American Journal of Climate Change, 2023, 12, 700-718
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Effect of Temperature on Frost-Free Days and Length of Crop Growing Season across Southern Ontario

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How to cite this paper: Rudra, R. P., Shukla, R., Dickinson, T., Goel, P. K., & Dhiman, J. (2023). Effect of Temperature on Frost-Free Days and Length of Crop Growing Season across Southern Ontario. *American Journal of Climate Change, 12*, 700-718.
https://doi.org/10.4236/ajcc.2023.124030

Received: August 26, 2023
Accepted: December 24, 2023
Published: December 27, 2023

Abstract

Climate change has an impact on various climatic variables. In this study our focus is mainly on temperature characteristics of climate parameter. In temperate and humid regions like southern Ontario, the effect of climate change on Frost-free days in winter is distinctive. The average annual temperature is going upward but the extreme increase is in the winter temperature. Winter average temperature is going up by about 2˚C. However, extreme daily minimum temperature is going up by more than 3˚C. This climate effect has a great impact on the nature of precipitation and length of frost-free days. The snowfall over winter months is decreasing and the rainfall is increasing. However, the number of frost-free days during late fall months, early winter months, late winter months and early spring months are increasing. This result reveals an increase in length of the growing season. This research focuses on the effect of change in climatic variables on Frost-free days in Southern Ontario. Therefore, special attention should be given to the effect of change in climate Frost-free conditions on length of crop growing in winter season for potential investigation.

Keywords

Climate Change, Minimum Temperature, Frost-Free Days, Snowfall, Crop Growing Season, Southern Ontario

1. Introduction

The change in climatic parameters such as temperature, precipitation, evapotranspiration and other variables seriously affect the agriculture water management sector to increase the crop yield. In agriculture, climate change has a significant effect on plant water requirement, water quality and available moisture content in the soil. These effects were recently reported in serval reports worldwide (Bennett, 1959; Kundzewicz et al., 2007; Bates et al., 2008; Nelson et al., 2009; IPCC, 2013, 2014; Rudra et al., 2015; Neelin et al., 2017; Mapfumo et al., 2023). The agricultural sector has been noticeably affected by extreme climate events almost in every region of the world. The changing climate affects the frequency, intensity, duration of weather events, and variations in long-term trend of climatic variables. The long-term effects of climate change will include a decrease in sea ice and an increase in permafrost thawing, an increase in heat waves and heavy precipitation, and decrease in water resources in semi-arid regions. The frequency and intensity of these events are likely to be amplified in the future (IPCC, 2012; Alonso et al., 2017). At present, some observations show that there has already been an increasing trend of the various climate excesses over the past 50 years, such as an increase in the number of unusually warm days and nights at the global scale, a pole-ward shift in extra-tropical cyclones, an increase of the number of heavy precipitation events in some regions, and earlier occurrence of spring peak river flows in snowmelt and glacier-fed rivers (Rosenzweig et al., 2001; Tubiello et al., 2007; Piao et al., 2010; Schaap et al., 2011; Lobell et al., 2013; Shukla et al., 2017; Slater & Villarini, 2017; Rudra et al., 2022). The magnitudes of climate extremes, especially to agriculture which depends severely on weather event, have involved wide attention in the scientific community.

In Canada, climate data from many thousands of stations spanning all provinces and territories is freely available from environment Canada's historical weather database (ECCC, 2015; EPA, 2016). For example, international agencies, such as the Agriculture and Agri-Food Canada (AAFC) and Ministry of Environment (MOE) maintain a huge dataset from various studies (Agriculture Canada, 1977; AAFC, 2022). Data of two climate variables that are specifically important to the Canadian landscape are "Minimum Daily Temperature" (MinDT) and Frequency of "Frost-Free Days" (FFDs). The MinDT is as it sounds; it is the lowest recorded temperature on a given day. The frequency of FFDs can be defined as the number of days the MinDT exceeds zero degrees Celsius (0˚C) during winter period, or in other words the number of days when water near the surface will not freeze (Bonsal et al., 2001). MinDT and the frequency of FFD's are of particular interest to sectors that are highly dependent on the hydrologic cycle such as agriculture and local/urban watershed management, or sectors that are dependent on crop growth. When temperatures are at or below 0˚C precipitation is stored on the earth's surface as snow, and when temperatures are above 0˚C this snow storage melts. The melt-water is released and travels through various hydrological processes to surface waters, soil, and groundwater (Bonsal et al., 2001; Yagouti et al., 2008; Ahmed et al., 2014).

When the MinDT and frequency of FFD's change with the climate, the distribution of water within the hydrologic cycle will also change thus, there is the potential for previous hydrologic patterns to change dramatically (Cooter & Leduc, 1995; Calzadilla et al., 2013). Also, as the MinDT's and frequency of FFD's change, it will affect the degree of suitability for plant growth (Easterling & Apps, 2005). The following are some challenges that could be caused by changing MinDT's and frequency of FFD: 1) Changes to growing season length and position on calendar, 2) Changes to plant hardiness zones, 3) Changes to overland and stream flow magnitudes, return periods, and timing, 4) Quantity and timing of groundwater recharge and storage (Jarvis & Stuart, 2001). Although there is an abundance of research on the consequences and modeling of climate change at a global level, there is still much work to be done to translate these consequences to the regional level, which would allow for the development of practical solutions in effected sectors. A wave of research beginning in the 1980's focused on analyzing daily temperature extremes on a regional level (Karl et al., 1993; Brazdil et al., 1996; Manton et al., 2001; Klein Tank & Können, 2003; Rogers et al., 2007; Shukla & Khare, 2013; Neelin et al., 2017). This research relates to the overall yearly trends, seasonal trends analysis of climatic variable for many stations around the world using variety of different methods. Much of this research is focused on uncovering the relationships between temperature extremes and other physical parameters; as such there has been little to no focus on observing extreme temperature data alongside important temperature thresholds such as 0˚C.

