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**AR TICLE**

Climate change impacts on precipitation and temperature in Prince Edward Island, Canada

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**Abstract**

To understand climate change impacts on Prince Edward Island (PEI), Canada, historical daily precipitation and temperature of the island was investigated between the pe- riods: 1931–60 (1940s), 1961–90 (1970s), and 1991–2020

(2000s) in its eastern, central, and western parts. Observed climatic data were utilized, augmented by some validated modeled data of Pacific Climate Impact Consortium (PCIC) for missing years. Statistically significant warming of the is- land was found ranging from 1.14°C in the east to 0.75°C in the west from the 1970s to 2000s. The warming trend dur- ing the period was distributed throughout the year including winters. In the east, mean monthly temperature significantly increased in all the months except for January, March, and June. Significant increase in temperature was found solely during August (+0.80°C) in central, and for August (+0.64°C), September (+0.99°C), and October (+0.73°C) in western parts. Proportionate increase in annual minimum temperature was greater than the maximum, particularly in eastern (+1.57°C) and central (+0.75°C) parts and thus in- dicated moderated cold there. Over the same 30-year pe- riod, annual precipitation increased 6 percent in the east but decreased 5 and 8 percent in the central and the western PEI, respectively. The changes in precipitation were not

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statistically significant, except snowfall reduction (−20%) in the west, which was a statistically significant change. Interannual precipitation variations during wet and dry years having 20 and 80 percent probabilities of exceedance, respectively, ranged 350–470 mm/year during 1991–2020. Rainfall intensities, measured by hourly data, increased from 1.15 to 2.24 mm/hr, on average in central and western parts, respectively, in 2004–17 compared to 1970s. Impacts of the rising temperatures, decreasing precipitation, and un- even and intense rainfalls patterns on water resources and rainfed agriculture need further investigations. Climate change adaptations be included in existing water policies to mitigate the impacts.

**KEYWORDS**

Canada, climate change, precipitation patterns, Prince Edward Island, rainfall intensity, warming

# | INTRODUCTION

Greenhouse gas emissions have been continuously increasing since pre-industrial era, leading to warming and other climatic changes around the globe (Karl & Trenberth, 2003; Pachauri et al., 2014; Trenberth, 2011). International Panel on Climate Change (IPCC) reported a significant decline in the number of cool days and nights worldwide and increased warm days and nights. It also reported an increased precipitation on larger areas than the areas with decreased precipitation (Masson-Delmotte et al., 2018; Mbow et al., 2017). There have been evidences of more frequent and intense droughts as well (Dai, 2012). Warming also causes precipitation transformation to more-rain-less-snow pat- tern causing floods, besides accentuating snowmelt, and evaporative stress (Berghuijs et al., 2014; Masson-Delmotte et al., 2018; Medeiros et al., 2017). However, impacts of climate change vary region to region (Sharma & Goyal, 2020); therefore, regional assessments are necessary for sustainable man- agement of natural resources (Schewe et al., 2014).

Climate change impacts significantly vary across Canada. Warming is a major concern, as average temperature rise during 1948–2016 is 1.7°C, which is twice the average global rate. Northern parts of Canada experienced stronger warming where annual temperature raise remained 2.3°C. Winters have gone warmer by 1.5–3°C, mostly in western and southern parts, whereas northeastern parts including Atlantic Canada indicated minimal changes during winters (Government of Canada, 2019). Significant variations in precipitation have also been reported by IPCC. Precipitation increased in northern parts and decreased in Prairies (Parry et al., 2007). Regional variations in precipitation has been assessed to vary spatially in the range −10 and +35 percent (Zhang et al., 2000).

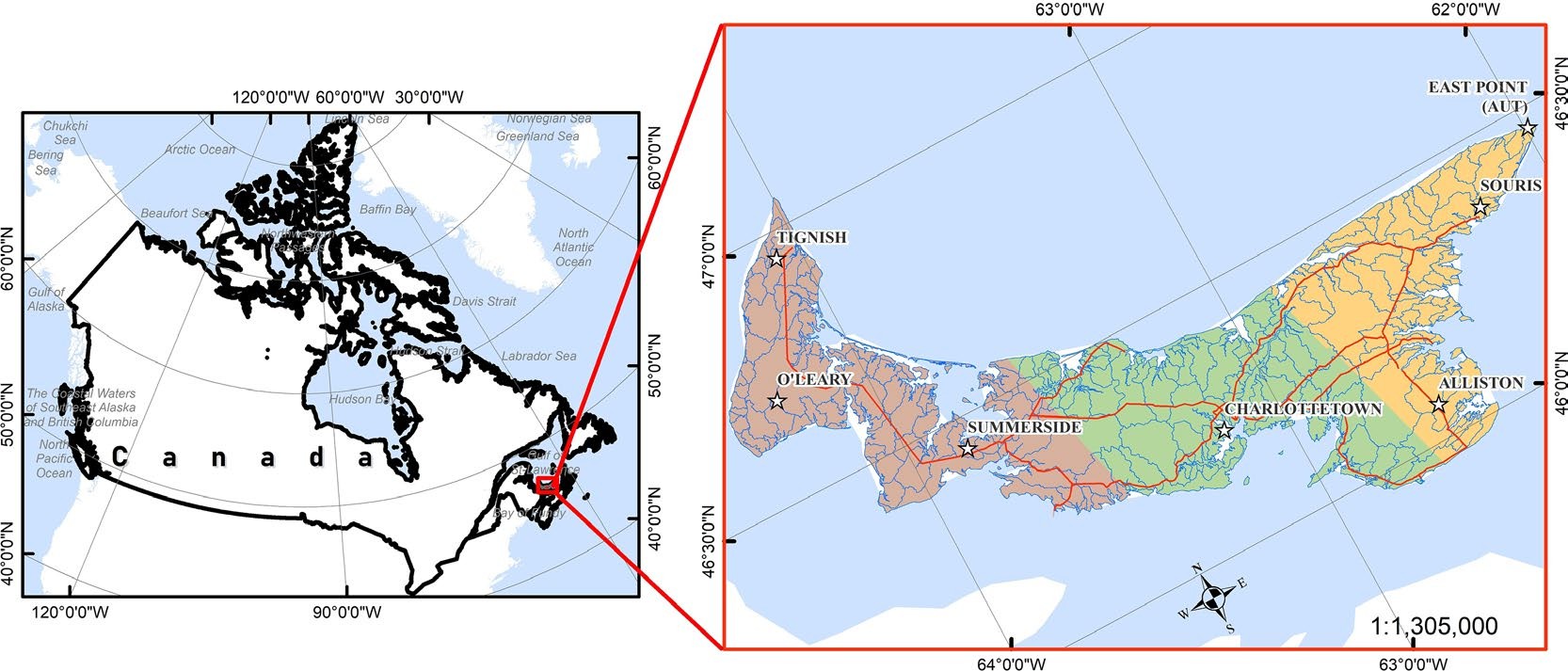
Atlantic Canada includes provinces of New Brunswick, Nova Scotia, Newfoundland and Labrador, and the study area, that is, Prince Edward Island (PEI), on the east coast of Canada. The province is rich in freshwater resources with relatively high precipitation around 1,100 mm per year in recent years (McDougall et al., 1988). The warming was relatively gentler, 0.5°C during the last 50 years (Arnold & Fenech, 2017), and more hot days and early springs were recorded (Hodgkins et al., 2011).

