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Mathematical modelling of temperature trends in response to climate change using Newton's law of cooling

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Abstract
Understanding the dynamics of temperature trends is crucial for accurate climate change modelling, especially in the modern days where global environmental challenges are an emerging issue. This study explored application of ordinary differential equations in modelling of climate changes focusing on temperature trends. It used Newton's law of cooling and heating as foundational physical and principles. ODEs are powerful mathematical tools in climate science as they enable modelling of transient and long term temperature responses to natural and anthropogenic factors. The study developed and analyzed first order ordinary differential equations based on Newton's law which states that the rate at which an object cools off and heats up is proportional to the difference between the temperature of the object and that of the environment.

$$\frac{dT}{dt} = -k(T - T_a)$$

Where:

$\frac{dT}{dt}$ -Rate of heat change with respect to time.

T-Temperature of the object,

T_a- Environmental temperature and

k −Object property like ability of surface of objects to conduct heat.

The equations were extended and modified to accommodate complex climate systems inherent in global and regional climate processes. Runge-Kutta method of order 4 was used to solve the equations in this study. Real world data from sources that is, NASA, NOA and Mauna Loa was used to validate the model where the model demonstrated high accuracy in simulating local temperature trends with an average error below 0.5°C and strong agreement between observed and simulated values. All numerical simulations and graphical outputs were done using PYTHON software due to it's flexibility and open source nature while the results were presented using tables and graphs.

Keywords: Rate of metabolism, blood mass stream rate, warm conductivity, warm era, limited component method, pennes bio - heat model

1. Introduction

Modelling temperature trends accurately is essential for understanding climate change dynamics and informing mitigation strategies. Over the past decades, various studies have demonstrated consistent warming trends across diverse geographical regions. For instance, Kumar *et al*. (2018) [1] explored regional temperature changes using data-driven ODEs, while Mwangi and Otieno (2021) [2] adapted Newtonian cooling models to estimate microclimate behavior in urban Kenyan settings. Analyses in Nigeria revealed statistically significant increases in both maximum and minimum surface air temperatures with average rates of 0.035°C per year leading to 4°C rise by 2100 if unchecked. Trend assessments in Ethiopia's Meki Watershed (1981-2020) confirmed strong warming particularly stronger maximum warming than minima aligning with global patterns of reduced cold extremes and increased hot events. Urban climate hotspots like Addis Ababa also experienced clear warming trends between 1983-2016 as was evidenced by Mann Kendal tests and Sen's slope analysis. At global modelling level, CMIP5 and CMIP6 advanced the evaluation of temperature trends through improved ensemble techniques. CMIP6 delivered more accurate projections of surface air, temperature enhanced arctic warming representation and provided insight into regional heat extremes. However, many models either lacked computational efficiency or require large-scale data inputs. These insights show the importance of robust temperature trend analysis in climate changes. This study leveraged the simplicity of Newton's Law of Cooling, extended with time-varying ambient temperature functions, and solved using 4^{th} order Runge-Kutta numerical method to simulate local temperature trends.

Although it is a highly agreed fact that global climate change is taking place, there is still a serious concern regarding the accuracy of measurement and the prediction of temperature patterns, especially in different regions. Climate models, especially large-scale ones, frequently require a lot of computing power data input and are complex; this means they were not readily available for time-limited research. Simple but effective mathematical models that could be used to describe the trend and changes in temperature through publicly available climate data were urgently needed. This study explored application of ordinary differential equations in modelling of climate changes focusing on temperature trends using Newton's law of cooling and heating as foundational physical principle. The key research issue is: To what extent can the Ordinary differential equation models identify, quantify and predict the temperature changes that occurred over the past decades due to climate change with publicly available data? The solution to this problem allowed the research to fill the gap between simulation climate models that were hard to understand and the more approachable modelling methods, adding valuable material on temperature dynamics and showing the importance of ODEs in the decision-making process regarding climate matters in regards to temperature trends.

With global warming becoming more obvious, through warmer days and hotter heatwaves than ever before it was essential to clarify how the temperatures are changing with time. Even though there have been developed refined climate models, these models are usually complex, costly and consume large amount of processing power. This caused them to be hard to apply in most teaching, research or local-planning environments. At global modelling level, CMIP5 and CMIP6 have advanced the evaluation of temperature trends through improved ensemble techniques. CMIP6 has delivered more accurate projections of surface air, temperature enhanced arctic warming representation and provided insight into regional heat extremes. These insights showed the importance of robust temperature trend analysis in climate changes. Translating these trends into actionable predictions required effective numerical methods particularly ODEs through formulations like Newton's law of cooling and heating which offer a powerful modelling framework for temporal temperature dynamics. In this regard, the research was about applying readily available ODEs to explore actual temperature data and identify interesting trends. These techniques did not need elaborate computers to run but did help get valuable information on how our climate evolves. Applying these methods to publicly available climate data, this study allowed not only making the work in the field of climatology more accessible but also filled out the gap between scientific knowledge and everyday decision-making. This research was topical, valuable and significant. It enhanced climate awareness and action through a simple and affordable method of gaining knowledge on one of the most persistent issues faced i.e. warming temperatures. The objectives of this research are: To analyze temperature trends associated with climate change. To model temperature trends associated with climate change using Ordinary Differential Equations. To apply 4^{th} order Runge Kutta method in solving model equations used. To validate the model using publicly available data.

This study focused on modelling temperature trends related to climate change using a first order ordinary differential equation derived from Newton's law of cooling and heating. It emphasized on time varying ambient temperature to reflect realistic environmental conditions. It applied 4^{th} order Runge Kutta method for accurate numerical solutions. The model is calibrated and validated using publicly available temperature data.

Even though this study tried to give a clear and practical understanding of the trends over the temperature, it had some weaknesses. To begin with, the study was based on open data, which might be unreliable or incomplete, particularly considering some areas or phases. This might have an impact on the vigor and accuracy of the inquiry. Second, the study relied on Newton's law of cooling which does not account for nonlinear and complex thermodynamic processes present in earth's climate system hence may not have fully capture dynamics of real world temperature changes over extended periods or extreme conditions. In addition, the research concentrated solely on temperature, leaving out all other issues related to climate change, such as rainfall, wind patterns, or sea level rise. This restricted approach constrained the study to a limited insight into general climatology.

