

An Investigation of the Effects of Climate Change on Maple Sugaring

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1. Abstract

The maple sugaring industry is especially prominent in Northeastern US, and there are increasing concerns regarding the effects of climate change on this important cultural and commercial activity. This study uses temperature data gathered from St. Johnsbury, Vermont (44.42°N, 72.0194° W; elevation: 213.4 m) between 1897 and 2025 as a sample station to investigate trends and variability in temperatures between January 1st and May 31st that directly affects the outcome of sugaring seasons. This builds on previous studies to examine how the maple sugaring industry has already been impacted by climate change, using a purely temperature-based approach. Sugaring days were defined as days with diurnal minimum temperatures $\leq 0^{\circ}\text{C}$ and maximum temperatures $\geq 2^{\circ}\text{C}$, and a Gantt chart was created to visualize consecutive days which met these criteria during past sugaring seasons. At St. Johnsbury, the median day of the sugaring season has shifted 7 days earlier in the season, from about March 26th to March 19th, across the full 128-year period, while the number of sugaring days remained consistent at around 55 days per year. A similar, though slightly larger trend was found in the median day of 3 or more consecutive sugaring days, which shifted 8.5 days earlier across the period of record. However, no significant trends were found in the overall variability in the number of sugaring days per season. Additionally, an analysis of average diurnal temperature range (DTR) in St. Johnsbury was conducted to investigate whether the amplitude of diurnal

freeze/thaw cycles is changing. The analysis showed an overall decrease of -0.5°C in average DTR throughout the dataset.

2. Introduction/Background

Maple sugaring is a significant cultural and commercial activity in North America, accounting for a 2024 estimated production value of around \$200 million USD in the United States (US Department of Agriculture, National Agricultural Statistics Service [NASS], 2025) and around \$600 million USD in Canada (Agriculture and Agri-Food Canada, 2025). Most of this production takes place in the Northeastern United States and Southeastern Canada, with Quebec accounting for approximately 90% of maple syrup production in Canada, and Vermont accounting for just over 50% of maple syrup production in the United States (NASS, 2025).

Trends in global temperatures have been extensively researched both in a historical and future context. Many studies have empirically determined that temperatures are increasing both globally and regionally in the Northeast (Guilbert et al., 2014, Burakowski et al., 2022, Donat et al., 2013, Karmalkar and Bradley 2017, Wuebbles et al., 2016). This change in the climate has been found to differ between seasons, with the cold season warming faster than the warm season in the Northeast (Burakowski et al., 2022, Donat et al., 2013, Karmalkar and Bradley 2017). Furthermore, previous studies have investigated differential increases between daily minimum and maximum temperatures. Studies have generally found steeper increases in minimum temperatures than maximum temperatures globally and in the Northeast US (Vose et al., 2005, Donat et al., 2013, Young and Young, 2025). This difference in trend between minimum and maximum temperatures is an indication of a long-term decrease in diurnal temperature range (DTR). Additional studies have specifically investigated DTR with one study on global DTR finding a decreasing rate in global DTR of around $-0.036^{\circ}\text{C}/\text{decade}$ from 1901 to 2014 (Sun et

al. 2019). Because daily temperatures above and below freezing are the primary driver for sugar maple sap flow, these decreasing trends in DTR may have direct long-term impacts on the maple sugaring industry.

Many studies have investigated the effects of climate change on the Northeast's maple sugaring season both historically and in future projections. The sugar maple (*Acer saccharum*) is an environmentally sensitive tree species with a limited range in North America, mainly constrained to the Eastern US and Canada (Putnam and Reich, 2017). For the sugar maple to produce sap that can be collected and processed to create maple syrup, the trees must experience a diurnal temperature cycle which oscillates above and below the freezing mark (Milburn and O'Malley, 1984). This makes the late winter to early spring season the most ideal time period to collect sap, as this is when diurnal temperature cycles enable sap flow, and the sugar content of the sap peaks. A positive relationship has been found between maple sugaring yields and the number of diurnal freeze/thaw cycles in the spring. (Houle and Duchesne, 2014, Kurokawa et al., 2022). Exact diurnal minimum and maximum temperatures that allow for sugar maple sap production have not been determined and have been found to vary among individual trees depending on several physical and environmental factors (Zarrinderakht et al., 2024, Duchesne and Houle, 2014, Rademacher et al. 2024). Despite these complications, Rapp et al. 2019 used combined temperature and sap flow data to empirically determine optimal sugaring day temperature thresholds. According to this study, sugaring days were defined by minimum temperatures equal to or below 1.5°C and maximum temperatures equal to or above 1°C based on sap flow using gravity-based collection methods. According to the results from that study, sap was collected on 46.7% of days that met the defined temperature threshold (Rapp et al., 2019).