Arnold and Fenech (2017) predicted a rise in annual mean temperatures here up to 2.4°C on average by 2080s. They also observed decline in precipitation at central PEI and forecasted a further decline by 6 percent during 2011–40. The annual maximum daily precipitation was found to increase during the period 1990–2000 (Tan et al., 2017). The questions arise, can we use PCIC modeled data to fill any meteorological data gaps for analysis? What is temporal and spatial patterns of warming in PEI during the last 60 years? What is intra-annual (month wise) distribution of warming? How total pre- cipitation and its snowfall–rainfall distribution has changed across the island over the same period? What is intra-annual distribution of precipitation changes? How has rainfall intensity changed? What are expected rainfall and snowfall in wet and dry years? Do the precipitation and temperature changes are statistically significant? and, What likely effects of the changes may possibly be on water resources and water policy?

Detailed historical precipitation and temperature analyses have been conducted in the study, which includes changes in quantity and intensity of rainfall and snowfall in different parts of PEI over the pe- riods 1931–60, 1961–90, and 1991–2020. Interannual variations of rainfall and snowfall expectancy, that is, expected rainfall/snowfall depth (mm) during normal, dry or wet years, were investigated. Changes in the mean monthly precipitation and temperature were analyzed over the periods and its statistical significance.

# | MATERIALS AND METHODS

PEI is the smallest and most populous province of Canada. It has an area of 5,750 km2 accommodat- ing 158,000 people. The population density thus becomes 27 persons/km2 against Canadian average of 4 person/km2 (Statistics Canada, 2020). It is located on the east coast in the Gulf of St. Lawrence between latitudes 45°57′ and 47°04 N′ and longitudes 61°55′ and 64°25′ W (Figure 1). The island is about 230 km long, 6–30 km wide having 1,600 km long coastline, wherein elevation varies from 0 to 127 m above mean sea level. The major sources of livelihood are agriculture, fishery, and tourism. Climate is cool and humid with long and mild winters and moderately warm summers. Annual precip- itation is around 1,100 mm, of which 80 percent is rainfall and the rest is snowfall. The precipitation is relatively evenly distributed along the year (Francis, 1989; MacDougall et al., 1988). The study area



**FIGURE 1** Geographic location of Prince Edward Island in Atlantic Canada and its eastern, central, and western zones

was divided into three zones to delineate the impacts of climate change on precipitation and tempera- ture. The zones comprise eastern, central, and western PEI represented by Alliston, Charlottetown, and Summerside weather stations, respectively, as shown in Figure 1. The zones also correspond to administrative boundaries, that is, Kings, Queens, and Prince Counties, respectively.

Rainfall, snowfall, and temperature are measured at the stations by rain gauges (standard/tipping bucket), Nipher/Lambrecht gauges, and Stevenson screen thermometers/temperature sensors, respec- tively. Selection of the stations was based on their locations to represent their respective regions, as well as availability of the longest and uninterrupted data. Meteorological data, that is, hourly, and daily precipitation, and daily minimum, maximum and mean temperatures were ascertained from Environment Canada and processed.

Temporally, data of each station/zone were divided into three analytical periods, that is, 1931–60, 1961–90 and 1991–2020. The 30-year analytical periods were adopted for comparative analysis as per guidelines of World Meteorological Organization (WMO). WMO specifically defines a climate normal as, “*Period averages computed for a uniform and relatively long period comprising at least three consecutive ten-year period*.” Moreover, it establishes the period from 1961 to 1990 as a stan- dard reference period for long-term climate change assessments (WMO, 2017). Nevertheless, requi- site data were missing for several years at the three stations and were essentially required for climatic analysis. The missing data for Alliston was from 1982 to 1994, for Charlottetown: 1943, 1945, and 2020, and for Summerside: 1946, 1951–71, 1984, 1999, 2001, and 2020. For this purpose, the Pacific Climate Impacts Consortium (PCIC) modeled data were used to fill the gaps. The PCIC provides daily data of precipitation, minimum and maximum daily temperatures at 10 km × 10 km, from 1951 to 2,100. Therefore, missing data of years prior to 1950, that is, 1931–35 for Alliston, 1931– 42 for Charlottetown, and 1931–41 for Summerside had to be excluded and processed accordingly. Comparative analysis has therefore been restricted to the analytical periods 1961–90 and 1991–2020, though values of the analytical period 1931–60 are also given.

The PCIC data are computed by 12 different statistical-downscaling methods to convert coarse resolution (100 km × 100 km or more) to fine resolution at a gridded resolution of 300 arc-seconds or roughly 10 km × 10 km. The Bias Correction/Constructed Analogues with Quantile (BCCAQ) downscale method was adopted because of its ability to accurately resolve event-scale spatial gradients.

BCCAQ is a hybrid method that combines results from Bias Correction/Constructed Analogues (BCCA) (Maurer et al., 2010) and quantile mapping (QMAP) (Gudmundsson et al., 2012). BCCAQ is designed to resolve event-scale spatial gradients more accurately and passed the greatest num- ber of tests for hydrologic extremes by Werner and Cannon (2015). Daraio et al., (2019) also used BCCAQ technique to downscale PCIC data for flood mapping and infrastructure design in Newfoundland and Labrador. Jiang et al., (2017) used modeled data to develop future scenar- ios of temperature and precipitation in Alberta after calibrating those against observed values of 1961–90.