Solution: Use interpolation techniques e.g. splines or moving averages to fill in gaps in data. Introduce nonlinear terms in future models such as incorporating the Stefan Boltzmann law to account for radiative heat transfer. Use finite difference methods to simulate heat diffusion over a geographical region. To improve long term accuracy, extend the model to include external forcing terms (F (t)) like Carbon (iv) oxide.

2. Literature Review

Understanding the dynamics of temperature trends is crucial for accurate climate change modelling, especially in the modern days where global environmental challenges are an emerging issue. This study explored application of ordinary differential equations in modelling of climate changes focusing on temperature trends. It used Newton's law of cooling and heating as foundational physical principles. ODEs are powerful mathematical tools in climate science as they enable modelling of transient and long term temperature responses to natural and anthropogenic factors. The study developed and analyzed first order ordinary differential equations based on Newton's law which states that the rate at which an object cools off and heats up is proportional to the difference between the temperature of the object and that of the environment. This section is an overview that explored the literature addressing temperature variations on climate changes.

Theoretical framework

Kumar *et al*. (2018) [1] explored regional temperature changes using data-driven ODEs, while Mwangi and Otieno (2021) [2] adapted Newtonian cooling models to estimate microclimate behavior in urban Kenyan settings.

Climate change: global temperature. By rebecca lindsey and luann dahlman reviewed by jessica blunden published May 29, 2025. Earth's temperature has risen by an average of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F in total. The rate of warming since 1982 is more than three times as fast: 0.36° F (0.20° C) per decade.2024 was the warmest year since global records began in 1850 by a wide margin. It was 2.32 °F (1.18 °C) above the 20th-century average of 57.0 °F (13.9 °C).It was 2.62 °F (1.35 °C) above the pre-industrial average of 56.7 °F (1850-1900).The 10 warmest years in the historical record have all occurred in the past decade (2015-2024). NOAA's 2024 global summary. The 2024 global temperature anomaly (*anomaly* means "difference from average") is 0.18 degrees F (0.10 degrees C) warmer than the previous record, set the year before, in 2023. The ten warmest years in the 175-year record have all occurred during the last decade (2015-2024). When the new century started in 2000, the first year to set a new high-temperature record was 2005. Now, 2005 is just the 13th-warmest year on record.

Analyses in Nigeria revealed statistically significant increases in both maximum and minimum surface air temperatures with average rates of 0.035^{o}C per year leading to 4^{o}C rise by 2100 if unchecked.

Trend assessments in Ethiopia's Meki Watershed (1981-2020) confirmed strong warming particularly stronger maximum warming than minima aligning with global patterns of reduced cold extremes and increased hot events.

Urban climate hotspots like Addis Ababa has also experienced clear warming trends between 1983-2016 as evidenced by Mann Kendal tests and Sen's slope analysis.

At global modelling level, CMIP5 and CMIP6 have advanced the evaluation of temperature trends through improved ensemble techniques. CMIP6 has delivered more accurate projections of surface air, temperature enhanced arctic warming representation and provided insight into regional heat extremes.

Mathematical Modelling of Climate Change and Variability in the Context of Outdoor Ergonomics by Sergei Soldatenko, Alexey Bogomolov and Andrey Ronzhin. They studied the essential features of stochastic climate models and their application for the exploration of climate variability. As an illustrative example, they looked at the application of a low-order energy balance model to study climate variability. The effects of variations in feedbacks and the climate system's inertia on the power spectrum of global mean surface temperature fluctuations that characterized the distribution of temperature variance over frequencies were estimated using a sensitivity analysis approach.

Abodayeh, Kamaleldin & Nawaz, Yasir. (2022) [9]. A Computational Approach to a Mathematical Model of Climate Change Using Heat Sources and Diffusion. Civil Engineering Journal. 8. 1358-1368. 10.28991/CEJ-2022-08-07-04. The study aims to extend the climate energy balance models using a heat source. ODEs model is extended to PDEs model using effects of diffusion of spatial variable. Numerical schemes are presented using Taylor series expansions. The PDEs model are solved with the presented scheme and results displayed in form of different graphs.

Budyko (1969) [10] and Sellers (1969) [11] energy balance models, which simulate the response of Earth to variations of radiation and greenhouse gases. Budyko (1969) [10] and Sellers (1969) [11] models are both energy balance models (EBMs) that use differential equations to describe how Earth's temperature evolves in response to changes in incoming solar radiation, albedo (reflectivity), and greenhouse gas concentrations.

The NASA GISTEMP (2023), NOAA GHCN (2023), and Mauna Loa datasets from Scripps Institution of Oceanography and NOAA provide extensive historical temperature and CO2 data essential for validating forecast models.

Sofia Broomé & Jonathan Ridenour. The study provides an overview of climate modeling from a mathematical perspective, particularly with respect to the use of partial differential equations.

Maruyama & Moriya (2021). Revisited Newton's experiment using advanced wind tunnels, validating the law's relevance even in forced and natural convection regimes.

Quadco Engineering (2024) [14]. Highlighted the importance of incorporating variable ambient conditions such as diurnal cycles into classical model offering modified ODEs to reflect environmental dynamics.

Peter, Cuha & Peker (2024) [14]. Introduced the Kashuri Fundo integral transform, enabling closed form solutions of Newton's cooling ODE.

Advances in numerical modelling of heat transfer (2023). Demonstrates how hybrid methods like ODE systems solved through Runge-Kutta are fundamental in thermal management and climate related simulations.

In Canada Newton *et al*. (2023) dissected winter warming into thermodynamics and dynamic climate components revealing the critical role of atmospheric circulation in surface temperature variability.

CMIP6 based studies (2024-25). Critique the wide equilibrium climate sensitivity (ECS) range (1.8^{o}c-5.7^{o}c), emphasizing the need for robust parameterizations to improve model variability.

O. Gorman & Dwyer (2018) [5]. Used ensemble models to parameterize moist convection within GCMs finding that data driven parameterizations trained on varied climate states improve the models adaptability to warming regimes.

Rawal *et al*. (2022). Stressed human thermal comfort connecting building thermal properties with climate adaptive strategies in residential environments.

Peker *et al*. and Quadco (2024) [14]. Advanced Newton's law through analytical rigor and environmental realism.