In this study, the influence of changing Frost-free days and length of crop growing season were analyzed by estimating the temporal trend in winter minimum daily temperature (WMinDT) and FFDs on a monthly timescale over a 70 years period for southern Ontario Canada. The main objective of this study, 1) To examine the temporal changes in Minimum Daily Temperature (MinDT) on a monthly and seasonal timescale; 2) Assess the shift in Normal Probability Frequency Distribution Curve of WMinDT; 3) Analyze the relationship between the FFDs and extreme WMinDT across the southern Ontario, Canada respectively.

2. Study Area and Data Sources

2.1. Study Area

In this study, seven stations were selected in populated cities of southern Ontario, Canada to know the temporal daily temperature trend (**Figure 1**). These selected seven stations are 1) Sault Ste. Mari, near to Lake Huron 2) Sudbury near to Lake Nipissing, 3) Ottawa and 4) Fergus, 5) Toronto, 6) Wood stock, 7) Windsor respectively. The southern Ontario region has warm/hot summer with normal thunderstorm activities. In this region of Canada, late spring to early autumn months is affected with severe storms viz., high damaging wind, hail and tornadoes etc., existences possible in peak seasons. The Winsor to London corridor was affected by such type of weather events. London experiences approximately

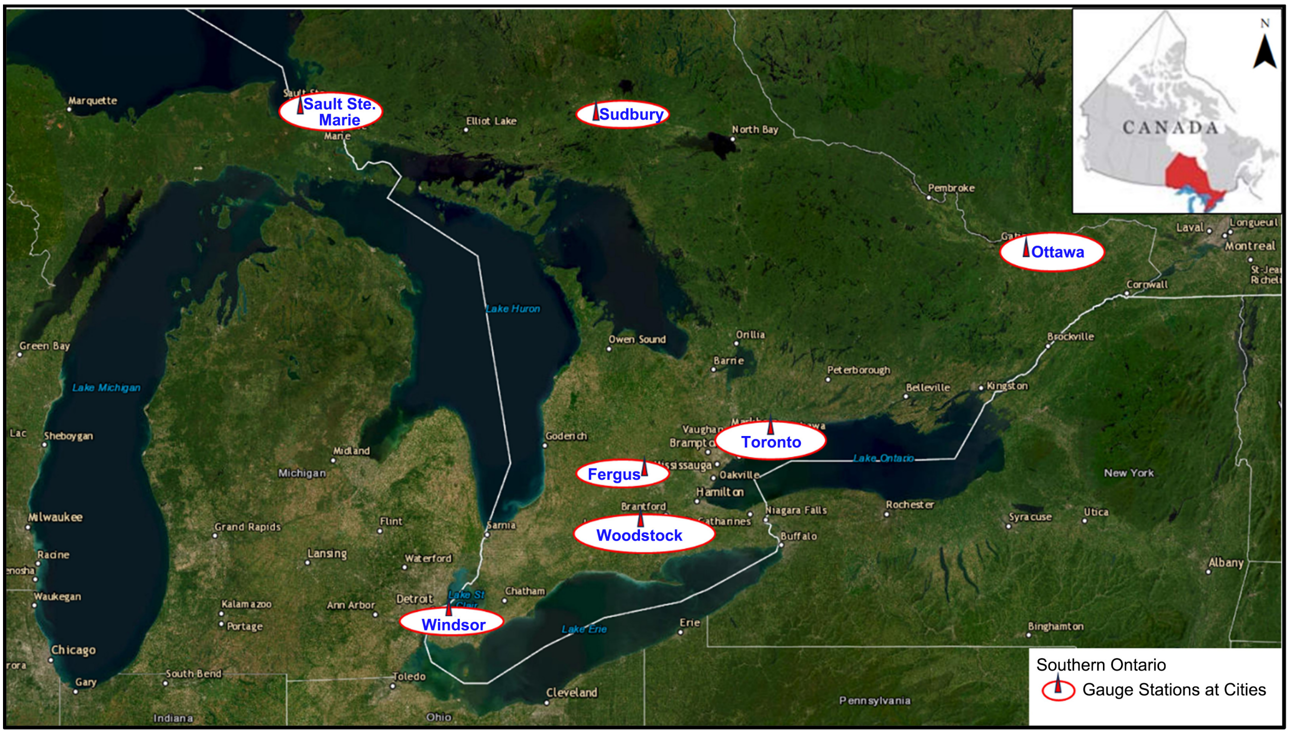

Figure 1. Location map of selected stations across Southern Ontario.

30% more snowfall than Windsor, because of its relative location to Lake Huron and the resulting snowbelt in Middlesex counties.

2.2. Data Sources and Collection

The climate variable used in this analysis is the MinDT, or in other words the lowest recorded temperature in a day. This data is available for a seven meteorological stations of Canadian southern Ontario locations on Environment Canada's National Climate Data and Information Archive. The available length of data for this study is 70 years (1940 to 2010), more than sufficient for long-term trend analysis (Qian et al., 2012; Shukla et al., 2015; Shukla et al., 2023). However, in this analysis all the winter months were included since the data was readily available. Since the data analysis were done to examine temporal trend in temperatures time series monthly scale, the data was arranged in a chronological fashion, but with each month separated from each other. For example, all days in January month, temperatures would be in one column, from 1940 to 2010 years accordingly.