The modeled climatic data under Representative Concentration Pathway (RCP) 4.5 were obtained for Alliston, Charlottetown, and Summerside, as the durations belong to post-industrial period. The modeled data were validated against observed values to fill the data gaps. The time series observed, and modeled data were converted into mean monthly precipitation, mean monthly minimum tem- perature, and mean monthly maximum temperature for the three stations for the periods as given in Table 1. The mean monthly observed values were compared with the RCP4.5 PCIC data. Coefficient of determination, P-bias, and Root mean square error were determined to establish authenticity of PCIC data.

**TABLE 1** The PEI weather stations used in the study

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Station** | **Latitude** | **Longitude** | **Elevation (m)** | **Annual Precipitation (mm)** | **Data Availability Statement** | **Missing Data** |
| Alliston | 46.07 | −62.60 | 61 | 980 | 1936–2020 | 12 years |
| Charlottetown | 46.29 | −63.13 | 49 | 1,148 | 1943–2020 | 3 years |
| Summerside | 46.44 | −63.83 | 20 | 1,029 | 1942–2020 | 26 years |

## | Probability of exceedance

Probability of Exceedance (PoE) is the probability of occurrence of a rainfall depth (mm) greater than some specified value and is normally expressed in percentage. Rainfall probability under vari- ous weather conditions, that is, wet, normal, and dry periods is required for better management and planning of water resources (Smith, 1992). The rainfall depth expected against a PoE value of 80 percent refers to dry years, whereas values for 50 and 20 percent PoE refer to normal and wet years, respectively (Dirk, 2013).

The PoE curves were developed for expected annual rainfall and snowfall for each of the 30-year analytical periods. Snowfall can be descripted as snow water equivalent and precipitation refers to the sum of rainfall and snow water equivalent (mm). The PoE curves were developed for the three stations, that is, Alliston, Charlottetown, and Summerside for the three analytical periods, that is, 1931–60, 1961–90, and 1991–2020, excluding the missing data prior to 1950, following standard WMO (1983) formula, which is *PoE* = (*r* − 0.44)∕(*n* + 0.12) × 100,where *r* is the rank (rank 1 is the year with the highest rainfall) and *n* is the total number of years, that is, 30. The PoE values and their respective rainfall depths were plotted on x–y graphs with best-fit linear curves with its coefficient of determinations (R2). A few outliers were removed at the edges to improve degree of fitness as proposed by Dirk (2013). As temporal distribution of precipitation is quite important, therefore PoE curves of mean monthly precipitation were also developed for the wet, normal, and dry years having 20, 50, and 80 percent PoEs, respectively. Comparative analysis of the PoEs for the three analytical periods was done to demarcate changes in precipitation expectancy, separately for eastern, central, and western PEI.

## | Statistical analysis

The mean monthly and annual precipitations of the three stations were computed from the daily data for the three analytical periods as detailed below. The changes occurred between the periods 1961–90 and 1991–2020 have been analyzed and discussed. Mean monthly minimum, mean monthly maximum, and mean monthly temperatures were computed from the daily data for the three analytical periods at the three stations. Just like precipitation, the changes occurred between the periods 1961–90 and 1991–2020 and change percentages are given and discussed.

Two-way analysis of variance (ANOVA) was used to evaluate the differences in the mean values of the three 30-year period. Prior assumptions, that is, independent observations, normal distribution, and within-groups homoscedasticity were verified for each hypothesis. The means were compared

*Mi* − *Mj*

with Tukey's pairwise comparisons test at 95% confidence (α = 0.05): *HSD* = √ *MSw* , where HSD is the

honest significant difference; *M* − *M* is the difference of pairs of means; *MSw* =*n* mean square within

*i*

*j*

group; and *n* = number of observations in each group (30). Two sample *t*-test was applied for finding

significant difference in rainfall intensities over time, having two data groups. Kedhiri (2016) used f- test and *t*-test to find statistical significance of temperature over time in PEI. Minitab 18 (State College, Pennsylvania State University, PA: Minitab, Inc.) was used in the calculation of ANOVA and multiple means comparisons tests.

## | Intensity–duration–frequency

The Intensity–Duration–Frequency (IDF) curves establish relationship between rainfall intensity (mm/hr), rainfall duration (hr), and frequency/reciprocal of PoE (fraction). Rainfall IDF curves were developed by ascertaining hourly rainfall data from Environment Canada, provided on request with copyright permission. The data of rainfall months, that is, May to October were used in the analysis, as the rest are either exclusive snowfall or mixed precipitation months. The data were available for Charlottetown (1960–90 and 2007–16) and Summerside (1964–91 and 2004–17) only. The curves were developed for wet, normal, and dry years having 20, 50, and 80 percent PoEs, respectively. Daraio et al., (2019) used the technique to develop IDF curves on 1 percent PoE for flood risk map- ping of Newfoundland and Labrador. Switzmand et al., (2017) also developed IDF curves using Environment Canada data for Toronto and Windsor. Peck et al., (2012), however, recommended that IDF curves may not be exclusively used to study rainfall patterns under changing climate. That is why PoEs, means, and IDF were discussed together. Colorado State University (2020) procedure was adopted for the curves. Temporal variations in rainfall intensities of different duration events have been individualistically presented and discussed for each of the two stations.

# | RESULTS AND DISCUSSION

The PCIC modeled data have been used to fill gaps in observed data. The data were therefore tested against available observed values, from 1943 to 2020. The observed mean monthly precipitation, mean monthly maximum, and mean monthly minimum temperatures at Alliston, Charlottetown, and Summerside were correlated with the respective PCIC data (BCCAQ downscaled RCP4.5) as shown in Figure 2. The observed and modeled (RCP4.5) values were matched by coefficient of determination (R2), P bias, and root mean square error (RMSE) as given in Table 2.

It is evident from the table and the figures that most of the modeled values are very close to the observed values. All the R2 values are above 0.90 except for Summerside precipitation. The RMSE for mean monthly precipitation remained around 5 mm/month, mostly the modeled values were un- derpredicting precipitation (negative P bias); however, the difference remained minor. The modeled values of mean monthly maximum temperature at Alliston were higher than the observed values, thereby exhibiting a relatively higher P bias of above +10 percent and RMSE of 1.20°C. Other than that, all the three indicators showed negligible difference between the observed and modeled values of temperature. The modeled data were therefore considered appropriate to fill the missing values.