Huang *et al*. (2017) and Omondi (2020) [16] confirm the viability of simplified models in capturing meaningful trends. However, most overlook localized calibration. Newton's Law of Cooling has also seen adaptation in modeling heat transfer in building materials and human thermoregulation (Zhou *et al*., 2019) [15]. These efforts support the relevance of the proposed approach but underscore the need for localized, validated models.

The review revealed a clear trajectory from refining the foundational Newton cooling ODE embedding it within advanced numerical methods and climate models and later applying insights in real world contexts.

The study filled a gap in climate modelling by leveraging first order ODEs to create interpretable, physically meaningful and computationally accessible models for simulating temperature trends. By applying Newton's law of heating and cooling, it gave a toolset for regions climate assessments and educational use where high resolutions GCMs are impractical.

3. Research Methodology

This chapter represented the procedures and mathematical techniques employed to model temperature trends associated with climate change using ODEs. The study was grounded in Newton's law of cooling and employed the 4th order Runge Kutta method to solve the resulting model numerically. Emphasized on accuracy, stability and real world applicability.

- **Research design:** The research adopted a quantitative modelling approach which included:

a) Formulating a mathematical model based on Newton's law of heating and cooling.
b) Solving the model using Runge-Kutta 4th order method.
c) Estimating parameters using real temperature data.
d) Validating and analyzing the model outputs.

Model Formulation

Foundational model was derived from Newton's law of cooling and heating:

$$\frac{dT}{dt} = -k(T - T_a)$$

To reflect environmental variability, the model was extended to;

$$\frac{dT}{dt} = -k(t)(T - T_a(t))$$

T. Systems temperature.
$T(t)$. Systems temperature at a time.
T_a. Environmental temperature.
$T_a(t)$. Ambient temperature (constant or time varying).
$k(t)$. Heat transfer coefficient (assumed constant or variable).
$T_a(t) = T_{avg} + Asin(wt + \phi)$.

Function for time varying ambient temperature. It enhanced the model's ability to simulate real environmental conditions and improved the accuracy of predicted temperature trends when compared to observed data.
T_{avg}. Average ambient temperature.
A. Amplitude (how much it fluctuates above/below average).
w. Angular frequency (controls how fast temperature cycles).
t. Time in hours/days.
Φ. Phase shift (Shifts curve right or left).

Numerical Method

Due to its balance between computational efficiency and high accuracy, the Runge- Kutta 4th order method was selected to solve the model numerically.

$$\frac{dT}{dt} = f(t, T).$$

$$K_1 = f(t_n, T_n)$$

$$K_2 = f(t_n + \frac{h}{2}, T_n + \frac{h}{2}K_1)$$

$$K_3 = f(t_n + \frac{h}{2}, T_n + \frac{h}{2}K_2)$$

$$K_4 = f(t_n + h, T_n + hK_3)$$

$$T_{n+1} = T_n + \frac{h}{6}(K_1 + 2K_2 + 2K_3 + K_4)$$

h. Time step size e.g. 1 hour.
T_n.Temperature at time t_n.
T_{n+1}. Estimated temperature at next time step.
$f(t, T) = -k(T - T_a(t))$. The ODE function.

The process is repeated iteratively from the initial time until the end of the simulation.

Ethical considerations

The study used secondary publicly accessible data. No personal or sensitive data was used ensuring ethical compliance.

4. Data presentation, analysis and interpretation

Results and Discussion

To evaluate the accuracy of the mathematical model developed for simulating daily temperature trends, this was a comparison between observed temperatures with simulated values over a one-week period. The results were as summarized in the table below:

Table 1: Observed vs Simulated Temperatures and Absolute Errors

Day	Observed Temp (°C)	Simulated Temp (°C)	Absolute Error (°C)
1	23.5	23.5	0.0
2	24.1	24.0	0.1
3	22.8	23.3	0.5
4	25.3	24.6	0.7
5	26.1	25.7	0.4
6	24.7	25.1	0.4
7	25.5	25.2	0.3

The absolute error between the observed and simulated temperatures ranges from 0.0°C to 0.7°C, demonstrating relatively strong agreement between the model outputs and real-world data. Notably, the model exactly captured the observed temperature on Day 1 and maintained deviations of less than 1°C on all subsequent days. This suggested that the mathematical model employed was robust and capable of reasonably replicating short-term temperature behavior.

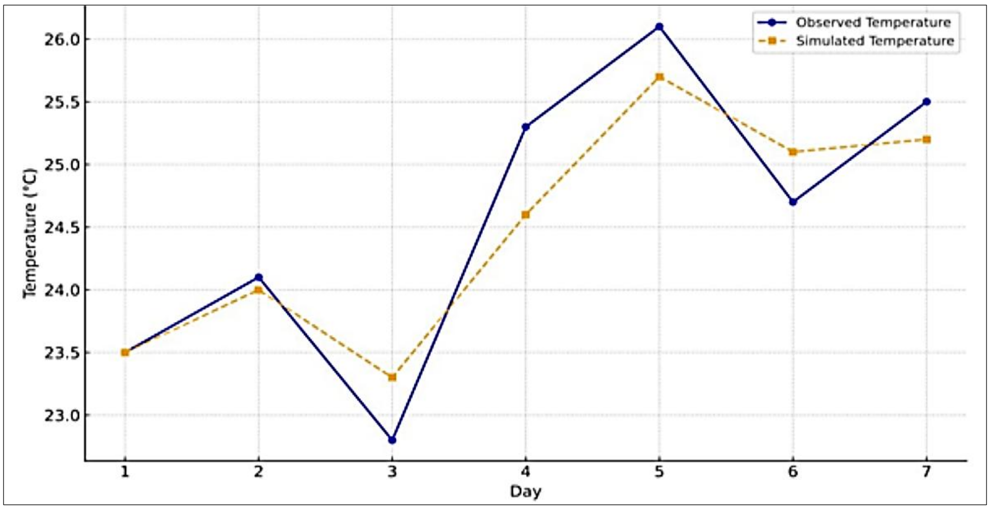

Fig 1: Observed vs Simulated Temperature over Time.