3. Methodology

This section describes the methodology to analyses the linear temporal trend in Minimum Daily Temperatures (MinDT) and Frequency of Frost-Free Days (FFDs). Also, represents equations which indicate the relationship between Frost Free Days (FFDs) and Mean Winter Minimum Daily Temperature (WMinDT) accordingly.

3.1. Method Used to Analyse the Minimum Daily Temperatures (MinDT) and Frequency of Frost-Free Days (FFDs)

In this Study, once the data was arranged in an appropriate manner, the mean monthly minimum daily temperature was determined for each month for each year. For example, the mean MinDT of January 1940 was calculated, then the mean of January 1950, repeated for all months for all years. To analyze the trend in MinDT the linear trend line function was fitted to the data used. This method used to create a best-fit straight line for simple long-term data sets. This straight line generally shows the increasing or decreasing trend at a steady rate. A linear trendline equation used to calculate the least square fit for a line are:

$$y = m * x + c \tag{1}$$

where, m is the gradient or slope of the line, and c is the intercept, the y is constant, when $x = 0$.

If the day had an MinDT greater than zero, it is counted as a frost-free day, else it is not. In each month, the number of FFDs was counted using the minimum daily temperature data with the help of "COUNTIF" function in Microsoft Excel. The "COUNTIF" function counts the number of values in a range of data if the particular value fulfills the specified criteria. For example, "COUNTIF" to count the number of FFDs could look something like the following: "=COUNTIF (AI282:AI312, '>0')", where AI282:AI312 is the range of values that need to be examined and ">0" is the criteria that makes the function only count the values if they are greater than zero. Henceforth, the mean of WMinDT was calculated by arithmetic mean which is defined as:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

where, $\overline{x}$ stand for mean winter daily minimum temperature n is the number of temperature points; and x_i is each temperature value. The mean of WMinDT of each winter year was calculated by using the above formula for each selected station and then values of mean were obtained and plotted in order to observe the trends for a period of 70 years.

3.1.1. Significance Test for the Slope

Linear regression t-test is required to determine if the slope of the regression line differs significantly from zero. To apply t-test, find the slope of regression line, standard error of the slope, the degree of freedom, t-score test statistic, and p-value associated with test statistic. The general formula for a t test:

$$t = \frac{\text{Statistic-Hypothesized value}}{\text{Estimated standard error of statistic}} \tag{3}$$

where, Statistic is the sample value of the slope, and the hypothesized value is 0. The number of degrees of freedom for this test is: $df = N - 2$, where, df is degrees of freedom and N is the number of pairs of scores. The estimated standard error of slope is computed by using the following formula:

$$S_{est} = \sqrt{\frac{\left(1-r^2\right)SSY}{N-2}} \tag{4}$$

where, r^2 is the coefficient of determination, and SSY is the sum of squared of Y from the mean of Y. The p-vale is the probability that a t-test has degree of freedom. (The p-value could be determined by using the t Distribution Calculator. P < Significance level, than the slope of regression line significantly different from zero. P > Significance level, than the slope of regression line not significantly different from zero).

3.1.2. Linear Correlation Coefficient

The linear correlation coefficient is used to measure the strength and direction of a linear relationship between two variables. It is denoted by r which is a dimensionless quantity.

The mathematical formula for computing r is:

$$r = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^2}\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}} \tag{5}$$

where, n is the number of pairs of data. And the correlation coefficient takes on values ranging between +1 and −1. If x and y have a strong positive linear correlation, r is close to +1. An r value of exactly +1 indicates a perfect positive fit. Positive values indicate a relationship between x and y variables such that as values for x increase, values for y also increase. A correlation greater than 0.8 is generally described as strong, whereas a correlation less than 0.5 is generally described as weak.

3.2. Relationship between Frost Free Days (FFDs) and Mean Winter Minimum Daily Temperature (WMinDT)

The correlation between the number of FFDs per month and the mean WMinDT of that month was explored to develop a possible relationship between these two variables. The decadal averages of the number of FFDs per month were plotted verses the decadal averages of the winter minimum monthly daily temperatures, and a linear regression was calculated for each station. This analysis was repeated for selected four stations across southern Ontario, Canada. The selected stations were then placed together, with similar latitude and geographic location and these data points were placed together on a single scatter plot. The FFDs and mean WMinDT data of months were arranged in decades from 1940 to 2010 for each of the stations. A defined relationship was estimated through these data points using the non-linear regression function in Minitab and Maple software. However, the exceedance probability of the specified event is represented by the probability density function. A probability distribution is a plot of the probability density versus the data values, which in turn describes the behaviour of a random variable. The mathematical representation of this plot is called the probability density function $f(t)$. The integral of the frequency distribution of

WDMT under the curve above 0˚C represents the number of FFDs.

$$\left(\frac{\text{FFD}}{\text{No. of Data Points}}\right)=1-\int_{-\infty}^{0} f\left(t\right)\mathrm{d}t \tag{6}$$

Therefore, probability distribution function (PDF) for WDMT is represented by a number of FFDs as function of time $\{f(T_m, t)\}$; then equation will be.

$$f\left(T_m,t\right)=\frac{1}{\sqrt{2\pi}\sigma\left(t\right)}\mathrm{e}^{\left[\frac{-\{T_m-\mu(t)\}^2}{2\{\sigma(t)\}^2}\right]} \tag{7}$$

where, T_m is WDMT with respect to time (t), $\mu(t)$ is the mean of WDMT, as $f(t)$; and $\sigma(t)$ is the standard derivation of WDMT, as $f(t)$ respectively.

