation amount for the 5-day interval ending *k*, period *j*.

Rx5day = max (RR_{kj})

Let RR_{wj} be the daily precipitation amount on wet days, $w\ (RR \geq 1mm)$ in period *j*. If *W* represents number of wet days in *j*

$$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$$

Let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the 1961-1990 periods.

$$R95p_j = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn}95$$

Let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the 1961-1990 periods

$$R99p_j = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn}99$$

B: Tables of generated data on different months for 4 stations 1018620,

3031093, 1133270 and station 1126150

Table II-1 Generated data on September for station 1018620 from 1951 to 1971

Simulation year		1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1962	1963	1964	1965	1966	1967	1968	1969	1970
Previous status (0/1)		1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0
Daily Precipitation (Units of 0.1mm) Generated For September On Station. 1018620	1	0.0	20.7	0.0	117.4	0.0	0.0	0.0	3.0	263.1	14.7	0.0	0.0	0.0	0.0	115.3	0.0	0.0	0.0	0.0
	2	0.0	10.1	0.0	0.0	0.0	19.7	0.0	3.0	10.4	0.0	24.4	13.1	3.2	0.0	0.0	3.0	0.0	0.0	0.0
	3	0.0	5.8	0.0	12.8	0.0	0.0	0.0	32.1	58.2	0.0	90.3	41.1	3.0	0.0	0.0	0.0	18.6	0.0	70.9
	4	0.0	0.0	0.0	14.7	0.0	0.0	102.5	25.2	20.2	3.0	4.6	3.0	18.4	0.0	0.0	0.0	47.0	0.0	12.5
	5	0.0	0.0	0.0	0.0	13.7	39.9	153.4	44.9	0.0	18.3	114.6	3.0	0.0	4.6	0.0	0.0	0.0	281.1	4.1
	6	0.0	0.0	0.0	0.0	4.6	62.7	51.5	17.5	0.0	0.0	37.6	0.0	0.0	43.2	0.0	0.0	0.0	0.0	11.6
	7	4.0	0.0	0.0	0.0	17.7	0.0	23.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.0	0.0	48.2	0.0	13.8	0.0	3.0	0.0	16.8	3.0	0.0	39.2	23.4	0.0	0.0	0.0	0.0	122.2	3.2
	9	0.0	10.8	0.0	0.0	51.6	0.0	0.0	0.0	17.4	98.3	0.0	0.0	39.7	0.0	0.0	0.0	0.0	197.3	3.0
	10	0.0	101.3	0.0	128.7	11.7	12.7	0.0	0.0	188.6	0.0	0.0	10.1	0.0	0.0	265.8	0.0	0.0	31.5	0.0
	11	0.0	0.0	55.7	3.0	0.0	0.0	0.0	0.0	17.1	0.0	0.0	17.4	0.0	5.3	3.6	0.0	0.0	59.5	0.0
	12	0.0	0.0	3.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	12.6	0.0	0.0	0.0	0.0
	13	0.0	0.0	46.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7	0.0	0.0	17.4	0.0
	14	0.0	0.0	3.0	0.0	33.1	54.3	0.0	0.0	27.9	0.0	0.0	3.0	3.8	0.0	0.0	0.0	0.0	3.8	0.0
	15	0.0	43.0	0.0	0.0	46.8	4.1	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	8.7	0.0	0.0	229.7	0.0
	16	0.0	0.0	0.0	3.2	0.0	3.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.5	111.5
	17	3.4	0.0	0.0	0.0	0.0	41.0	48.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.9	0.0	245.2	3.0	0.0
	18	0.0	0.0	0.0	0.0	92.0	0.0	260.2	0.0	10.5	11.6	0.0	0.0	0.0	0.0	45.9	0.0	3.0	0.0	0.0
	19	0.0	0.0	96.8	17.0	19.6	0.0	0.0	0.0	0.0	20.0	0.0	0.0	16.1	0.0	14.6	3.0	0.0	3.0	0.0
	20	0.0	0.0	39.4	3.0	0.0	0.0	127.5	0.0	4.8	33.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0
	21	0.0	0.0	0.0	94.5	29.1	0.0	45.9	4.6	24.4	17.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	22	0.0	0.0	0.0	5.7	3.0	0.0	0.0	16.9	94.1	24.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	23	0.0	0.0	10.2	0.0	0.0	59.8	62.3	0.0	0.0	57.7	0.0	0.0	17.4	0.0	0.0	0.0	12.3	0.0	0.0
	24	6.2	3.4	0.0	3.1	0.0	16.5	3.0	0.0	49.8	54.7	0.0	0.0	49.9	5.8	0.0	3.0	0.0	0.0	0.0
	25	3.0	3.0	0.0	5.5	0.0	3.0	0.0	0.0	51.1	24.0	0.0	0.0	32.3	52.9	0.0	0.0	0.0	204.5	0.0
	26	0.0	10.5	0.0	51.0	0.0	0.0	0.0	0.0	3.0	3.0	11.2	0.0	5.5	3.0	0.0	79.9	0.0	3.9	0.0
	27	0.0	112.5	0.0	151.6	0.0	0.0	0.0	0.0	96.4	85.9	62.2	0.0	3.0	168.5	0.0	3.5	0.0	0.0	0.0
	28	0.0	0.0	0.0	0.0	0.0	0.0	8.1	0.0	11.0	3.0	54.0	124.7	0.0	3.4	0.0	0.0	0.0	3.0	3.0
	29	0.0	15.0	32.4	0.0	0.0	0.0	31.9	3.0	0.0	0.0	0.0	8.0	5.0	0.0	0.0	0.0	0.0	38.4	0.0
	30	0.0	0.0	0.0	0.0	0.0	0.0	17.0	121.8	0.0	0.0	44.4	0.0	7.2	0.0	0.0	98.1	0.0	10.0	0.0
Monthly maximum (0.1mm)		6.2	112.5	96.8	151.6	92.0	62.7	260.2	121.8	263.1	98.3	114.6	124.7	49.9	168.5	265.8	98.1	245.2	281.1	111.5
Mean rainfall (0.1mm)		0.6	11.2	11.2	20.5	11.2	10.6	32.1	9.1	32.3	15.7	14.9	8.7	7.6	9.9	17.1	6.3	10.9	41.1	7.3
Non precipitation days		26	19	21	15	18	19	15	20	11	14	20	20	16	21	21	24	25	13	22
Precipitation days		4	11	9	15	12	11	15	10	19	16	10	10	14	9	9	6	5	17	8

Table II-2 Generated data on April for station 3031093 from 1986 to 2006

Simulation year		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1998	1999	2000	2001	2002	2003	2004	2005	2006
Previous status (0/1)		1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0	1
Daily Precipitation (Units of 0.1mm) Generated For April On Station. 3031093	1	0	14.24	0	0	3.488	35.3	0	2	41.85	2	0	0	0	0	2.147	0	13.79	0	4.956	37.12
	2	0	2.046	0	0	39.18	10.1	2.82	38.94	0.00	0	8.928	0	0	0	2.718	0	83.39	0	37.77	2.189
	3	0	35.28	0	0	0	0	0	4.769	129.75	0	2.563	0	55.94	0	0	2	2	0	0	35.42
	4	0	0	2.648	2.83	0	45.8	73.4	0	0.00	2	0	0	0	0	0	2.26	0	0	0	45.54
	5	0	0	0	2.2	0	2	0	41.23	16.18	4.23	0	0	26.94	2.63	92.54	0.00	0.00	0.00	0.00	103.27
	6	0	0	0	0	9.955	79.8	2	0	0.00	2	7.763	0	0.00	2.15	0.00	2.00	20.91	0.00	0.00	2.00
	7	53.9	3.299	2	8.91	0	2.61	2.44	0	2.00	0	53.91	0	0.00	2.39	10.19	18.70	105.08	6.72	0.00	4.28
	8	11.6	2.597	4.245	4.76	0	0	4.7	0	2.00	4.02	2	0	0.00	0.00	2.39	0.00	2.14	41.33	2.13	4.35
	9	6.93	2	55.25	84.6	19.18	5.26	0	0	39.39	2.18	157.6	0	15.39	2.45	2.00	0.00	0.00	0.00	7.68	54.59
	10	0	18.91	2.901	4.18	79.63	15.2	0	0	2.00	0	0	0	0.00	0.00	29.70	2.85	2.93	0.00	29.38	0.00
	11	13.3	0	10.04	4.27	0	0	0	0	0.00	21.5	0	0	0.00	2.80	45.05	2.00	2.00	0.00	2.00	0.00
	12	11.5	0	36.2	4.11	4.618	0	2.29	5.382	0.00	4.16	0	0	0.00	0.00	20.70	12.74	4.25	0.00	7.55	22.79
	13	0	0	0	20.7	118.1	0	2.66	13.74	3.56	2.18	0	2	0.00	0.00	0.00	27.11	0.00	2.01	2.00	4.66
	14	0	0	0	2	2	2	0	0	45.86	12	2	2	150.97	2.00	2.15	0.00	0.00	2.00	0.00	7.82
	15	0	0	33.45	4.78	0	2.72	11.9	0	0.00	37.2	2	4.69	0.00	2.16	2.00	0.00	21.06	2.90	2.34	29.99
	16	0	0	18.98	14.1	0	0	0	2	8.19	0	2.298	0	0.00	0.00	2.00	0.00	0.00	0.00	10.55	0.00
	17	0	86.83	4.39	0	2.549	0	0	118.2	9.70	0	0	2.43	0.00	11.11	0.00	2.30	0.00	2.55	2.00	0.00
	18	0	0	2.164	2.6	0	34.8	0	42.02	13.57	0	0	0	0.00	2.41	0.00	20.11	0.00	37.69	0.00	2.96
	19	0	0	0	0	84.13	0	0	6.007	0.00	35	45.97	8.97	0.00	0.00	11.31	0.00	0.00	5.60	0.00	0.00
	20	0	43.87	0	0	0	0	0	20.24	0.00	4.58	0	13.1	39.98	0.00	2.82	0.00	0.00	2.89	3.74	0.00
	21	0	21.45	0	0	0	35.1	33.5	80.45	0.00	2.81	0	2.46	2.73	0.00	2.42	0.00	0.00	45.66	72.18	0.00
	22	0	94.97	0	0	4.668	25.4	0	6.074	0.00	0	0	2.76	4.14	19.26	2.02	0.00	0.00	0.00	0.00	0.00
	23	0	7.18	41.98	0	39.05	0	2	0	36.71	0	0	0	85.43	0.00	74.37	0.00	0.00	0.00	0.00	0.00
	24	0	40.52	0	0	2.857	10.3	0	0	11.89	45.3	5.458	0	0.00	0.00	5.71	0.00	20.44	0.00	0.00	0.00
	25	0	15.95	0	0	41.77	13.7	0	4.505	0.00	7.71	26.91	0	2.00	0.00	2.00	0.00	0.00	0.00	0.00	3.55
	26	18.9	3.183	0	0	2	11.8	0	2.088	0.00	13.9	0	0	8.39	0.00	37.90	0.00	4.31	2.00	0.00	0.00
	27	0	4.478	0	4.11	2	6.64	0	6.418	0.00	17.1	0	2.18	0.00	0.00	0.00	0.00	4.62	3.72	0.00	0.00
	28	0	11.09	0	20.4	2	0	0	0	0.00	20.1	0	7.42	0.00	0.00	279.18	0.00	0.00	118.30	6.26	21.64
	29	0	52	3.058	4.72	2	0	0	0	0.00	10.5	0	91.2	0.00	91.76	0.00	0.00	0.00	2.56	2.70	10.38
	30	0	0	4.995	2	0	0	4.34	0	0.00	0	8.599	4.88	2.07	28.61	0.00	0.00	3.11	6.14	2.00	0.00
Monthly maximum (0.1mm)		53.9	95.0	55.2	84.6	118.1	79.8	73.4	118.2	129.8	45.3	157.6	91.2	151.0	91.8	279.2	27.1	105.1	118.3	72.2	103.3
Mean rainfall (0.1mm)		3.9	15.3	7.4	6.4	15.3	11.3	4.7	13.1	12.1	8.3	10.9	4.8	13.1	5.7	21.0	3.1	9.7	9.4	6.5	13.1
Non precipitation days		24	12	16	13	12	13	19	14	16	10	17	18	19	18	9	20	16	15	14	13
Precipitation days		6	18	14	17	18	17	11	16	14	20	13	12	11	12	21	10	14	15	16	17

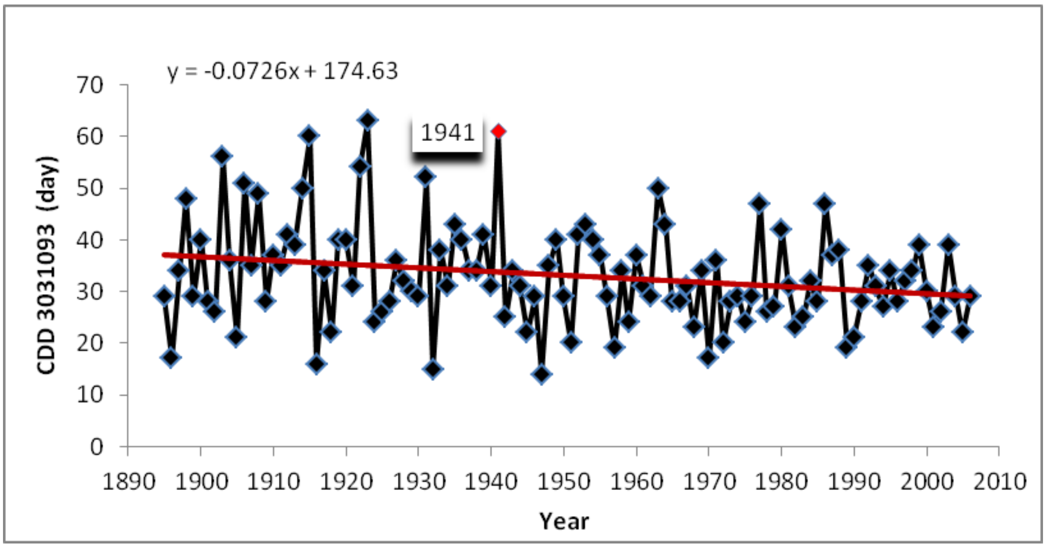
Table II-3 Generated data on January for station 1133270 from 1954 to 1974

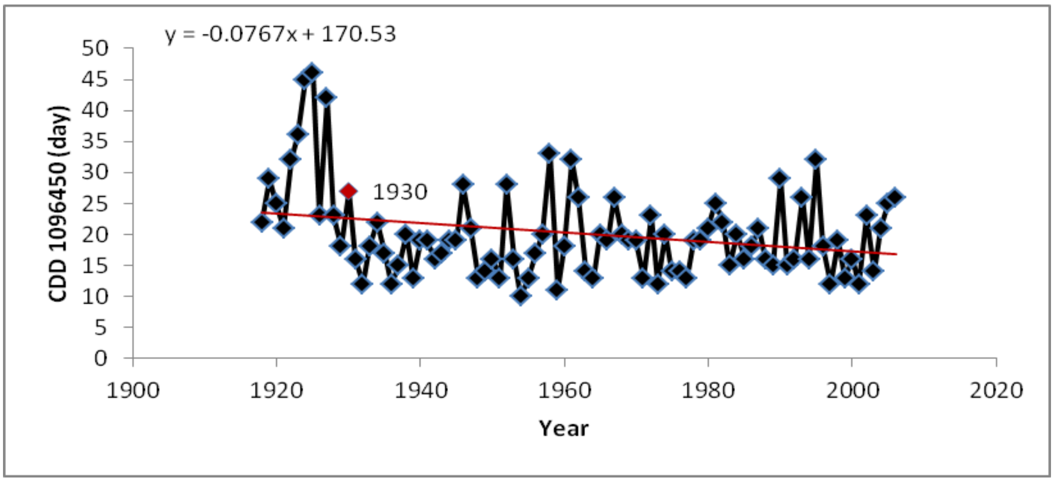
Simulation year		1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Previous status(0/1)		1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0	1
Daily Precipitation (Units of 0.1mm) Generated For January On Station. 1133270	1	0	14.2	0	0	3.49	35.3	0	2	41.9	2	0	0	0	0	2.15	0	13.8	0	4.96	37.1
	2	0	2.05	0	0	39.2	10.1	2.82	38.9	0	0	8.93	0	0	0	2.72	0	83.4	0	37.8	2.19
	3	0	35.3	0	0	0	0	0	4.77	130	0	2.56	0	55.9	0	0	2	2	0	0	35.4
	4	0	0	2.65	2.83	0	45.8	73.4	0	0	2	0	0	0	0	0	2.3	0	0	0	45.5
	5	0	0	0	2.2	0	2	0	41.2	16.2	4.23	0	0	26.9	2.63	92.5	0	0	0	0	103
	6	0	0	0	0	9.96	79.8	2	0	0	2	7.76	0	0	2.15	0	2	20.9	0	0	2
	7	54	3.3	2	8.91	0	2.61	2.44	0	2	0	53.9	0	0	2.39	10.2	19	105	6.72	0	4.28
	8	12	2.6	4.24	4.76	0	0	4.7	0	2	4.02	2	0	0	0	2.39	0	2.14	41.3	2.13	4.35
	9	6.9	2	55.2	84.6	19.2	5.26	0	0	39.4	2.18	158	0	15.4	2.45	2	0	0	0	7.68	54.6
	10	0	18.9	2.9	4.18	79.6	15.2	0	0	2	0	0	0	0	0	29.7	2.8	2.93	0	29.4	0
	11	13	0	10	4.27	0	0	0	0	0	21.5	0	0	0	2.8	45.1	2	2	0	2	0
	12	11	0	36.2	4.11	4.62	0	2.29	5.38	0	4.16	0	0	0	0	20.7	13	4.25	0	7.55	22.8
	13	0	0	0	20.7	118	0	2.66	13.7	3.56	2.18	0	2	0	0	0	27	0	2.01	2	4.66
	14	0	0	0	2	2	2	0	0	45.9	12	2	2	151	2	2.15	0	0	2	0	7.82
	15	0	0	33.5	4.78	0	2.72	11.9	0	0	37.2	2	4.69	0	2.16	2	0	21.1	2.9	2.34	30
	16	0	0	19	14.1	0	0	0	2	8.19	0	2.3	0	0	0	2	0	0	0	10.6	0
	17	0	86.8	4.39	0	2.55	0	0	118	9.7	0	0	2.43	0	11.1	0	2.3	0	2.55	2	0
	18	0	0	2.16	2.6	0	34.8	0	42	13.6	0	0	0	0	2.41	0	20	0	37.7	0	2.96
	19	0	0	0	0	84.1	0	0	6.01	0	35	46	8.97	0	0	11.3	0	0	5.6	0	0
	20	0	43.9	0	0	0	0	0	20.2	0	4.58	0	13.1	40	0	2.82	0	0	2.89	3.74	0
	21	0	21.5	0	0	0	35.1	33.5	80.5	0	2.81	0	2.46	2.73	0	2.42	0	0	45.7	72.2	0
	22	0	95	0	0	4.67	25.4	0	6.07	0	0	0	2.76	4.14	19.3	2.02	0	0	0	0	0
	23	0	7.18	42	0	39	0	2	0	36.7	0	0	0	85.4	0	74.4	0	0	0	0	0
	24	0	40.5	0	0	2.86	10.3	0	0	11.9	45.3	5.46	0	0	0	5.71	0	20.4	0	0	0
	25	0	16	0	0	41.8	13.7	0	4.5	0	7.71	26.9	0	2	0	2	0	0	0	0	3.55
	26	19	3.18	0	0	2	11.8	0	2.09	0	13.9	0	0	8.39	0	37.9	0	4.31	2	0	0
	27	0	4.48	0	4.11	2	6.64	0	6.42	0	17.1	0	2.18	0	0	0	0	4.62	3.72	0	0
	28	0	11.1	0	20.4	2	0	0	0	0	20.1	0	7.42	0	0	279	0	0	118	6.26	21.6
	29	0	52	3.06	4.72	2	0	0	0	0	10.5	0	91.2	0	91.8	0	0	0	2.56	2.7	10.4
	30	0	0	4.99	2	0	0	4.34	0	0	0	8.6	4.88	2.07	28.6	0	0	3.11	6.14	2	0
Monthly maximum(0.1mm)		53.9	95.0	55.2	84.6	118.1	79.8	73.4	118.2	129.8	45.3	157.6	91.2	151.0	91.8	279.2	27.1	105.1	118.3	72.2	103.3
Mean rainfall(0.1mm)		3.9	15.3	7.4	6.4	15.3	11.3	4.7	13.1	12.1	8.3	10.9	4.8	13.1	5.7	21.0	3.1	9.7	9.4	6.5	13.1
Non precipitation days		24	12	16	13	12	13	19	14	16	10	17	18	19	18	9	20	16	15	14	13
Precipitation days		6	18	14	17	18	17	11	16	14	20	13	12	11	12	21	10	14	15	16	17