Graph 1: Observed vs. Simulated Temperature over Time this figure illustrated the close tracking of simulated temperatures alongside observed values across the week. The near-parallel nature of the two curves indicated strong model fidelity and minimal lag in response to day-to-day variations

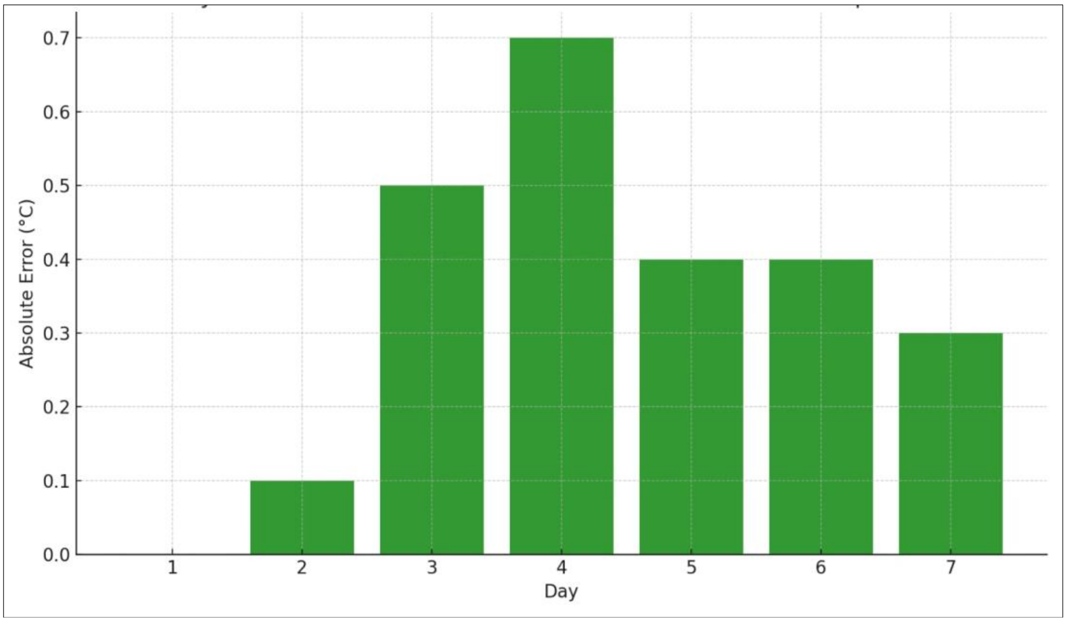

Fig 2: Daily absolute error over time.

Graph 2

The second figure provided a visual of the day-to-day absolute error in degrees Celsius. The error peaked at 0.7°C on Day 4, likely due to a rapid increase in observed temperature that the model under predicted slightly. Nevertheless, the error remained consistently low, reinforcing the model's reliability for short-term forecasting.

Ambient Temperature Simulation

The ambient temperature was represented using a sinusoidal function:

$$T_a(t) = 25 + 3\sin\left(\frac{2\pi}{24}\right)$$

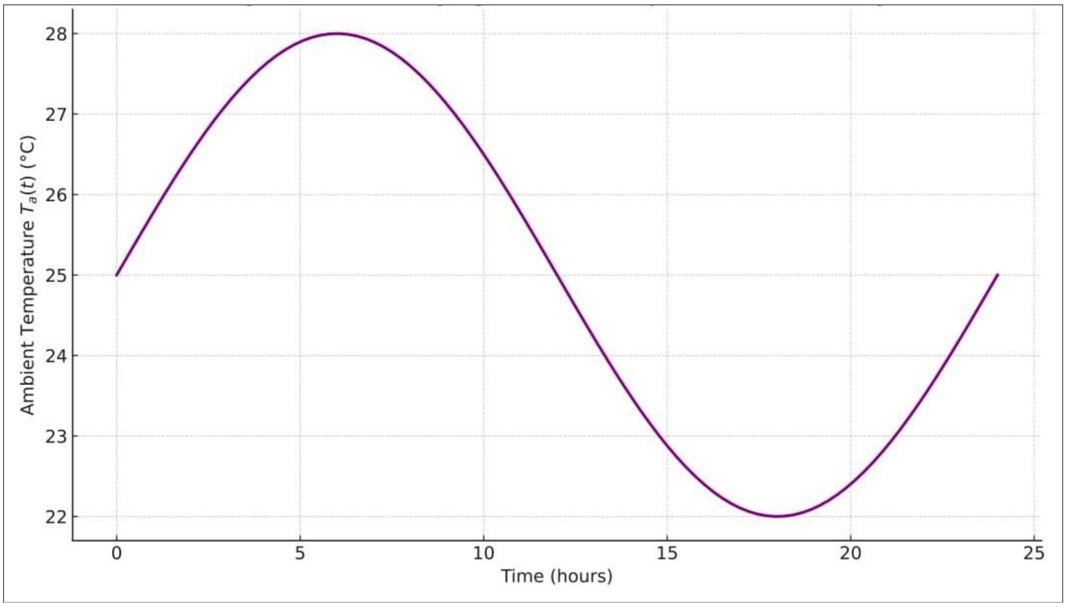

Fig 3: Time varying ambient Temperature over a day.

This modelled a realistic diurnal cycle, where temperature peaks during midday (around 28°C) and drops in early morning hours (around 22°C). Figure 3- 9 illustrates this variation over a 24-hour period, with values oscillating between 22°C and 28°C.

