

Warming Degrees and Flowering Trees*

Understanding Temperature's Role in Earlier Cherry Blossom Blooming Times in
Kyoto, Japan

Luca Carnegie

Chris Lu

Russell Luchin

Randall Ni

Abstract

This is the abstract of your paper. Write a brief summary of your research, including your objectives, methods, key results, and main conclusions. Keep it concise but informative.

Table of contents

1	Introduction	2
2	Literature Review	2
3	Data	3
4	Modeling	9
4.1	Model Specification	9
4.2	Results	9
5	Discussion	9
5.1	Implications of Findings	9
5.2	Ecological Implications	9
5.3	Cultural Implications	9
5.4	Limitations	9
5.5	Future Research Directions	10
5.6	Conclusion	10
6	References	10
	Appendix	10

*Code and workflow available at: <https://github.com/lcarnegie/sakura>

1 Introduction

Before the advent of modern technology, people understood themselves, their environments, and their cultures through the cycle of life and death. The Japanese tradition of *hanami* (loosely translated as ‘flower-viewing’) is an important cultural tradition that honors this perspective, being associated with the flowering birth of cherry blossom trees in the late spring. In the city of Kyoto in particular, local newspapers have recorded the dates of tree flowering since the late 19th century, but researchers like Aono and Saito (2010) have been able to corroborate flowering dates as far back as the year 812 CE, through the examination of historical records such as diaries, poetry and other written documents describing *hanami* parties throughout the ages. However, rising global temperatures have created anomalous climate conditions in recent years. This highlights a need to understand the historical and modern links between temperature and cherry blossom bloom timing. Without it, cherished traditions like *hanami* may struggle to adapt to climate shifts, risking their disappearance as unique customs.

Work such as Allen et al. (2014) analyzes cherry blossom blooming data over a relatively brief 29-year timespan. However, this narrow temporal window represents only a fraction of the documented flowering history, limiting their model’s ability to capture the relationship between blossoms and the significant climate shifts of the past 150 years - shifts that are clearly visible in Aono and Saito (2010)’s more comprehensive dataset.

We also seek to answer the question of whether warmer temperatures lead to earlier blooming times. To achieve this, we instead analyse and model the nearly 1200-year record compiled by Aono and Saito (2010) in tandem with modern data compiled by the Japanese Meteorological Agency (JMA), collected and compiled together by Cookson (2020). Section 2 does a broad review of existing work surrounding cherry blossoms, their significance, and efforts to understand their behaviour related to climate. Section 3 covers the data sources, methodology, and conducts an exploratory analysis of the dataset. Section 4 proposes a model of cherry blossom flowering day as a function of mean March temperature in Kyoto and lists its results. Section 5 critically examines the data and results, comes to several conclusions about the dataset, and proposes new areas of exploration. This analysis highlights the consequential effects for wildlife that function around the timing of blooming *sakura*, the need for flexibility in planning *hanami* celebrations going forward, as well as the need for wider ranging data to inform more precise predictions of blooming days.

2 Literature Review

The relationship between sakura blooming date and other factors was first examined in depth. A notable amount of scholarship addresses the relationship between different variables and the flowering dates of sakura, from humanistic cultural studies perspectives ranging to scientific plant biology, phenological modeling, and climatology studies.

Acevedo (2021) provides a rich cultural context for understanding cherry blossom phenology in Kyoto. Her research highlights a 1200-year flowering record of *Prunus jamasakura* in Kyoto, describing it as “the longest and most complete phenological record in existence.” These records, compiled from imperial court documents, poetry, and newspaper accounts of *hanami* celebrations, reveal that Kyoto’s cherry trees have responded to major climate fluctuations throughout history, with progressive advancement in bloom dates occurring after approximately 1830. This shift aligns with the end of the Little Ice Age and the onset of modern warming trends. Beyond scientific significance, Acevedo explores how sakura in Kyoto have traditionally served as indicators of agricultural prosperity, with early-falling petals considered inauspicious for rice harvests, demonstrating their enduring role as both cultural and climatic storytellers in Japanese society.

According to Aono and Kazui (2008), cherry trees in Kyoto are currently experiencing warmer conditions than at any time in the past twelve centuries, resulting in average flowering dates that are seven days earlier in the 1971-2000 period compared to historical averages.

Next, Xu et al.’s research provides significant physiological evidence supporting the temperature-flowering relationship in cherry trees (Xu et al. 2023). Their study not only documented how temperature fluctuations caused 2-3 day shifts in flowering periods between 2016-2017, but also established varying cold tolerance rankings among cherry varieties that influence bloom timing. The authors revealed the underlying hormonal mechanisms—specifically changes in ABA, ZR, IAA, and GA3 levels—that regulate flower bud differentiation in response to temperature changes. This work strengthens our understanding of how temperature directly affects cherry blossom phenology through specific physiological pathways, offering valuable context for examining historical sakura flowering records in Kyoto and predicting how future climate patterns might alter traditional bloom timing.