If $\mu(t) = A + B_t$, $\sigma(t)= C + D_t$ and by considering the number of FFDs as a function of time the derived equation would be

$$\left(\frac{\text{FFD}}{\text{No. of Data Points}}\right)=1-\int_{-\infty}^{0}\frac{1}{\sqrt{2\pi}\left(C+D_t\right)}\mathrm{e}^{-1/2\left[T_m-(A+B_t)/(C+D_t)\right]^2}\mathrm{d}T_m \tag{8}$$

Note: Detailed description of probability frequency distribution model for estimating FFD per winter. And the probability relationship between FFDs and mean of WDMT are exponential in nature explained by Rudra et al., 2022. The relationship is determined by the definition of FFD as an exceedance variable, and the assumption that the frequency distribution of WDMT is bell-shaped, akin to the normal probability distribution (Rudra et al., 2022).

4. Results and Discussion

In this study, the results of assessments are presented in the three sections: Firstly long-term temporal trend analyses were applied on monthly mean MaxDT (maximum daily temperature), MinDT (minimum daily temperature), diurnal temperature range (DTR) and in the number of Frost-Free Days (FFDs) datasets for a period of (**Figure 2** & **Figure 3**). Henceforth, linear correlation coefficient (r) was evaluated for the rate of change in the number of FFDs and rate of change in mean WminDT of selected stations (**Table 1**). In the second part, assessments of shift in Normal Probability Frequency Distribution Curve (NPFC) were taken into account to know the decadal variation in WminDT between the 1940 to 2010 years (**Figure 4**). However, in the third section the decadal relationship between number of FFDs and Mean WMinDT across southern Ontario were compared and discussed (**Figure 5**), respectively.

4.1. Long-Term Temporal Trend Analysis of Monthly Mean Minimum Daily Temperature (MinDT) for the Period of 1940 to 2010

This section examines characteristics of minimum and maximum daily temperature datasets over a period of 70 year in southern Ontario, Canada (**Figure 2**). Henceforth, the mean monthly maximum and minimum temperatures are derived from an average of the daily maximum and minimum temperatures. The

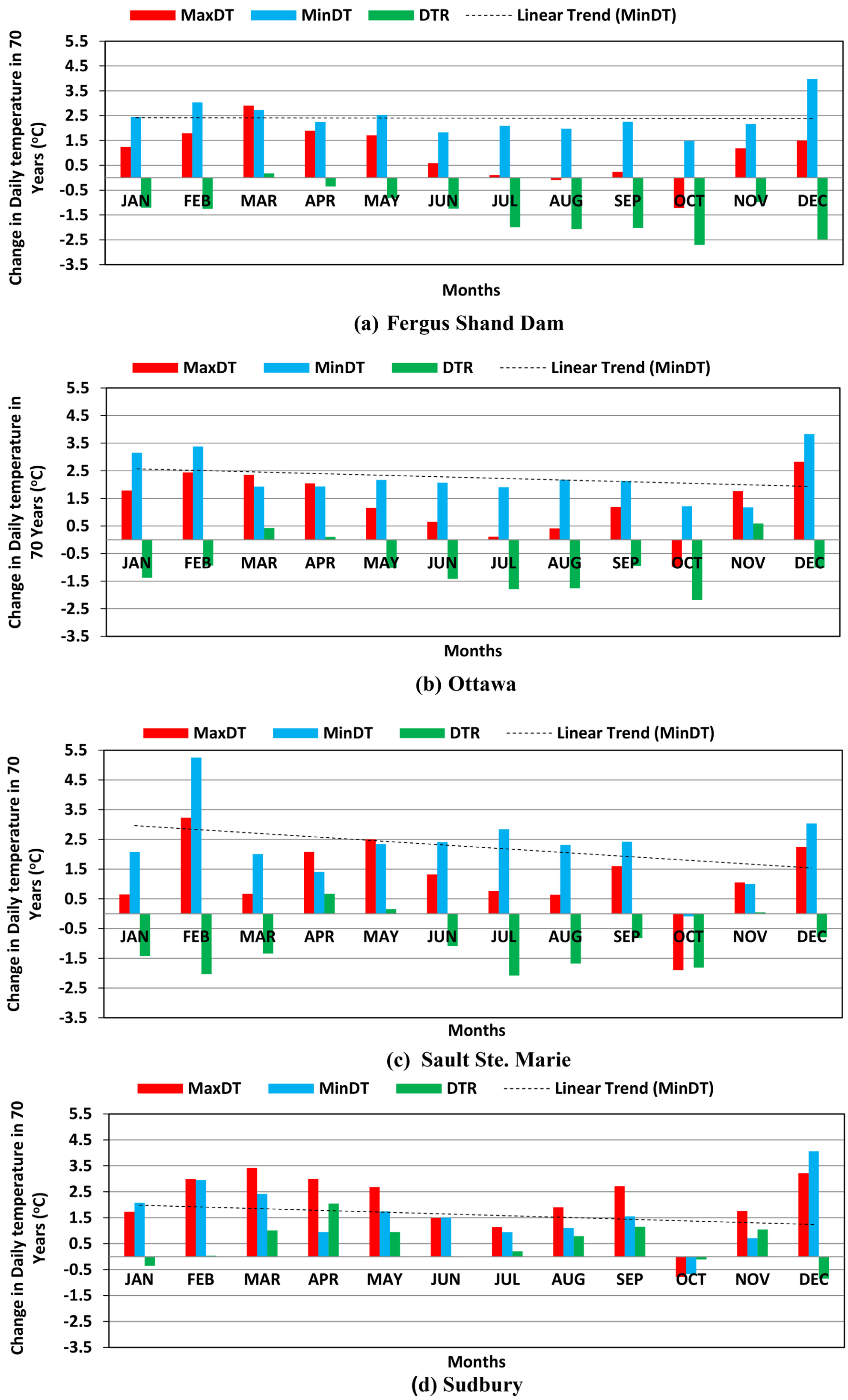

Figure 2. Long-term temporal trend of Maximum and Minimum daily temperature with their range over a period of 70 years for following stations: (a) Fergus Shand Dam, (b) Ottawa, (c) Sault Ste. Marie and (d) Sudbury, of southern Ontario Canada.