By relating average temperatures over sugaring seasons to season start and end dates, consistent trends have been found showing that the tapping seasons have been shifting earlier in the year (Perkins, 2018), and modeling suggests this trend will continue in the future (Rapp et al., 2019, Duchesne et al., 2009, Houle et al., 2015, Filteau, 2025). Additionally, previous studies have projected a northward shift of the ideal latitudes for maple sugaring in the future, with sap yields expected to decrease in the southern range and increase in the northern range of the sugar maple (Rapp et al., 2019, Houle and Duchesne, 2014). This northward shift has been projected to be as far as 400km, from 43° N to 48° N by 2100 (Rapp et al., 2019).

Survey-based studies have investigated the level of concern and planned response to climate change among maple syrup producers in the Northeast. Many producers have reported noticing changes in the sugaring season start and end dates through the years. In one survey of 33 maple syrup producers, 55% of respondents had noticed an earlier shift in the start of the sugaring season over time while 64% of respondents reported noticing an earlier shift in the end of the sugaring season. 73% of the producers in the survey reported that they believed year-to-year variability of the start of the sugaring season was increasing over time (Murphy et al., 2012). Other studies have found that producers view temperature as one of the most impactful environmental factors on maple sap quality (Ahmed et al., 2023). Producers are increasingly concerned about the effects of climate change on their production as temperatures increase, with many producers willing to make changes to their operations in response (Kuehn et al., 2017, Legault et al., 2019). However, the broad trend in maple sap yield cannot be directly correlated to changes in temperature, as improvements in sap collection techniques and technologies have made a large impact on sap yield during a sugaring season. For instance, the use of a vacuum tubing system for sap collection instead of gravity-based collection has been found to increase

sugaring season sap yield by around 95% (Dyola et al., 2026). Furthermore, improved sanitation practices among producers have been shown to elevate sap yield as well (Houle and Duchesne, 2014, Perkins et al., 2019). These changes in practices may help producers adapt to and mitigate the effects of climate change, even if changes in temperatures adversely impact sap production.

The goal of this research is to examine the effects of climate change, specifically increasing temperature, on the maple sugaring season. Many forward-looking studies have modeled how maple syrup production will be impacted by future climate changes, with less of an emphasis on how the sugaring season has already changed historically. This study used a purely temperature-based approach without reference to the method of collection or physical characteristics of trees, to examine how the temperatures during the sugaring season have changed in an area with a high concentration of maple syrup producers. This approach could then be used to examine the consistency and variability of sugaring seasons over time. Another objective of this study was to develop methods to elucidate characteristics of the maple sugaring season at a single station, which could then be expanded to other stations with long periods of record in the surrounding area.

3. Data and Methodology

St. Johnsbury, Vermont was selected as the temperature station used in this study for its location within a high-volume area for maple syrup production and its consistent and long record of temperature data. Historical temperature records were found and accessed through the Global Historical Climatology Network (GHCN; Menne et al., 2012). Only the daily minimum and maximum temperature data were collected from the site for this study. The station is located at 44.42°N, 72.0194° W, and an elevation of 213.4 m (700ft). The St. Johnsbury station has a temperature record of around 132 years, from Mar. 1st, 1894, to the present, though only up to

Dec. 31st, 2025, was used in this study. Missing data for the month of May in 1896 led to a temporal range of 1897-2025 used for this study to ensure each year contained a complete dataset for each sugaring season, defined as Jan. 1st through May 31st of each year.

Daily minimum and maximum temperature thresholds were necessary to define a sugaring day for temperature analysis. For this study, a sugaring day was defined as a day with a maximum temperature $\geq 2^{\circ}\text{C}$ and a minimum temperature $\leq 0^{\circ}\text{C}$ based on expert opinion (T. Rademacher, personal communication, March 30, 2026). This was a more stringent temperature threshold than the one proposed by Rapp et al. 2019, ensuring a higher probability that each day in the dataset is one on which sap could be collected from trees. These values do not consider the thermal inertia of the trees and are based upon the assumption that the temperature threshold for sugaring would remain consistent throughout the season. It is also important to note that this temperature threshold does not account for differences between vacuum and gravity collection techniques, which may differ in their required temperatures for sap collection.

Using the defined minimum and maximum temperature threshold of a sugaring day, a filtered dataset was developed of only those days meeting the sugaring day temperature criteria. This dataset was also filtered to only include days in the months of January through May, which is the rough extent of the maple sugaring season in the Northeast. All data was processed, and figures developed using Python version 3.13.11.

4. Results

The dataset was first analyzed to determine the frequency of sugaring days in each sugaring season from 1897-2025. A linear regression trendline was fit to the data to analyze any trends throughout the dataset. Over the full 128-year period, no significant trend (0.0437 days/decade;

$r^2 = 0.0004$; $p < 0.82$) was found in the number of sugaring days each season, with high variability about the trend (Fig. 1a). An additional analysis of the variability of the data was performed by investigating the 15-year rolling standard deviation of the full dataset. This analysis also showed no significant trend in the variability of sugaring days throughout the dataset (0.0566 days/decade, $p < 0.223$) (Fig. 1b). A notable outlier can be found near the beginning of the dataset in 1901, which moderately skews the first 5 years on the 15-year rolling standard deviation analysis.