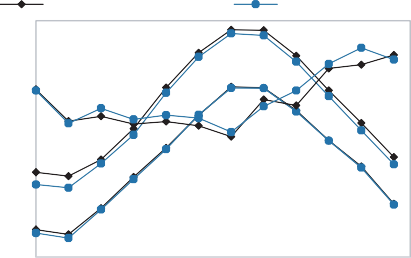
## | Eastern PEI

The PoE curves for annual rainfall and snowfall at Alliston, which represent eastern PEI, have been shown in Figure 3, whereas statistical means are given in Table 3. All the linear best-fit lines of the curves had R2 values around 0.90, hence were good fits; however, 2–3 outliers per fit were removed

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**| 7**

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**a)**

25

15

Modeled (RCP4.5)

Mean Monthly Max Temperature

Observed

5

Mean Monthly Precipitation

-5

Mean Monthly Min Temperature

-15

140

120

100

80

60

40

20

0

Temperature ( C)

**(b)**

25

Precipitation (mm)

Temperature ( C)

15

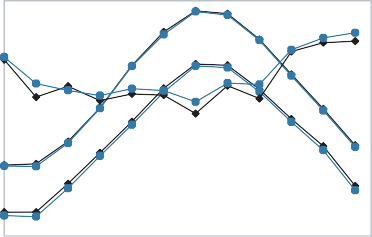
5

-5

-15

Modeled (RCP4.5)  Observed

140



Mean Monthly Max Temperature

Mean Monthly Precipitation

Mean Monthly Min Temperature

Precipitation (mm)

120

100

80

60

40

20

0



**(c)**

25

15

Temperature ( C)

5

-5

-15

 Modeled (RCP4.5)  Observed

120

Mean Monthly Min Temperature

Mean Monthly Precipitation

Mean Monthly Max Temperature

100

Precipitation (mm)

80

60

40

20

0

**FIGURE 2** Observed climatic parameters and PCIC RCP 4.5 modeled values at Alliston (a), Charlottetown (b), and Summerside (c) representing eastern, central, and western PEI, respectively

**TABLE 2** Correlational parameters between the observed and modeled values (PCIC RCP 4.5) for mean monthly precipitation, mean monthly maximum, and mean monthly minimum temperature

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Station** | **Coefficient of Determination (R2)** | **P bias (%)** | **RMSE**  **(mm or °C)** |
| Mean Monthly Precipitation | Alliston | 0.93 | −2.76 | 4.86 |
| (mm) | Charlottetown | 0.95 | −3.61 | 4.62 |
|  | Summerside | 0.86 | −1.98 | 4.49 |
| Mean Monthly Maximum | Alliston | 0.98 | +10.52 | 1.20 |
| Temperature (°C) | Charlottetown | 0.99 | +2.15 | 0.26 |
|  | Summerside | 0.99 | +2.79 | 0.33 |
| Mean Monthly Minimum | Alliston | 0.99 | +3.35 | 0.10 |
| Temperature (°C) Charlottetown | | 0.99 | +7.37 | 0.60 |
| Summerside | | 0.99 | −2.10a | 0.22 |

aNegative P bias indicate modeled values are lesser than observed values.

at the edges to improve fitness, as suggested by Dirk (2013). The R2 values therefore further improved to above 0.90. The expected precipitation (rainfall +snow water equivalent) in normal years (PoE

=50%) during the period 1936–60 (1940s) was around 800 mm, which increased to about 1,100 mm during 1970s and to about 1,200 mm during 2000s (Table 3).

The maximum increase in both the rainfall and snowfall took place from 1940s to 1970s and was found to be statistically significant (α = 0.05). Vincent and Mekis (2006) also reported significant

**8**

**|**

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100

80

60

PoE (%)

40

20

0

1936-1960 1961-1990 1991-2020

100

80

60

PoE (%)

40

20

0

1936-1960 1961-1990 1991-2020

300 500 700 900 1100 1300



R² = 0.92

R² = 0.97

R² = 0.98



R² = 0.98

R² = 0.92

R² = 0.92

Rainfall (mm)

0 50 100 150 200 250 300 350

Snowfall (cm)

**FIGURE 3** PoEs for rainfall (left) and snowfall (right) at Alliston

**TABLE 3** Change in annual precipitation over time at Alliston

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **1936–60 (1940s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** | **Change (%) (1970s–2000s)** |
| Rainfall (mm/year) | 685b | 897a | 953a | +56 | +6 |
| Snowfall (cm/year) | 152b | 219a | 229a | +10 | +5 |
| Precipitation (mm/year) | 837b | 1116a | 1182a | +66 | +6 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method.

increase in snowfall during the period 1950–2003 in northeastern Canada. Arnold and Fenech (2017) reported increased precipitation in Atlantic Canada. Afterwards during the 2000s, there was a minimal (6%) increase, that too mostly in rainfall (56 mm) as snowfall merely increased by 10 cm per year. MacDougall et al., (1988) reported average annual precipitation at Alliston as 900 mm. It justifies the results as the determined values vary from around 800 to 1,100 mm over the analytical periods.

The precipitation expected during dry years (PoE = 80%) was 570 mm (rainfall: 480 mm; snow- fall: 90 cm) during the 1940s, which substantially increased to 930 mm (rainfall: 760 mm; snowfall: 170 cm) during 1970s and to 1,010 mm (rainfall: 820 mm; snowfall: 190 cm) during 2000s. Similarly, expected precipitation during wet years (PoE = 20%) increased from 1,020 mm to 1,275 mm and to 1,340 mm during the same periods. The rainfall range between wet and dry years has been narrowed between 820 mm and 1,100 mm.

Analysis of the monthly distribution (Figure 4, Table 4) shows that rainfall has maximally in- creased in the months of October and November and least in summer months. Rather, months of May to September indicate slight decline or no change from 1970s to 2000s, neither annual nor monthly changes during those periods were found significantly different. Mekis and Vincent (2011) reported 20 percent increase in rainfall during 1950–2009 in the neighboring Arctic Canada. Growing season in PEI lasts from mid-May to mid-October (Maqsood et al., 2020). Therefore, increase in rainfall in the final months of cultivation and slight reduction during summer months may have negative conse- quences for agriculture.