Allen et al. (2014), “Modeling daily flowering probabilities” offers an approach to rigorous quantitative predictions about cherry blossom phenology under climate change in Japan. They analyzed four cherry taxa (*Prunus spachiana*, *P. × yedoensis*, *P. jamasakura*, and *P. lannesiana*) using flexible Bayesian survival regression models applied to a 29-year dataset from Tama Forest Cherry Preservation Garden in Hachioji. Their approach incorporated both chilling requirements and heat accumulation mechanisms, finding that early-flowering species like *P. spachiana* were particularly sensitive to warming temperatures. The models predicted that all studied cherry taxa will flower approximately 30 days earlier by 2100 under the A1B emissions scenario, with 2-6 days greater uncertainty around mean flowering dates. Allen et al. found that sequential models (where trees require chilling before responding to warming) better predicted flowering times than simpler approaches. The study demonstrates that while cherry trees will continue to meet their chilling requirements under projected climate scenarios, accelerated heat accumulation will drive the dramatic advancement in flowering times.

3 Data

To investigate the relationship between mean March temperature and blooming date in Kyoto, historical data on cherry blossom blooming dates (Aono and Saito 2010), as well as data collected through modern measurement techniques (Agency 2025a) (Agency 2025b) were analyzed. Cookson (2020) provided both datasets assembled in a single repository, though the modern data sources were last updated in 2020.

All of the data was transformed in Python (Foundation 2025), using the **pandas** (T. pandas development team 2025) and **numpy** (T. N. development team 2025) packages. For this analysis, the average (mean) march temperature, bloom date, day of year of blooming and year were made of interest.

In the historical data, Aono and Saito (2010) reconstructs the mean march temperature in Kyoto for some of the years, based on the blooming date, but also provided observed temperatures taken from local newspapers for a given year when possible. We prioritized used observed temperatures, but if none were available, then the reconstructed one was used. This created a dataset of 827 observations, from the year 812-2015. A sample of the table can be seen in Table 1.

Table 1: Historical Cherry Blossom Blooming

	Year	Bloom Date	Day of Year	March Temp (°C)
0	812	0812-04-01	92	9.9
1	815	0815-04-15	105	6.0
2	831	0831-04-06	96	8.6

Table 1: Historical Cherry Blossom Blooming

	Year	Bloom Date	Day of Year	March Temp (°C)
3	851	0851-04-18	108	5.2
4	853	0853-04-14	104	6.3

With the modern data, Cookson (2020) combined average monthly temperatures and blooming date in a single dataset for several cities across Japan. We filtered this data to solely Kyoto, and solely average march temperatures to match the historical data from Aono and Saito (2010). This created a dataset with 67 observations ranging from 1953 to 2015. A sample can be seen in Table 2.

Table 2: Modern Cherry Blossom Blooming

	Year	Bloom Date	Day of Year	March Temp (°C)
0	1953	1953-04-05	95	-0.9
1	1954	1954-03-29	88	-2.5
2	1955	1955-03-28	87	-1.3
3	1956	1956-04-01	92	-2.0
4	1957	1957-04-07	97	-2.9

In our data exploration, the `matplotlib` (Hunter 2007) and `seaborn` (Waskom 2021) packages were used to visualize and explore the data. The historical dataset was visualized and explored first.

