



RESEARCH ARTICLE

Long-term trends and variability of soil temperature in contrasting agro-climatic zones of Tamil Nadu, India

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Abstract

Soil temperature is a key regulator of soil physical, chemical and biological processes, influencing nutrient cycling, root growth and overall ecosystem functioning. Long-term evaluation of soil thermal regimes is essential for understanding climate-driven changes in agricultural systems. This study analysed daily morning and afternoon soil temperature at 5, 10 and 20 cm depths (2009–2019) at Kovilpatti (semi-arid) and Ooty (high-altitude), Tamil Nadu, India. Trend detection was performed using the Mann-Kendall or modified Mann-Kendall test based on data independence and Sen's slope estimator quantified trend magnitude ($^{\circ}\text{C yr}^{-1}$). Soil temperature exhibited strong seasonal, depth-wise and diurnal variability at both locations, with Kovilpatti consistently recording higher temperatures and greater diurnal amplitudes than Ooty. Results revealed significant cooling trends in Ooty, particularly during winter at shallow depths (e.g., $-0.49^{\circ}\text{C yr}^{-1}$ at 5 cm in January), indicating increasingly colder soil conditions during winter, which could stress soil biota. In contrast, Kovilpatti showed widespread warming in morning soil temperatures across depths and seasons (up to $0.41^{\circ}\text{C yr}^{-1}$ at 10 cm in February), while afternoon temperatures exhibited mixed patterns, including notable cooling at 10 cm during monsoon and post-monsoon periods. Depth-wise analysis confirmed increasing morning temperature with depth and decreasing afternoon temperature with depth at both sites. These contrasting trends highlight the influence of regional climate on soil thermal behaviour. Rising soil temperatures in semi-arid regions may intensify thermal stress and necessitate modified irrigation and soil conservation practices. Thus, understanding such site-specific soil temperature responses is critical for developing climate-resilient agricultural management strategies.

Keywords: agro climatic zones; climate change; diurnal variability; Mann-Kendall test; Sen's slope; soil temperature regime

Introduction

India has diverse landscapes ranging from high plateaus and hills to fertile plains and arid regions, supporting a wide variety of soil types shaped by complex environmental influences (1). Among soil physical properties, soil temperature is a key driver of physicochemical and biological processes, regulating microbial activity, organic matter decomposition, nutrient mineralisation, root development and seed germination (2–4). Even small shifts in soil thermal regimes can alter nutrient cycling, soil moisture dynamics, crop phenology and pest-disease interactions, ultimately influencing agricultural productivity and ecosystem functioning (5, 6).

Soil temperature is highly sensitive to climatic variability and exhibits strong spatial and temporal fluctuations, including seasonal and diurnal fluctuations driven by changes in radiant energy and heat transfer processes at the soil surface (7, 8). These variations are further modulated by topography, soil texture, vegetation cover and moisture availability, making soil thermal behaviour a critical indicator of ecosystem response to climate change. Soil temperature responds differently from air temperature due to soil

thermal properties, highlighting the importance of long-term monitoring and analysis (9, 10). Long-term trend detection in soil temperature is essential for understanding how climate variability affects soil processes, crop performance and land management strategies. Nonparametric statistical tools such as the Mann-Kendall (MK) and modified Mann-Kendall (MMK) tests, along with Sen's slope estimator, are widely used to identify monotonic trends in environmental time series due to their robustness and minimal distributional assumptions (11). Despite the importance of soil thermal regimes, long-term soil temperature trend studies remain limited in many parts of India, particularly across contrasting agro-climatic zones.