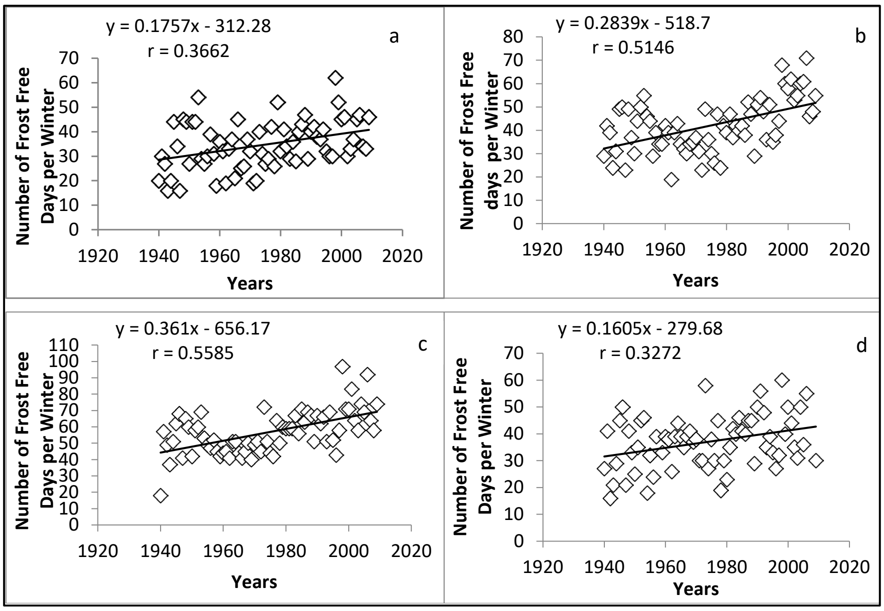

Figure 3. Time series plot for frost free days per winter of (a) Ottawa; (b) Toronto; (c) Windsor; (d) Woodstock station from 1940 to 2010, with fitted linear least square regression line.

Table 1. Trend analyses results of the Frost-Free days and WMinDT for the selected stations.

S. No	Southern Ontario Station with latitude	Frost free days: Rate of change in number of FFDs per year	Frost free days: Linear correlation coefficient (r)	WMinDT: Rate of change in mean WDMT (˚C/year)	WMinDT: Linear correlation coefficient (r)
1	Ottawa (45.38˚N)	0.18*	0.37	0.03*	0.14
2	Toronto (43.68˚N)	0.29*	0.52	0.02*	0.38
3	Woodstock (43.14˚N)	0.16*	0.33	0.02*	0.26
4	Windsor (42.28˚N)	0.36*	0.56	0.01*	0.30

*Slope is significantly different from 0 at significance level 0.1.

mean monthly diurnal temperature range (DTR) is defined as the difference between the mean monthly maximum and minimum temperatures. Hence, the comparison of maximum, minimum daily temperatures and DTR are represented in Figure 2. The data in Figure 2 show daily temperature trend over 70 years for four major stations (a) Fergus Shand Dam, (b) Ottawa, (c) Sault Ste. Marie and (d) Sudbury) across the southern Ontario. For the Fergus Shand Dam station, the mean MinDT shows an increasing trend, about an average of 2.7˚C during non-growing season (Nov to April). During the December month, the mean MinDT is increasing by 4˚C but throughout growing season (May to Oct) average value of Min DT is below 2˚C. However, for the same station, mean MaxDT shows the increasing trend for the month of March (2.8˚C) and maximum DTR is found in October month over 70 years of period.