Snowfall increased from January to March, with less difference between dry and wet years during the analytic period. Particularly, the snowfall increase was statistically significant during March. It continued increasing consistently right from 1940s to date. Based upon that long historic record,

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**| 9**

**(a) (b)**

 1936 - 1960  1961 - 1990  1991 - 2020

Normal Years

1936 - 1960  1961-1990  1991-2020

150

130

Precipitation (mm)

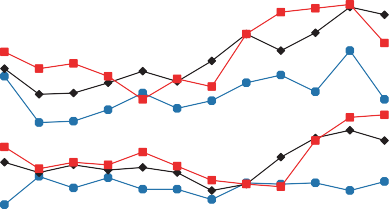
110

90

70

50

200

170

Precipitation (mm)

|  |
| --- |
|  |
| Wet Years |
|  |
|  |
| Dry Years |
|  |

140

110

80

50

20

**FIGURE 4** Temporal variation of precipitation over time at Alliston in normal (a), dry and wet years (b), having 50, 80, and 20 percent PoEs, respectively

**TABLE 4** Change in monthly precipitation (mm) over time at Alliston

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mean monthly Precipitation (mm)** | **1936–60 (1940s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** | **Change (%) (1970s–2000s)** |
| January | 70b | 89ab | 102a | +13 | +15 |
| February | 63b | 76ab | 87a | +11 | +14 |
| March | 59c | 77b | 92a | +15 | +19 |
| April | 67a | 81a | 86a | +5 | +6 |
| May | 70a | 86a | 81a | −5 | −6 |
| June | 64a | 81a | 84a | +3 | +4 |
| July | 61a | 75a | 81a | +6 | +8 |
| August | 77a | 94a | 95a | +1 | +1 |
| September | 79a | 99a | 101a | +2 | +2 |
| October | 72b | 114a | 122a | +8 | +7 |
| November | 86b | 126a | 131a | +5 | +4 |
| December | 69b | 118a | 120a | +2 | +2 |
| Total | 837b | 1116a | 1182a | +66 | +6 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method

further increase in snowfall can be expected from January to March. Almost the similar trends were found for dry and wet years. If same is projected, further increase can be expected in precipitation.

Temperature analysis did not show any unexpected results (Figure 5, Table 5). All the months had a significant increase in temperatures except January, March, and June. The annual temperature increased by 1.14°C during 2000s, which is significantly higher than that during 1970s (5.72°C). The recent trends (2000s) were however found close to those prevailed during 1940s.

Overall, significant warming of eastern PEI was found during 2000s as compared to 1970s. All the months showed statistically significant warming, except January, March, and June, wherein warm- ing was non-significant. Proportionate increase in mean monthly minimum temperatures was more than the mean monthly maximums, which bring evidence of a bit moderated winters. Statistically non-significant increase in precipitation was found (6%) during 2000s than 1970s; however, snowfall increase up to 19 percent during March was statistically significant.

 1936-1960  1961-1990  1991-2020

25

Mean Monthly

Mean Monthly Min

Mean Monthly Max

20

15

Temperature (°C)

10

5

0

-5

-10

-15



**FIGURE 5** Temporal variation in temperatures at Alliston

**TABLE 5** Change in mean monthly temperatures over time at Alliston

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Mean monthly Temperature (°C)** | **1936–60 (1940s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** |
| January | −5.87a | −6.82a | −5.83a | +0.99 |
| February | −6.14a | −7.61b | −5.79a | +1.82 |
| March | −2.48a | −2.61a | −1.66a | +0.95 |
| April | 3.24ab | 2.41b | 3.61a | +1.20 |
| May | 9.18ab | 8.74b | 9.83a | +1.09 |
| June | 14.74a | 14.66a | 15.38a | +0.72 |
| July | 19.13ab | 18.42b | 19.68a | +1.26 |
| August | 18.81ab | 18.45b | 19.36a | +0.91 |
| September | 14.73ab | 13.94b | 15.32a | +1.38 |
| October | 9.09ab | 8.66b | 9.68a | +1.02 |
| November | 3.60ab | 3.31b | 4.30a | +0.99 |
| December | −2.89ab | −2.89b | −1.52a | +1.37 |
| Annual | 6.26b | 5.72c | 6.86a | +1.14 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method

## | Central PEI

The region is represented by the weather station located at Charlottetown, which provided data from 1943 to 2020. PCIC-modeled data were used against missing 3 years. The PoE curves with the best- fit linear lines for rainfall and snowfall and average annual precipitation are shown in Figure 6 and Table 6, respectively.

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**| 11**

100

80

60

PoE (%)

40

20

 1943-1960  1961-1990  1991-2020

 1943-1960  1961-1990  1991-2020

1



00

R² = 0.9888

80

60

R² = 0.9512

40

R² = 0.9825

20

0

PoE (%)

0

R² = 0.9369

R² = 0.9748

R² = 0.9899

600 700 800 900 1000 1100 1200

Rainfall (mm)

100 150 200 250 300 350 400 450

Snowfall (cm)

**FIGURE 6** PoEs for rainfall (left) and snowfall (right) at Charlottetown

**TABLE 6** Change in annual precipitation over time at Charlottetown

**Parameter**

**1943–60**

**(1950s)**

**1961–90**

**(1970s)**

**1991–2020**

**(2000s)**

**Change**

**(1970s–2000s)**

**Change (%)**

**(1970s–2000s)**

Rainfall (mm) 838a 869a 868a −1 0

Snowfall (cm) 266b 334a 273ab −61 −19 Precipitation (mm) 1104a 1203a 1141a −62 −5

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method

It is evident from the information that precipitation has increased from1950s to 1970s. Bootsma (1994) also found significant increase in precipitation at Charlottetown from 1930 to 1980. Similarly, Zhang et al., (2000) determined that snowfall–rainfall ratio had increased during 1950–1998, particu- larly in Northern Canada. Accordingly, the results indicate that snowfall significantly increased from 1950s to 1970s while the rainfall increase during the period was minimal. However, precipitation after 1970s has been declining and particularly snowfall. The decline was however not found statistically different than that during 1961–90. In accordance, Arnold and Fenech (2017) reported 5 percent de- cline in precipitation at Charlottetown since during the last 50 years.