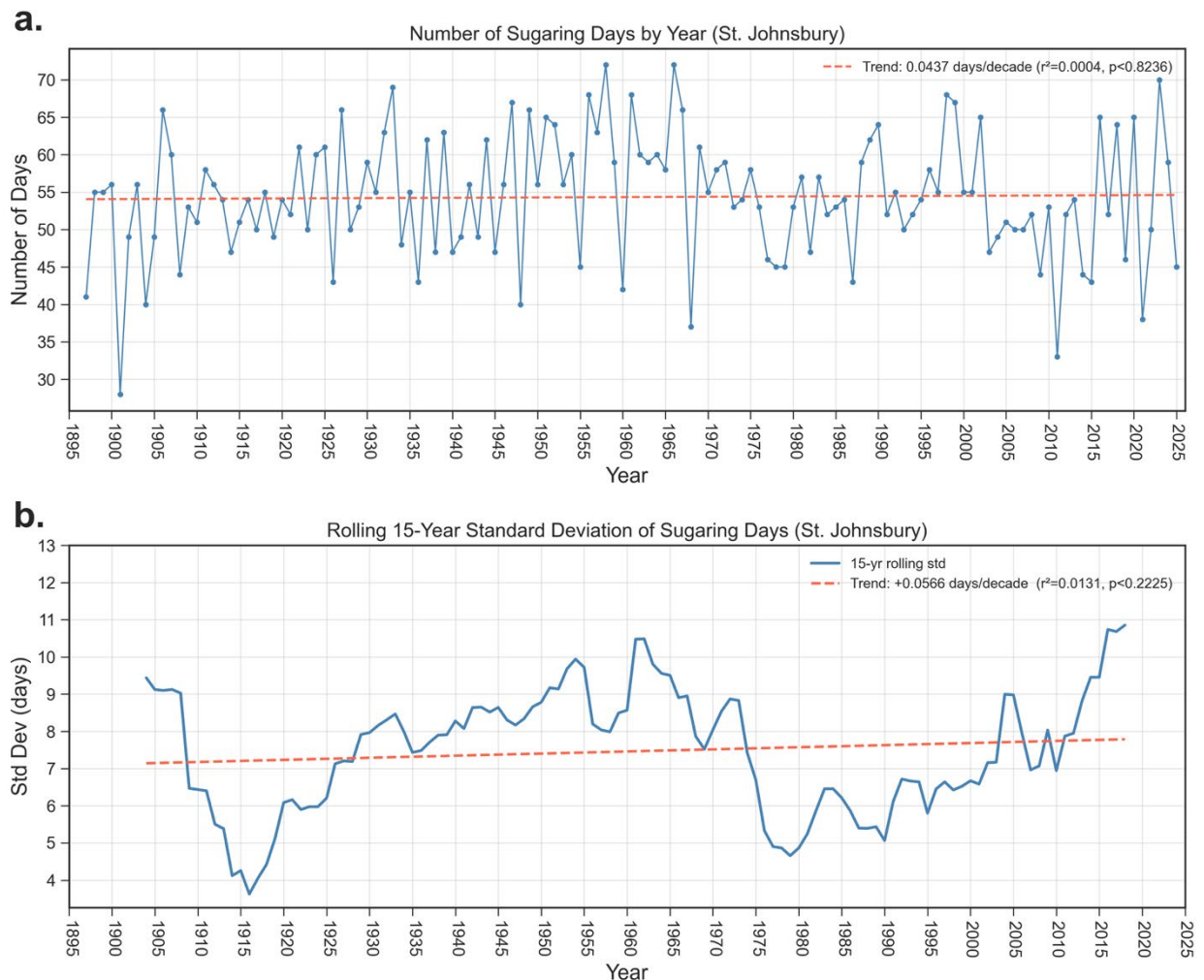


Fig. 1: Time series graphs with trendlines displaying the number of sugaring days, defined as days with maxima $\geq 2^\circ\text{C}$ and minima $\leq 0^\circ\text{C}$, in each sugaring season (top panel, a)

and the rolling 15-year centered standard deviation (e.g. first point at 1904 refers to the standard deviation of sugaring days between 1897 and 1911) of sugaring days per season (lower panel, **b**).

Although the number of sugaring days in a season can have a major impact on sap yield, the timing of the maple sugaring season is also important to producers. To analyze any trends in the timing of the season, the median day of year of all sugaring days in each season was determined and plotted (Fig. 2). The median day of year of the sugaring season was found to be significantly decreasing (-0.542 days/decade, $p < 0.0018$), although with high year-to-year variability. This indicates the median day of sugaring days shifted earlier by about 7 days across the full 128-year period from about March 26th to March 19th.