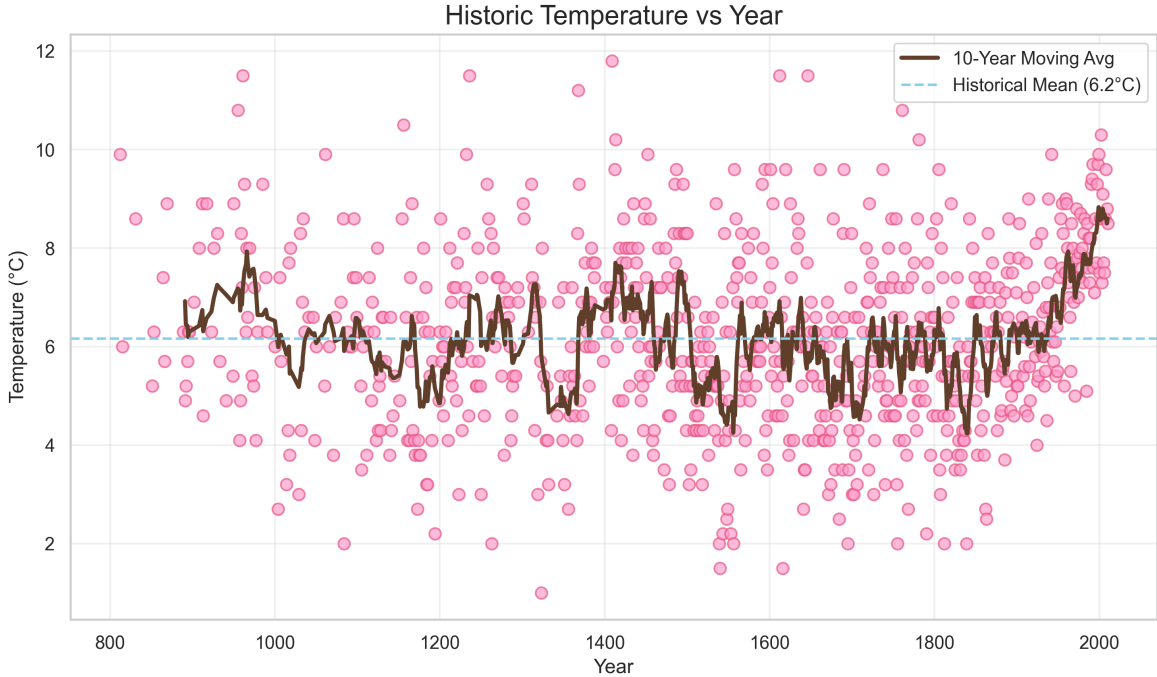


Figure 1

Figure 1 displays historical annual temperature records (in °C) from the year 800 CE to 2000 CE. Each pink dot represents the recorded temperature for a given year, while the solid teal line represents

a 10-year moving average, smoothing out year-to-year fluctuations to highlight longer-term trends. The dashed horizontal line represents the historical mean temperature of 6.2°C. Notably, the data show considerable fluctuations over the centuries, with a relatively stable pattern through much of the pre-industrial era. However, a sharp and continuous rise in average temperature is observed beginning in the late 19th to early 20th century, suggesting significant warming recently. This trend aligns with broader patterns of climate change and may have implications for phenological events such as the timing of sakura (cherry blossom) flowering.

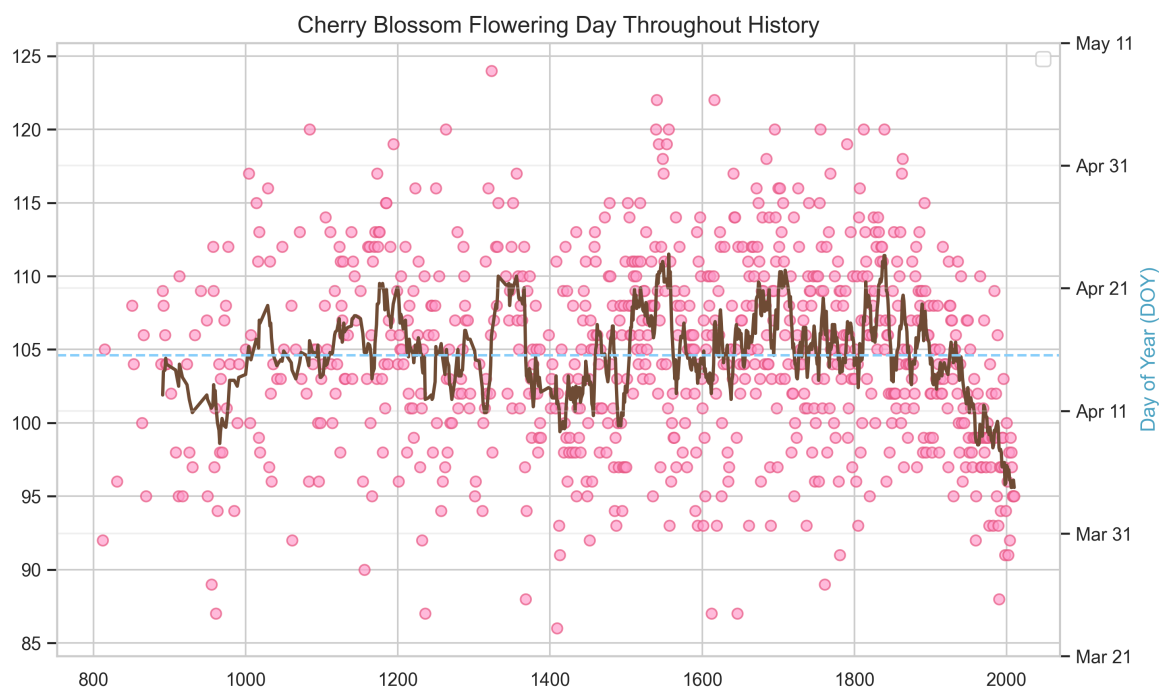


Figure 2

Figure 2 showcases the annual full flowering dates of sakura from 800 to 2000 CE, plotted as day-of-year (DOY) values, where higher values indicate later blooming in the calendar year. Each pink dot corresponds to an individual year's observed full bloom date, and the solid brown line shows a 10-year moving average; the dashed horizontal line indicates the historical mean, which is 104.6. The data suggest that while flowering dates have fluctuated across centuries, a notable trend toward earlier blooming began in the late 19th and 20th centuries. This shift coincides with the period of modern climate warming seen in the corresponding temperature graph, suggesting that rising spring temperatures are advancing sakura bloom time.