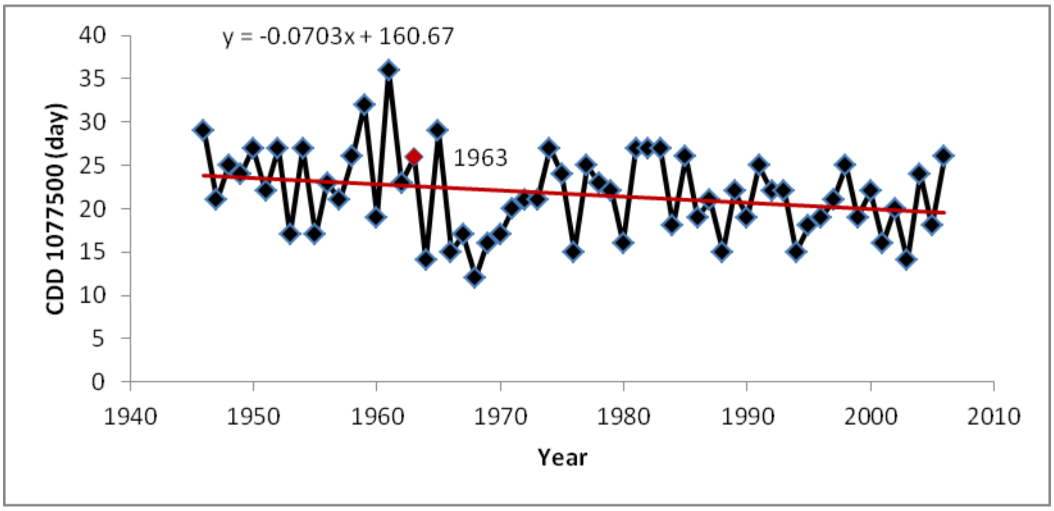
Table II-4 Generated data on December for station 1126150 from 1954 to 1974

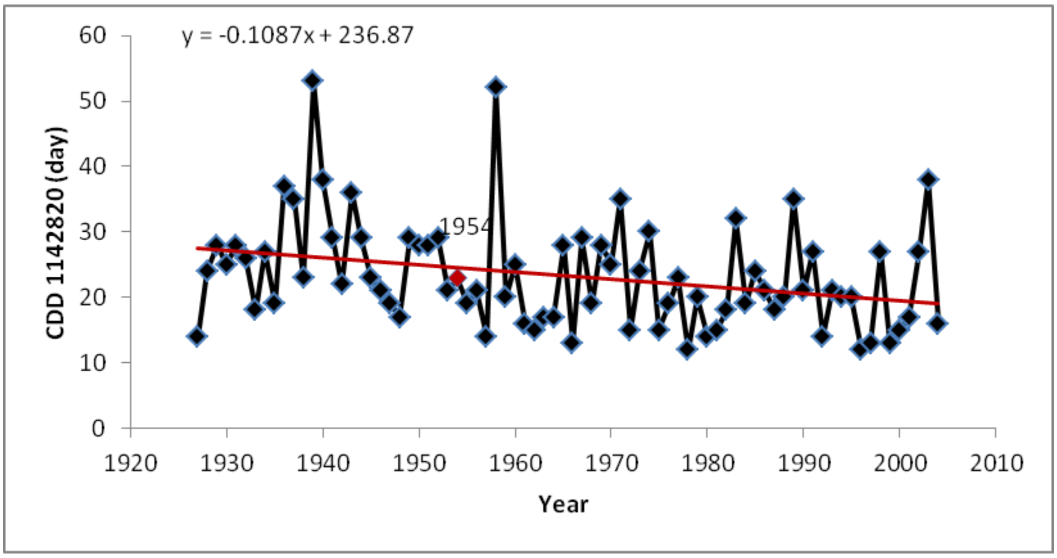
Simulation year		1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Previous status (0/1)		1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0	1
Daily Precipitation (Units of 0.1mm) Generated For December On Station. 1126150	1	0	0	0	2.95	32.2	2.018	0	2	118	6.03	6.65	2.33	2	2	0	85	0	2.42	2	5.96
	2	0	23.6	0	99.6	10.2	0	0	42	72.5	4.27	15.9	51.5	33	24	2	0	0	28.8	0	2
	3	37.11	10.3	2.98	0	9.63	0	0	2	2	28	2.23	6.62	0	73	2	0	0	25.6	0	50.7
	4	0	32.1	2	6.84	35.3	11.29	0	2	15.4	0	83.4	0	37.9	4.97	11.8	36	0	6.85	38.9	2
	5	0	2.79	5.85	126	2.13	2	0	22.4	0	0	4.74	0	2.91	58.2	2	59	0	0	17.5	2
	6	9.113	62.4	2	2.28	73.9	140.2	2	22.9	2	0	0	0	0	4.35	0	4	0	0	55.4	67
	7	73.91	17.2	3.63	2	4.31	0	24	73.6	15.2	2.51	3.24	2	6.09	0	0	0	0	0	4.71	50.5
	8	45.23	17.1	0	10.8	32.1	0	0	0	0	56.2	0	7.82	10.5	0	2	0	0	0	3.25	2.08
	9	4.738	2	2	4.59	24.3	2	2.78	101	9.3	41.7	0	0	22.7	0	35.7	0	0	2	2	25.6
	10	2.501	12.6	0	2	30.3	2.67	2	4.44	91.3	4.28	0	0	2.67	3.15	54.2	3	42.9	2	0	0
	11	2.979	2	3.01	6.78	19.8	0	9.79	69.3	5.63	97.2	22.4	3.44	0	31.9	0	38	28.1	5.15	0	0
	12	2	46.5	9.75	0	0	17.44	2	2	9.34	2	4.55	2	32.6	2.38	0	3	0	2	0	97.5
	13	11.34	0	2	0	2.67	0	0	6.87	2	85	5.86	3.62	4.86	4.46	0	18	0	5.93	32.9	0
	14	0	0	6.81	0	19.3	0	2	2.57	5.94	2	54.5	2.47	8.43	2.32	0	5.3	0	0	7.28	21
	15	2	0	99.6	6	32.6	2.649	2.57	0	2	10.1	2	2.58	2.09	6.52	0	15	0	0	2	12.9
	16	95.08	0	2	0	0	0	2	0	5.48	37.5	7.34	35.4	11.9	0	0	5.6	0	2	2	50.2
	17	46.52	0	0	0	4.13	29.47	2	31.9	18.9	2.07	2.75	48	2	6.27	2.93	9.1	2	9.92	0	139
	18	4.281	0	2.49	2.43	7.97	3.002	2.37	32.2	3.89	2.42	3.33	0	0	8.02	32.7	80	3.62	3.68	2	4.14
	19	0	0	0	2	3.85	0	12	10.5	2.26	0	0	2.27	2.51	12.6	0	6.5	10.7	0	21.8	0
	20	0	0	2.93	2	15.5	0	51.8	5.61	10.5	0	0	4.21	2	2	0	0	2	0	2.21	0
	21	2.766	2.88	2	2.13	0	0	0	4.07	0	9.67	0	55.4	11.6	2	0	2	2	2	0	75.7
	22	2.605	2	79.6	4.15	2.92	0	2	2	0	9.09	60.6	22.4	2.09	0	0	2	6.1	2	4.27	67.1
	23	0	6.55	2	40.1	2.73	2.732	6.67	5.93	0	0	14.1	9.96	6.46	0	0	57	6.64	0	47.1	3.53
	24	2.214	2	2	99.6	0	6.125	0	0	0	36.7	99.8	2	2	2	0	0	12.1	54.4	0	2.43
	25	137.7	4.07	25.3	0	3.49	2.055	4.42	0	69.2	0	0	2.04	90.6	2.99	0	0	22	0	5.66	0
	26	59.84	35.5	9.67	0	3.26	2	9.17	10.4	103	0	0	0	3.72	2	0	2.6	2.11	15.3	2	0
	27	2	15.2	38.2	0	11.9	0	17.6	2	19.3	0	2.55	2.17	0	0	9.44	9.6	2.94	2	4.73	0
	28	25.34	0	5.09	2.47	84.6	10.1	2	68.7	0	4.8	0	9.84	0	0	5.71	0	52	25.6	5.33	0
	29	14.39	49.6	12.4	2	2	24.48	2	25.9	99.9	4.01	2.49	10.2	0	0	0	41	0	2	32.7	21.5
	30	0	4.47	24.2	0	23.4	3.587	19	2	0	2	0	3.81	35.2	0	0	9.6	5.26	17.8	59.1	4.42
	31	0	21.4	51.4	111	2	10.72	17.1	4.7	0	2	0	47.8	0	0	3.31	0	2.35	2	21.8	2
Monthly maximum (0.1mm)		137.7	62.4	99.6	125.5	84.6	140.2	51.8	101.2	118.1	97.2	99.8	55.4	90.6	73.0	54.2	84.7	52.0	54.4	59.1	139.1
Mean rainfall (0.1mm)		18.8	12.0	12.9	17.3	16.0	8.9	6.4	18.0	22.0	14.5	12.9	11.0	10.8	8.2	5.3	15.9	6.5	7.1	12.1	22.9
Non precipitation days		10	10	6	10	4	13	9	5	9	9	12	7	8	11	19	10	15	10	8	9
Precipitation days		20	20	24	20	26	17	21	25	21	21	18	23	22	19	11	20	15	20	22	21

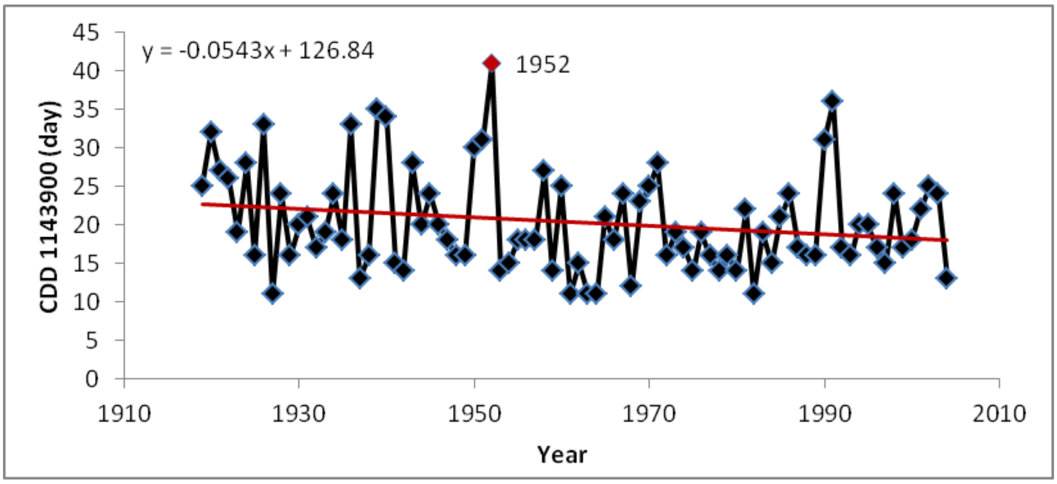
C: Figures for time series plot of 10 precipitation indices with detected significant change points (labeled and marked in red) and the regression line fitted for stations with statistically significant change at 0.05 significant level (P values ≥ 0.95)

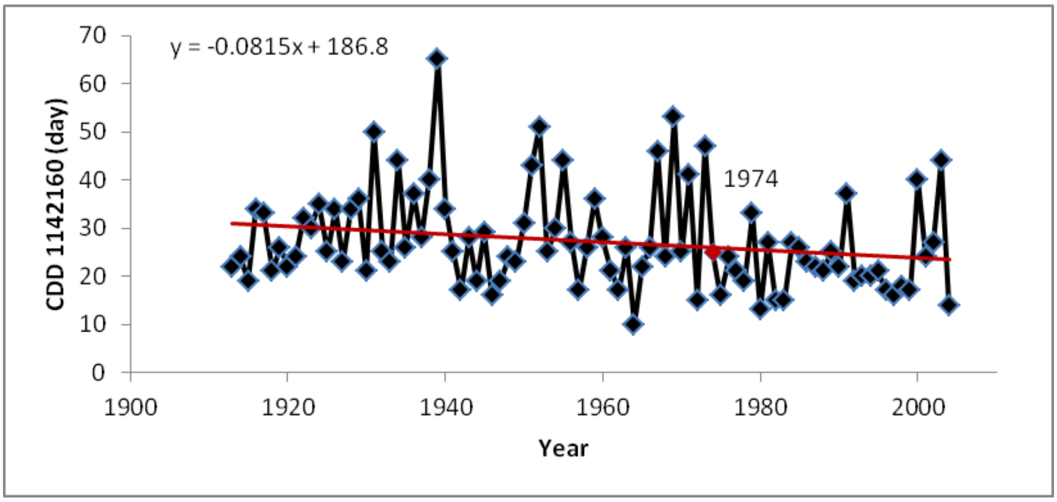


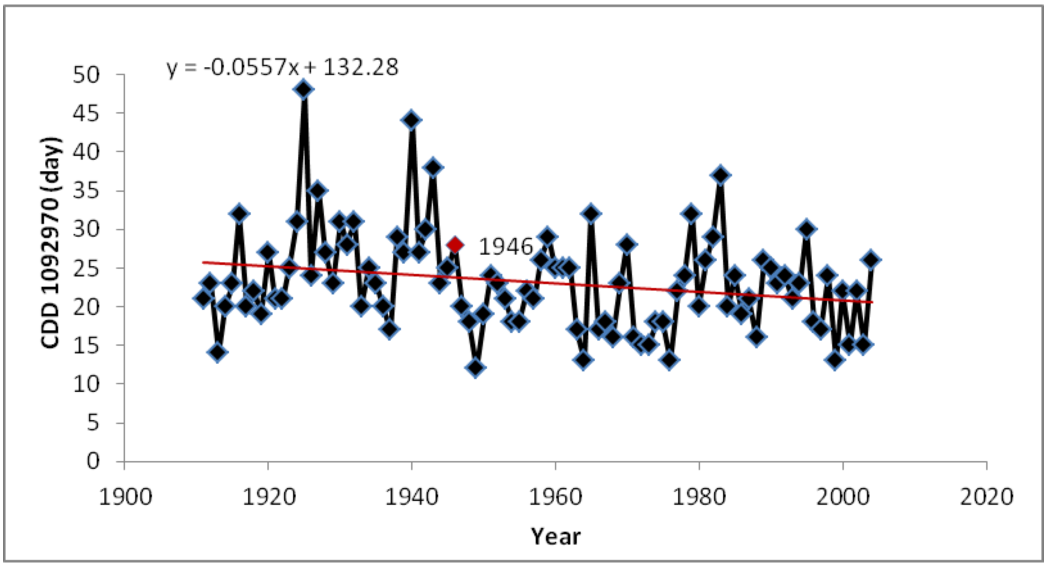


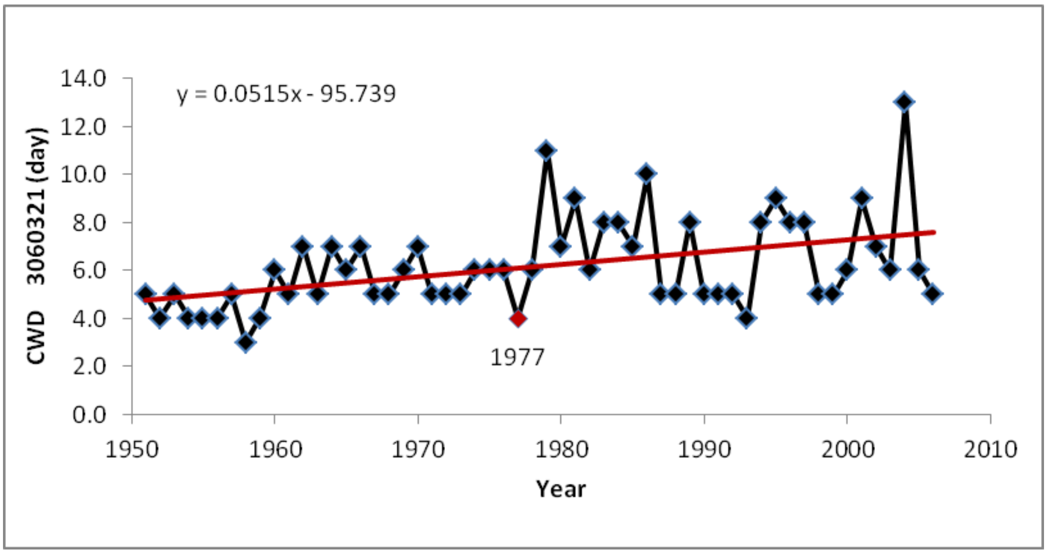


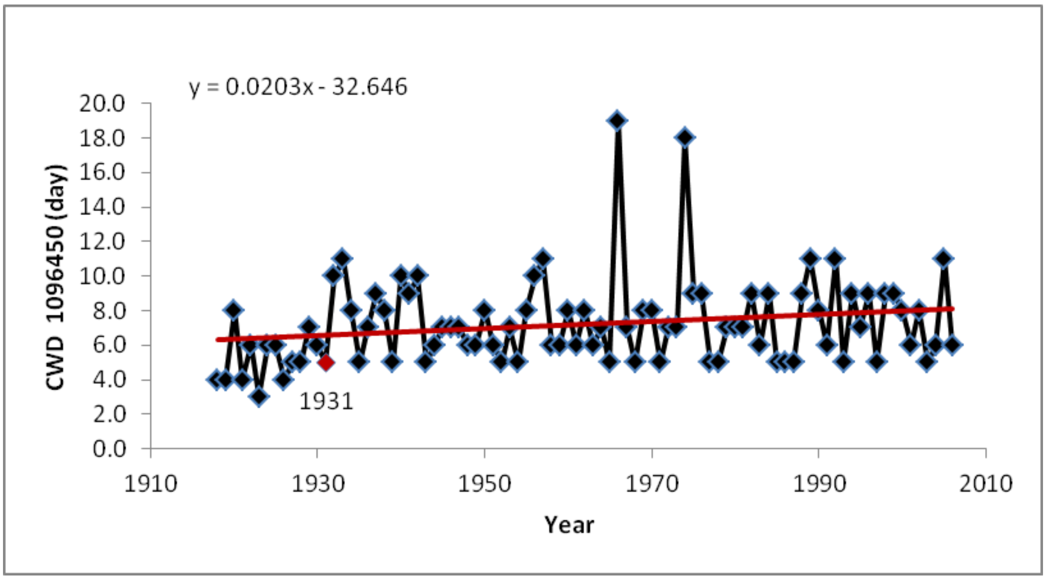

y = -0.1087x + 236.87
CDD 1142820 (day)
60
50
40
30
20
10
0
1954
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