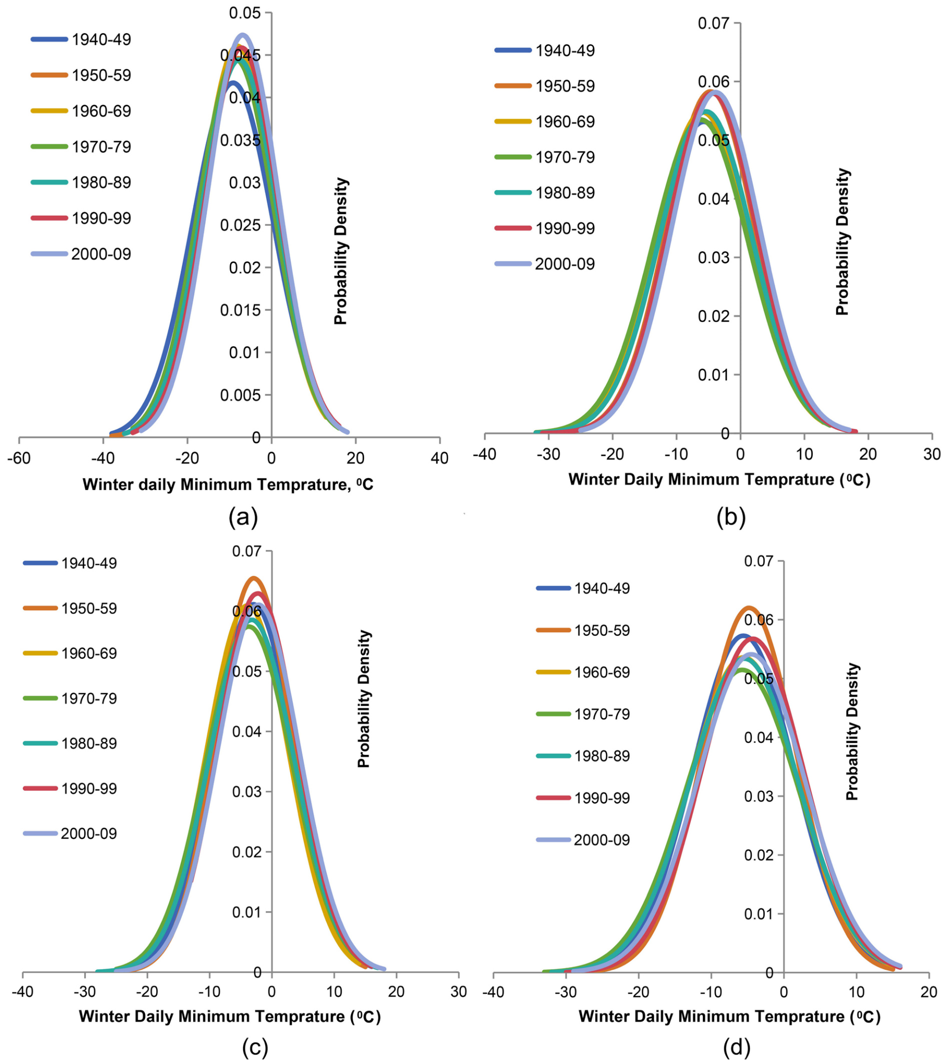

Figure 4. Normal probability distribution of WMinDT of (a) Ottawa; (b) Toronto; (c) Windsor; (d) Woodstock station for the period of 1940 to 2009.

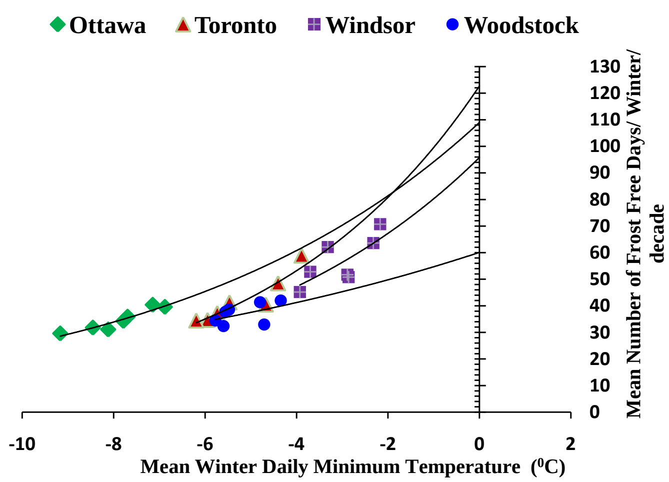

Figure 5. Linear regression between mean numbers of FFDs and mean of winter daily minimum temperature for 4 stations across Southern Ontario, Canada.

The Ottawa station (in the eastern region of Ontario) follows the increasing trend similar to Fergus Shand Dam for MinDT. The average increase in MaxDT was 1.3˚C and DTR declined by −0.94˚C for all the month. Sault Ste. Marie station (in the northern Agricultural region) also showed a significantly increasing trend during the non-growing season. The month of February showed a rise of 4.8˚C in a period of 70 years. The MaxDT and DTR at this station followed the trend similar to Fergus Shand Dam station (**Figure 2(c)**). Sudbury station also followed a similar MinDT trend in growing season as other stations in southern Ontario. An average MinDT increased by 2.1˚C during non-growing season. The MaxDT and DTR also showed an increasing trend, by about an average of 2.1˚C and 0.5˚C, respectively (**Figure 2(d)**). Moreover, the outcomes of regression assessments of the mean WminDT across southern Ontario over the period of 70 years are shown in **Table 1**. Among selected stations, for example Ottawa station shows the substantial variation in the mean WminDT over the 70 years. Further, there is a large variability in the mean WminDT across stations as affirmed by the relatively small *r* value. Therefore, the rate of change in mean WMinDT is significantly different from zero (for a 0.1 level of significance) for selected stations (**Table 1**). Across southern Ontario, the rate of change in mean WMinDT values vary from 0.01˚C /year to 0.03˚C /year (1˚C to 3˚C in 100 years), with an overall means computed to 0.02˚C/year (2˚C in 100 years) respectively evident in **Table 1**. However, the observed increase trend in WMinDT result found to be significant because other studies in southern Ontario, Canada shows the similar upward trend (Zhang et al., 2000; Vincent et al., 2015, Rudra et al., 2022). Vincent et al., (2015) revealed that the mean air temperature in southern Canada was risen by 1.6˚C between the year 1900 to 2012. In southern Canada, yearly mean air temperature during 1900-1998 increased by 0.5˚C to 1.5˚C (Zhang et al., 2000).