Figure 3 showcases the cherry blossom flowering date distribution by century (9th to 21st), measured in day-of-year (DOY). The dashed pink line represents the average flowering day of the year (~105 days). It was quite consistent until the 20th century (1900s), where we can see a large drop; this trend has also been carried into the 21st century, where it dropped further.

A common thread emerges across all of the plots - warmer temperatures as time goes on has led to cherry blossoms blooming earlier and earlier every year. Furthermore, the significant shifting blooming days relative to temperature point to this historical data being ineffective in understanding the present relationship between temperature and blooming day. Since blooming days and temperatures have shifted so much in the last 150 years, examining more modern data is more effective in uncovering current trends. Given this, another more current dataset from Cookson (2020) was examined next.

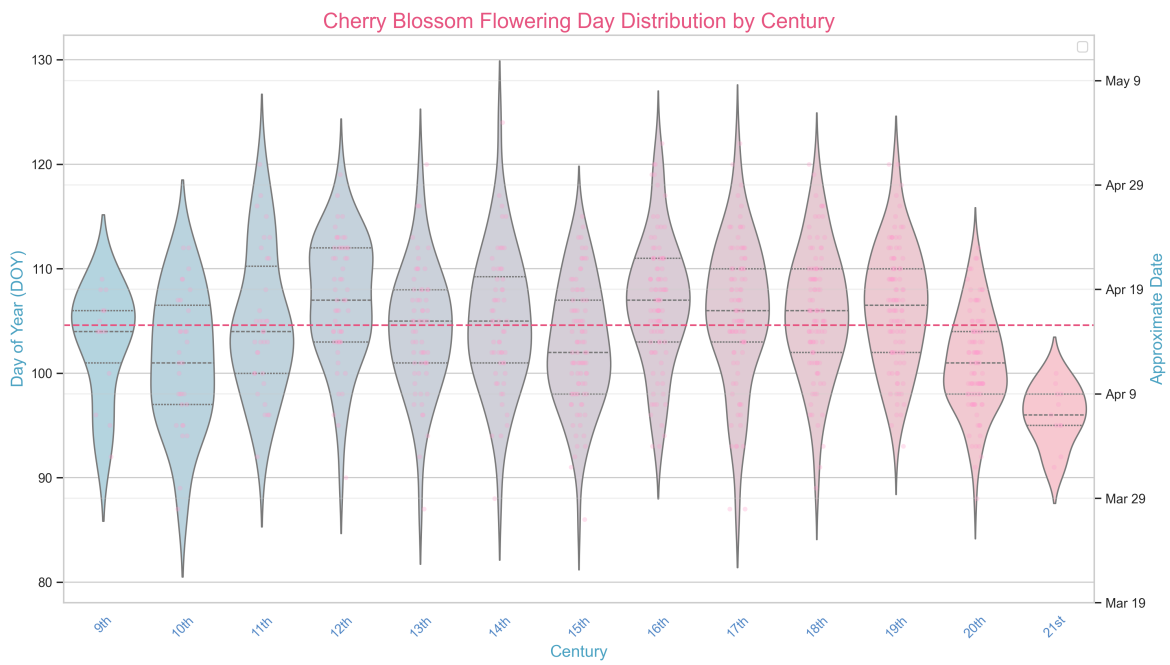


Figure 3

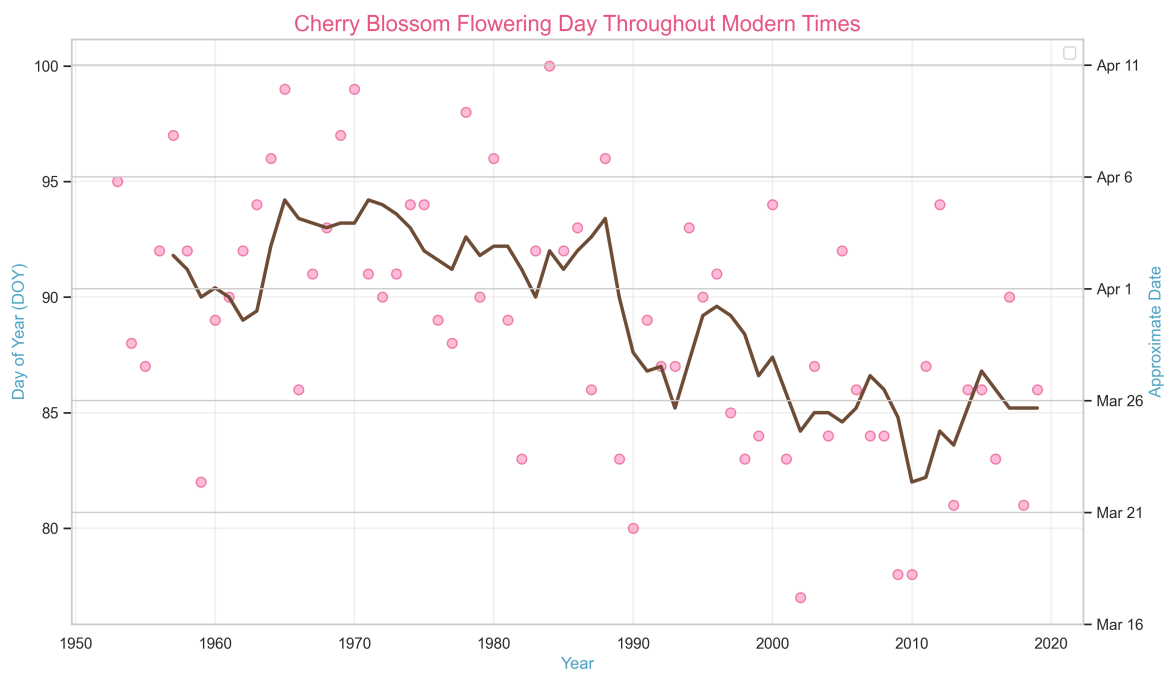


Figure 4