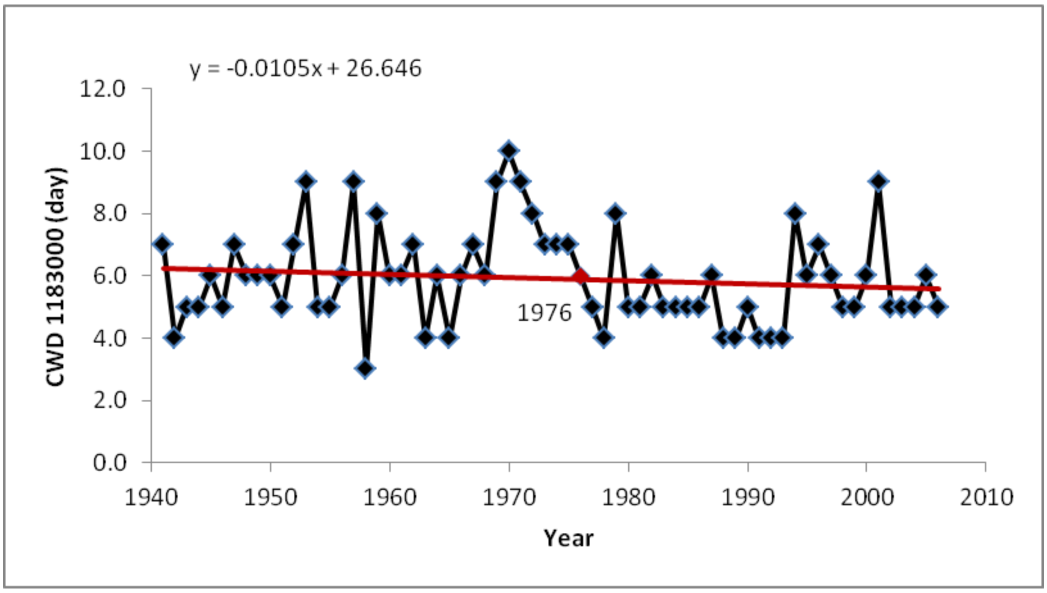

y = -0.0543x + 126.84
1952
CDD 1143900 (day)
45
40
35
30
25
20
15
10
5
0
1910
1930
1950
1970
1990
2010
Year

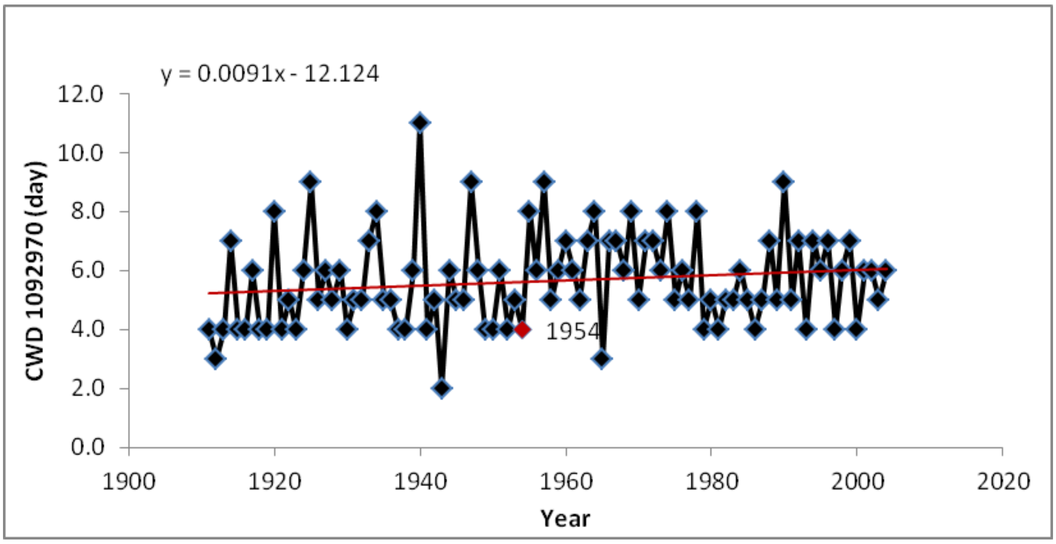

y = -0.0815x + 186.8
1974
CDD 1142160 (day)
70
60
50
40
30
20
10
0
1900
1920
1940
1960
1980
2000
Year

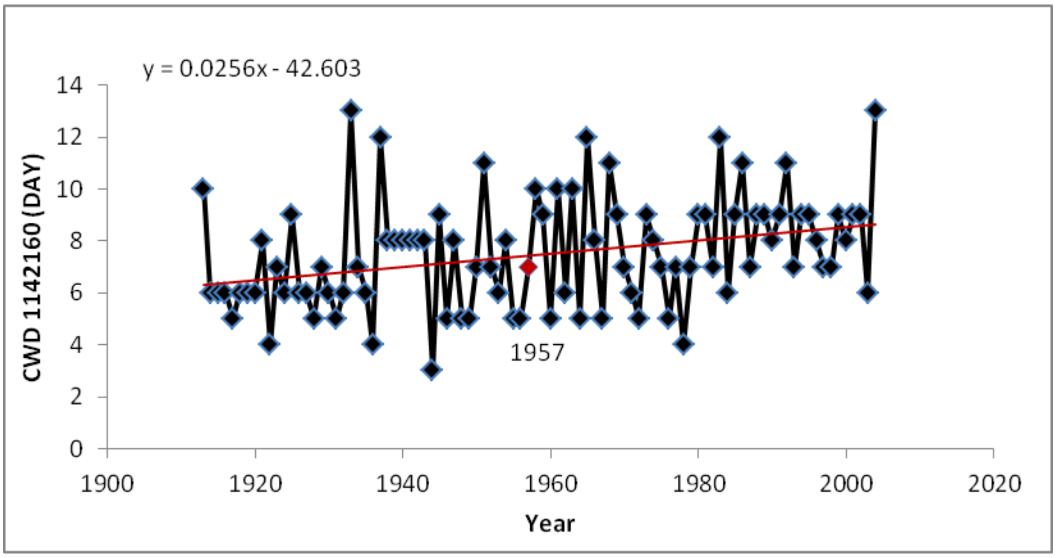

y = -0.0557x + 132.28
CDD 1092970 (day)
50
45
40
35
30
25
20
15
10
5
0
1946
1900
1920
1940
1960
1980
2000
2020
Year

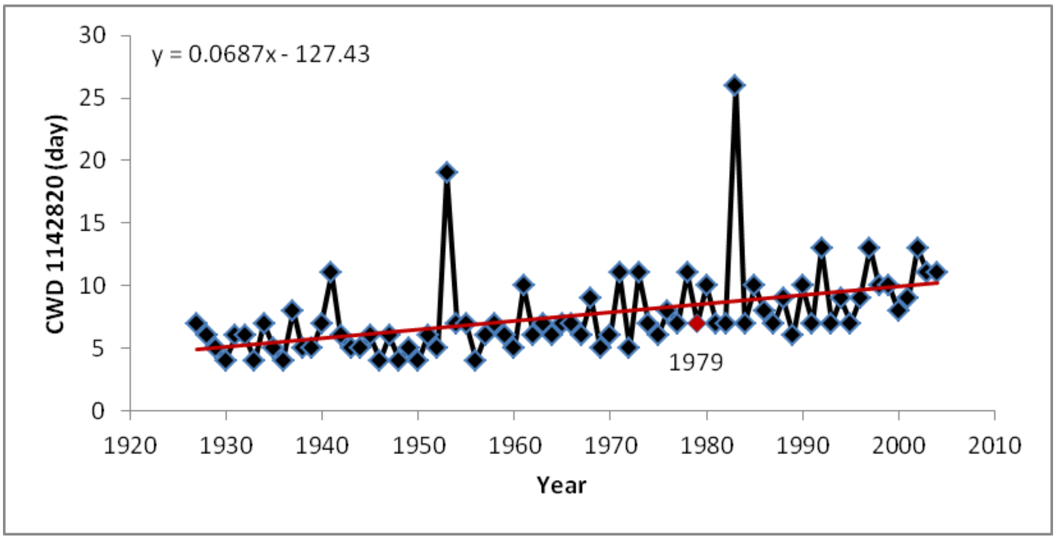

y = 0.0515x - 95.739
CWD 3060321 (day)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1977
1950
1960
1970
1980
1990
2000
2010
Year

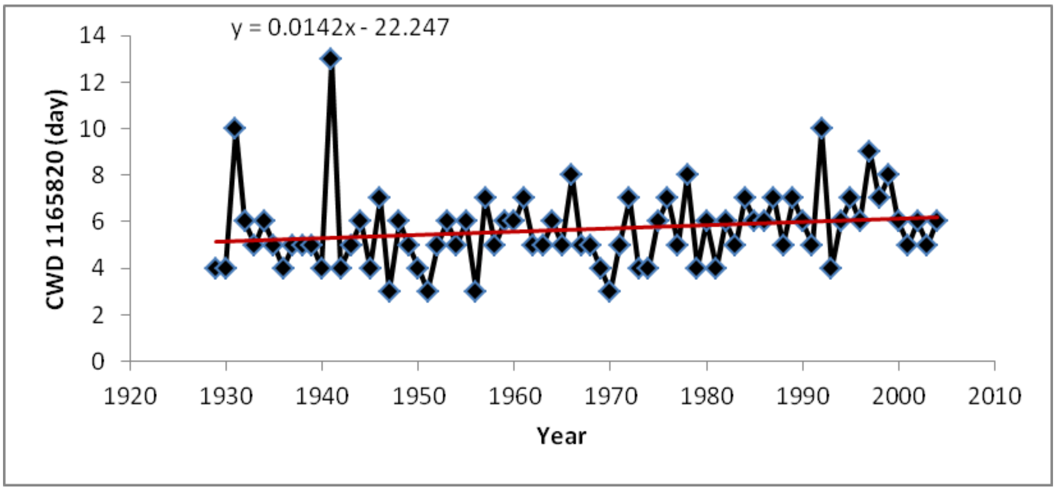

y = 0.0203x - 32.646
CWD 1096450 (day)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1931
1910
1930
1950
1970
1990
2010
Year

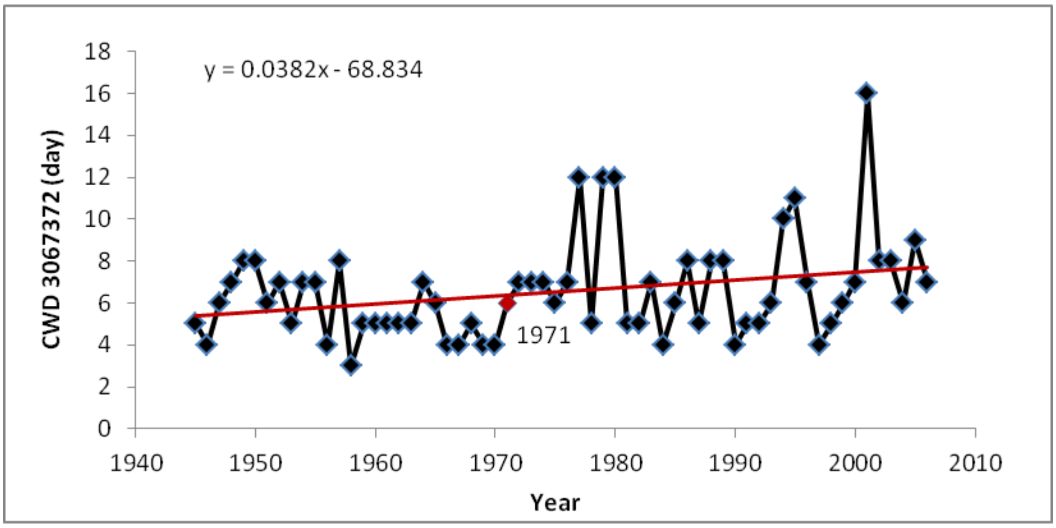

y = -0.0105x + 26.646
CWD 1183000 (day)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1940
1950
1960
1970
1980
1990
2000
2010
Year
1976

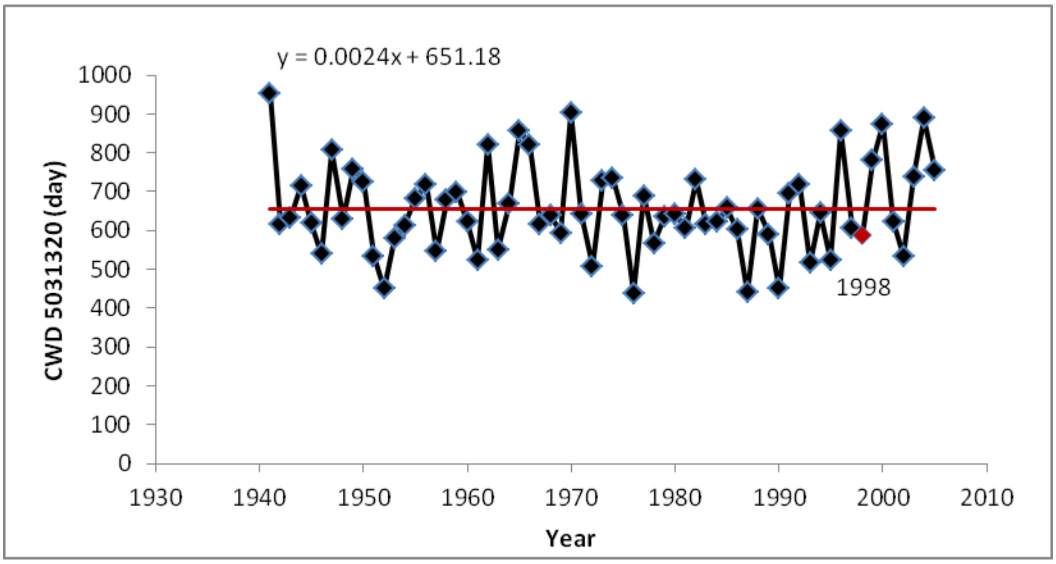

y = 0.0091x - 12.124
CWD 1092970 (day)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1900
1920
1940
1960
1980
2000
2020
Year
1954

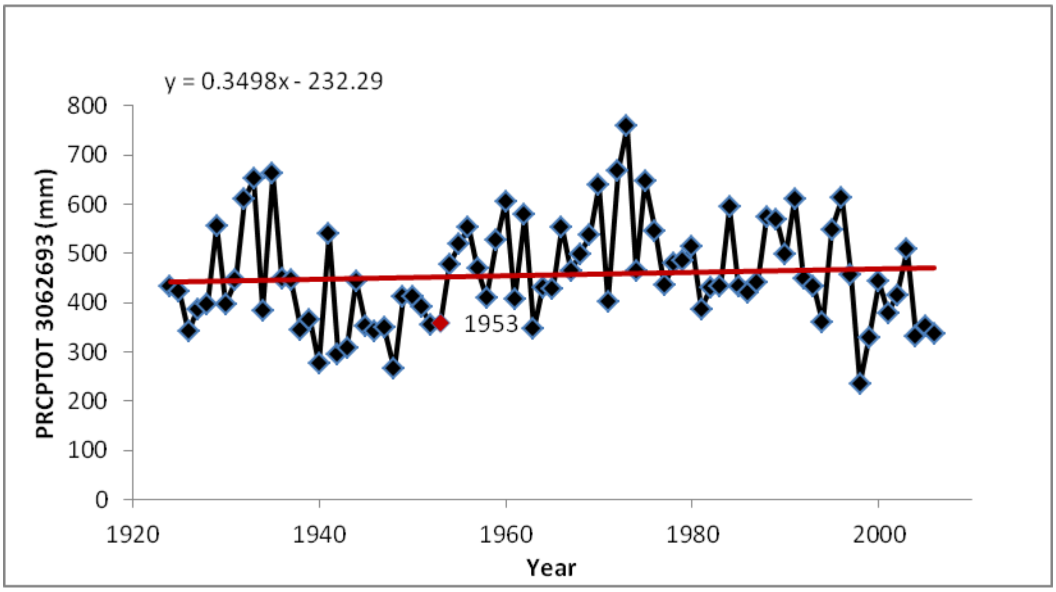

y = 0.0256x - 42.603
CWD 1142160 (DAY)
14
12
10
8
6
4
2
0
1900
1920
1940
1960
1980
2000
2020
Year
1957

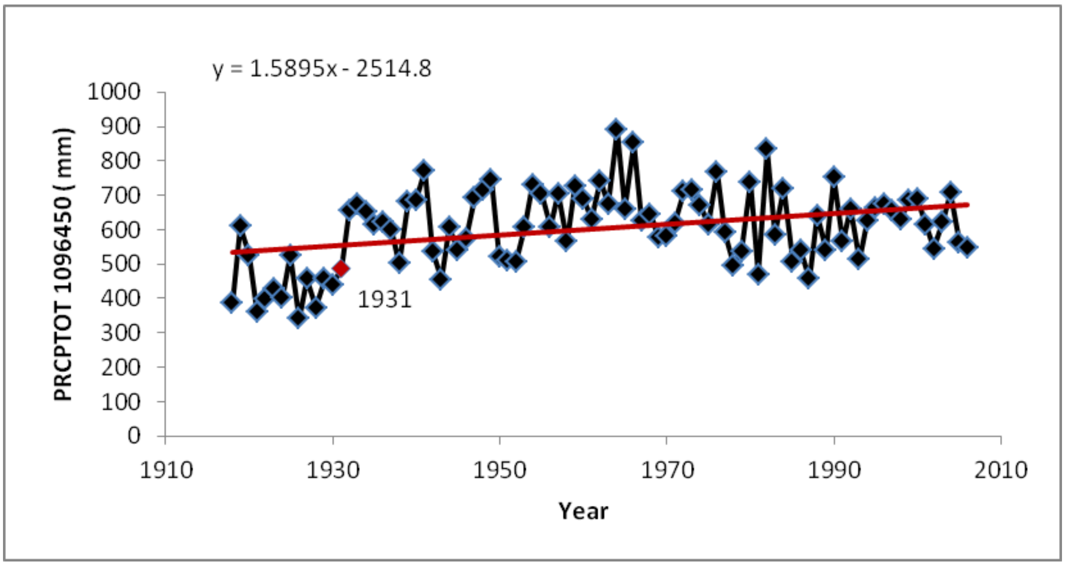

y = 0.0687x - 127.43
CWD 1142820 (day)
30
25
20
15
10
5
0
1979
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

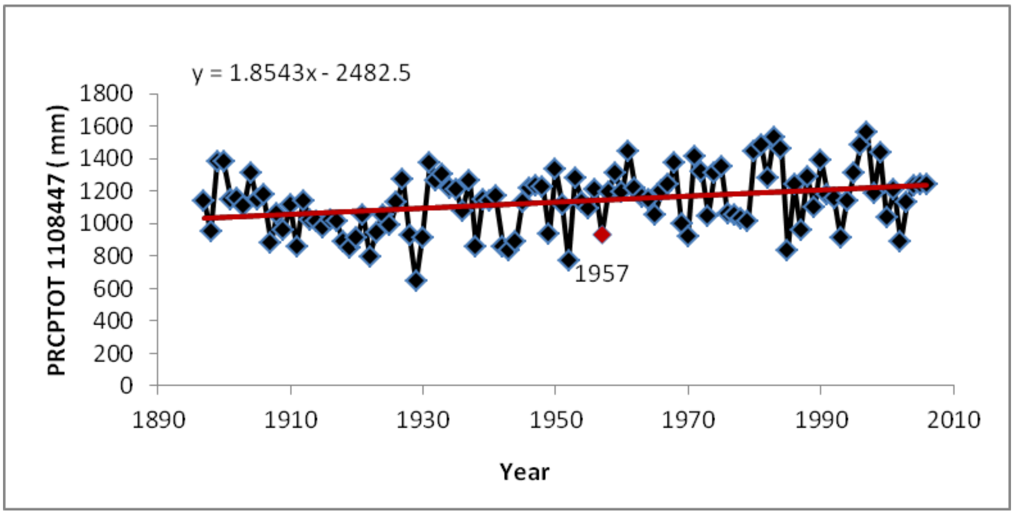

y = 0.0142x - 22.247
CWD 1165820 (day)
14
12
10
8
6
4
2
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