Tamil Nadu provides an ideal setting for such an investigation, with its sharp climatic gradients ranging from hot semi-arid plains to cool high-altitude hill ecosystems. Understanding how soil temperature behaves across these environments is crucial for anticipating climate-driven impacts on agriculture, especially in regions where soil moisture stress, extreme temperatures, or seasonal cooling can influence crop growth and soil biological activity. This study analysed soil temperature data (2009–2019) from

Kovilpatti and Ooty to characterise monthly, seasonal and annual variability at 5, 10 and 20 cm depths; quantify long-term trends using Mann-Kendall and Sen's slope; and assess ecological and agricultural implications. By comparing 2 climatically distinct regions, this research provides insights into how soil thermal regimes respond to environmental drivers and highlights the need for location-specific climate-resilient land management strategies. This study hypothesised that soil temperature trends differ significantly between semi-arid and high-altitude environments due to climatic and soil thermal differences.

Materials and Methods

Study area

The study was conducted at 2 contrasting agro-climatic locations in Tamil Nadu. Agricultural Research Station, Kovilpatti (9°11'24" N and 77°52'50" E), located at a mean sea level (MSL) of 107 m, is situated in the Thoothukudi district and it falls within the hot and dry semi-arid zone. The predominant soil type in this region is black soil (Vertisols). The region receives an average annual rainfall of about 704.7 mm, largely from the monsoon and it serves as the main source of groundwater recharge. Air temperatures remain high throughout the year, with normal maximum and minimum values of approximately 35 and 22 °C, respectively, creating conditions conducive to strong surface heating and soil moisture stress.

In contrast, Horticultural Research Station, Ooty (11°24'23" N and 76°42'31" E) is located in the Nilgiris hills at a high-altitude of 2285 m above MSL. It experiences a humid temperate to sub-tropical climate. The predominant soil texture is clay loam. Annual rainfall is substantially higher, varying between 950 and 1550 mm. Temperatures are markedly cooler, with maxima of 16.6–28 °C and winter minima of 0–9 °C.

Data acquisition and preprocessing

Soil temperature data were collected at daily intervals from 2 distinct observatories, Kovilpatti and Ooty, representing semi-arid and high-altitude agro-climatic regions, respectively. A liquid in glass mercurial soil thermometer, which works based on the thermal expansion of mercury, is fixed at the desired depth (5, 10 and 20 cm). At each site, observations were recorded twice daily (morning and afternoon) at 3 soil depths: (5, 10 and 20 cm). The dataset spans the period 2009–2019 for both locations and was subjected to quality checks to ensure completeness and reliability before analysis (Table 1). For temporal assessment, the daily data were aggregated into monthly, seasonal and annual averages. Seasonal classification followed the India Meteorological Department (IMD) scheme: Winter (January–February), pre-monsoon (March–May), southwest monsoon (June–September) and post-monsoon (October–December). This structured temporal grouping enabled consistent comparison of soil temperature variability and long-term trends across depths and agro-climatic zones.

Table 1. Data acquisition and observation details of 2 observatories

Particulars		Kovilpatti	Ooty
Total period (Yrs)		11 (2009–2019)	11 (2009–2019)
Time of data taken	Morning	7.18 am	7.24 am
	Afternoon	2.18 pm	2.24 pm
Instrument		Soil thermometer	Soil thermometer
Number of observations (all depths and both morning and afternoon)		24102	24102

Autocorrelation

Before applying trend analysis, the independence of observations was assessed because soil temperature data often exhibit a memory, where a value at time t is correlated with previous values. Lag-1 autocorrelation coefficients were computed using RStudio for each time series and tested at the 95 % confidence level. When the autocorrelation was not significant, the standard MK test was used; when significant, the MMK test was adopted to account for serial dependence and ensure reliable trend detection (12).

Trend computing methods

Preliminary exploratory data analysis included evaluating the data structure, computing descriptive statistics such as the mean and standard deviation (SD) to summarise central tendency and variability, estimating slope using the Theil-Sen estimator and examining autocorrelation through the autocorrelation function. If the data were independent (i.e., no significant autocorrelation detected), the standard MK test, known for its robustness with large sample sizes and non-normal data, was applied. When autocorrelation was present, the MMK test was preferred because it adjusts the variance of the MK statistic to correct for serial correlation. Sen's slope estimator was used to quantify the magnitude of monotonic trends, providing a reliable measure of annual temperature change even in the presence of outliers.