The trend analysis of the time series of the number of FFDs per winter for selected stations is presented in **Figure 3**. The outcome of this analysis indicates that there is substantial upward temporal trend variability in the FFDs datasets from decade to decade, for the selected stations across. During southern Ontario winter conspicuous increase was observed in the number of continuous FFDs and as revealed by the relatively linear Correlation coefficient (*r*) values (**Figure 3**). Rate of change in the number of FFDs per winter per year is significantly different from zero (for a 0.1 level of significance) and positive for all selected (**Table 1**). However, across southern Ontario the rate of change in the number of FFDs values widely range from 0.18 to 0.36 FFDs per year, accordingly. The overall mean was computed to be 0.24 FFDs/year for all the stations, the results from the linear regression analyses. Hence, it observed that the relation between rate of change of FFDs with their corresponding stations latitude were established. As the southern Ontario station latitude decreases with respect to selected location the rate of changes of FFDs per year also declining respectively. For instance, in Canada provinces at higher latitudes or elevation may be covered by snow round the year from this observation some Canadian studies derived the relationship between latitude and change in FFDs (Barnett et al., 2005; Rudra et al., 2022). Therefore, the rate of increase in the number of frost-free days is significantly correlated with latitude in southern Ontario.

4.2. Shift in Normal Probability Frequency Distribution (NPFD) Curve

In this study, the shift in the frequency distribution curve, the WDMT data per decade i.e., 1940-49 up-to 2000-2009 were plotted using Microsoft Excel program using "FREQUENCY", function shown in **Figure 4**. This Figure shows the NPFD of daily temperature per winter values for the station located at Ottawa, Toronto, Windsor, Woodstock station for the decades (1940-2009), respectively.

The Ottawa station data suggests that the mean of WMinDT value increased over time from 1940-49 to 2000-09. The value of the mean WMinDT is −9.17˚C in the decades from 1940-49 which increased to −6.88˚C in the decades from 2000-09. That is an effective increase of 2.29˚C; while the standard deviation appears to have decreased between the two periods i.e. 9.56 to 8.42. Hence, the two trends have emerged from the data of **Figure 4(a)**. In **Figure 4(a)** light blue colour trend line, the position of the minimum temperature in the most recent decades from 2000-09 has shifted upward compared to the earlier decades from 1949-49 (drak bliue line). However, these trend lines indicate that the frequency distribution of WMinDT has been increasing steadily over time as the curve's was squeezing and moving toward the right. The shapes of these frequency distributions have been changing in the most recent decades e.g. the standard deviations have been decreasing. Therefore, the results indicated that the distribution in more recent decades has shifted upwards and towards the right side, which is the hotter part of the distribution. Similarly, outcomes of other three selected stations across southern Ontario for the shift in normal probability distribution of WMinDT for the period 1949 to 2009 are shown in **Figures 4(b)-(d)**. The rate of increase in the number of FFDs is also determined by accumulating the frequency distribution of WMinDT from the positive end of the curve. Therefore, the shift towards the right observed here showed an increase in the number of FFDs per year according.

4.3. Decadal Analysis of Relationship between Mean Number of Frost-Free Days (FFDs) and Mean Winter Minimum Daily Temperature (WMinDT) across Southern Ontario

On decadal, basis average monthly number of FFDs was plotted against WMinDT to develop a possible relationship. The number of FFDs per month was put on as scatter plot with respect to x-axis time series. Hence, the "number of FFDs per month" were averaged together to give an average number of FFDs per month per decade and a linear regression was computed for each station. To develop a more accurate relationship between these variables, four stations of southern Ontario plotted together in a way of logistic curve with their respective datasets (**Figure 5**). However, this analysis indicates a very clear relationship between the exponential growth of FFDs and mean WMinDT up until 0˚C. **Figure 5** illustrates the relationship between FFDs and mean WMinDT for southern group stations (Ottawa, Toronto, Windsor and Woodstock) with a significantly rising temporal trend in FFDs at winter months of each decade for the period of 1940 to 2010 respectively. Hence, result of all the stations display that the FFD are increasing with an increase in mean WMinDT. In addition, **Table 2** represents Southern Ontario zone wise station showing the range of number of FFDs during 100 year of period.

Generally, as the latitude increases, the temperature will decrease, and the months will slide down along the logistic curve while keeping the same curve shape. The intervals for each station demonstrate the robustness of the relationships, and the fact that latitude and geographic location influence the shape of the relationship. The curve varies in different shape for selected stations. This difference is particularly visible between −10˚C and 0˚C (**Figure 5**). Therefore, overall, it was found that the increase rate of FFDs is more in Windsor area as compared to Ottawa, although Toronto and Woodstock increase rate of FFDs was similar, but slightly differ with each other.

Table 2. Station showing number of FFDs/100 years over Southern Ontario.

S. No	Southern Ontario Cities	Number of Stations	Number of FFDs per 100 years
1	Ottawa	1	18
2	Woodstock	1	16
3	Toronto	1	29
4	Windsor A	1	36

5. Discussion on Climate Change Effect on FFDs and Length of Crop Growing Season

Through this study we would like to draw attention of readers towards changing climatic conditions effecting the change in number of FFDs and significantly influence the period of growing crop. The results of this study offer a clear insight into how the number of frost-free days (FFDs) during the winter season increases exponentially as the mean minimum daily temperatures in winter steadily climb (**Figure 5**). This signifies a decrease in snowfall during the non-growing season and an increase in rainfall. These findings strongly suggest an expansion in the duration of the growing season supported by many other studies across southern Ontario, Canada (Zhang et al., 2000; Qian et al., 2010; Vincent et al., 2015; Vincent et al., 2018; Major et al., 2021). Major et al. (2021) observed that climate change has prompted a shift in the way we determine the start and end dates of the growing season in a particular cold climate region. Rather than relying on fixed calendar dates, a more accurate representation of the growing season length can be achieved by considering the dates of the last spring frost and the first fall frost, as well as the number of frost-free days (days with minimum air temperature above 0˚C). This reduces the risk of harm to early spring crops and provides a more accurate reflection of the variability within the growing season. When minimum air temperatures drop to or below −2˚C, there is a potential for plant damage, commonly referred to as a killing frost (Qian et al., 2010).