Figure 4 above presents the annual full flowering dates of cherry blossoms in Japan from 1950 to 2020, measured in day-of-year (DOY), where higher values represent later blooming. Each pink dot marks the full flowering day for a given year, while the solid blue line shows a 5-year moving average, smoothing short-term fluctuations to reveal broader temporal trends. Over the 70-year span, there is a clear downward trend, indicating progressively earlier flowering.

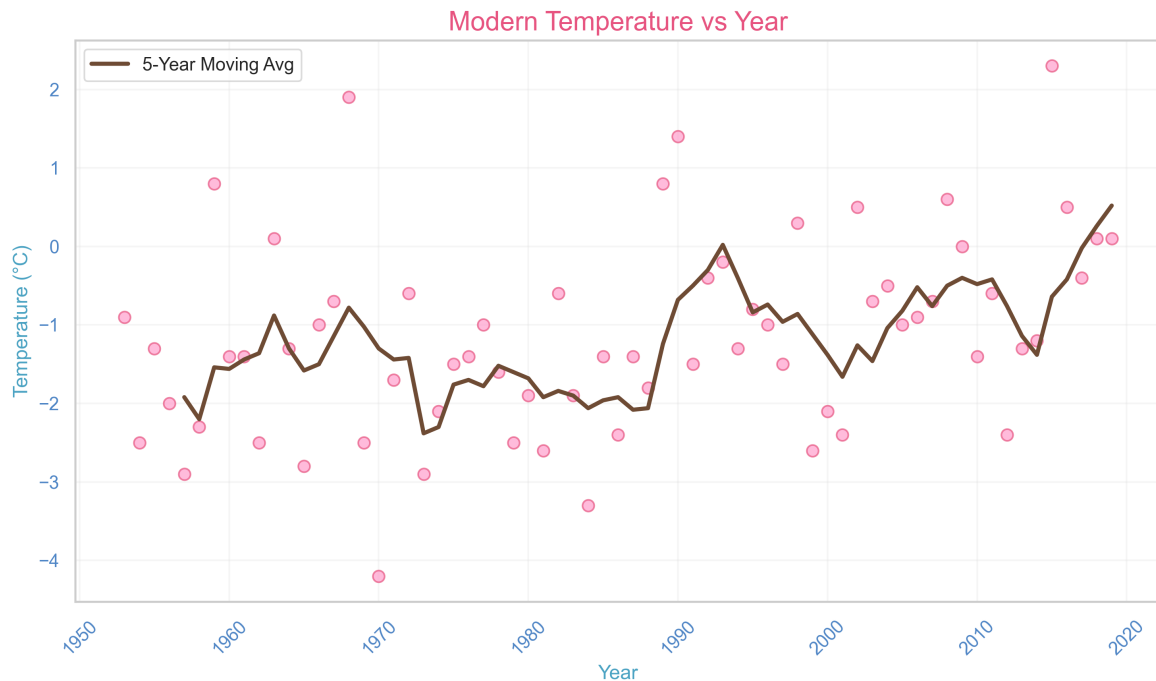


Figure 5

Figure 5 shows the annual spring temperature in Japan from 1950 to 2020, measured in degrees Celsius (°C) relative to a baseline average. Each pink dot represents the average March temperature for a given year, and the solid blue line indicates a 5-year moving average to highlight underlying climate trends. The overall trajectory shows a clear increase in average March temperatures over the 70-year period, particularly after 1990, reflecting the impact of modern global climate change. This warming trend corresponds closely with the earlier flowering of cherry blossoms during the same time frame shown in the earlier figure. Together, both graphs reinforce the connection between rising spring temperatures and timing shifts in sakura blooming.