Mann-Kendall (MK) test

The Mann-Kendall (MK) test was applied to detect the presence of monotonic trends in the time series (13). The test was conducted under the null hypothesis of no trend. The standardised z-statistic was computed to assess statistical significance at the selected confidence level ($\alpha = 0.05$). A trend was considered statistically significant when the calculated z-value exceeded the corresponding critical threshold. The test statistic is computed as follows,

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(X_j - X_i) \quad (\text{Eqn. 1})$$

Where X_i and X_j represent the values of the sequences i and j respectively and n denotes the length of the time series. The mean and variance of S are given by:

$$E[S] = 0$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m T_i i(i-1)(2i+5)}{18} \quad (\text{Eqn. 2})$$

Where, T_i represents the count of data points within the tied group, m denotes the number of tied rank groups

Modified Mann-Kendall (MMK) trend test

When significant serial autocorrelation was detected, the MMK test was applied. This approach adjusts the variance of the MK statistic by incorporating the effective sample size derived from significant lag correlations, thereby reducing inflation of trend significance. Statistical significance was evaluated at the 95 % level using the adjusted test statistic (14, 15).

Sen's slope estimator

The magnitude of the detected trend was estimated using Sen's slope estimator. The median of all pairwise slopes was computed to quantify the annual rate of change in soil temperature. This estimate was reported alongside the MK/MMK test results to indicate the intensity of the identified trend (16).

Lag analysis using cross-correlation

Lag analysis between maximum temperature (T_{max}) and soil temperature at 5, 10 and 20 cm was performed separately for morning and afternoon observations at each station. Weekly averaged time-series data were standardised before analysis. Cross-correlation functions were computed and the lag corresponding to the maximum statistically significant correlation ($p < 0.05$) was identified as the effective response time. Analysis was conducted independently for each depth to capture depth-dependent thermal responses.

Statistical software

All statistical computations, data cleaning and visualisations were performed using RStudio (Version R 4.5.2). The key libraries used included tidyverse for data manipulation, modifiedmk for trend analysis, trend for slope estimation and writextl for exporting the results.

Results

Soil temperature exhibited significant temporal variability across depths at monthly, seasonal and annual time scales at both locations (Fig. 1–8).

Annual, monthly and seasonal variability

At Ooty, annual morning temperatures peaked at 20 cm in 2013 (18.1 °C), with the minimum at 5 cm in 2016 (14.2 °C). Afternoon temperatures followed a similar pattern, peaking at 5 cm in 2013 (27.6 °C) and reaching a minimum at 20 cm in 2011 (19.8 °C). Monthly analysis showed the highest morning temperatures at 20 cm in April (19.6 °C) and lowest at 5 cm in January (11.8 °C). Afternoon values reached a maximum at 5 cm in March (30.0 °C) and a minimum at 20 cm in July (18.8 °C). Seasonally, the pre-monsoon recorded the highest morning (19.3 °C at 20 cm) and afternoon (29.1 °C at 5 cm) temperatures, while the lowest values were observed in winter (12.6 °C at 5 cm) and monsoon (19.5 °C at 20 cm) respectively.

Kovilpatti exhibited substantially higher temperatures across all scales. The highest annual morning temperature was at 20 cm in 2016 (34.1 °C), while the lowest was at 5 cm in 2011 (26.5 °C). Afternoon temperatures peaked at 5 cm in 2011 (49.9 °C) and were lowest at 20 cm in 2009 (33.1 °C). Monthly averages showed maximum morning temperatures in April (35.0 °C at 20 cm) and minima in January (24.4 °C at 5 cm). Afternoon temperatures were highest in April (49.6 °C at 5 cm) and lowest in December (30.4 °C at 20 cm). Seasonally, the pre-monsoon recorded the highest morning (34.3 °C at 20 cm) and afternoon (48.6 °C at 5 cm) temperatures. Conversely, the lowest values occurred during winter (25.0 °C at 5 cm) and post-monsoon (31.9 °C at 20 cm).