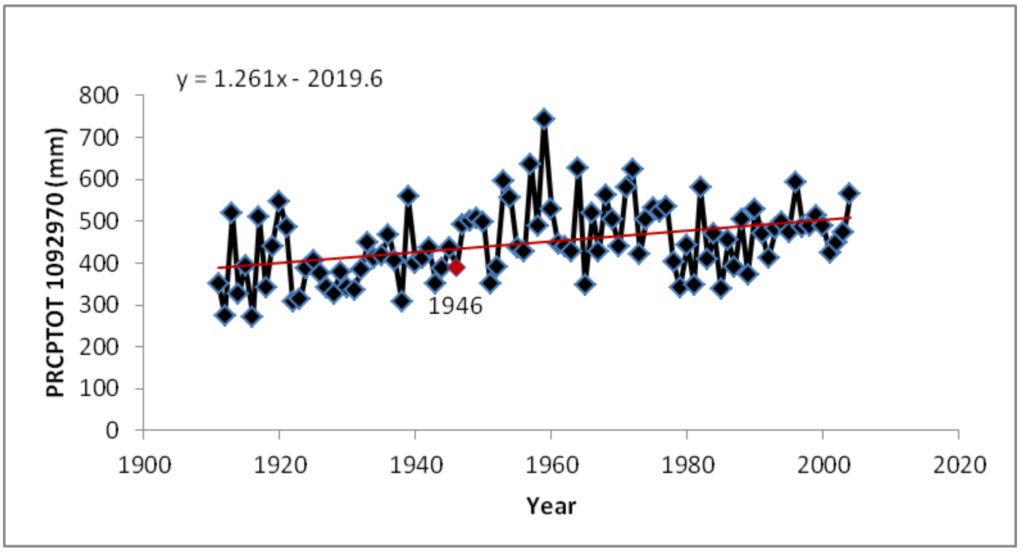

y = 0.0382x - 68.834
CWD 3067372 (day)
18
16
14
12
10
8
6
4
2
0
1971
1940
1950
1960
1970
1980
1990
2000
2010
Year

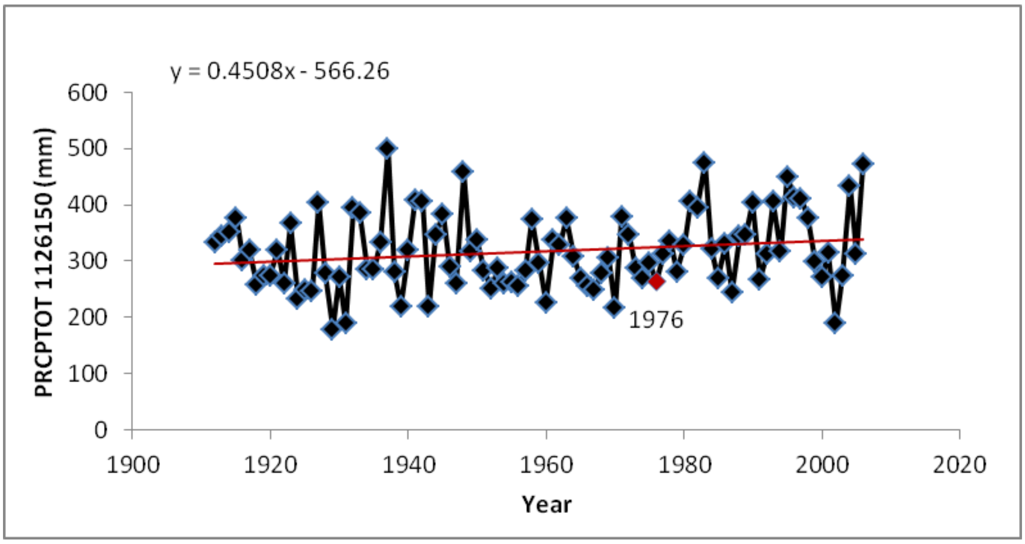

y = 0.0024x + 651.18
CWD 5031320 (day)
0
100
200
300
400
500
600
700
800
900
1000
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
1998

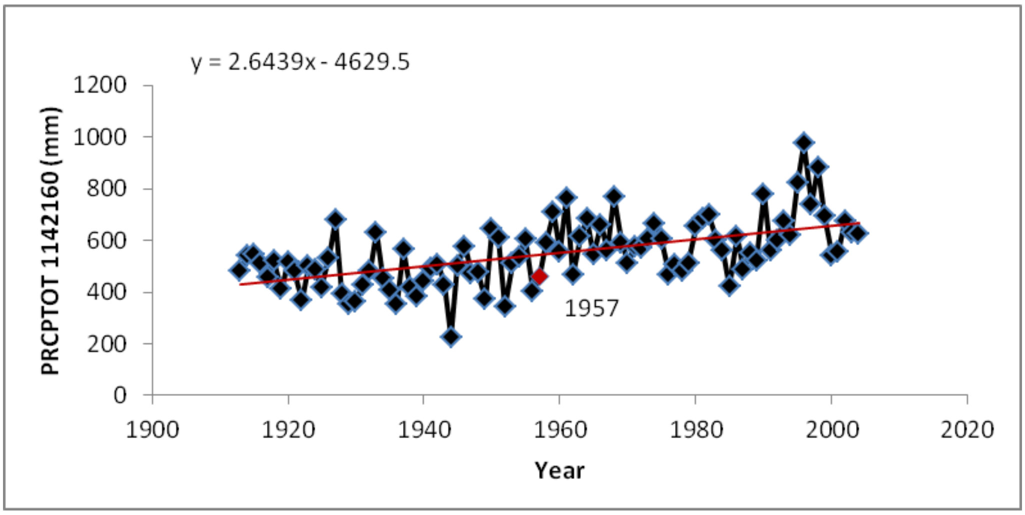

y = 0.3498x - 232.29
PRCPTOT 3062693 (mm)
0
100
200
300
400
500
600
700
800
1920
1940
1960
1980
2000
Year
1953

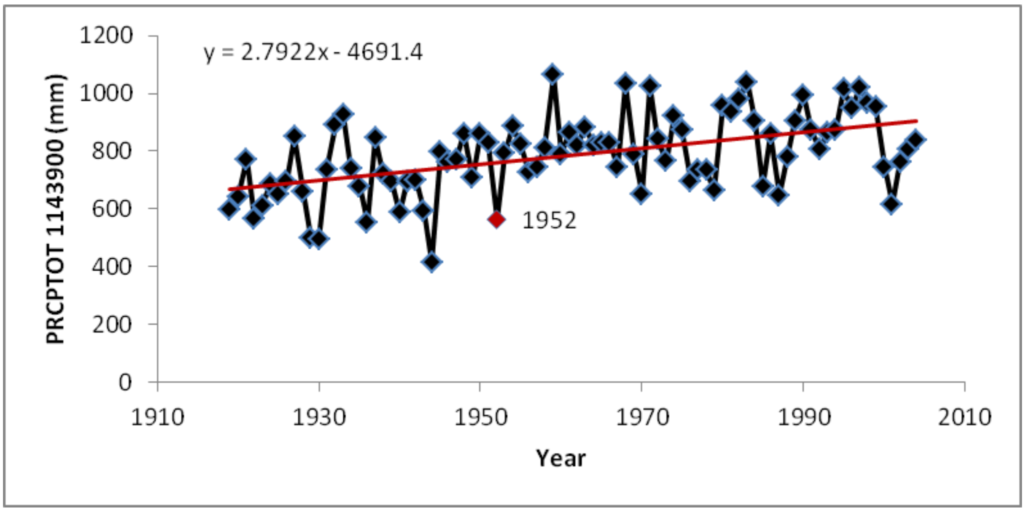

y = 1.5895x - 2514.8
PRCPTOT 1096450 (mm)
0
100
200
300
400
500
600
700
800
900
1000
1910
1930
1950
1970
1990
2010
Year
1931

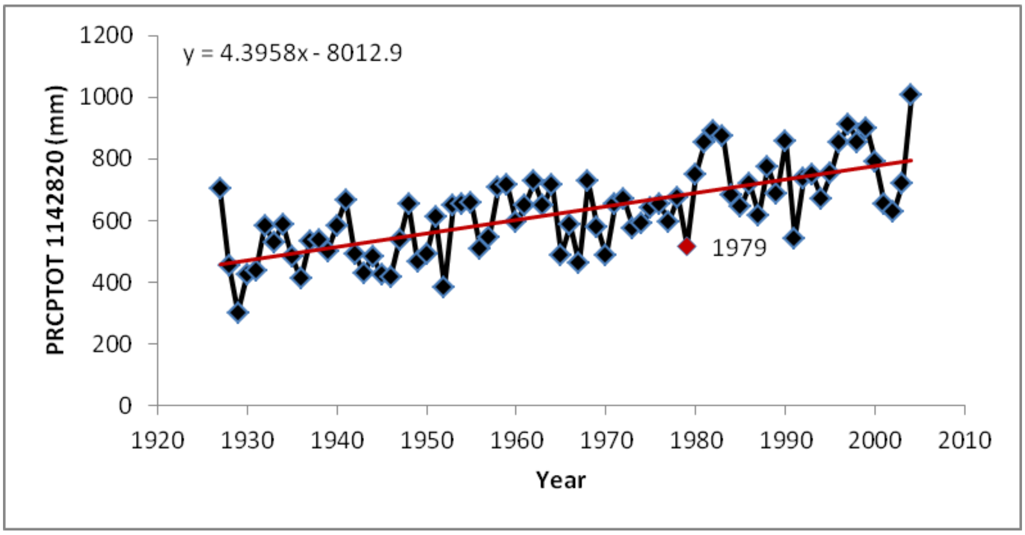

y = 1.8543x - 2482.5
PRCPTOT 1108447 (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
1890
1910
1930
1950
1970
1990
2010
Year
1957

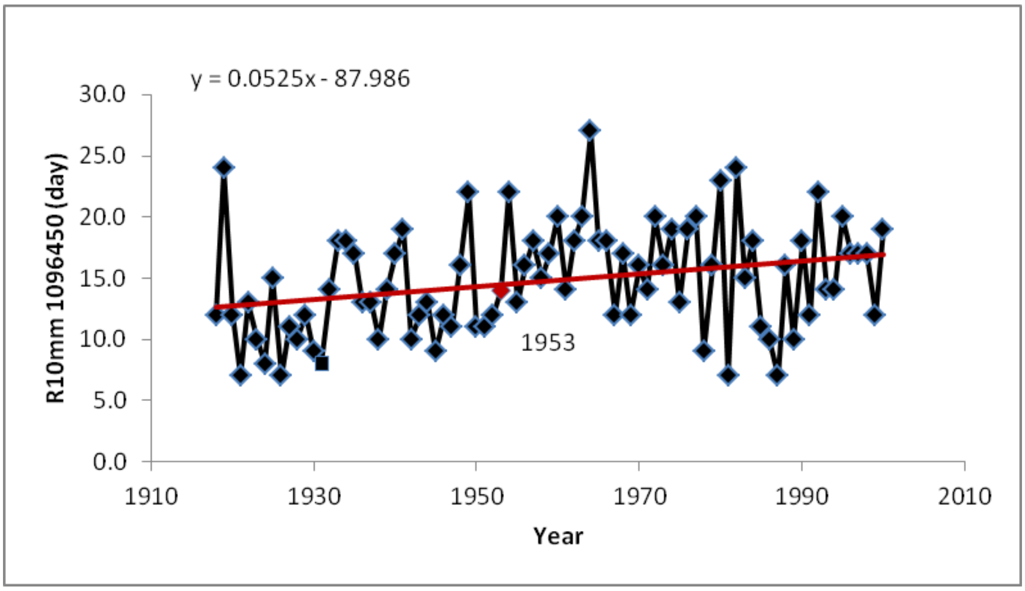

y = 1.261x - 2019.6
PRCPTOT 1092970 (mm)
800
700
600
500
400
300
200
100
0
1900
1920
1940
1960
1980
2000
2020
Year
1946

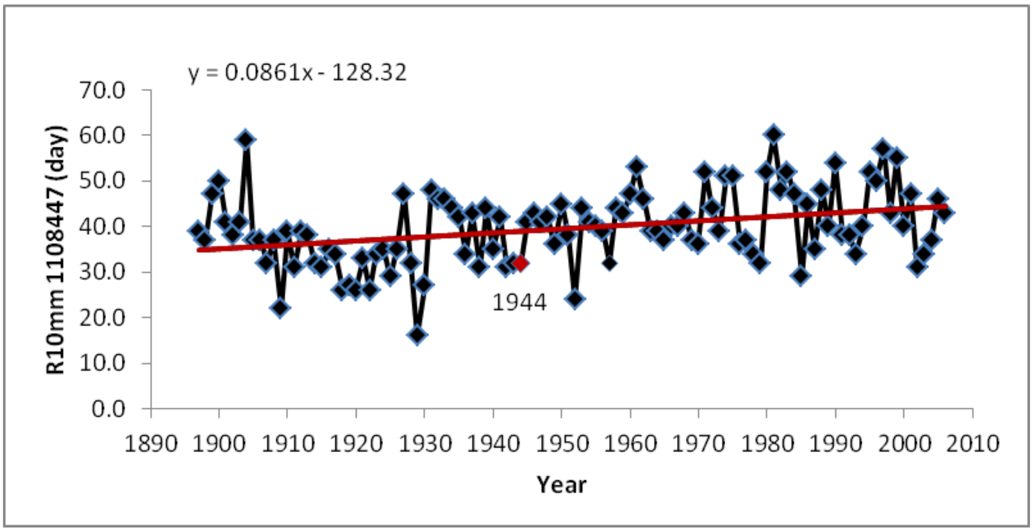

y = 0.4508x - 566.26
PRCPTOT 1126150 (mm)
600
500
400
300
200
100
0
1900
1920
1940
1960
1980
2000
2020
Year
1976

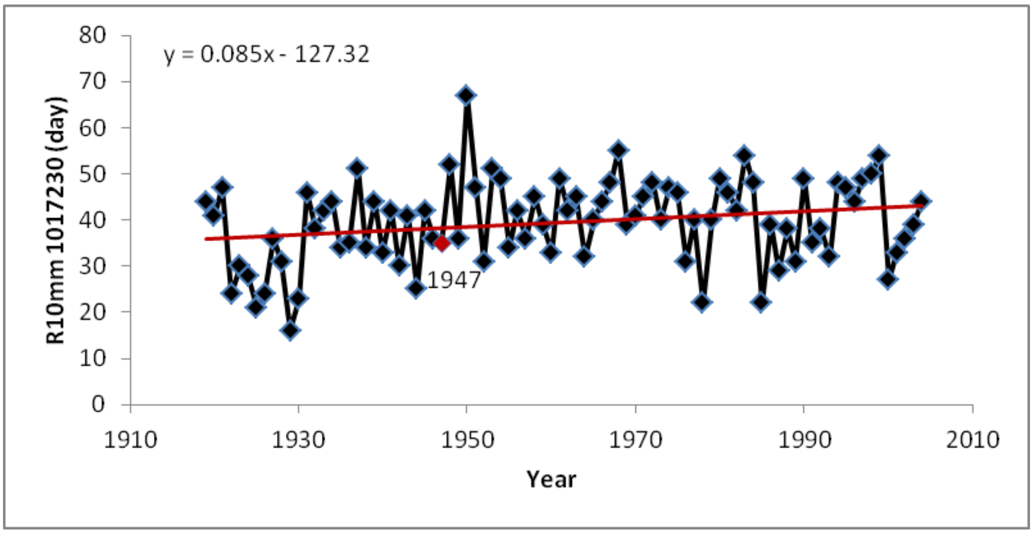

y = 2.6439x - 4629.5
PRCPTOT 1142160 (mm)
1200
1000
800
600
400
200
0
1957
1900
1920
1940
1960
1980
2000
2020
Year

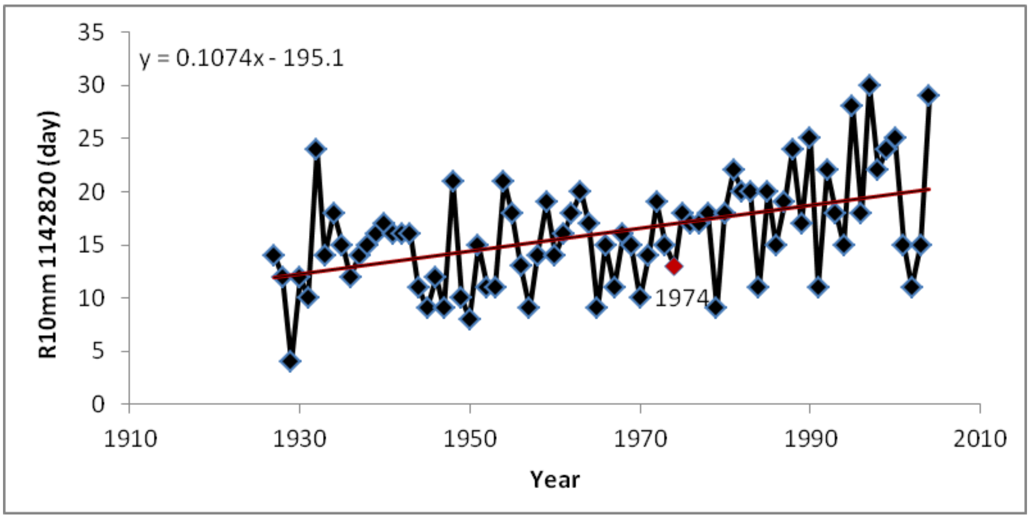

y = 2.7922x - 4691.4
PRCPTOT 1143900 (mm)
1200
1000
800
600
400
200
0
1952
1910
1930
1950
1970
1990
2010
Year

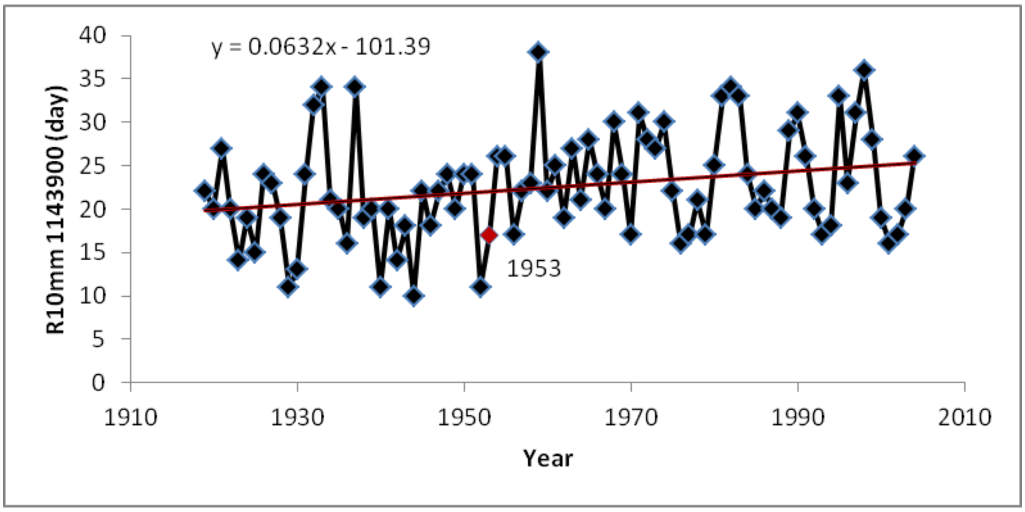

y = 4.3958x - 8012.9
PRCPTOT 1142820 (mm)
1200
1000
800
600
400
200
0
1979
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

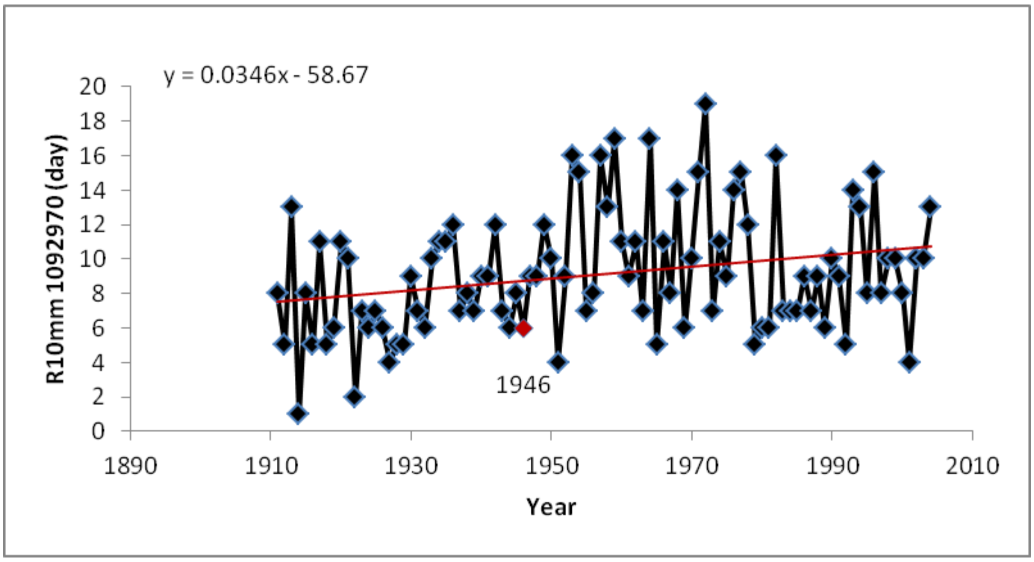

y = 0.0525x - 87.986
R10mm 1096450 (day)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1953
1910
1930
1950
1970
1990
2010
Year