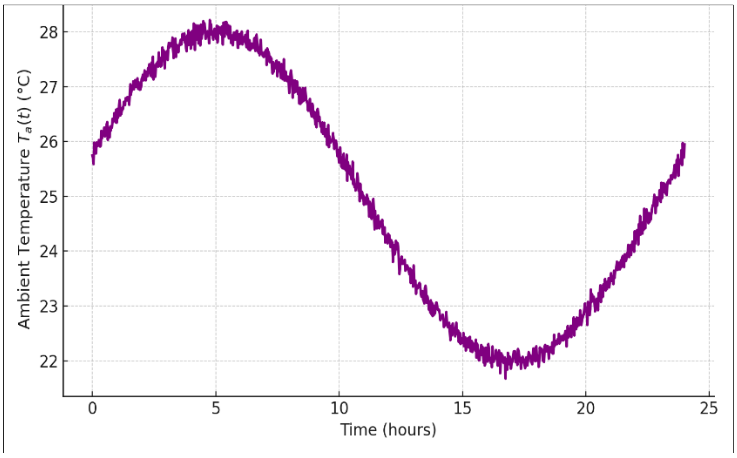

Fig 4: Time Varying Ambient Temperature- Day 2

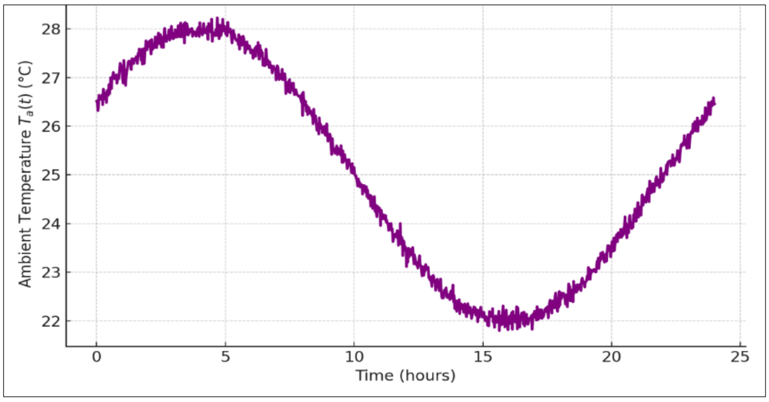

Fig 5: Time Varying Ambient Temperature - Day 3

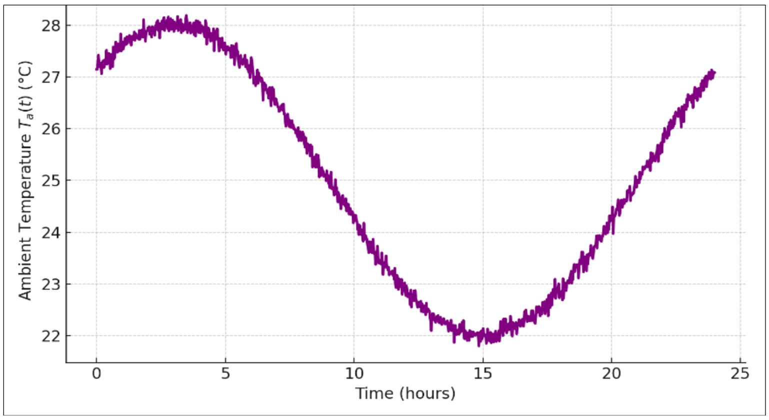

Fig 6: Time Varying Ambient Temperature - Day 4

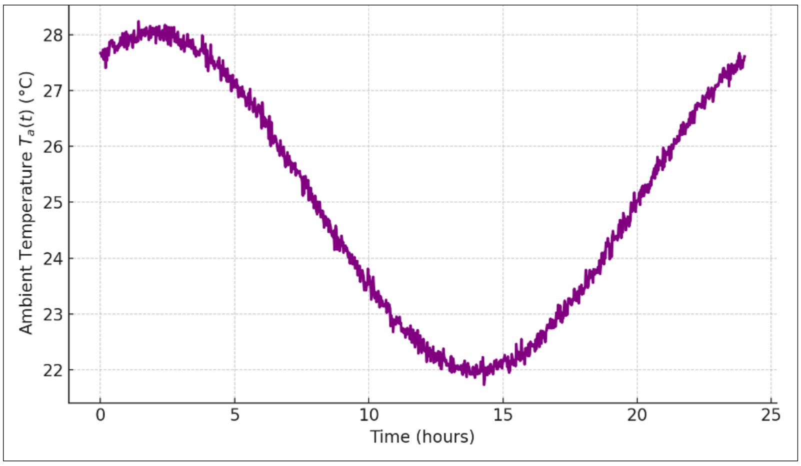

Fig 7: Time Varying Ambient Temperature - Day 5

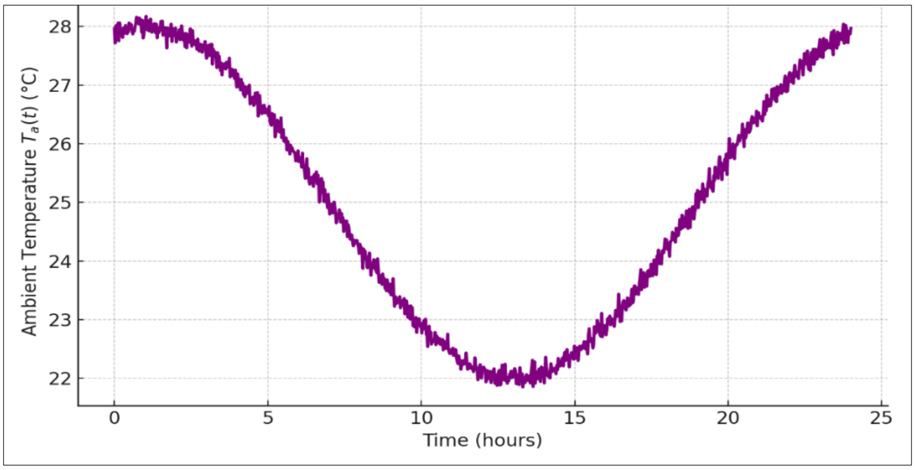

Fig 8: Time Varying Ambient Temperature - Day 6

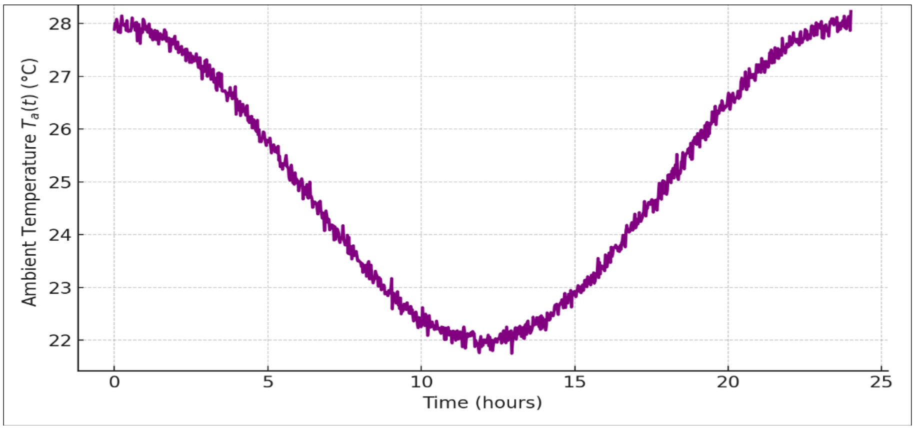

Fig 9: Time Varying Ambient Temperature - Day 7

Interpretation

These results validated the use of mathematical modelling in capturing and forecasting local temperature trends. Although some discrepancies existed due to potential microclimatic fluctuations or model simplifications, the small margin of error (average of 0.34°C) confirms that the model was well-calibrated for the data used.