Overall, Kovilpatti consistently experienced higher soil temperatures than Ooty, with the pre-monsoon season representing the period of greatest thermal stress, particularly during the afternoon.

Depth-wise soil temperature gradient

Depth-wise analysis revealed consistent vertical temperature patterns at both sites. At Ooty, morning soil temperatures increased with depth, ranging from 14.6 °C at 5 cm to 17.6 °C at 20 cm. Conversely, afternoon temperatures decreased with depth, from 26.1 °C at 5 cm to 20.6 °C at 20 cm. Kovilpatti showed similar trends with higher magnitudes: morning temperatures rose from 27.9 °C at 5 cm to 32.5 °C at 20 cm, while afternoon temperatures declined from 44.3 °C at 5 cm to 34.0 °C at 20 cm.

Thermal stratification varied by site and season. At Ooty, the largest monthly temperature difference occurred between 5 and 20 cm during March afternoons (7.2 °C), while the smallest was between 5 and 10 cm in August mornings (1.1 °C), indicating reduced monsoon stratification. Kovilpatti exhibited stronger stratification, with a maximum afternoon difference of 14.3 °C between 5 and 20 cm in March. The minimum difference occurred in November mornings between 5 and 10 cm (0.6 °C). Overall, the strongest thermal gradient consistently occurred in the afternoon between 5 and 20 cm. Kovilpatti's annual depth-wise contrast (10.3 °C) was nearly double that of Ooty (5.5 °C), highlighting greater thermal stress and surface heating in the semi-arid environment.

Diurnal variability

Diurnal variability, calculated as the absolute difference between morning and afternoon soil temperatures, showed a clear depth-dependent pattern at both sites, with the highest amplitudes consistently occurring at 5 cm. At Ooty, the annual mean diurnal range decreased with depth, measuring 11.4 °C at 5 cm, 7.1 °C at 10 cm and 3.0 °C at 20 cm. Monthly analysis showed the highest diurnal amplitude at 5 cm in February (15.8 °C) during winter, while the lowest occurred at 20 cm in June (1.6 °C) during the monsoon. Kovilpatti exhibited stronger diurnal fluctuations overall. The annual mean diurnal range was 16.4 °C at 5 cm, decreasing to 12.9 °C at 10 cm and reaching a minimum of 1.4 °C at 20 cm. The maximum monthly diurnal difference occurred at 5 cm in March (21.4 °C) during the pre-monsoon, whereas the lowest amplitude was observed at 20 cm in July (0.9 °C) during the monsoon. Overall, diurnal variability was greatest at shallow depths, with Kovilpatti showing substantially higher amplitudes than Ooty, reflecting stronger surface heating and cooling cycles in the semi-arid environment.

Trend pattern

Trend analysis revealed contrasting soil temperature responses between the 2 locations and all the reported trends were presented with 95 % confidence intervals (CI). The morning and afternoon soil temperature trends over the month (A), season (B) and annual (C) for Ooty are given in Fig. 1 and 2 respectively. At Ooty, significant decreasing trends were observed across multiple temporal scales, particularly during winter. Morning soil temperature declined at 10 cm in February (-0.2 °C yr⁻¹; $p = 0.006$) and August (-0.1 °C yr⁻¹; $p = 0.005$) and at 20 cm in January (-0.3 °C yr⁻¹; $p = 0.043$). Afternoon temperatures showed stronger cooling, with the largest decreases at 5 cm in January (-0.5 °C yr⁻¹; $p = 0.001$) and February (-0.6 °C yr⁻¹; $p = 0.003$). Seasonal analysis confirmed winter cooling, with morning temperatures declining by approximately -0.3 °C yr⁻¹ at 10 and 20 cm ($p = 0.013$ and $p = 0.029$ respectively) and afternoon temperatures decreasing by -0.5 °C yr⁻¹ at 5 cm ($p = 0.001$). Annual trends also reflected cooling at 10 cm in the morning (-0.1 °C yr⁻¹; $p = 0.008$) and 5 cm in the afternoon (-0.2 °C yr⁻¹; $p = 0.029$).