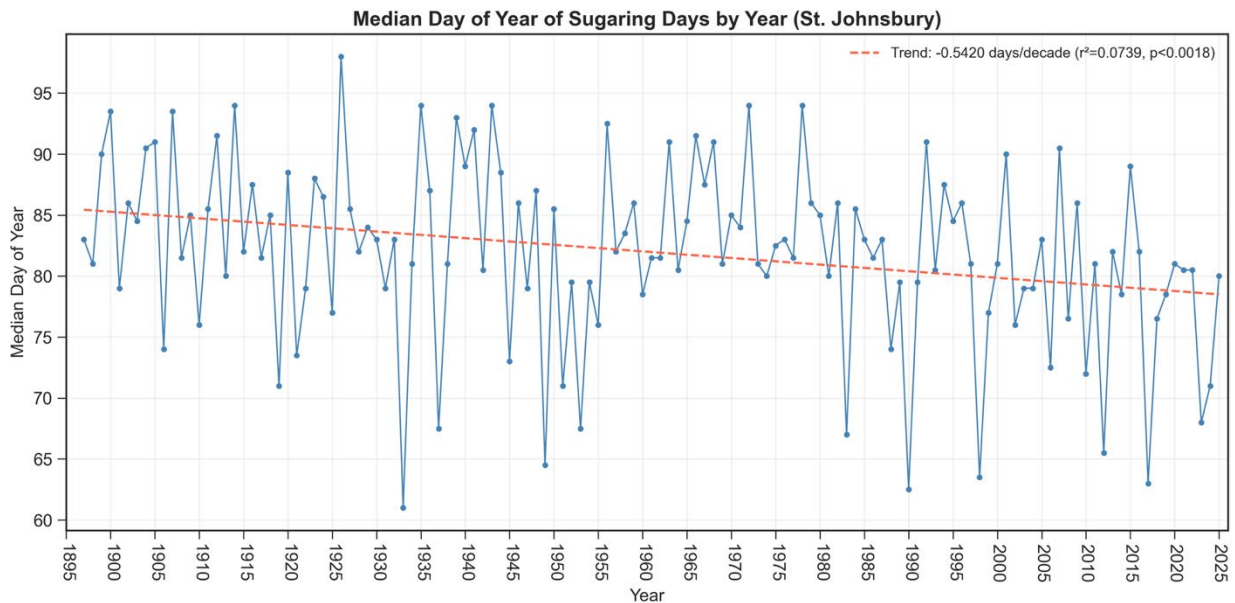


Fig. 2: Time series graph with a linear regression trendline displaying the median day of year of sugaring days in each season.

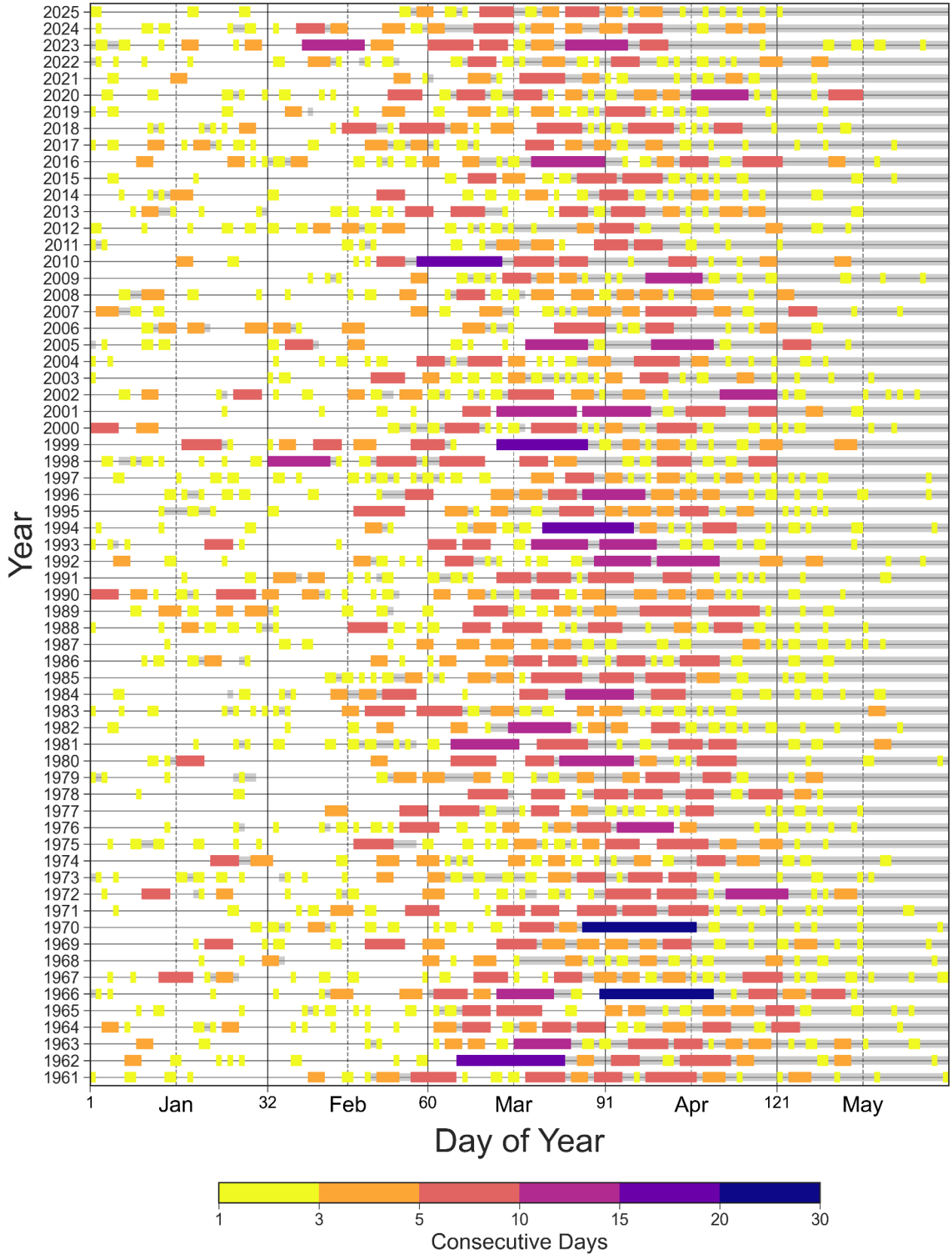
In addition to the number of sugaring days per season, another analysis was performed to investigate the grouping of sugaring days within each season. A Gantt chart was created to