The monthly precipitation pattern during normal years (Figure 7, Table 7) also shows decline during 2000s except in the months August, September, and October. During those months, there is no,

**(a) (b)**

140

130

Precipitation (mm)

120

110

100

90

80

70

1943-1960  1961-1990  1991-2020

200

Precipitation (mm)

180

160

140

120

100

80

60

40

20

1943-1960  1961-1990  1991-2020

Wet Years

Dry Years

**FIGURE 7** Temporal variation in precipitation over time at Charlottetown in normal (a), dry and wet years (b), having 50, 80, and 20 percent PoEs, respectively

**TABLE 7** Change in mean monthly precipitation (mm) over time at Charlottetown

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mean monthly Precipitation (mm)** | **1943–60 (1950s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** | **Change (%) (1970s–2000s)** |
| January | 110a | 106a | 100a | −6 | −6 |
| February | 95a | 91a | 86a | −5 | −5 |
| March | 80a | 92a | 84a | −8 | −9 |
| April | 81a | 92a | 80a | −12 | −13 |
| May | 85a | 97a | 79a | −18 | −19 |
| June | 81a | 91a | 88a | −3 | −3 |
| July | 76a | 82a | 79a | −5 | −4 |
| August | 95a | 88a | 96a | +8 | +9 |
| September | 83a | 94a | 94a | 0 | 0 |
| October | 90a | 114a | 118a | +4 | +4 |
| November | 124a | 123a | 112a | −11 | −9 |
| December | 104a | 133a | 125a | −8 | −6 |
| Total | 1104a | 1203a | 1141a | −62 | −5 |

*Note:* Means that do not share a letter are significantly different at α = 0.05 (95% confidence) as per Tukey's method

or slightly increasing trend during normal years. Similar is the case for wet years, where precipitation expectancy has declined from 1970s to 2000s except those months (August, September, and October). However, during dry years, precipitation expectancy has declined all along the year.

Climatic impacts on rainfall intensity have been scanned in the form of IDF curves. Its variations over time at Charlottetown are given in Figure 8 and Table 8. It can be noted that rainfall intensities have increased over time. All the events for the latest period (2007–16) except those spanning 5 min show increased rainfall intensities ranging from 6 to 26 percent compared to its respective values during 1970s. Abbas et al., (2020) conducted flood risk analysis of Charlottetown for 1919–2018 and found a decreasing trend in number of intense precipitation events per year. It therefore indicates that the number of intense events are decreasing with a simultaneous increase in intensity. Similar trends

**(a)**

60

Rainfall Intensity (mm/hr)

50

40

30

20

10

0

1960-90  2007-16

**(b)**

90

Rainfall Intensity (mm/hr)

80

70

60

50

40

30

20

10

 1960-90  2007-16

Wet Years

Dry Years

0 2 4 6 8 10 12

Rainfall duration (hours)

0

0 2 4 6 8 10 12

Rainfall duration (hours)

**FIGURE 8** Changes in rainfall intensities over time as reflected in the 12-hr IDF curves for (a) normal

(PoE = 50%) and (b) wet (PoE = 20%) and dry (PoE = 80%) years at Charlottetown, based on hourly data acquired with copyright permission from Environment, Canada

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**| 13**

**TABLE 8** Change in rainfall intensities over time at Charlottetown at 50% PoE (2-Yr Return Period)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Rainfall Intensity (mm/hr)** | | | | |
| **Rainfall Duration** | **1960–90** | **2007–16** | **Change** | **Change Percentage** |
| 05 min | 59.8 (9.5a) | 57.4 (10.6b) | −2.4 | −4 |
| 15 min | 35.3 (5.81a) | 38.0 (6.63b) | +2.7 | +8 |
| 30 min | 24.0 (4.04a) | 26.6 (4.74b) | +2.6 | +11 |
| 01 hr | 17.1 (3.33a) | 19.2 (3.91b) | +2.1 | +12 |
| 02 hr | 12.4 (1.91a) | 14.4 (2.25b) | +2.0 | +16 |
| 06 hr | 6.1 (0.84a) | 8.2 (1.10b) | +2.1 | +34 |
| 12 hr | 3.7 (0.54a) | 4.9 (0.64b) | +1.2 | +32 |

*Note:* Values in brackets are statistical means of rainfall intensities (mm/hr). Means that do not share letters are significantly different at α = 0.05 (95 confidence) as per Tukey's method.

were found for the dry years; however, minimal change in rainfall intensities can be expected during wet years. PEI soils mostly belong to Hydrologic Soils Group (HSG) A and B, having less runoff gen- eration and more infiltration (McDougall et al., 1988; SLC, 2010); therefore, it is less likely to affect groundwater recharge during the summer's month.

The temperature analysis of the region (Figure 9, Table 9) reveals that temperatures had signifi- cantly dropped from 1940s to 1970s, in accordance with Bootsma (1994), who determined a cooling of 0.8°C during 1930–80. Since 1970s onward, annual temperature has significantly increased by 0.46°C. The maximum warming took place during the summer months of July, August, and September as well as in the early winters (December and January). On the other hand, the months of February and October showed decline in mean monthly temperature. Similarly, the mean monthly minimum and mean monthly maximum temperature also shows rising temperature trends.

 1943-1960  1961-1990  1991-2020

25

Mean Monthly Min

Mean Monthly

Mean Monthly Max

20

15

10

Temperature (°C)

5

0

-5

-10

-15

**FIGURE 9** Temporal variation in mean monthly minimum, mean monthly maximum, and mean monthly temperatures at Charlottetown

**TABLE 9** Change in mean monthly temperatures (°C) over time at Charlottetown

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Mean monthly temperature (°C)** | **1943–60 (1950s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** |
| January | −6.21a | −7.82ab | −7.20b | +0.62 |
| February | −6.67a | −7.09a | −8.04a | −0.95 |
| March | −3.03a | −3.43a | −2.88a | +0.55 |
| April | 2.81a | 2.27a | 3.09a | +0.82 |
| May | 8.64a | 8.78a | 9.14a | +0.36 |
| June | 14.06a | 14.44a | 14.57a | +0.13 |
| July | 18.66a | 18.36a | 18.99a | +0.63 |
| August | 18.06ab | 17.95b | 18.75a | +0.80 |
| September | 14.28a | 13.40a | 14.64a | +1.24 |
| October | 8.67a | 8.63a | 8.09a | −0.54 |
| November | 3.37a | 2.54a | 3.12a | +0.58 |
| December | −3.55a | −4.19a | −2.92a | +1.27 |
| Annual | 5.75a | 5.20b | 5.90a | +0.70 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95 confidence) as per Tukey's method

Comparatively, rise in mean monthly minimum temperature was greater than the mean monthly maximum ones. Zhang et al., (2000) reported more rise in minimum temperatures, particularly in southern Canada. Jiang et al., (2017) also projected maximum rise in temperatures during the winter months (January, February, and March) in Central Canada. All the months indicated rise in mean monthly temperature except February, which is getting colder instead. However, the warming trend was found significant for August only. Moderation of winters is evident from the warming found in the colder months of December and January. Overall, mean annual temperature at Charlottetown has gone up from 5.20°C to 5.90°C from 1970s to 2000s, which is statistically significant as well. Arnold and Fenech (2017) also reported an increase of 0.5°C in mean annual temperature at Charlottetown during the last 50 years and predicted to continue.