Figure 6 above presents the frequency distribution of average March temperatures in Japan from 1950 to 2020. The temperature values are plotted on the x-axis in degrees Celsius (°C). The distribution is centered around -1.5°C, with a wider spread toward colder extremes and a thinner tail extending into positive temperatures. While most March temperatures during this period fall below freezing, the presence of warmer years, particularly in the latter decades, indicates a shift in climate norms. These warming trends align with observed shifts in cherry blossom phenology, where earlier flowering is increasingly correlated with milder spring conditions.

Figure 7 highlights the frequency distribution of sakura full flowering dates in modern Japan, measured in day-of-year (DOY), for the period between 1950 and 2020. Each bar represents how often flowering occurred within a specific DOY range. The distribution is roughly normally distributed, with the majority of flowering dates clustered between DOY 83 and DOY 95 (approximately March 24 to April 4), suggesting a central tendency in late March.

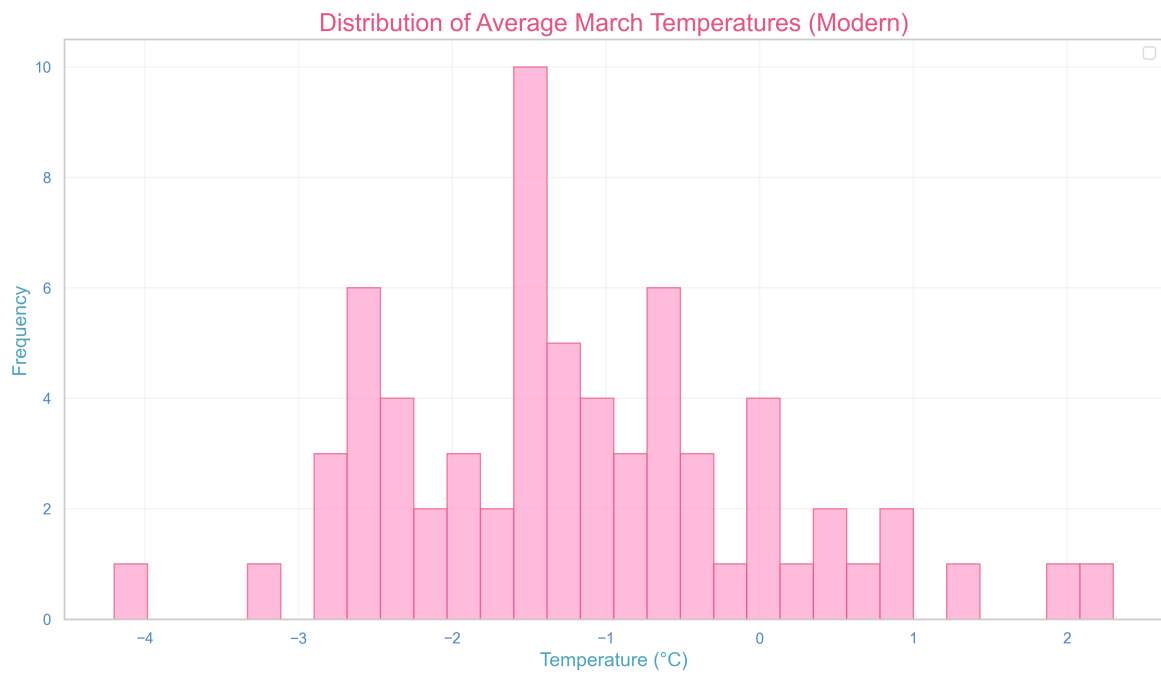


Figure 6

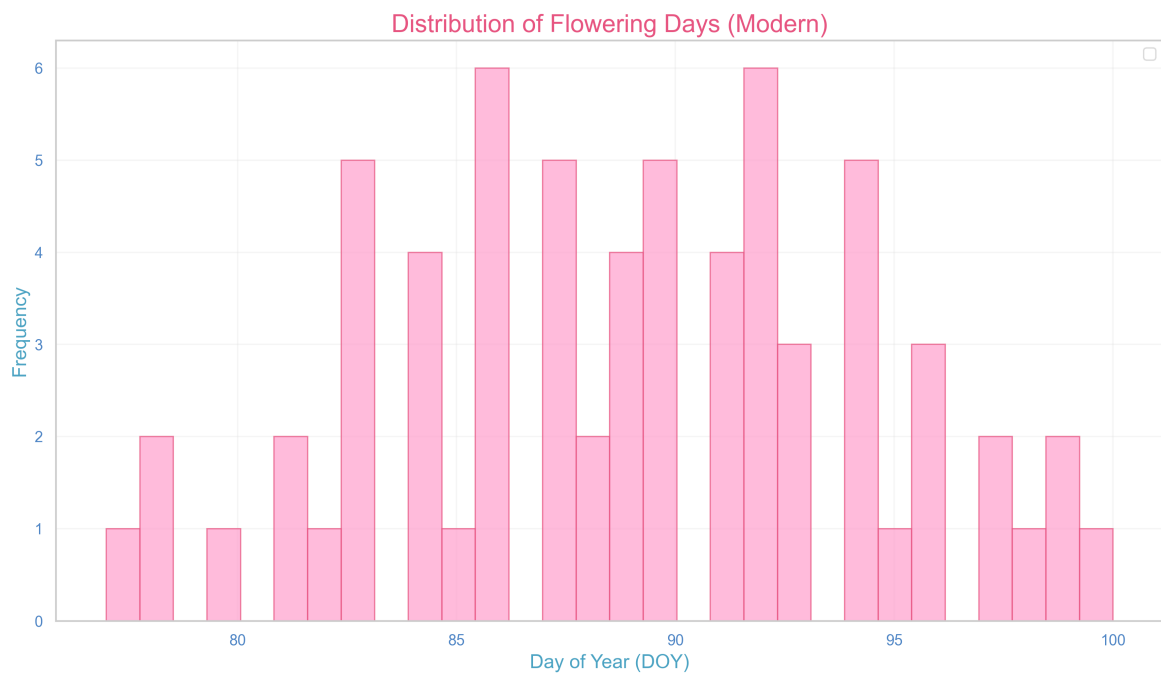


Figure 7

Exploring the data collected in the last 60 years has highlighted its similarity to the historical dataset. As temperatures have gotten warmer, cherry blossoms in Kyoto have tended to bloom earlier and earlier as the years have progressed. Although the temperatures in the modern dataset tend to be a bit cooler on average than the ones noted in the historical dataset, the clear negative relationship between temperature and blooming day endures. To be able to more exactly quantify this relationship, however, we construct a model.

4 Modeling

4.1 Model Specification

4.2 Results

5 Discussion

5.1 Implications of Findings

Our statistical analysis reveals a significant inverse relationship between pre-flowering March temperatures and sakura bloom dates, with higher temperatures consistently associated with earlier flowering time. This temperature-dependent pattern aligns with the documented global warming trend observed over recent centuries, particularly the accelerated temperature increase in the modern era.

The predictive models generated through our research demonstrate robust statistical evidence that the progressive elevation of mean March temperatures, driven by global warming, will likely continue to advance cherry blossom flowering dates in coming decades. This phenological shift carries significant ecological, cultural, and economic implications. The alteration of these biorhythms may disrupt established ecological synchronizations between cherry trees and their pollinators, potentially affecting ecosystem functionality and biodiversity dynamics.

From a cultural perspective, the temporal shift in cherry blossom seasons need adjustments to traditional hanami celebrations and tourism schedules, which have historically been calibrated to conventional blooming periods. In addition, these modifications could impact cultural practices that have remained relatively consistent for centuries and negatively impact tourism economy that is built around it.