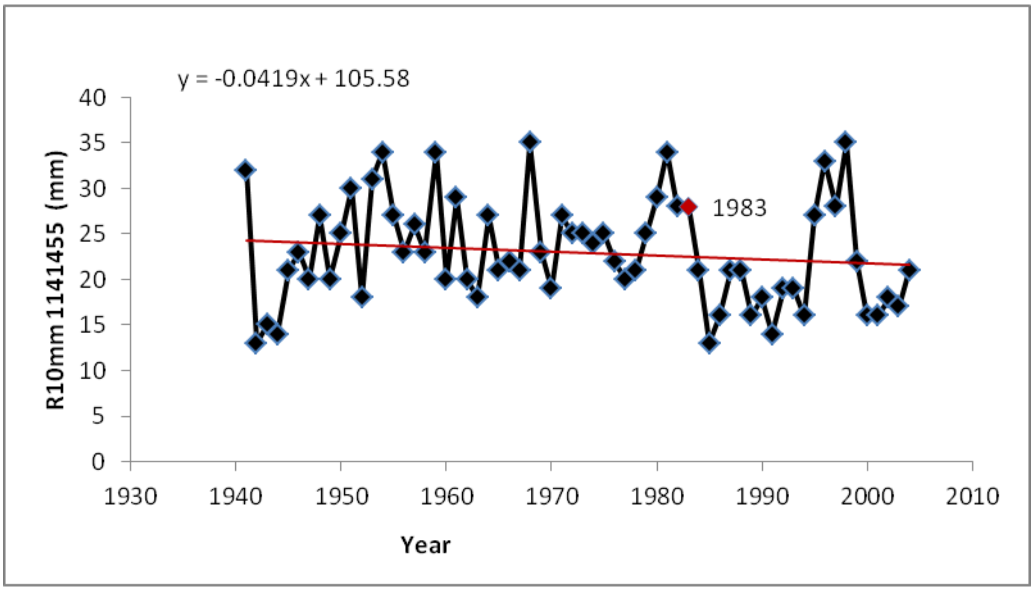

y = 0.0861x - 128.32
R10mm 1108447 (day)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1944
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

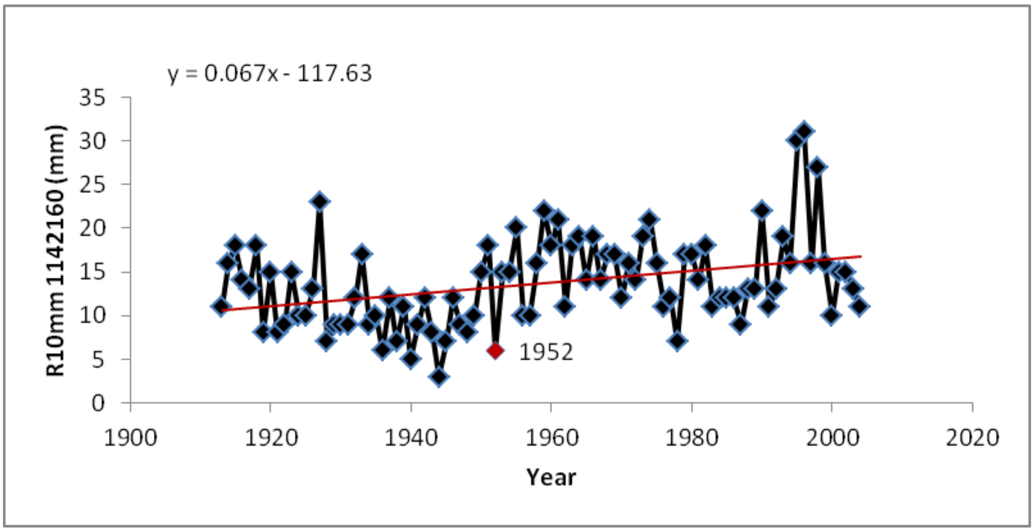

y = 0.085x - 127.32
R10mm 1017230 (day)
80
70
60
50
40
30
20
10
0
1947
1910
1930
1950
1970
1990
2010
Year

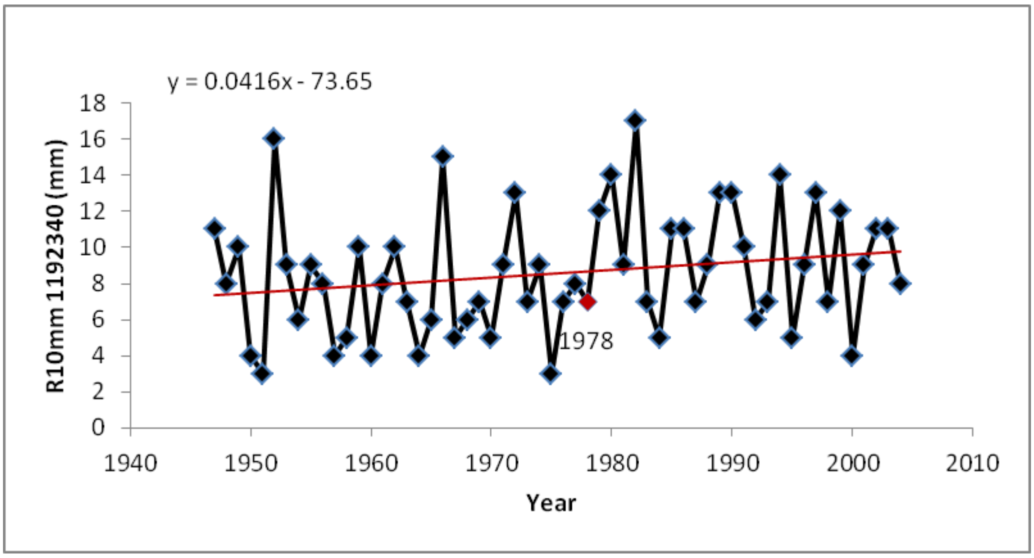

y = 0.1074x - 195.1
R10mm 1142820 (day)
35
30
25
20
15
10
5
0
1974
1910
1930
1950
1970
1990
2010
Year

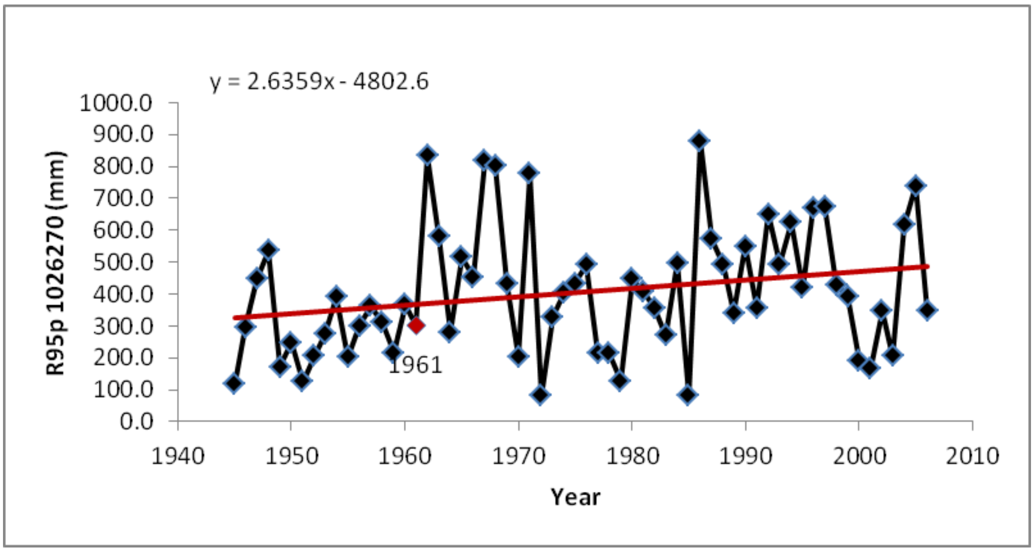

y = 0.0632x - 101.39
R10mm 1143900 (day)
40
35
30
25
20
15
10
5
0
1953
1910
1930
1950
1970
1990
2010
Year

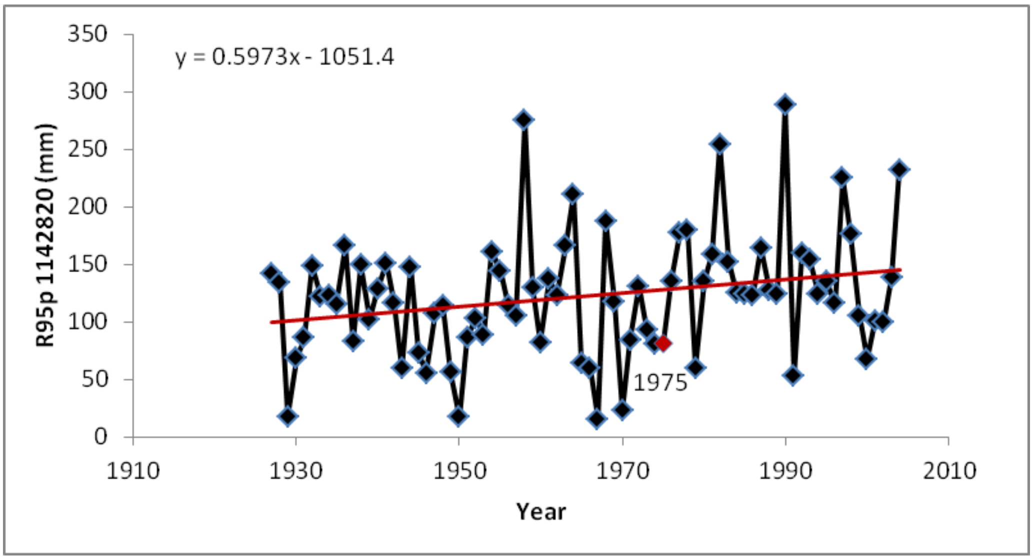

y = 0.0346x - 58.67
R10mm 1092970 (day)
20
18
16
14
12
10
8
6
4
2
0
1946
1890
1910
1930
1950
1970
1990
2010
Year

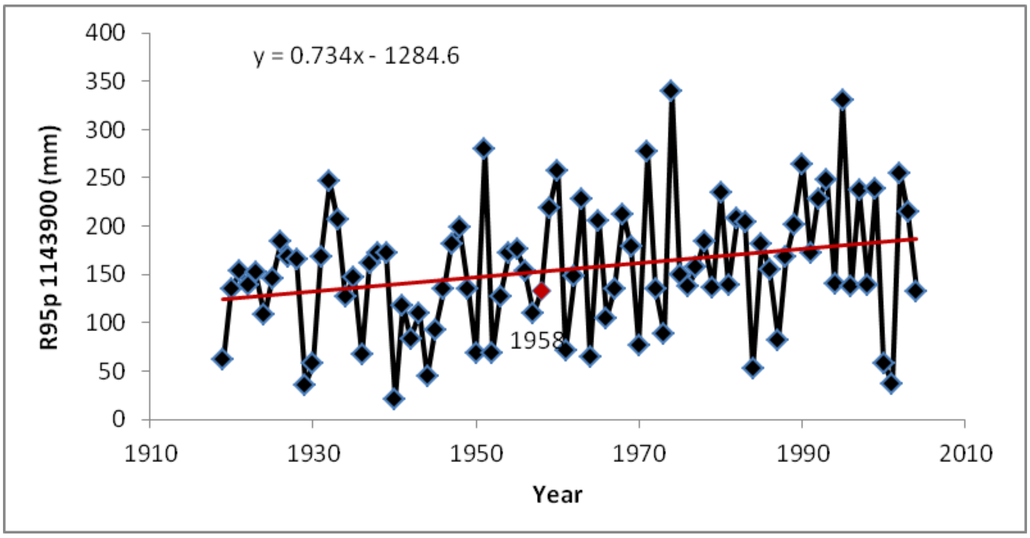

y = -0.0419x + 105.58
R10mm 1141455 (mm)
0
5
10
15
20
25
30
35
40
1983
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

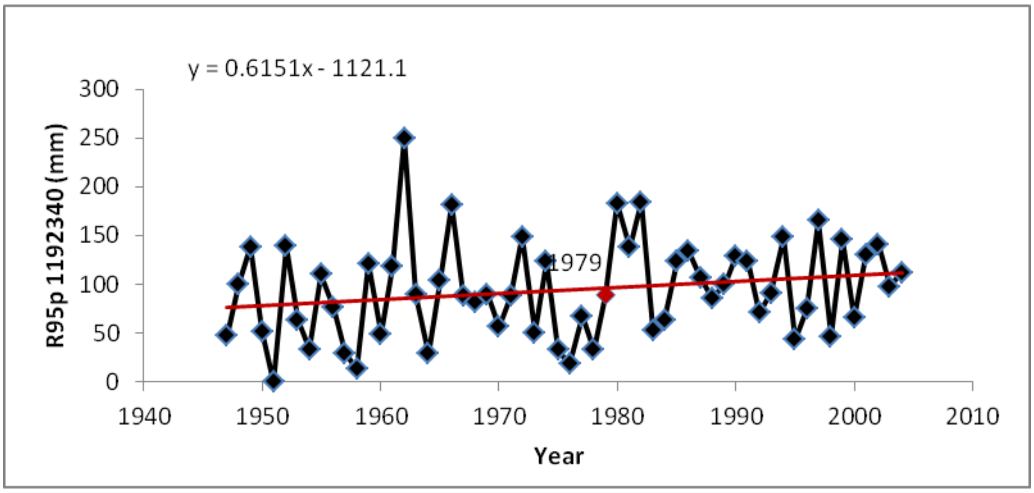

y = 0.067x - 117.63
R10mm 1142160 (mm)
0
5
10
15
20
25
30
35
1952
1900
1920
1940
1960
1980
2000
2020
Year

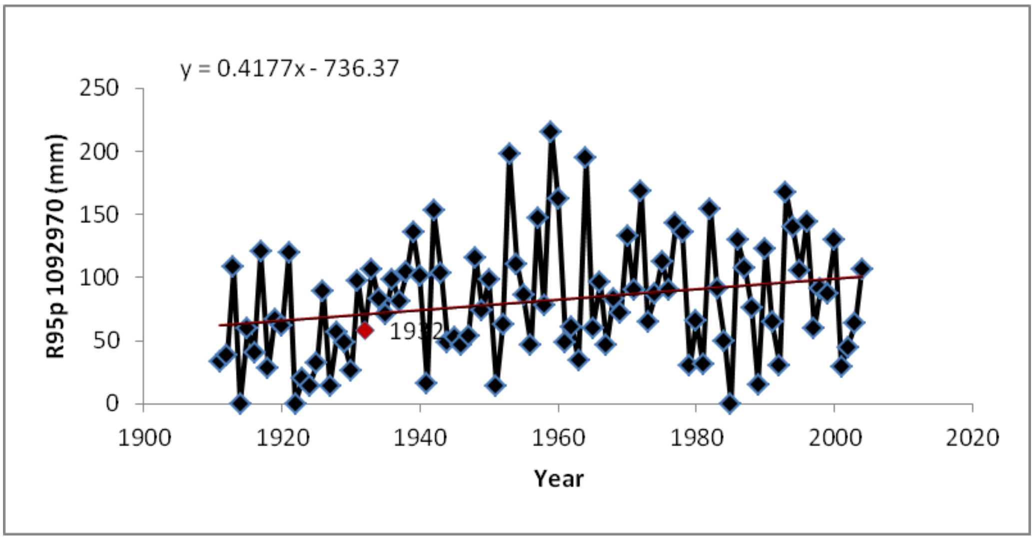

y = 0.0416x - 73.65
R10mm 1192340 (mm)
0
2
4
6
8
10
12
14
16
18
1978
1940
1950
1960
1970
1980
1990
2000
2010
Year

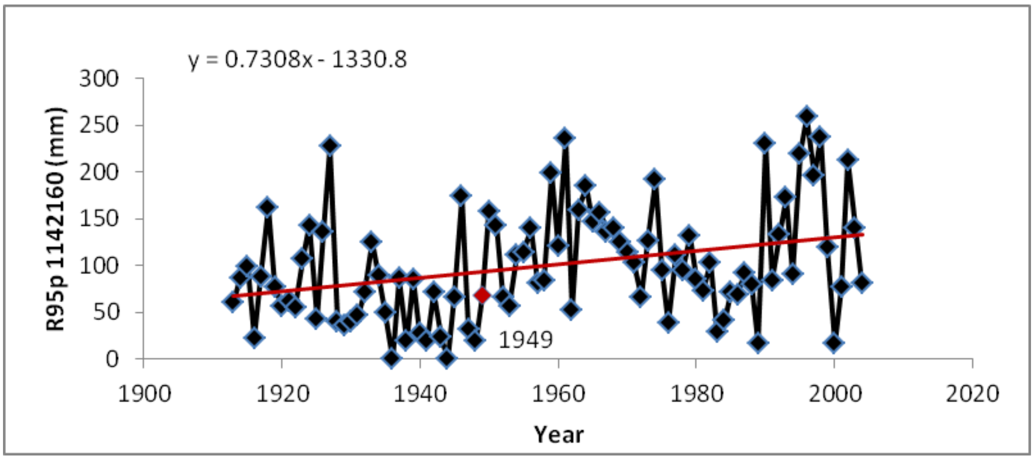

y = 2.6359x - 4802.6
R95p 1026270 (mm)
1000.0
900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
1961
1940
1950
1960
1970
1980
1990
2000
2010
Year

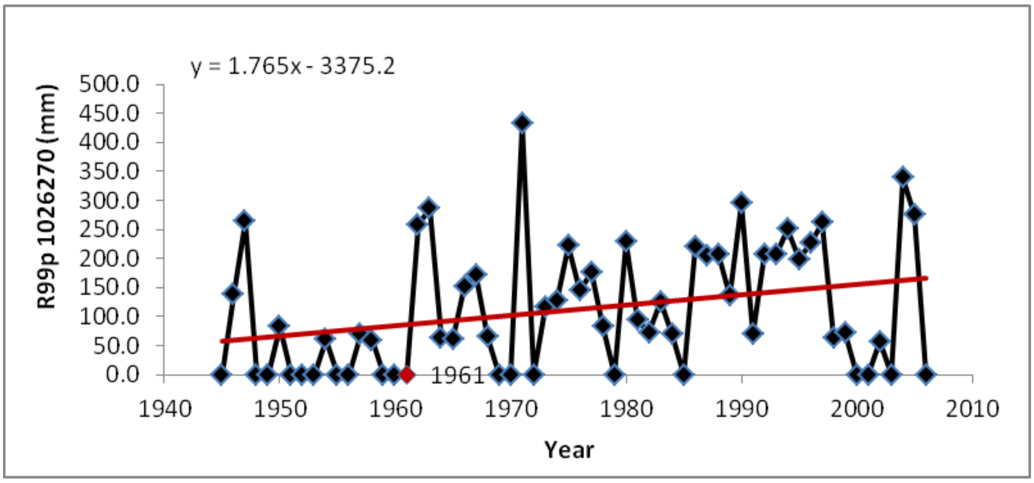

y = 0.5973x - 1051.4
R95p 1142820 (mm)
350
300
250
200
150
100
50
0
1975
1910
1930
1950
1970
1990
2010
Year