visualize the sugaring season in each year based on the defined temperature thresholds (Fig. 3).

Sugaring “run” categories were created based on the number of consecutive sugaring days.

Additionally, days in which both the minimum and maximum temperatures were above freezing were plotted on the Gantt chart to visualize the days where thaws occurred, which can negatively impact sap flow on subsequent sugaring days.

a. Consecutive Sugaring Days by Year (St. Johnsbury)



b. Consecutive Sugaring Days by Year (St. Johnsbury)

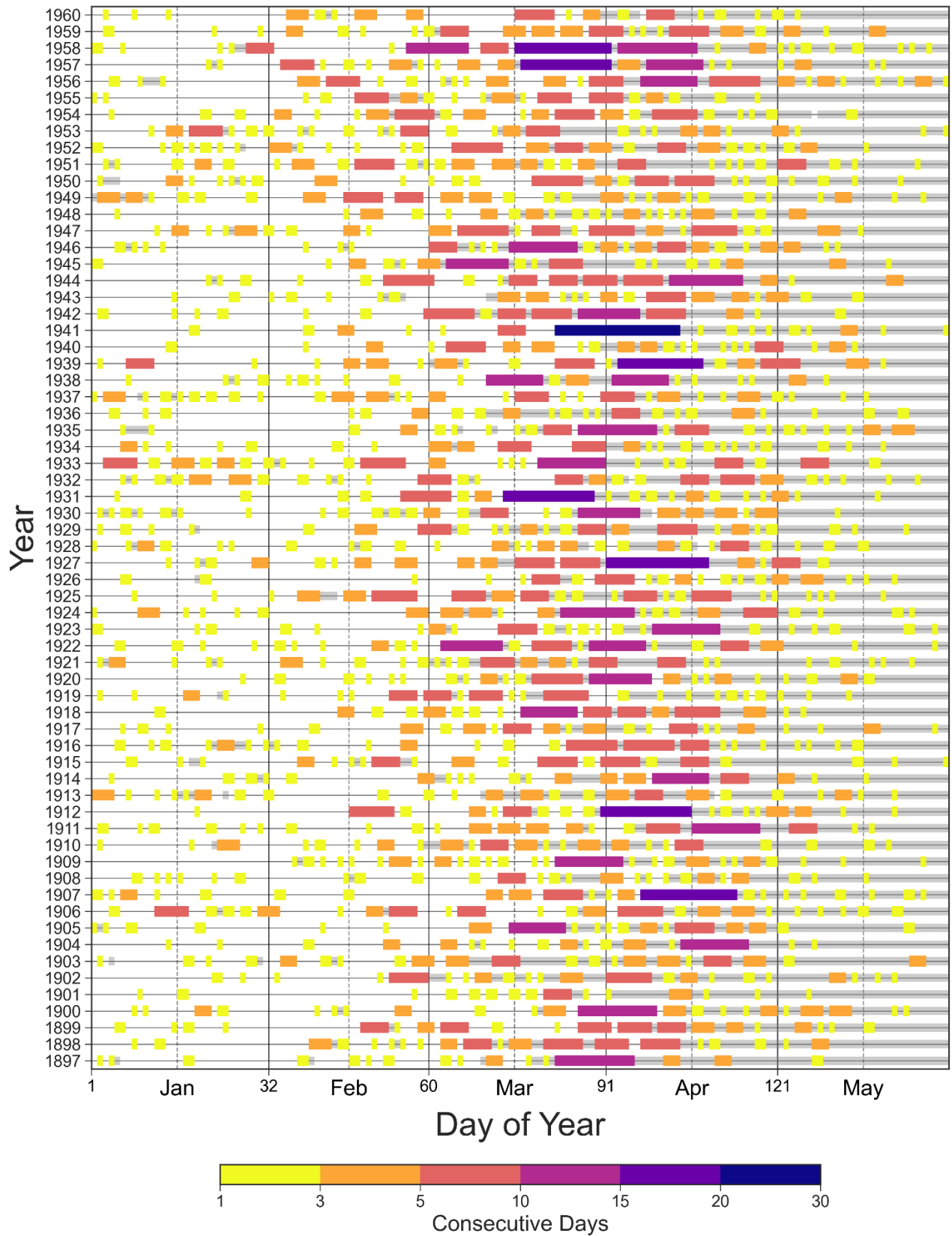


Fig. 3: Gantt charts showing all sugaring days in each sugaring season from 1897-2025. Consecutive runs are color-coded by length and x-axis month labels indicate the midpoint of the respective month, while the numbers refer to the day of year of the first of the month (e.g. day of year 60 corresponds to March 1st). Gray bars indicate days when both minimum and maximum temperatures were greater than 0°C. The chart is split between the 1961-2025 (Fig. 3a) and the 1897-1960 (Fig. 3b) time periods for readability.