5.2 Ecological Implications

5.3 Cultural Implications

5.4 Limitations

We would like to address several methodological limiting factors. Firstly, our analysis relies predominantly on data from Kyoto, representing a geographically limited subset that may not comprehensively reflect sakura phenological patterns across Japan's diverse climate regions. Secondly, although we used a merged dataset spanning from 800 CE to 2019, there are significant data gaps/missing values where we have to drop during the cleaning & merging of the two dataset. In addition, a notable limitation is the historical dataset's reliability, as large portions comprise of reconstructed values derived from local linear regression models or originated from primary sources that lack rigorous academic

verification protocols. This presents challenges for establishing data provenance and reliability in accordance with contemporary scientific standards. Lastly, while our findings highlight temperature as a statistically significant predictor of bloom timing, the single-variable approach inherently overlooks other potential ecological factors. Variables such as precipitation patterns, photoperiod fluctuations, soil conditions, and winter chilling requirements may also contribute significantly to the observed advancement in flowering dates. A more comprehensive multivariate model would potentially yield enhanced predictive capacity and ecological insights.

5.5 Future Research Directions

For future research, we would like to establish regression tree models to enhance predictive capabilities regarding sakura phenological patterns. Unlike traditional linear models, regression trees offer robust forecasting mechanisms that can better accommodate complex interactions between variables, prioritizing predictive accuracy over interpretive simplicity. Next, we recommend adding in additional environmental parameters beyond temperature. Variables warranting investigation including but not limited to precipitation frequency and intensity, atmospheric humidity gradients, soil composition metrics, photoperiod fluctuations, and cumulative chilling units during dormancy periods. Such multidimensional modeling would potentially explain a greater proportion of the observed variability in bloom timing and provide more nuanced insights into the complex biological mechanisms governing cherry blossom phenology. Lastly, future research could benefit from expanding the geographical scope beyond Kyoto to establish comparative phenological datasets across diverse microclimates and latitudinal gradients throughout Japan and other regions where cherry trees are important. This expanded spatial analysis would facilitate the identification of region-specific responses to climate variables and potentially isolate genetic adaptations to local environmental conditions.