In the context of Canada's growing season, both the median frost-free period, which spans from the last spring frost to the first fall frost, and the killing frost-free period have shown an increase of about 20 days per century, equivalent to 22.4 days between 1895 and 2007. Importantly, this trend is consistent across the country (Qian et al., 2010). Over the period from 1950 to 2010, the length of the growing season in Canada expanded by 1.7 days per decade (Natural Resources Canada, 2020). Between 1951 and 1980, most of the southern regions of Canadian provinces exhibited growing seasons ranging from 101 to 120 days. Similar northward extensions of the growing season were also observed in Ontario during the same time periods (Natural Resources Canada, 2020). The length of the growing season, defined as the duration between the last day with a temperature of 0˚C in spring and the first day with a temperature of 0˚C in fall, signifies the period of plant photosynthetic activity (Natural Resources Canada, 2020, 2021). This extension of the growing season is attributable to rising air temperatures, resulting in more days for plant growth and maturity. Each crop has specific temperature requirements, including maximum and minimum thresholds, as well as an optimal temperature range for achieving the highest growth rates (Qian et al., 2010; Hatfield et al., 2011). Cool-season crops such as spring wheat, barley, canola, oats, and rye, require lower air temperatures for growth compared to warm-season crops like corn, soybean, and sweet potatoes (Qian et al., 2010; An & Carew, 2015; Mapfumo et al., 2023).

In the southern region of Ontario, Canada, Vincent et al., (2018) conducted a study and discovered that the average growing season length, spanning from March to November, increased by 15 days. This extension was characterized by an earlier start by 6 days and a later end by 9 days between 1948 and 2016. A similar 15-day increase was observed in southern Canada exclusively, spanning from 1900 to 2016, as reported by Vincent et al., 2018. However, a somewhat smaller increase of 3 to 12 days in the Canadian region between 1920 and 2020 was noted in a study by Major et al., 2021. This discrepancy may be due to the inclusion of areas at higher latitudes in the latter regions compared to southern Canada. Moreover, a study reported a 20 day extension to the frost-free period for the later part of 1948-2016 across Canada, while a larger increase of 25 days was evident in southern Canada for 1900-2016. The number of frost days (number of days with minimum air temperature ≤ 0˚C) had decreased by 15 and 22.9 days for all of Canada and southern Canada (i.e., south of latitude 60˚N), respectively Reduced cold season length is a result of increasing winter air temperatures in Canada (Vincent et al., 2018; Mapfumo et al., 2023).

Conclusions akin to these findings were previously drawn in a study by Qian et al. (2010), which utilized data from 147 stations across Canada for the period between 1895 and 2007. The study highlighted that the growing season exhibited the most significant increase for overwintering crops, extending by 10.4 days per century (with a range of −1.4 to 23 days), followed by warm-season crops with an extension of 8.2 days (range of −5.3 to 16.7 days), and cool-season crops with a growth extension of 6.1 days (range of 0 to 15.2 days). These findings were based on a criterion of 5 consecutive days with temperatures above the minimum required for the onset of the growing season. The observation of a longer growing season for warm-season crops compared to cool-season crops was unexpected, especially considering that most climate changes have been reported during the cold season (Vincent et al., 2015; Jiang et al., 2017; Major et al., 2021; Mapfumo et al., 2023). The study by Qian et al. (2010) also revealed that the growing season started earlier by 6.4 days per century for overwintering and cool-season crops, and 5.6 days per century for warm-season crops. The end of the growing season was later by 2.4 days for warm-season crops, 2.6 days per century for overwintering crops, and no significant change was observed in the growing season for cool-season crops (Qian et al., 2010). As a result, these findings indicate a lengthened frost-free period, which extends the growing season. This expansion offers the potential for introducing new crop varieties and increases cropping opportunities, particularly for winter cereals (Larsen et al., 2018).

6. Conclusion

In this study, the temporal trend changes are observed in mean winter Minimum daily temperature and the number of Frost-free days (FFDs) across Southern Ontario Canada over the selected 70-year period. In southern Ontario the seven stations were selected to evaluate the trend in the mean Minimum daily temperature time series. However, it is observed that an average Minimum daily temperature is significantly increased during non-growing season for all selected stations. The mean Minimum daily temperature of selected stations: 1) Fergus Shand Dam, 2) Ottawa, 3) Sault Ste. Marie and 4) Sudbury are found to be increased about 2.7˚C, 2.5˚C, 2.4˚C and 2.1˚C during the period of 1940-2010 respectively. Therefore, it is also observed that the values of extreme daily minimum temperature are increasing by more than 3˚C throughout southern part of Ontario. Moreover, to know the FFDs estimation, in this study the relationship was developed between FFDs and mean winter Minimum daily temperature by selecting the four stations (Ottawa, Toronto, Windsor and Woodstock) across southern Ontario. This relationship confirms that FFDs throughout southern Ontario significantly increasing with an increase in mean WMinDT with high confidence level during the period of 70 years respectively. Hence, results clarify that number of FFDs per winter have increased exponentially when mean winter minimum daily temperatures rise progressively. Therefore, it means that the snowfall over non-growing season is decreasing, and the rainfall is increasing. This observation results indicate a rise in extent of the growing season. Also, this outcome affects the parameter of hydrological cycle in southern Ontario, especially in relations with agricultural water management. Finally, future research needs to focus on gaining a more detailed understanding of extreme events of climate change and its impacts, both natural and social response mechanisms, and adaptation measures of agricultural production management.

Acknowledgements

The authors are thankful to the University of Guelph (UG), Ontario, Canada for providing financial support during the study period.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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