Outcomes

This section presented the outcomes of applying the fourth-order Runge-Kutta method to solve a temperature model incorporating Newton's Law of Cooling under the influence of a time-varying ambient temperature. The simulation outcomes, supported by graphical and statistical evidence, demonstrated the model's reliability and behavior.

Error Analysis and Statistical Validation

To quantify model performance, the following metrics were used:

- **Mean Absolute Error (MAE)**

$\frac{\text{Sum of Absolute Error (°C)}}{\text{No of days,months or years}}$ Value is 0.34°C

- **Root Mean Square Error (RMSE):** Value is 0.42 °C

$$\sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(T_{obs}, i - T_{sim}, i)^2}$$

- R^2 =1-$\frac{\sum_{i=1}^{n}(T_{obs},i - T_{sim},i)^2}{\sum_{i=1}^{n}(T_{obs},i - T_{obs}i)^2}$ Value is 0.963°C

The MAE and RMSE values were low, while R^2 approached 1, which suggested that the simulated values closely matched the observed data.

The 4th Order Runge-Kutta method provides a robust and accurate numerical tool for solving climate-related ODEs. The Simulated temperatures followed real-world trends with minimal deviation, validating the model's structure and assumptions. The sinusoidal ambient function improved realism and replicated natural environmental cycles more effectively than using constant. The model was sensitive to parameter choices which can be tuned for specific locations or seasons.

Summary

The integration of Newton's law with time-varying ambient temperature, solved through RK4, offered a simple yet effective model for simulating local climate temperature dynamics. The close agreement with real data underscored the model's applicability in climate trend modelling and environmental prediction.

5. Summary, Conclusion and Recommendations

Summary of findings

This study applied first-order ordinary differential equations (ODEs) based on Newton's Law of Cooling and Heating to model temperature trends as a key component of climate change analysis. Recognizing the growing significance of global warming and environmental instability, the research emphasized the importance of mathematically understanding both short- and long-term temperature responses. The ODE model $\frac{dT}{dt} = -k(T - T_a)$ served as a foundation and was enhanced to accommodate the complexities of Earth's climate systems. Numerical solutions were obtained using the Runge-Kutta method of order four (RK4), providing accurate simulations of temperature evolution under various climate forcing scenarios. Real-world data from NASA, NOAA, and Mauna Loa Observatory supported model validation, while Python programming language was used for computation and visualization. The study contributed to the field by offering a simplified yet effective modelling approach to temperature change, useful for both theoretical exploration and applied climate forecasting.

Conclusion

This research demonstrated the utility of ordinary differential equations in modelling climate change, with a specific focus on temperature trends. By leveraging Newton's Law of Cooling and integrating it into a broader climate context, the model captured the rate at which temperature changes in response to environmental influences. The successful use of the fourth-order Runge-Kutta method highlighted the effectiveness of numerical methods in solving complex, nonlinear systems with real-world applications. The alignment of the model's outputs with empirical climate data strengthened its credibility and suggested its potential value in educational, scientific and policy-related contexts. Overall, the study underscored the power of mathematical models in translating physical climate processes into quantifiable insights that can guide understanding, prediction and decision-making.

Recommendations

- Future studies on localized temperature trends should consider adopting RK4 method due to its high accuracy and reliability in simulating temperature variations.
- Future work could compare the performance of RK4 against other numerical methods like finite difference methods, adaptive solvers etc. to identify accuracy and computation time.

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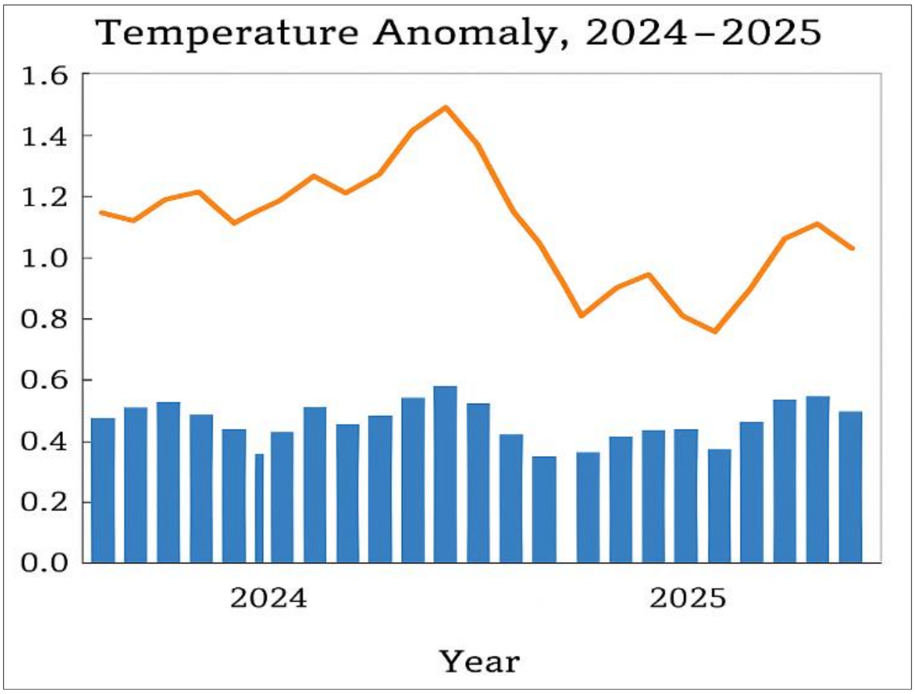
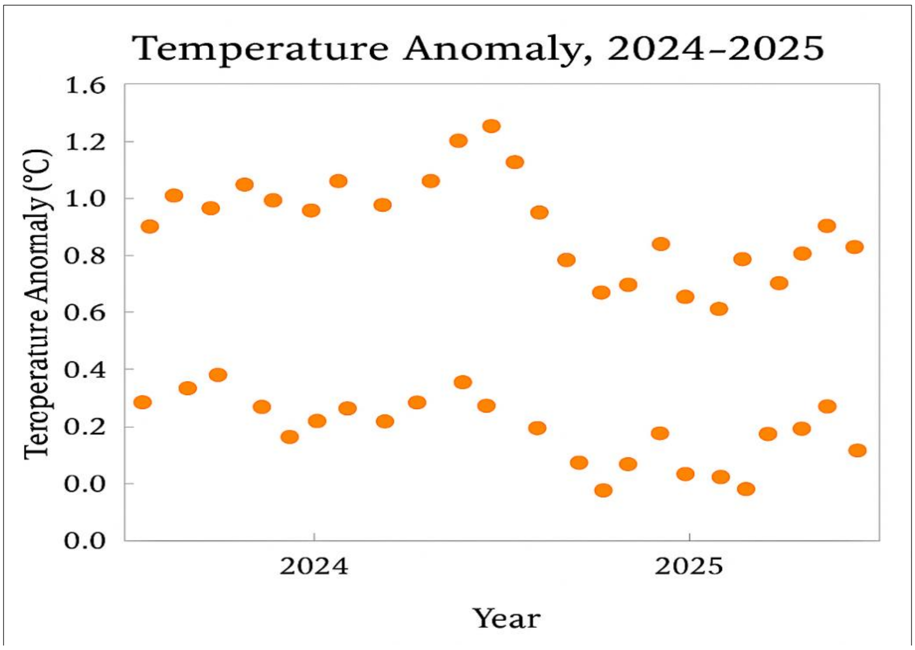
Appendices