5.6 Conclusion

The Japanese tradition of *hanami* is an important cultural tradition that honors the cycle of life and death. However, rising global temperatures have created an anomaly in recent years, highlighting the need to understand the historical and modern links between temperature and cherry blossom bloom timing. By exploring and modelling this data, we began to understand the quantitative relationships between temperature and blooming day, which allowed us to come to several conclusions. First, changes in temperature will have consequential effects for wildlife that function around the timing of blooming *sakura*. Next, the timing of celebrations such as *hanami* will be impacted by temperature changes, necessitating flexibility in honouring this tradition. Finally, there is a need for more a more comprehensive inquiry into the determinants of cherry blossom blooming, beyond solely the locale of Kyoto. This is so that more robust predictions of *sakura* blooming in Kyoto can be made. By gathering more data and make better predictions, the city of Kyoto will better be able to weather climate change and bridge their cherished traditions into the future.

6 References

Appendix

- Acevedo, Isabel. 2021. "Sakura Storytellers." *Arnold Arboretum*, March. <https://arboretum.harvard.edu/stories/sakura-storytellers/>.
- Agency, Japan Meteorological. 2025a. "Biological Seasonal Observation Information." <https://www.data.jma.go.jp/sakura/data/>.

- . 2025b. “Tables of Monthly Climate Statistics.” <https://www.data.jma.go.jp/stats/data/en/smp/index.html>.
- Allen, Jenica M., Maria A. Terres, Toshio Katsuki, Kojiro Iwamoto, Hiromi Kobori, Hiroyoshi Higuchi, Richard B. Primack, Adam M. Wilson, Alan Gelfand, and John A. Silander Jr. 2014. “Modeling Daily Flowering Probabilities: Expected Impact of Climate Change on Japanese Cherry Phenology.” *Global Change Biology* 20 (4): 1251–63. <https://doi.org/10.1111/gcb.12364>.
- Aono, Yasuyuki, and Keiko Kazui. 2008. “Phenological Data Series of Cherry Tree Flowering in Kyoto, Japan, and Its Application to Reconstruction of Springtime Temperatures Since the 9th Century.” *International Journal of Climatology* 28 (7): 905–14. <https://doi.org/10.1002/joc.1594>.
- Aono, Yasuyuki, and Shizuka Saito. 2010. “Clarifying Springtime Temperature Reconstructions of the Medieval Period by Gap-Filling the Cherry Blossom Phenological Data Series at Kyoto, Japan.” *International Journal of Biometeorology* 54 (2): 211–19. <https://doi.org/10.1007/s00484-009-0272-x>.
- Cookson, Alex. 2020. “Sakura (Cherry Blossom) Flowering Data.” <https://github.com/tacookson/data/tree/master/sakura-flowering>.
- Foundation, Python Software. 2025. “Python Language Reference, Version 3.9.” <https://docs.python.org/3/library/datetime.html>.
- Hunter, John D. 2007. *Matplotlib: A 2D Graphics Environment. Computing in Science & Engineering*. Vol. 9. 3. IEEE Computer Society. <https://doi.org/10.1109/MCSE.2007.55>.
- James, Gareth, Daniela Witten, Trevor Hastie, and Robert Tibshirani. 2021. “Survival Analysis.” In *An Introduction to Statistical Learning*, 2nd ed. Springer. <https://www.statlearning.com/>.
- Seabold, Skipper, and Josef Perktold. 2010. “Statsmodels: Econometric and Statistical Modeling with Python.” In *9th Python in Science Conference*. <https://www.statsmodels.org/>.
- team, The NumPy development. 2025. “NumPy.” Zenodo. <https://doi.org/10.5281/zenodo.5550190>.
- team, The pandas development. 2025. “Pandas.” Zenodo. <https://doi.org/10.5281/zenodo.3509134>.
- The Economist. 2017. “Japan’s Cherry Blossoms Are Emerging Increasingly Early.” *The Economist*, April. <https://www.economist.com/graphic-detail/2017/04/07/japans-cherry-blossoms-are-emerging-increasingly-early>.
- Waskom, Michael L. 2021. “Seaborn: Statistical Data Visualization.” *Journal of Open Source Software* 6 (60): 3021. <https://doi.org/10.21105/joss.03021>.
- Xu, Yanxia, Jingjing Li, Pengyi Wang, Wenhui Wang, Yuning Guo, Xueying Hao, Liyan Du, and Chunling Zhou. 2023. “The Exploration of Flowering Mechanisms in Cherry Plants.” *Plants* 12 (23). <https://doi.org/10.3390/plants12233980>.