Using the data from the Gantt chart, further analysis on sugaring runs could be performed.

An investigation into the timing of these runs was performed by finding the starting day of year for every run that consisted of 3 or more consecutive sugaring days. This allows for a greater focus on the middle of the sugaring season rather than early or late-season outliers. A linear trendline indicated that the median starting day of these runs had significantly decreased by 0.66 days/decade ($r^2 = 0.053$, $p < 0.0087$) (Fig. 4). The overall trend was marked by relatively high year-to-year variance, and a variable sample size, with each season containing between 2 and 12 runs. This overall decrease was slightly greater than the decrease seen in the median day of all sugaring days in each season and equates to a shift of around 8.5 days earlier across the full 128-year period.

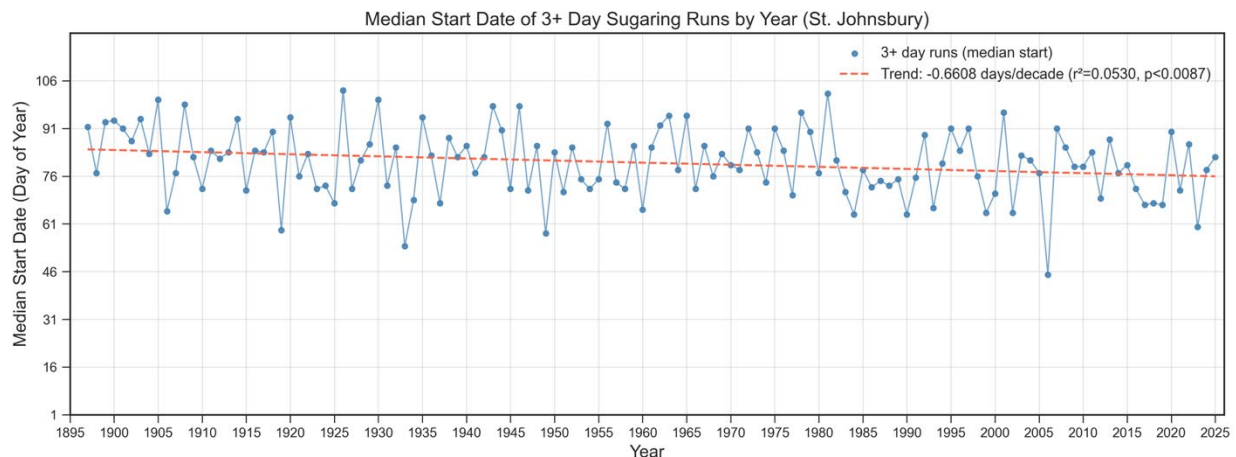


Fig. 4: Time series graph with linear regression trendline showing the median start date of 3+ day sugaring runs in each sugaring season by year.

The frequency of 3-plus day runs was also plotted and fitted with a linear regression trendline. This revealed a slight, though insignificant increase in the frequency of runs over time with a slope of 0.0519 3+ day runs per decade ($p < 0.219$). This equates to a total average increase of around 0.66 runs for the full period (Fig. 5).