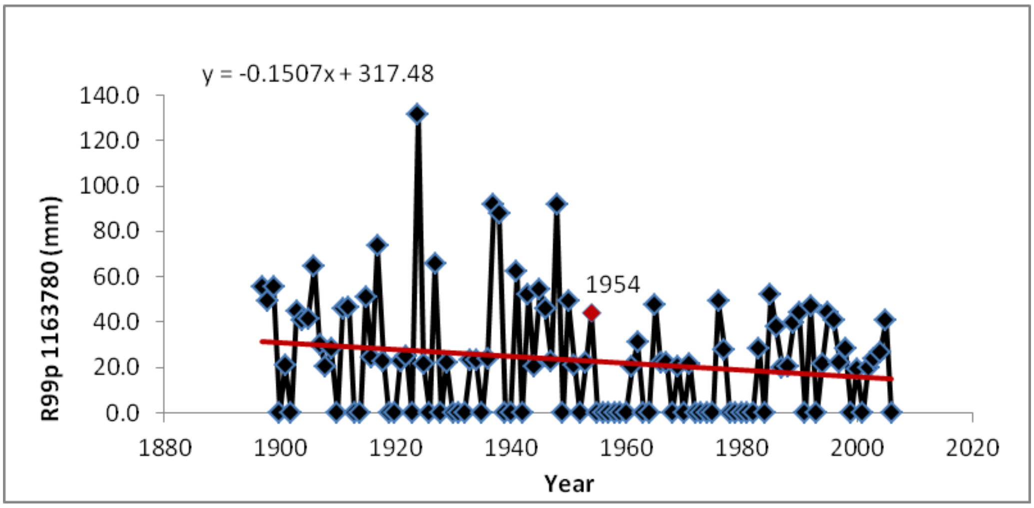

y = 0.734x - 1284.6
R95p 1143900 (mm)
400
350
300
250
200
150
100
50
0
1958
1910
1930
1950
1970
1990
2010
Year

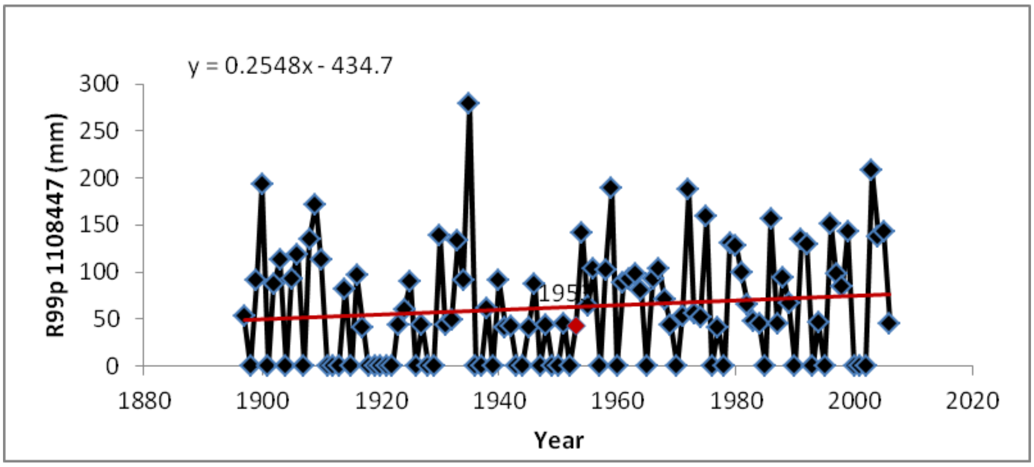

y = 0.6151x - 1121.1
R95p 1192340 (mm)
300
250
200
150
100
50
0
1979
1940
1950
1960
1970
1980
1990
2000
2010
Year

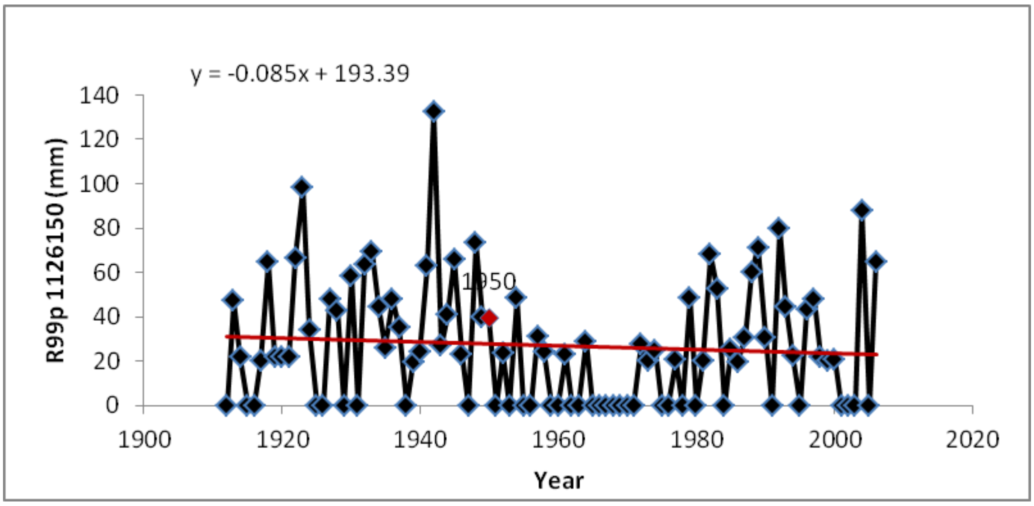

y = 0.4177x - 736.37
R95p 1092970 (mm)
250
200
150
100
50
0
1932
1900
1920
1940
1960
1980
2000
2020
Year

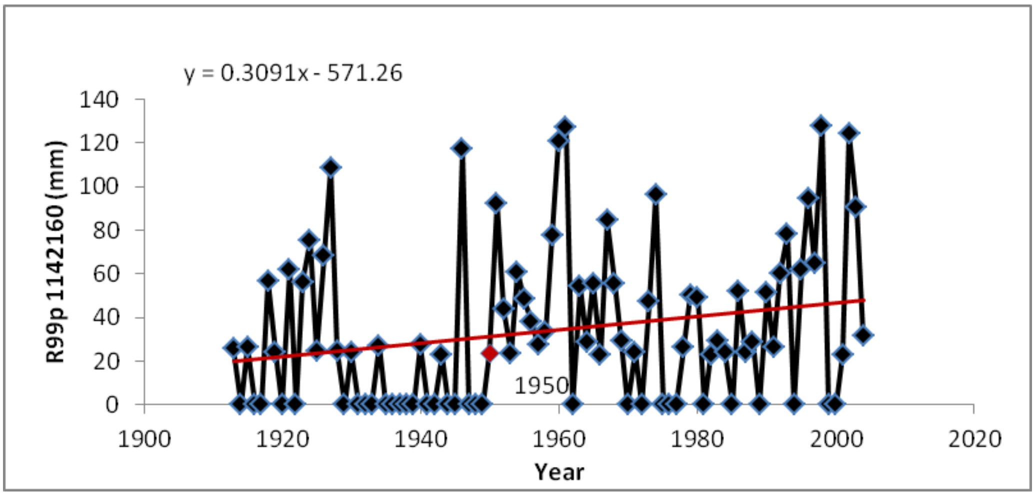

y = 0.7308x - 1330.8
R95p 1142160 (mm)
300
250
200
150
100
50
0
1949
1900
1920
1940
1960
1980
2000
2020
Year

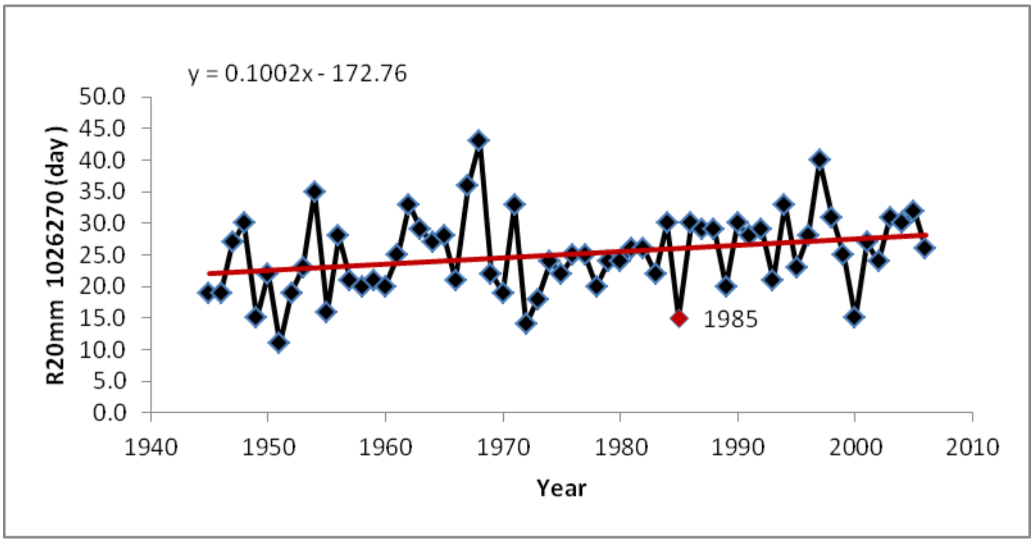

y = 1.765x - 3375.2
R99p 1026270 (mm)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
1961
1940
1950
1960
1970
1980
1990
2000
2010
Year

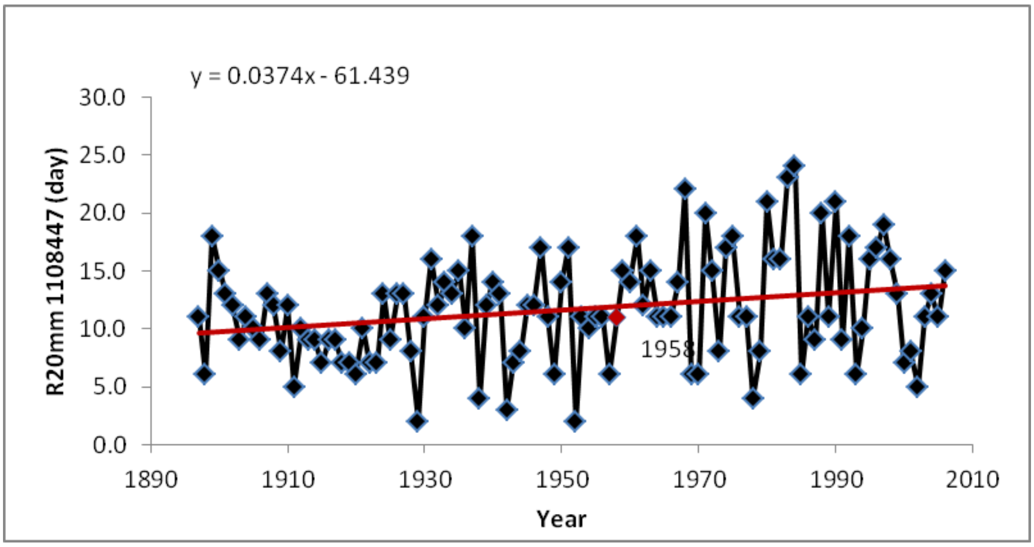

y = -0.1507x + 317.48
R99p 1163780 (mm)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1954
1880
1900
1920
1940
1960
1980
2000
2020
Year

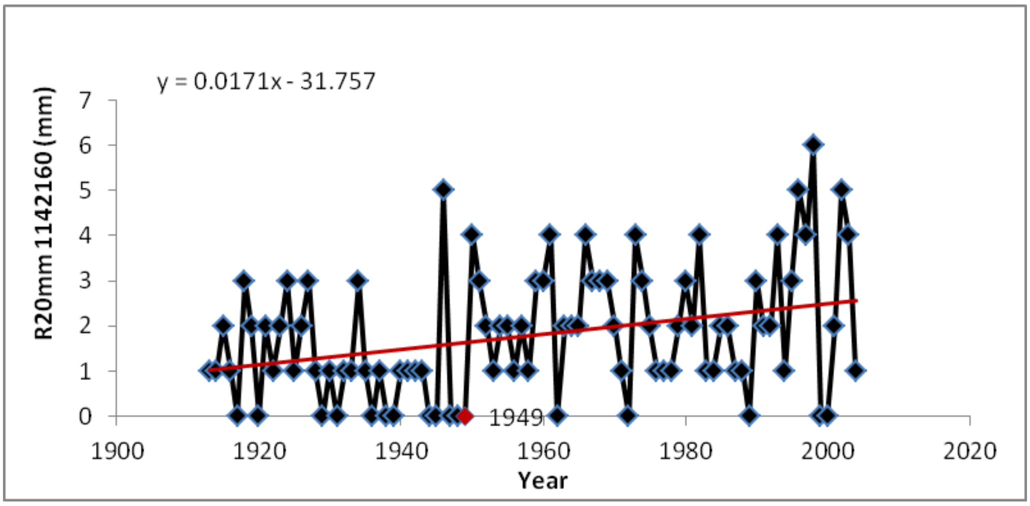

y = 0.2548x - 434.7
R99p 1108447 (mm)
300
250
200
150
100
50
0
195
1880
1900
1920
1940
1960
1980
2000
2020
Year

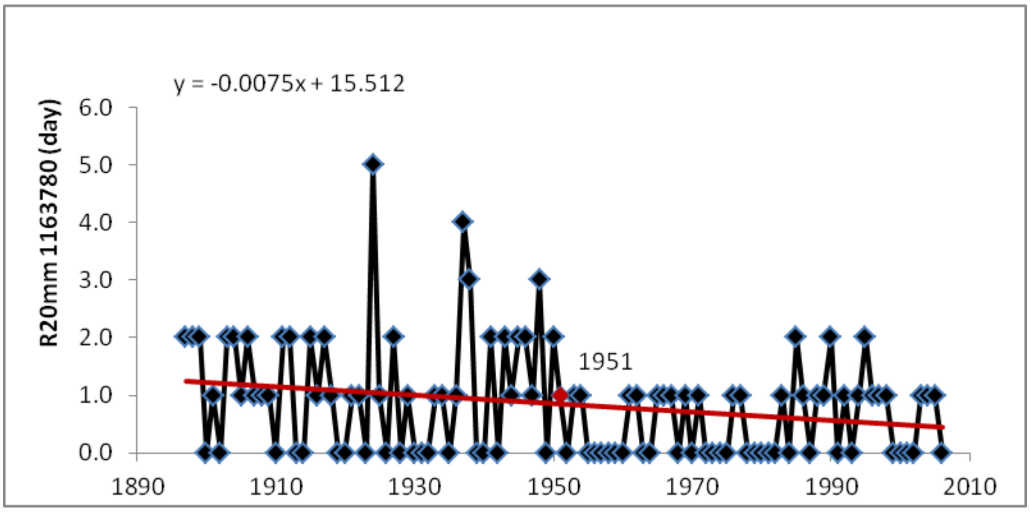

y = -0.085x + 193.39
R99p 1126150 (mm)
140
120
100
80
60
40
20
0
1900
1920
1940
1960
1980
2000
2020
Year
1950

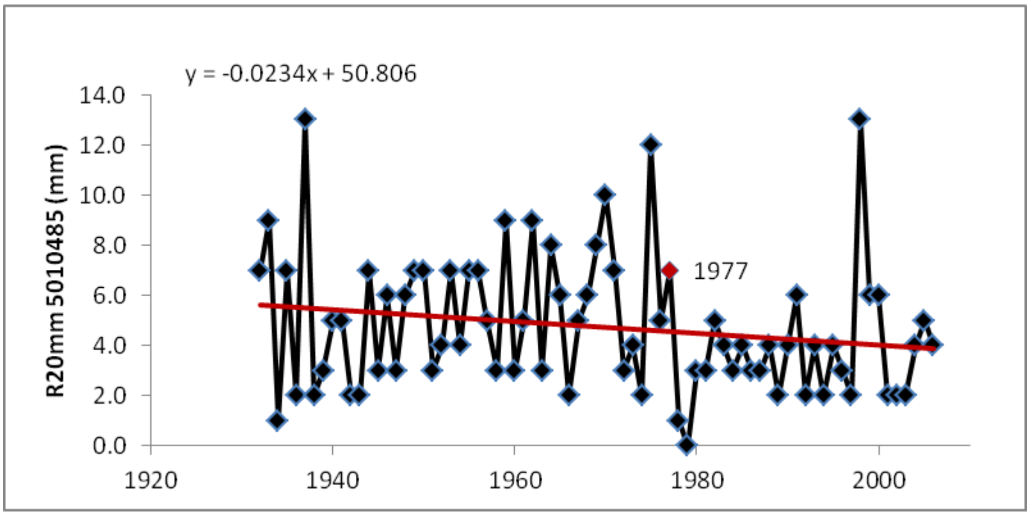

y = 0.3091x - 571.26
R99p 1142160 (mm)
140
120
100
80
60
40
20
0
1900
1920
1940
1960
1980
2000
2020
Year
1950

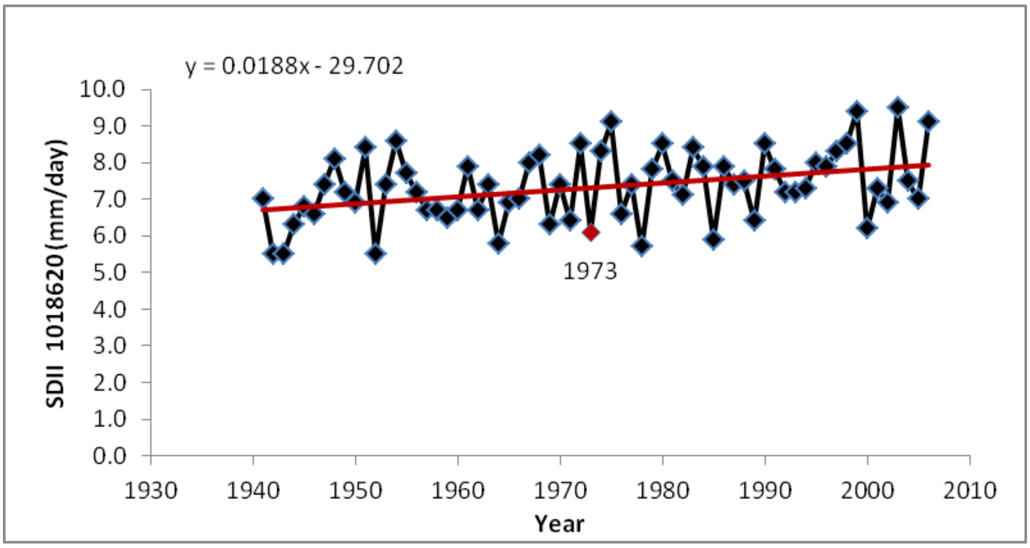

y = 0.1002x - 172.76
R20mm 1026270 (day)
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1940
1950
1960
1970
1980
1990
2000
2010
Year
1985

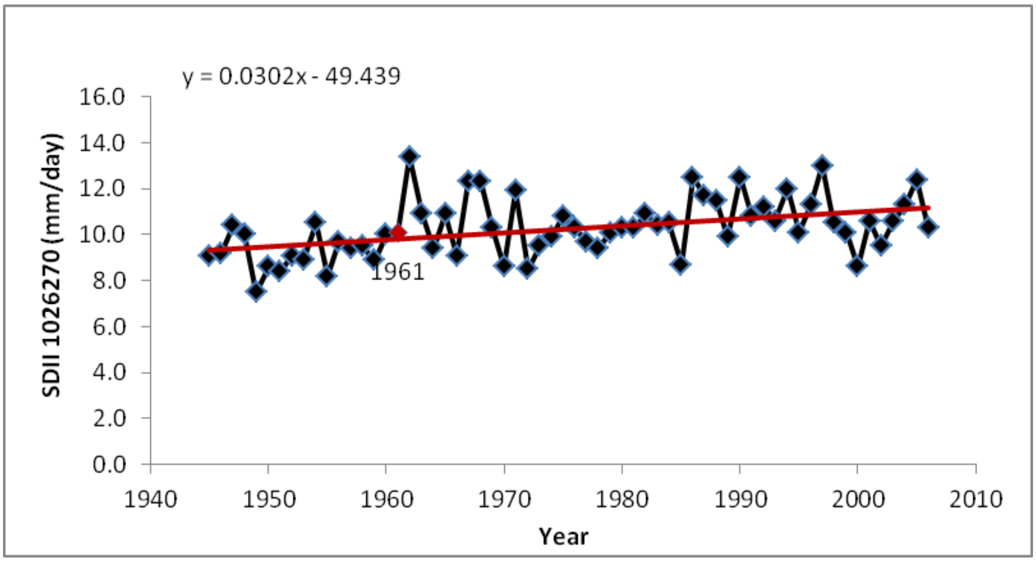

y = 0.0374x - 61.439
R20mm 1108447 (day)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1890
1910
1930
1950
1970
1990
2010
Year
1958