## | Western PEI

Summerside is located on western side of the PEI and weather stations installed there provided data for 1942–2020 (Table 1). PCIC modeled values were used for the missing 26 years data. The PoE curves for rainfall and snowfall and annual precipitation are given in Figure 10 and Table 10, respec- tively. It is evident from the information that precipitation in the region gone up during the 1970s but has been declining thereafter. The present (1991–2020) precipitation in the region is now 978 mm/ year, which is 8 percent decline since the 1970s. Particularly, the snowfall has significantly decreased by 20 percent. Jiang et al., (2017) predicted 25–35 percent reduction in snowfall by 2050s in Central Canada. The present precipitation in the region is even lower than what it used to be during the 1950s, that is, 1,010 mm. Considering the long-term trend, it can be concluded that precipitation, particularly snowfall has been declining in the western PEI.

Temporal distribution of the precipitation is depicted in Figure 11 and Table 11. Those indicate that precipitation has decreased in all the months except September and October in normal years. Similar was the trend for wet years; for dry years, the expected precipitation was even lesser than the

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**| 15**

 1942-1960  1961-1990  1991-2020

100

R² = 0.93

R² = 0.97

R² = 0.95

80

60

PoE (%)

40

20

0

500 600 700 800 900 1000

Rainfall (mm)

100

80

60

PoE (%)

40

20

0

1942-1960  1961-1990  1991-2020



R² = 0.98

R² = 0.95

R² = 0.97

50 100 150 200 250 300 350 400 450 500

Snowfall (cm)

**FIGURE 10** PoEs for rainfall (left) and snowfall (right) at Summerside

**TABLE 10** Change in annual precipitation over time at Summerside

**Parameter**

**1942–60**

**(1950s)**

**1961–90**

**(1970s)**

**1991–2020**

**(2000s)**

**Change**

**(1970s–2000s)**

**Change (%)**

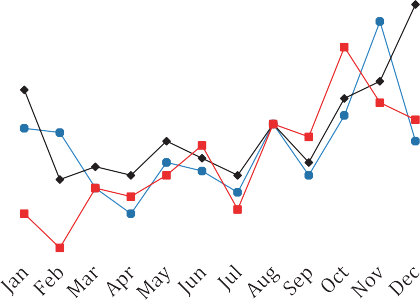
**(1970s–2000s)**

Rainfall (mm) 773a 762a 737a −25 −3 Snowfall (cm) 237b 300a 241b −59 −20 Precipitation (mm) 1010a 1062a 978a −84 −8

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method

**(a) (b)**

 1942-1960  1961-1990  1991-2020

120

|  |
| --- |
|  |
|  |
|  |
|  |
|  |
|  |

110

Precipitation (mm)

Precipitation (mm)

100

90

80

70

60

1942-1960  1961-1990  1991-2020

180

Wet Years

Dry Years

160

140

120

100

80

60

40

20



**FIGURE 11** Temporal variation in precipitation over time at Summerside in normal (a), dry and wet years (b), having 50, 80, and 20 percent PoEs, respectively

1970s dry years throughout except for the month of June. Statistically significant reduction of snowfall up to 30 percent was observed during January. Overall precipitation in the region has declined by 8 percent from 1970s to 2000s.

A perusal of the IDF curves (Figure 12) for the region shows that rainfall intensity has also increased during the recent past (2004–17). Particularly, short-duration rainfall events spanning 5–15 min shown a significant increase in rainfall intensity up to 19 percent than what it used to be during 1970s. However, all the rainfall events irrespective of the duration shown increase in rain- fall intensity. Simonovic et al. (2017) also reported Atlantic Canada with the largest potential of

**TABLE 11** Change in mean monthly precipitation over time at Summerside

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mean monthly Precipitation (mm)** | **1942–60 (1950s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** | **Change (%) (1970s–2000s)** |
| January | 94ab | 98a | 69b | −29 | −30 |
| February | 92a | 77ab | 62b | −15 | −19 |
| March | 75a | 80a | 76a | −4 | −5 |
| April | 70a | 79a | 73a | −6 | −8 |
| May | 82a | 86a | 78a | −8 | −9 |
| June | 78a | 82a | 85a | 3 | +4 |
| July | 71a | 78a | 70a | −8 | −10 |
| August | 86a | 90a | 90a | 0 | 0 |
| September | 87a | 82a | 80a | −2 | −2 |
| October | 85a | 97a | 109a | +12 | +12 |
| November | 103a | 100a | 95a | −5 | −5 |
| December | 87a | 113a | 91a | −22 | −19 |
| Total | 1010a | 1062a | 978a | −84 | −8 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95% confidence) as per Tukey's method

**(a)**

70

Rainfall Intensity (mm/hr)

60

50

40

30

20

10

1964-91  2004-17

**(b)**

105

Rainfall Intensity (mm/hr)

90

75

60

45

30

15

1964-91  2004-17

0

0 2 4 6 8 10 12

Rainfall duration (hour)

0

0 2 4 6 8 10 12

Wet Years

Dry Years

Rainfall duration (hours)

**FIGURE 12** Changes in rainfall intensities over time as reflected in the 12-hr IDF curves for (a) normal

(PoE = 50%) and (b) wet (PoE = 20%) and dry (PoE = 80%) years at Summerside, based on hourly data acquired with copyright permission from Environment, Canada

extreme events. However, considering high infiltration rates of PEI soils (McDougall et al., 1988; Qing, 2019), such increased intensities (Table 12) are less likely to affect groundwater recharge during summer.

Temperature analysis of the region as depicted in Figure 13 and Table 13 indicates that average annual temperature has significantly increased by 0.75°C since 1970s. However, it is not significantly higher what it used to be during the 1950s. The warming trend showed nearly uniform distribution throughout the year, however that in the months of August, September, and October was found to be statistically significant.