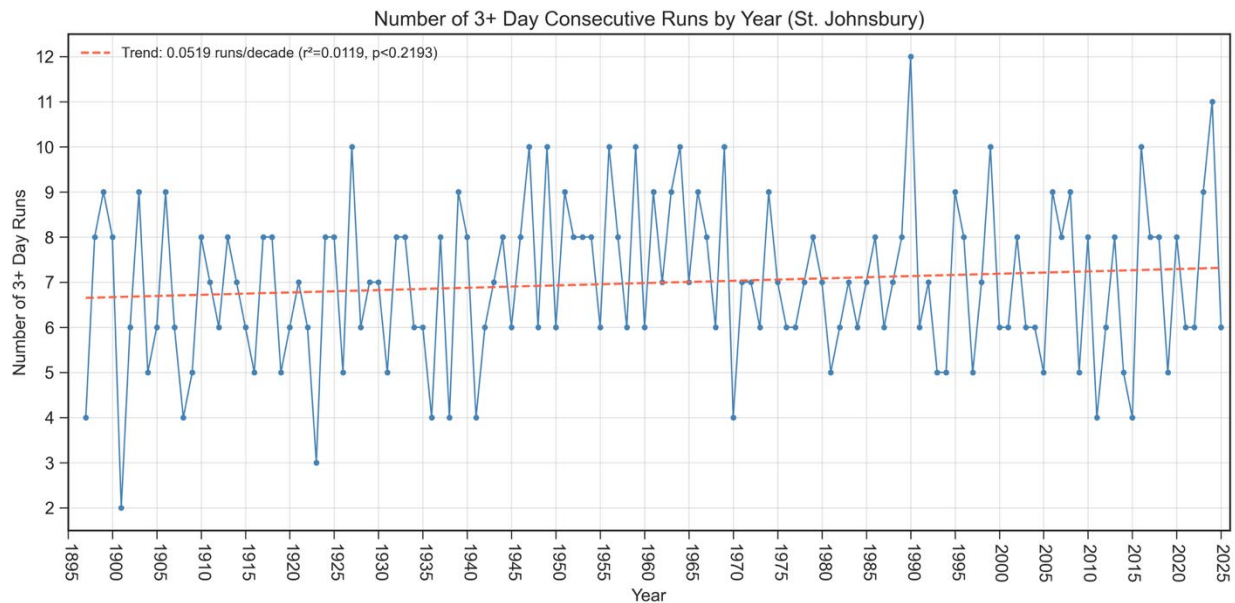


Fig. 5: Time series graph with linear regression trendline showing the number of 3+ day sugaring runs in each sugaring season by year.

Maple sugaring seasons are dependent on diurnal freeze/thaw cycles, and days with large diurnal temperature ranges (DTR) that encompass the freezing mark will often have higher sap yields. An analysis of the average DTR for all days in each sugaring season over the full period was conducted. A statistically significant but slight decrease in DTR ($-0.0394^{\circ}\text{C}/\text{decade}$; $p < 0.0452$) was seen throughout the full period. This negative slope equates to a total average decrease in DTR of -0.5°C across the full period.

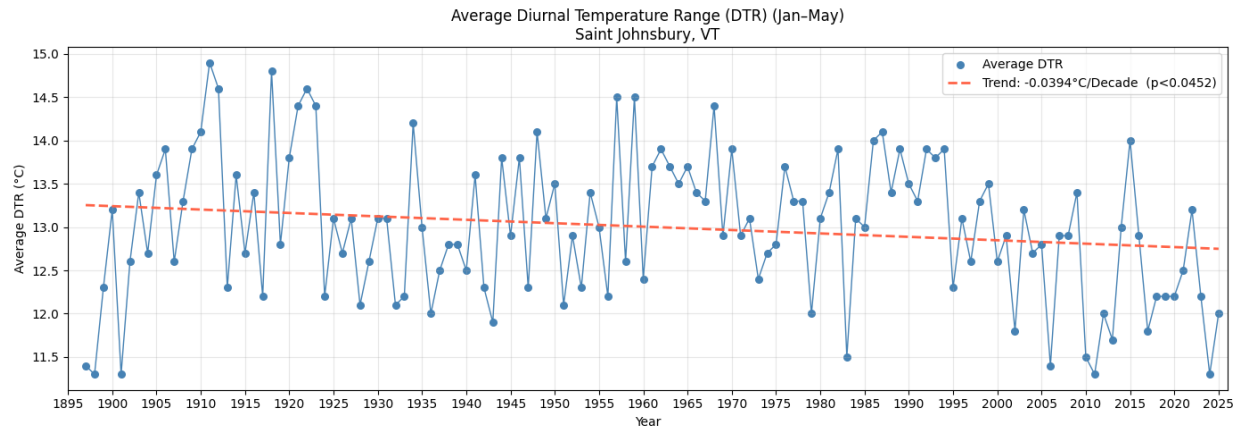


Fig. 6: Time series graph with linear regression trendline showing the average diurnal temperature range (DTR) for each sugaring season by year.

5. Discussion

This study analyzed the effects of a changing climate on the maple sugaring season from a purely temperature-based standpoint. These results at the individual station level provide support for previous research at larger scales regarding climatological trends during maple sugaring season.

Both the overall number of sugaring days within a season and their variability over a 15-year interval were not found to have any significant trend. This result suggests that while the median day of the sugaring season has been shifting earlier in the year, the number of sugaring days in each season has remained constant. A slight increase can still be seen in the variability in the number of sugaring days per sugaring season, and one notable outlier (1901) near the beginning of the dataset may be having an outside influence on the overall trend. However, this analysis only included one station and one method of analyzing variability. This finding would likely need to be compared with other stations in the region for the trends noted to be placed in their proper context.

Analyzing the median day of year of sugaring days for each season reveals a clear trend that is consistent with findings in previous studies. Previous studies have typically used producer surveys to analyze trends in sugaring season start dates based on the day on which producers would collect sap or boil for the first time of the season. This method has returned consistent results of an earlier shift in the sugaring season over time. National Agricultural Statistics Service (NASS) survey results between 1963-2012 revealed that the start of the sugaring season had shifted 8.3 days earlier in Vermont (Perkins, 2018). The St. Johnsbury record noted a similar, earlier shift in the sugaring season, though it was much less pronounced than the NASS survey results. St. Johnsbury showed an average shift of about 7 days from 1897-2025. This provides purely temperature-based support for the earlier season shift observed through alternative methods, though the elevated rate of the shift shown by the NASS survey results may also have been accelerated by changes in collection methods and/or techniques such as transitioning from gravity-based collection to vacuum collection over this time period.