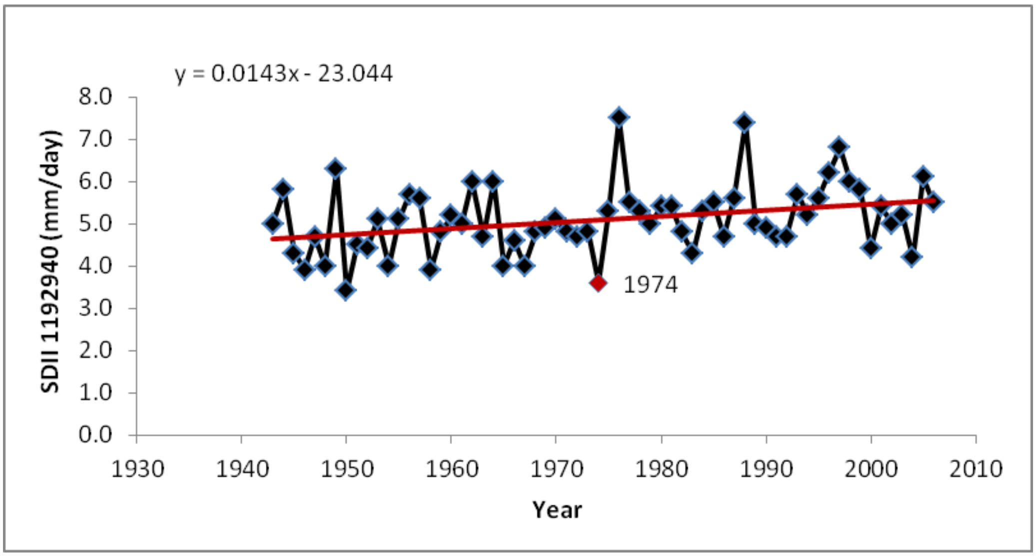

y = 0.0171x - 31.757
R20mm 1142160 (mm)
7
6
5
4
3
2
1
0
1900
1920
1940
1960
1980
2000
2020
Year
1949

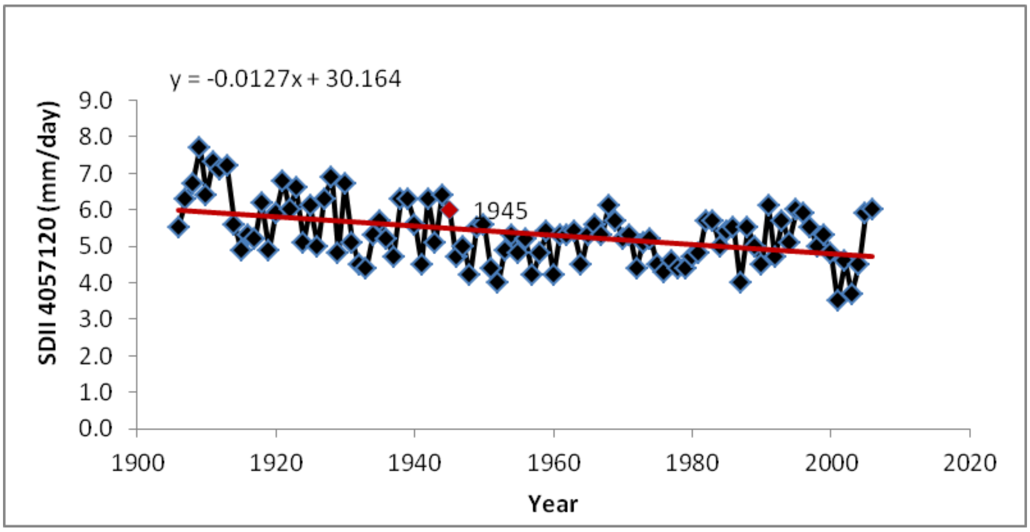

y = -0.0075x + 15.512
R20mm 1163780 (day)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1890
1910
1930
1950
1970
1990
2010
1951

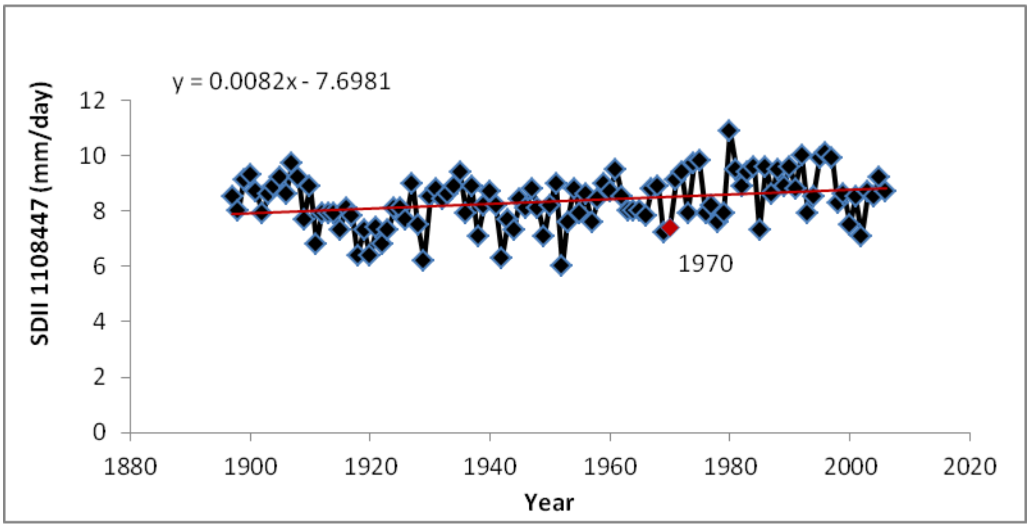

y = -0.0234x + 50.806
R20mm 5010485 (mm)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1977
1920
1940
1960
1980
2000

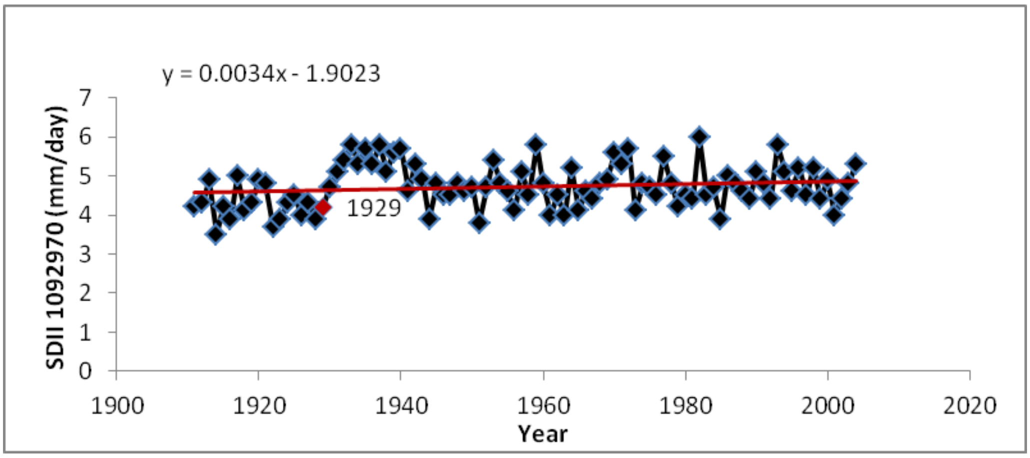

y = 0.0188x - 29.702
SDII 1018620 (mm/day)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1973
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

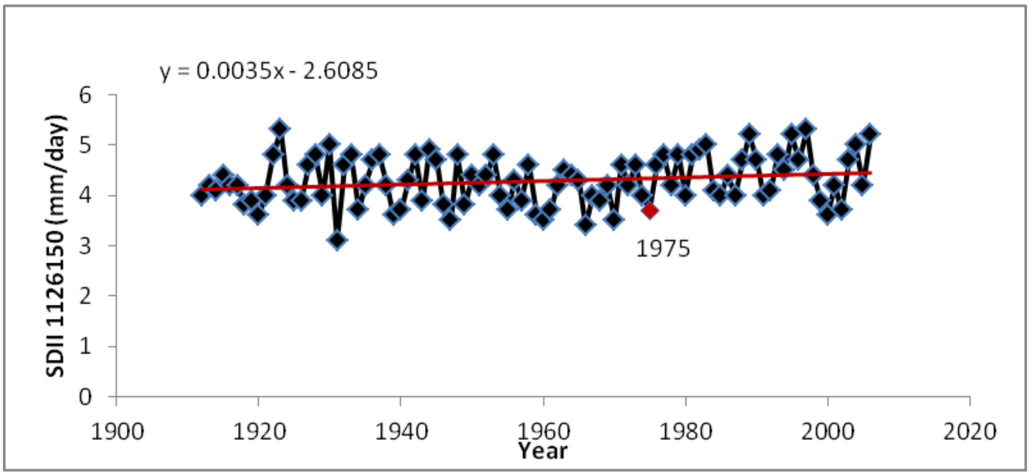

y = 0.0302x - 49.439
SDII 1026270 (mm/day)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1961
1940
1950
1960
1970
1980
1990
2000
2010
Year

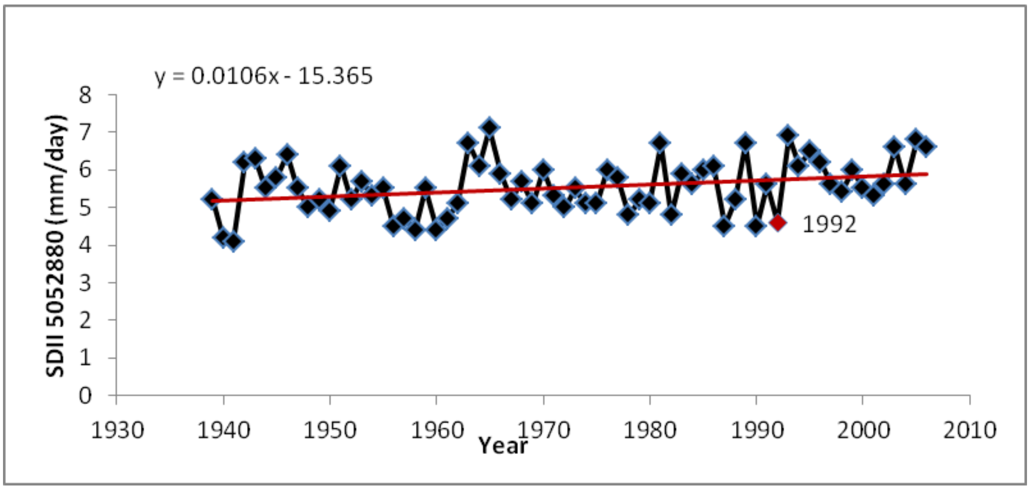

y = 0.0143x - 23.044
SDII 1192940 (mm/day)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
1974

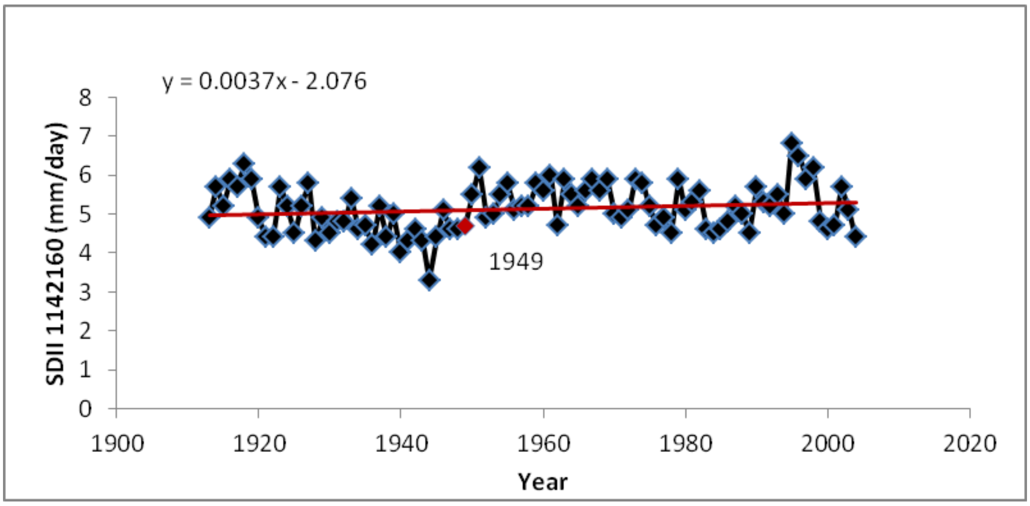

y = -0.0127x + 30.164
SDII 4057120 (mm/day)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1900
1920
1940
1960
1980
2000
2020
Year
1945

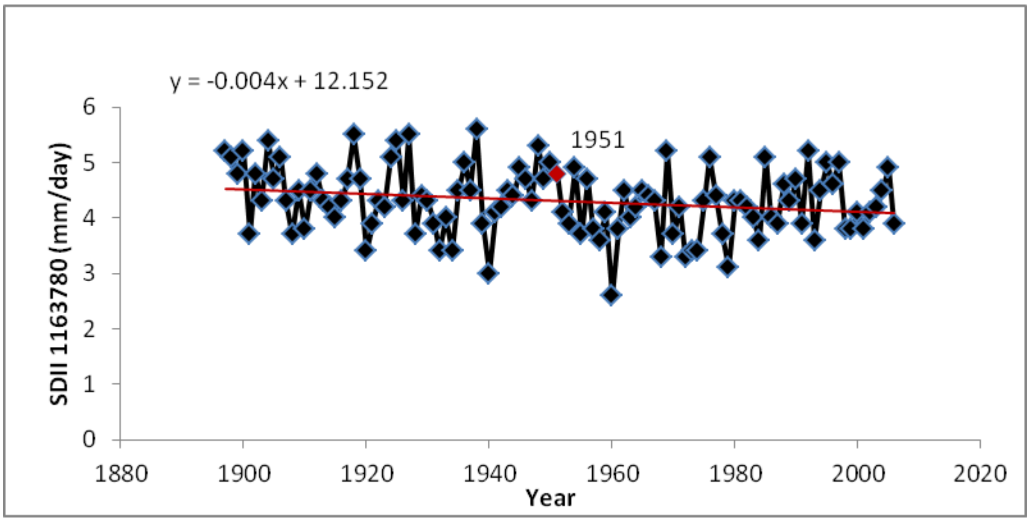

y = 0.0082x - 7.6981
SDII 1108447 (mm/day)
12
10
8
6
4
2
0
1880
1900
1920
1940
1960
1980
2000
2020
Year
1970

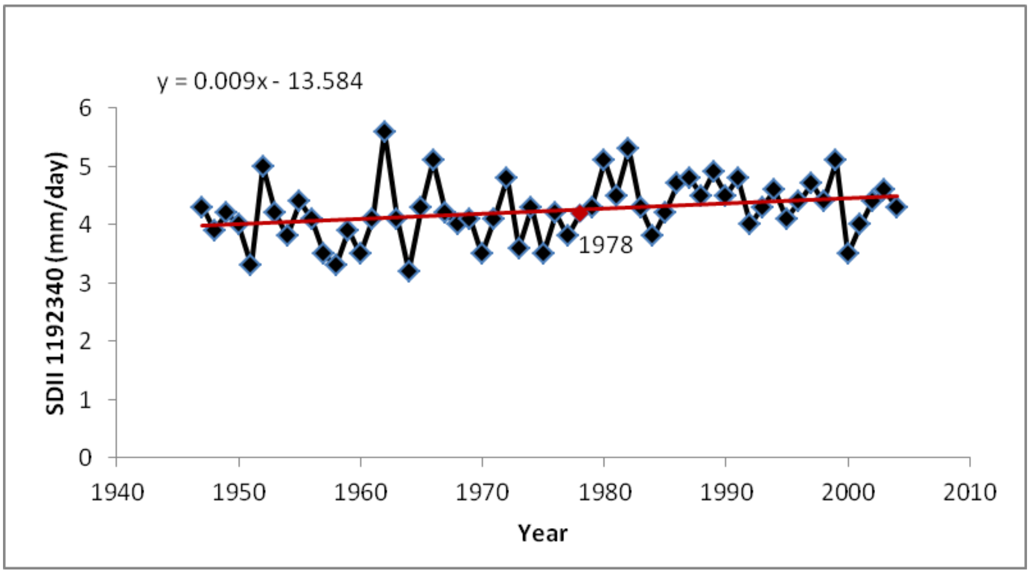

y = 0.0034x - 1.9023
SDII 1092970 (mm/day)
0
1
2
3
4
5
6
7
1929
1900
1920
1940
1960
1980
2000
2020
Year

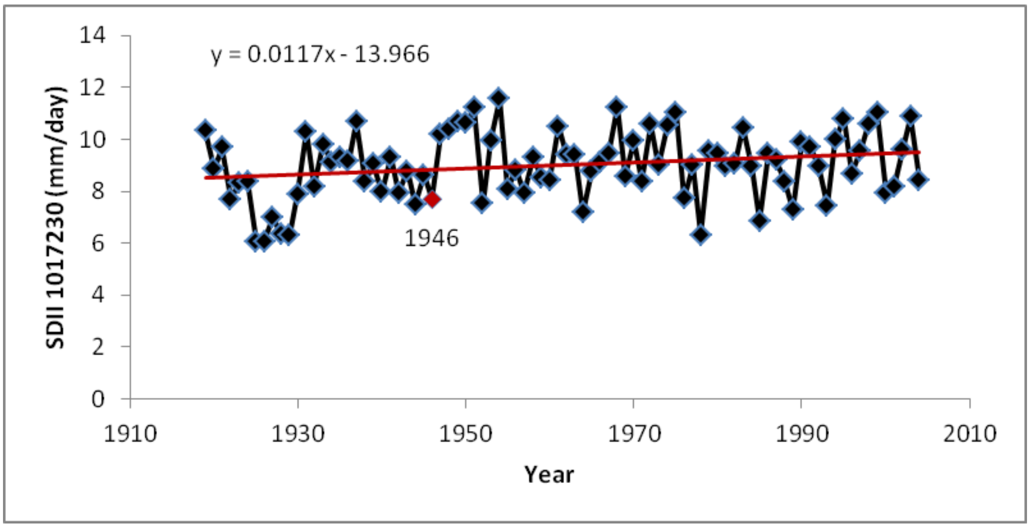

y = 0.0035x - 2.6085
SDII 1126150 (mm/day)
0
1
2
3
4
5
6
1975
1900
1920
1940
1960
1980
2000
2020
Year

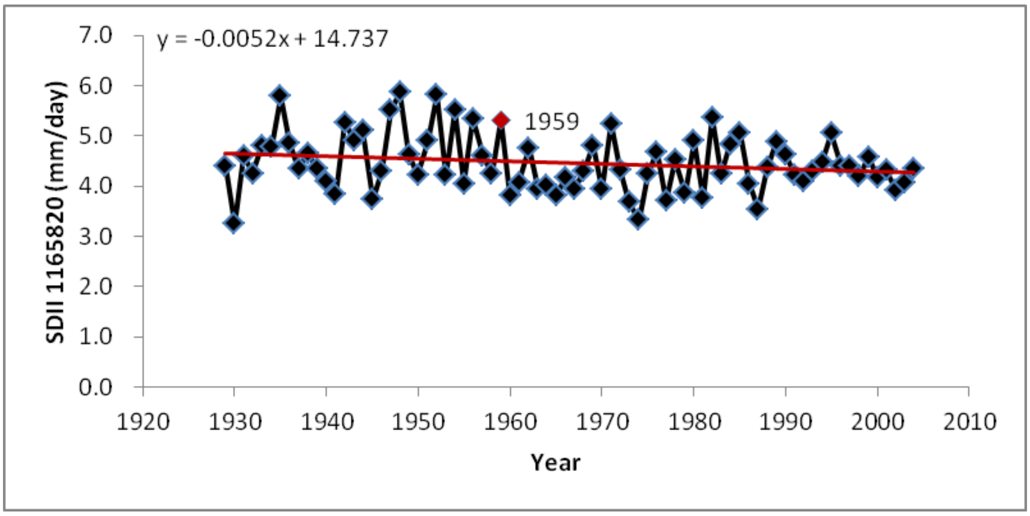

y = 0.0106x - 15.365
SDII 5052880 (mm/day)
0
1
2
3
4
5
6
7
8
1992
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