**TABLE 12** Change in rainfall intensities over time at Summerside at 50% PoE (2-Yr Return Period)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Rainfall Intensity (mm/hr)** | | | | |
| **Rainfall Duration** | **1964–91** | **2004–17** | **Change (mm/hr)** | **Change (%)** |
| 05 min | 64.5 (8.6a) | 67.6 (9.2b) | +3.1 | +5 |
| 15 min | 38.5 (5.2a) | 45.9 (5.7b) | +7.4 | +19 |
| 30 min | 27.3 (3.7a) | 30.1 (4.0a) | +2.8 | +10 |
| 60 min | 17.7 (2.6a) | 19.1 (2.7a) | +1.4 | +8 |
| 02 hr | 11.5 (1.8a) | 11.7 (1.8a) | +0.2 | +2 |
| 06 hr | 5.3 (0.9a) | 5.5 (0.9a) | +0.2 | +4 |
| 12 hr | 3.0 (0.5a) | 3.6 (0.5a) | +0.6 | +20 |

*Note:* Values in brackets are mean rainfall intensities (mm/hr). Means that do not share letters are significantly different at α = 0.05 (95 confidence) as per Tukey's method.

 1942-1960  1961-1990  1991-2020

25

Mean Monthly Min

Mean Monthly

Mean Monthly Max

20

15

Temperature (°C)

10

5

0

-5

-10

-15

**FIGURE 13** Temporal variation in mean monthly minimum, mean monthly maximum, and mean monthly temperatures at Summerside

## | Overall Perspective of Prince Edward Island

The assessed climate change impacts in PEI have been summarized in Table 14. It is evident from the table that all the minimum, mean, and maximum annual temperatures have significantly increased over the last 30 years than 1961–90. The determined temperatures and precipitations were found consistent with those reported by McDougall et al., (1988) for 1941–70. Proportionate increase in minimum temperatures at Alliston and Charlottetown is higher than the maximum values, which gives evidence that winters have warmed more, though summers’ temperatures have risen as well. Maqsood et al., (2020) also found more increase in mean daily minimum temperature (1.17°C) than mean daily temperature (0.77°C) during summers in PEI during 1989–2018. In Summerside, maximum tem- perature has increased more than minimum ones. Vasseur and Catto (2007) quantified warming of

**TABLE 13** Change in mean monthly temperatures over time at Summerside

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Mean monthly Temperature (°C)** | **1942–60 (1950s)** | **1961–90 (1970s)** | **1991–2020 (2000s)** | **Change (1970s–2000s)** |
| January | −6.92a | −7.87a | −6.96a | +0.91 |
| February | −6.32a | −7.74a | −6.73a | +1.01 |
| March | −2.66a | −3.11a | −2.57a | +0.54 |
| April | 3.06a | 2.53a | 3.17a | +0.64 |
| May | 9.43a | 9.08a | 9.59a | +0.51 |
| June | 14.61a | 14.87a | 15.06a | +0.19 |
| July | 19.16a | 18.84a | 19.42a | +0.58 |
| August | 18.54ab | 18.42b | 19.06a | +0.64 |
| September | 14.77a | 13.91b | 14.90a | +0.99 |
| October | 9.02ab | 8.37b | 9.10a | +0.73 |
| November | 3.26a | 2.66a | 3.20a | +0.54 |
| December | −3.83ab | −4.27b | −2.57a | +1.70 |
| Annual | 6.01a | 5.47b | 6.22a | +0.75 |

*Note:* Means that do not share letters are significantly different at α = 0.05 (95 confidence) as per Tukey's method.

**TABLE 14** Climate change impacts on annual precipitation and temperature in PEI (1970s–2000sa)

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Eastern PEI** | **Central PEI** | **Western PEI** |
| Rainfall (mm/year) | +56 | −1 | −25 |
| Snowfall (cm/year) | +10 | −61 | −**59** |
| Precipitation (mm/year) | +66 | −62 | −84 |
| Rainfall intensity (mm/hr)b | - | **+1.50** | +2.24 |
| Min Temperature (°C) | **+1.57** | **+0.75** | **+0.69** |
| Max Temperature (°C) | **+0.71** | **+0.69** | **+0.77** |
| Mean temperature (°C) | **+1.14** | **+0.70** | **+0.75** |

aBolded values are statistically significant at α = 0.05 (95% confidence) as per Tukey's method.; bDifference between those during 1970s and 2004–16.

Atlantic Canada including PEI to be 0.3°C and precipitation increase by 10 percent from 1948 to2005. King (2019) predicted that seasonal temperatures here would continue to nonlinearly increase during 2020–45. Khedhiri (2016) used PEI data of 1913–2013 to project mean monthly minimum and maxi- mum temperatures and predicted that temperature would continue to rise.

Precipitation has increased on the eastern side, whereas as we move westward it decreased partic- ularly snowfall, and especially in Summerside. Rainfall intensity has increased as well in the central and western parts, particularly in central PEI. Simonovic et al. (2017) projected future IDF behaviors up till 2,100 and indicated that east coast provinces including PEI have largest potential of extreme precipitation events. Findings of the study indirectly support occurrence of extreme precipitation events in PEI, with the reduction in overall precipitation and simultaneous increase in rainfall inten- sity. However, the impact on water resources in PEI by rising temperatures, reducing precipitation, and increasing rainfall intensity need further investigation.

# | CONCLUSIONS

Prince Edward Island has had undergone significant warming during the last 30 years. Average annual temperatures significantly risen throughout PEI during 1991–2020 than those in 1961–90 ranging from +0.70°C to +1.14°C. Warming occurred throughout year with a few exceptions. Nevertheless, proportionate increase in the average annual minimum temperature is relatively more (+0.69°C to +1.57°C) than the maximum (+0.69°C to +0.77°C), which would have moderated the colds. Precipitation has increased on the eastern side by 6 percent and decreased in the central (5%) to western (8%) sides, particularly snowfall has significantly reduced (20%) on the western side. Like annual precipitation, monthly precipitations mostly decreased in PEI except the month of October, wherein rainfall increased 4–12 percent in different parts. Rainfall intensity, irrespective of events’ duration has increased, in the central and western PEI. Interannual variations between dry and wet years ranged as high as 350–470 mm. It is critical to conduct further research on how reducing, un- even and intense precipitation patterns and significant rise in temperatures have had affected water balance and rainfed agriculture. Water policies should consider those climatic changes and adaptation strategies be devised accordingly. This would help sustainable management of water resources and rainfed agriculture on the island.

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