The Gantt chart created in this study provides an excellent visualization of the maple sugaring season. The chart highlights the seasonal pattern of sugaring days throughout the full dataset and allows for a historical analysis of individual sugaring seasons based on the distribution of sugaring days within a given season. The chart displays the most optimal times for sugaring in and around St. Johnsbury, Vermont, with January and May showing limited consecutive sugaring days for each year, representing the outer bounds of the sugaring season. A slight progression of days earlier in the season can be seen in the Gantt chart, in line with the median sugaring day analyses that were done. The peak number of sugaring days each season generally fell between March and April. However, the visualization of thaw days (denoted by smaller gray bars), defined by temperatures above freezing for the full 24-hour period, reveals

the days where sugaring may be less viable, with April containing more frequent thaw days between runs. This visualization of thaw days also reveals which seasons may have underperformed in the past due to earlier thaws. For example, the Gantt chart for St. Johnsbury in 2012 shows a long stretch of thaw days in March, which indicates that season likely resulted in lower sap production.

With the resulting dataset of sugaring runs derived from the Gantt chart, the median day shift in the start date of the 3+ day runs (0.66 days/decade) was comparable, though a bit greater than the shift in the as median sugaring day per season (0.54 days/decade). Additionally, the number of 3+ day runs was found to be relatively stationary. This presents a question of whether sugaring days may be becoming more clustered over time.

The average diurnal temperature range (DTR) was determined for each sugaring season and investigated for trends in the dataset. Although the amplitude of DTR is not necessarily directly impactful on sugaring, changes in average DTR can reveal long-term changes in sugaring seasons. Results in this study from the St. Johnsbury station align with other findings regarding global DTR change. One study reported an average global DTR change of $-0.036^{\circ}\text{C}/\text{decade}$ over the 1901–2014 period (Sun et al., 2019), while the St. Johnsbury record showed an average DTR decrease of $-0.036^{\circ}\text{C}/\text{decade}$ from 1897-2025. This decrease is a function of differential increases between minimum and maximum temperatures in the Northeast which has been reported by previous studies (Vose et al., 2005, Donat et al., 2013, Young and Young, 2025).

6. Future Work

Temperature data for this study was taken from St. Johnsbury, Vermont as a single, but representative location for individual station analysis. However, the use of only a single station

for this analysis comes with drawbacks and elevates the potential for trends in the data to be spurious. This could produce results that are not consistent with other stations, possibly masking true areawide trends. Therefore, expanding this study to include other stations for comparison is a crucial next step to verify trends found in this study or reveal differences between stations and regions where maple sugaring is prevalent. Additionally, this study used a purely temperature-based approach to maple sugaring and was not compared with sap production data from any producers in the vicinity of St. Johnsbury. Future work could gather data from one or more local maple syrup producers to compare the actual tapping days of producers to the temperature-based sugaring days outlined by the thresholds used in this study and elucidate the importance of consecutive sugaring days. This could provide valuable insight into the validity of the temperature threshold analysis, adding another dimension to the study that might inform changes to the temperature threshold to better represent reality.

Furthermore, many syrup producers extract sap from trees on differing terrain, and a relatively low solar zenith during the sugaring season likely results in a greater difference in conditions between north-facing and south-facing slopes during this time of the year than during other seasons. The additional solar insolation on south-facing slopes on a clear day may result in higher temperatures compared to north-facing slopes and a difference in sap flow across varying terrain. This variation must be considered when relating temperatures from a nearby station, such as St. Johnsbury, to any sap flow data collected from a nearby producer.

The creation of the Gantt chart in this study results in a dataset of consecutive sugaring days within each season. This dataset then presents the opportunity to analyze the clustering of sugaring days in future work. Throughout the dataset used in this study, a very slight, albeit statistically insignificant increasing trend was revealed in the 3+ day runs. If additional

temperature stations are included to increase the sample size, this may or may not reveal a tendency of sugaring days to cluster into consecutive days more often with earlier and potentially more concentrated sugaring seasons. Furthermore, the overall decrease in median day of year for the 3+ day runs was slightly greater than the decrease seen in the median day of all sugaring days in each season. Further testing could validate whether there is a statistical significance between the two slopes.

A fundamental assumption of this study is the definition of a sugaring day based on a constant maximum and minimum temperature threshold. This assumption ignores the thermal inertia of the maple trees throughout the season, during which the ideal temperatures for sugaring may change. For example, early season sugaring days may require stronger thaws with maximum temperatures further above freezing as the trees would be coming out of a more significant freezing period. The reverse may be true for the late season sugaring days, during which a lower minimum temperature may be required to induce sap flow. Future work could examine this potential shift in sugaring day criteria throughout the sugaring season, incorporating a more dynamic and realistic approach to the definition of ideal sugaring days.

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