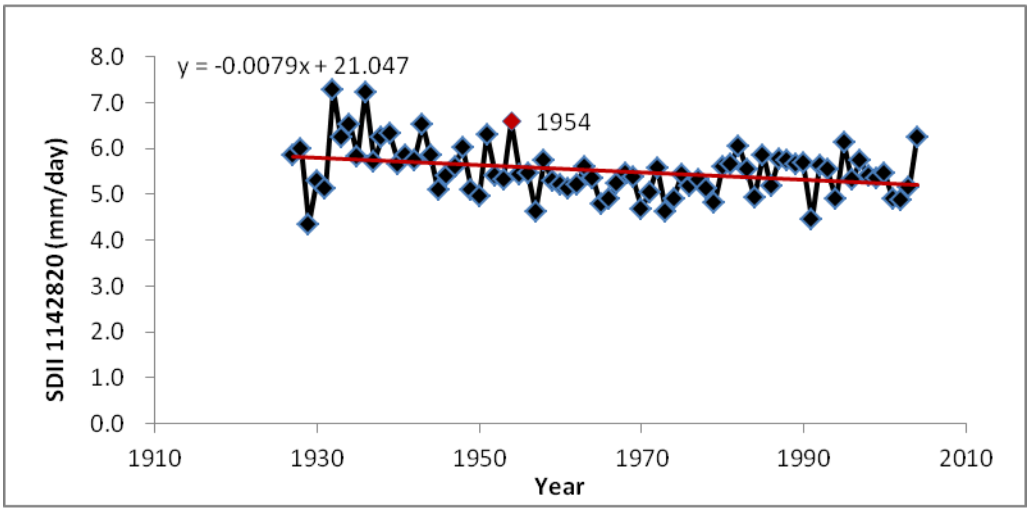

y = 0.0037x - 2.076
SDII 1142160 (mm/day)
8
7
6
5
4
3
2
1
0
1949
1900
1920
1940
1960
1980
2000
2020
Year

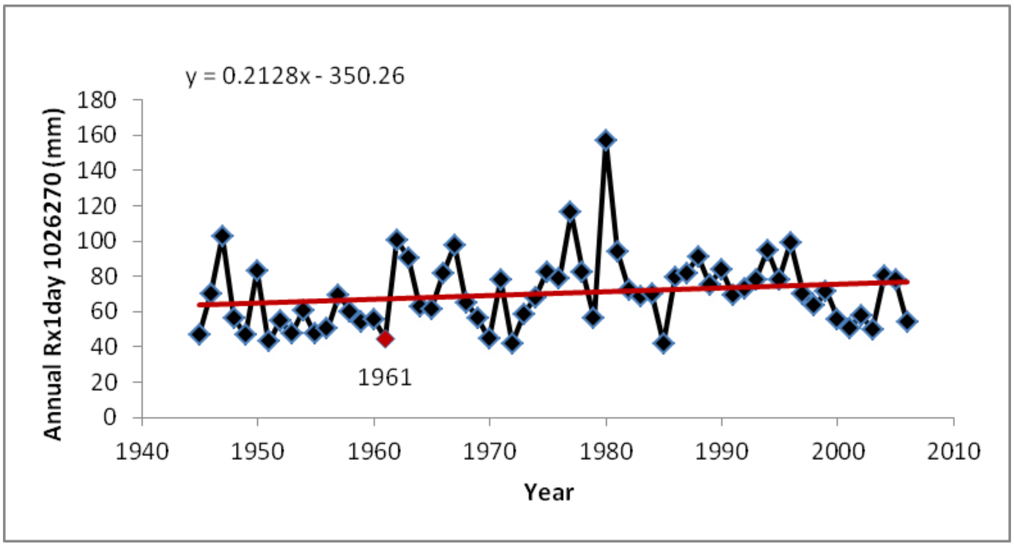

y = -0.004x + 12.152
SDII 1163780 (mm/day)
6
5
4
3
2
1
0
1951
1880
1900
1920
1940
1960
1980
2000
2020
Year

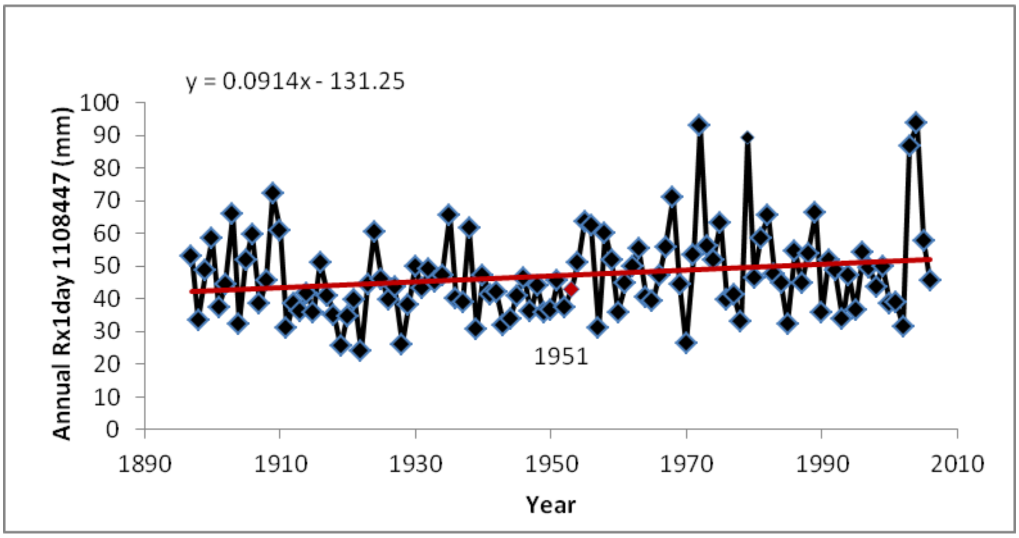

y = 0.009x - 13.584
SDII 1192340 (mm/day)
6
5
4
3
2
1
0
1978
1940
1950
1960
1970
1980
1990
2000
2010
Year

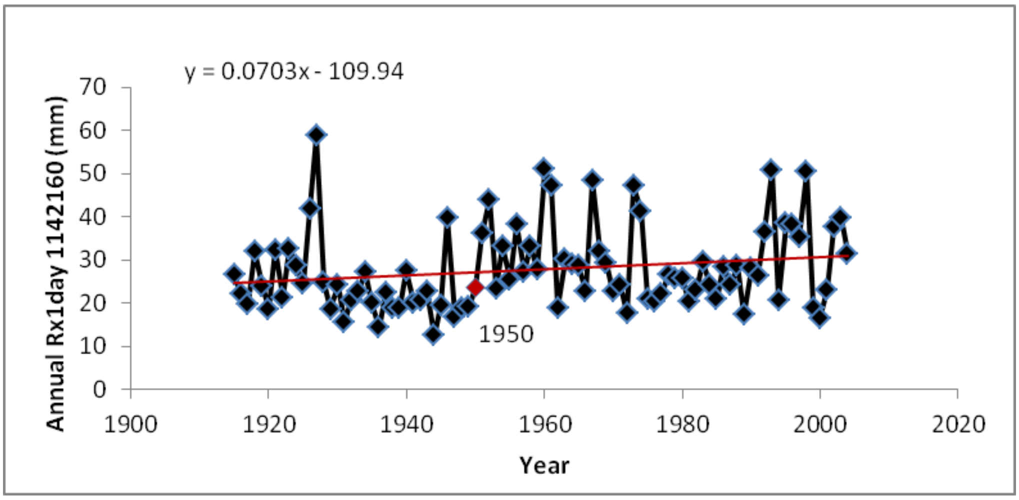

y = 0.0117x - 13.966
1946
SDII 1017230 (mm/day)
0
2
4
6
8
10
12
14
1910
1930
1950
1970
1990
2010
Year

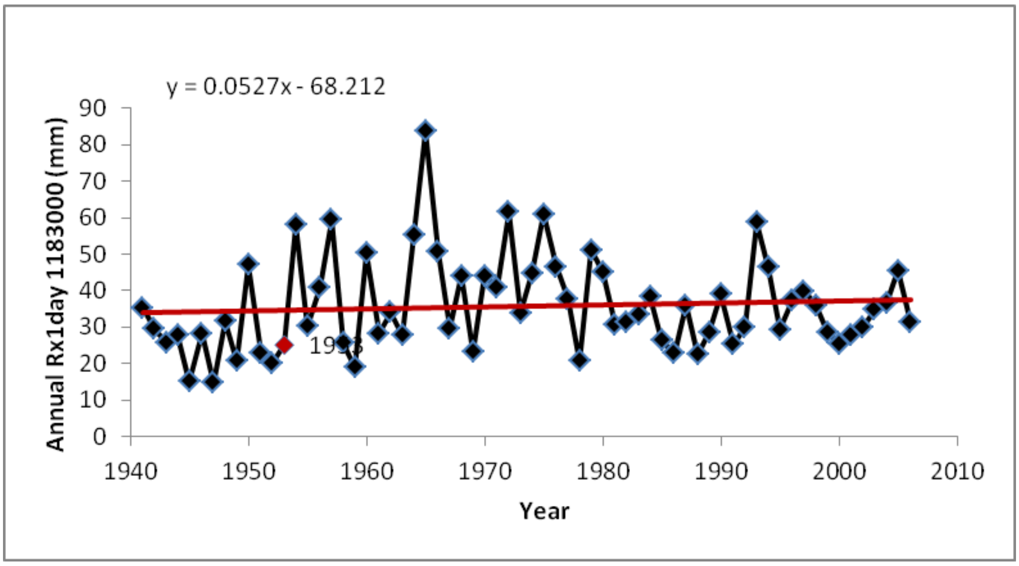

y = -0.0052x + 14.737
1959
SDII 1165820 (mm/day)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

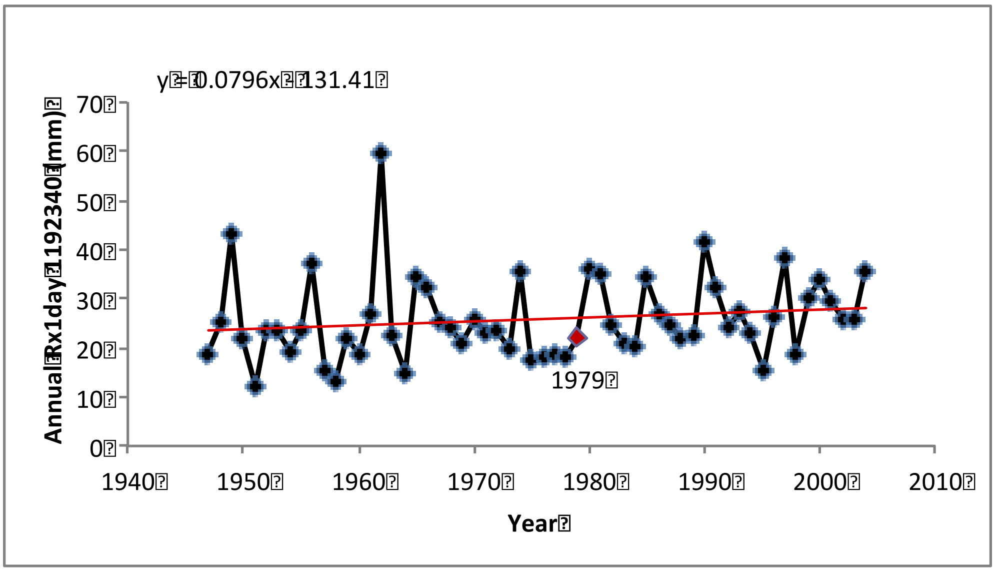

y = -0.0079x + 21.047
1954
SDII 1142820 (mm/day)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
1910
1930
1950
1970
1990
2010
Year

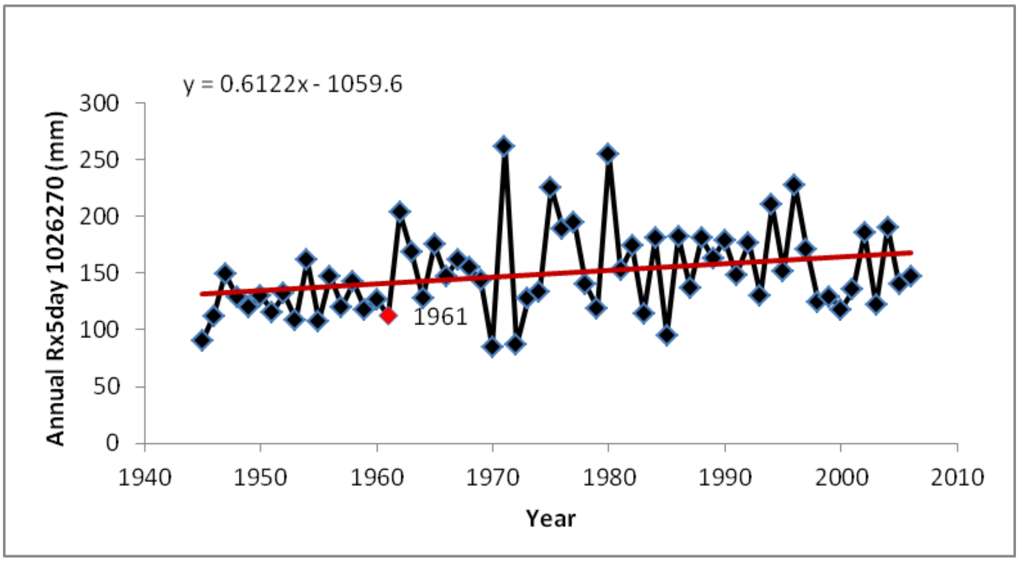

y = 0.2128x - 350.26
Annual Rx1day 1026270 (mm)
180
160
140
120
100
80
60
40
20
0
1961
1940
1950
1960
1970
1980
1990
2000
2010
Year

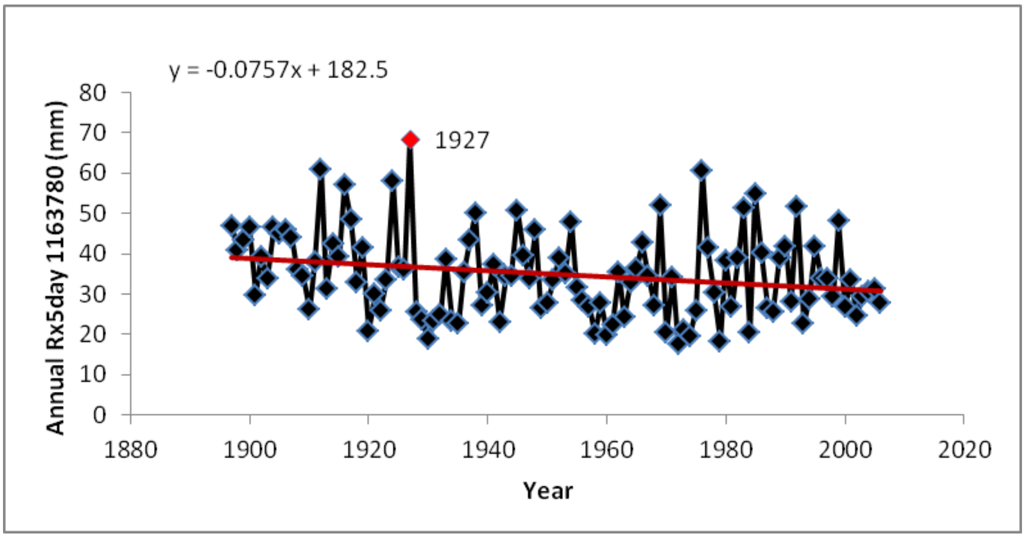

y = 0.0914x - 131.25
Annual Rx1day 1108447 (mm)
100
90
80
70
60
50
40
30
20
10
0
1951
1890
1910
1930
1950
1970
1990
2010
Year

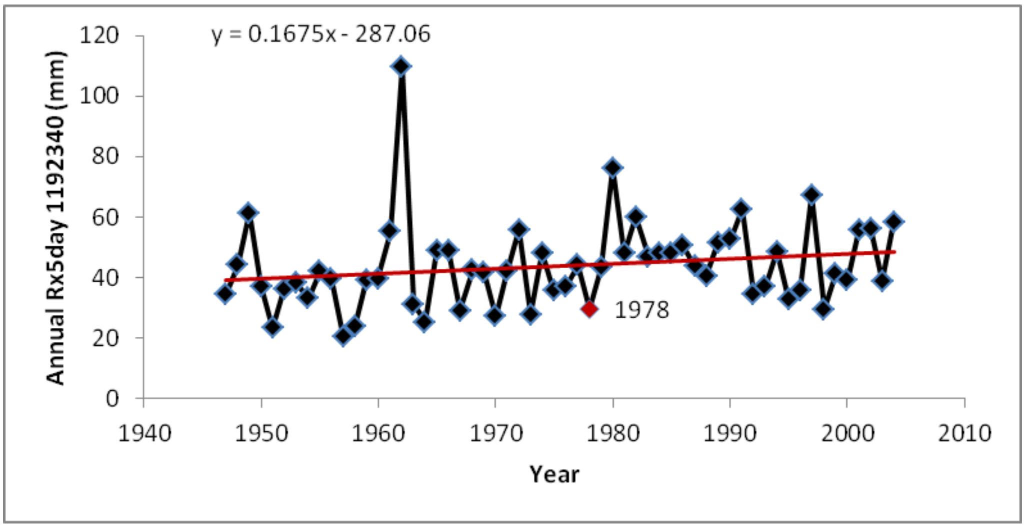

y = 0.0703x - 109.94
Annual Rx1day 1142160 (mm)
70
60
50
40
30
20
10
0
1950
1900
1920
1940
1960
1980
2000
2020
Year

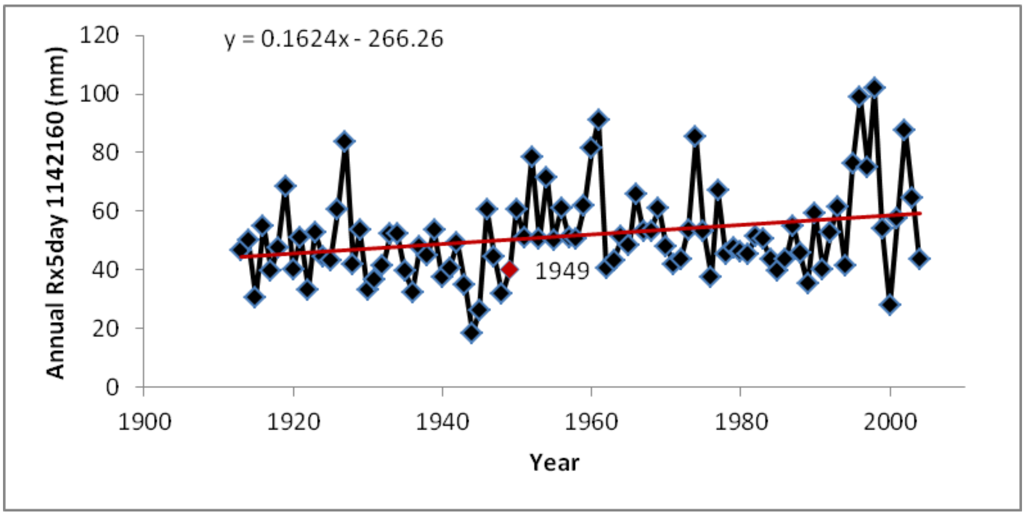

y = 0.0527x - 68.212
Annual Rx1day 1183000 (mm)
90
80
70
60
50
40
30
20
10
0
1953
1940
1950
1960
1970
1980
1990
2000
2010
Year


y = 0.0796x - 131.41
Annual Rx1day 1192340 (mm)
70
60
50
40
30
20
10
0
1979
1940
1950
1960
1970
1980
1990
2000
2010
Year


y = 0.6122x - 1059.6
Annual Rx5day 1026270 (mm)
300
250
200
150
100
50
0
1961
1940
1950
1960
1970
1980
1990
2000
2010
Year


y = -0.0757x + 182.5
1927
Annual Rx5day 1163780 (mm)
0
10
20
30
40
50
60
70
80
1880
1900
1920
1940
1960
1980
2000
2020
Year


y = 0.1675x - 287.06
1978
Annual Rx5day 1192340 (mm)
0
20
40
60
80
100
120
1940
1950
1960
1970
1980
1990
2000
2010
Year


y = 0.1624x - 266.26
1949
Annual Rx5day 1142160 (mm)
0
20
40
60
80
100
120
1900
1920
1940
1960
1980
2000
Year