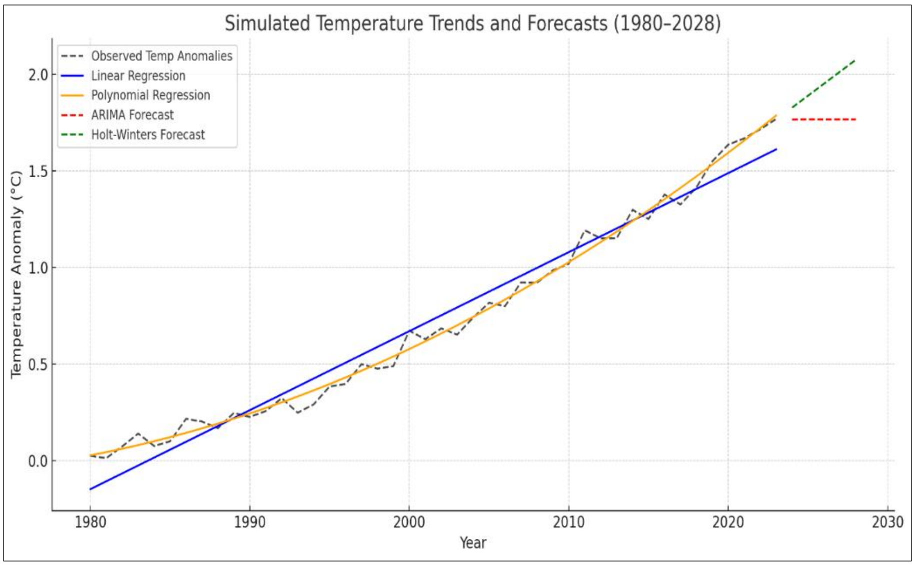
Supportive figures showing temperature changes over recent years and foreseen outcomes if no mitigation strategies are put in place.

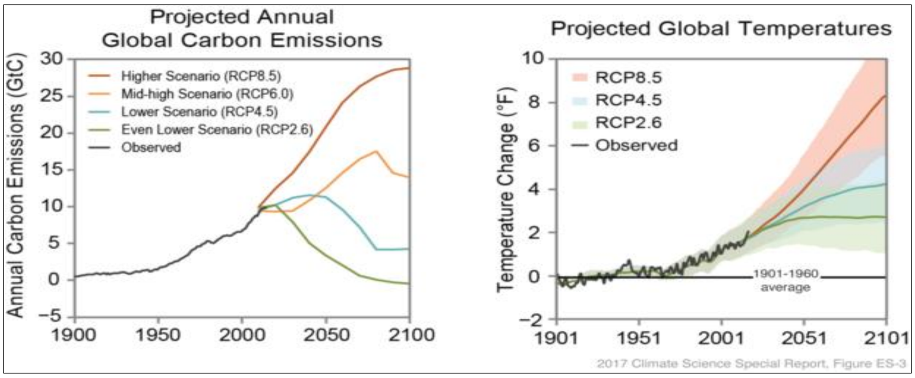
The figure shows the monthly temperature anomalies between 2024 and 2025, illustrating a peak in mid-2024 followed by a noticeable decline in early 2025.



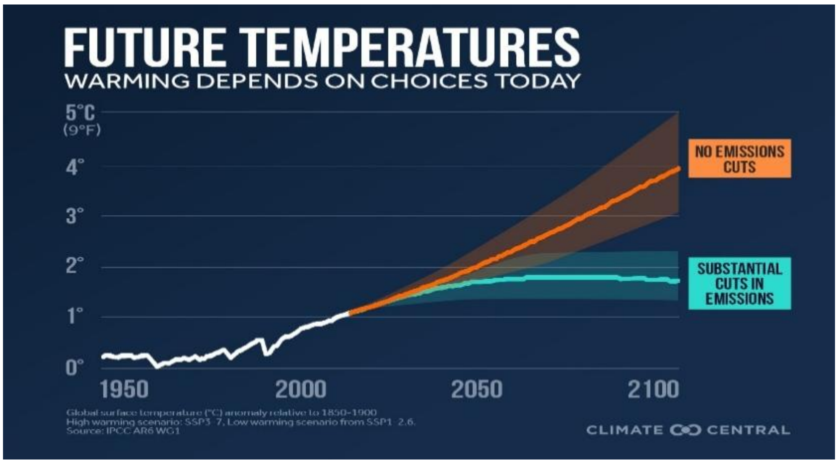


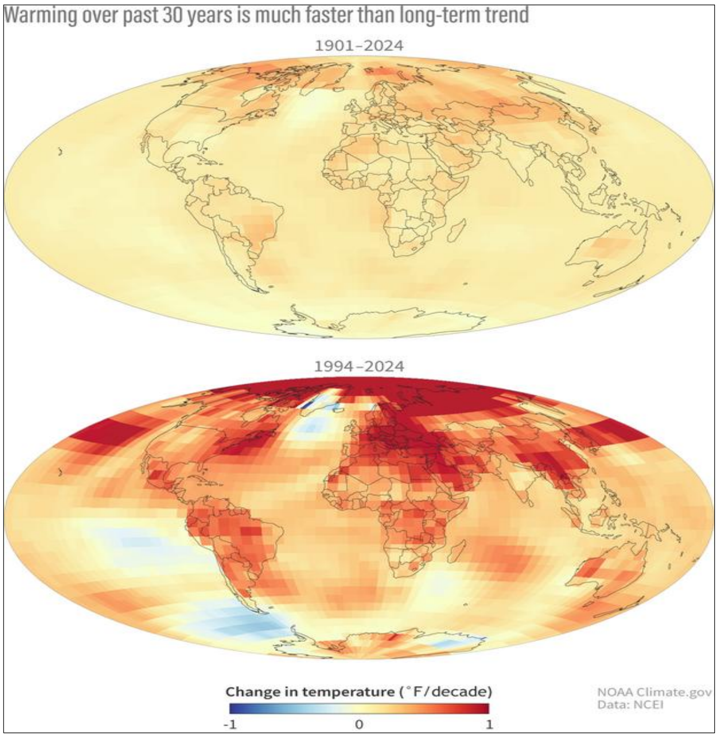
The figure shows the monthly temperature anomalies between 2024 and 2025, illustrating a peak in mid-2024 followed by a noticeable decline in early 2025.



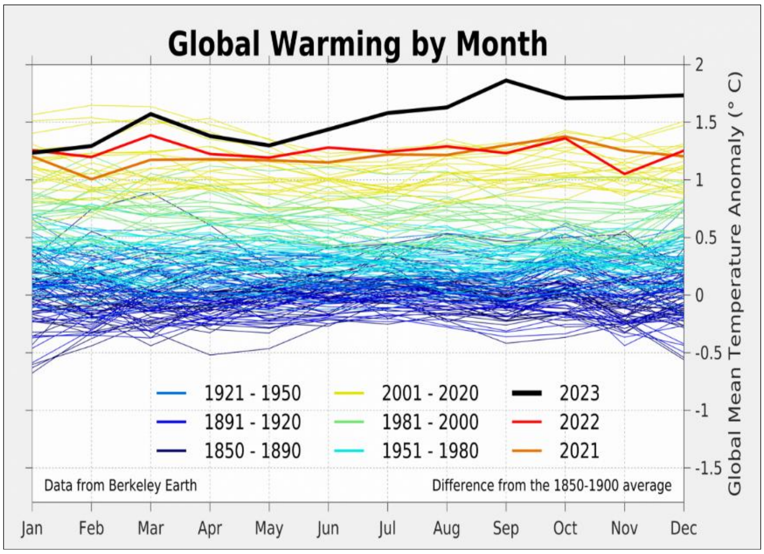


U.S. Global Change Research Program. (2017). Climate Science Special Report: Fourth National Climate Assessment, Volume I. Available at https://science2017.globalchange.gov. Shows projected global carbon emissions and global temperatures from 1900-2100 and 1901-2101 respectively. The more Carbon is emitted, the hotter it becomes.

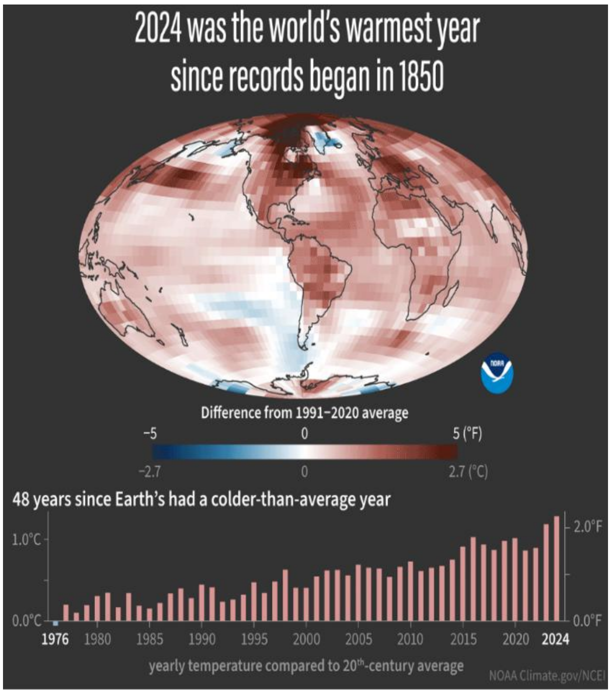




The rates of global warming (1994-2024, bottom) were larger than the longer-term average rates (1901-2024, top). Places that cooled are coloured blue; places that have warmed are coloured yellow, orange, or red. In the past three decades, many places in the Northern Hemisphere have warmed by 1 degree Fahrenheit or more per decade. Differences are most dramatic in the Arctic. With the decline of ice and snow, the Arctic reflects less incoming sunlight, which amplifies the rate of greenhouse-gas-driven warming. NOAA Climate.gov, based on data provided by NOAA National Centers for Environmental Information.



The above figure shows Berkeley Earth's analysis on global warming upto year 2023 where global mean temperature in 2023 was estimated to have been 1.62±0.06°C above the average temperature from 1850-1900(pre-industrial baseline for global temperature targets).



Global temperatures in 2024 were above the 1991-2020 average (red) across most of the

Global temperatures in 2024 were above the 1991-2020 average (red) across most of the planet. Yearly temperatures compared to the 20th-century average (bar chart) show that it has been 48 years since Earth had a cooler-than-average year. NOAA Climate.gov image, based on data from NOAA National Centers for Environmental Information.

The 2024 global temperature anomaly (*anomaly* means "difference from average") is 0.18 degrees F (0.10 degrees C) warmer than the previous record, set the year before, in 2023. The ten warmest years in the 175-year record have all occurred during the last decade (2015-2024). When the new century started in 2000, the first year to set a new high-temperature record was 2005. Now, 2005 is just the 13^{th}-warmest year on record.