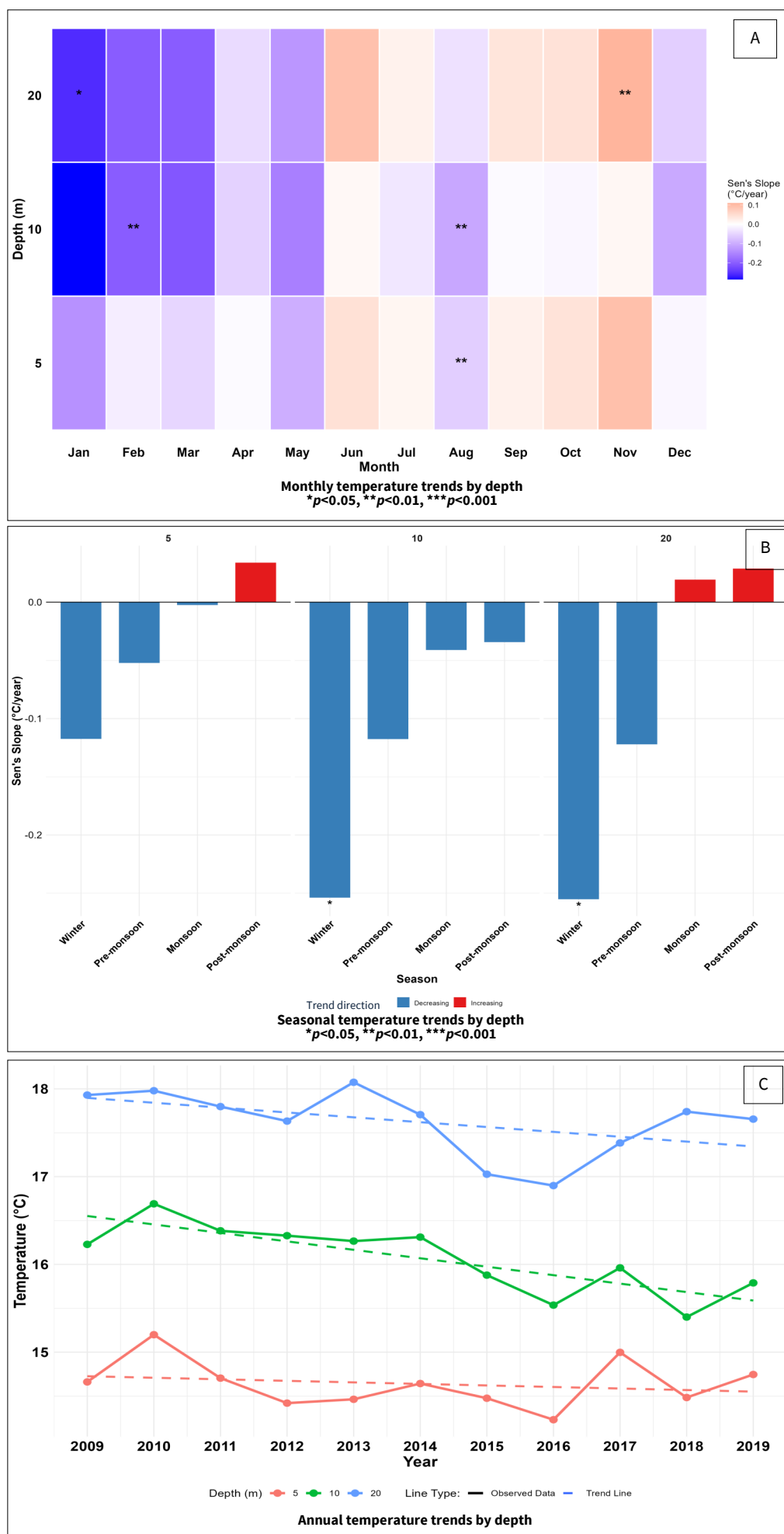


Fig. 1. Soil temperature trends for Ooty during the morning hours.

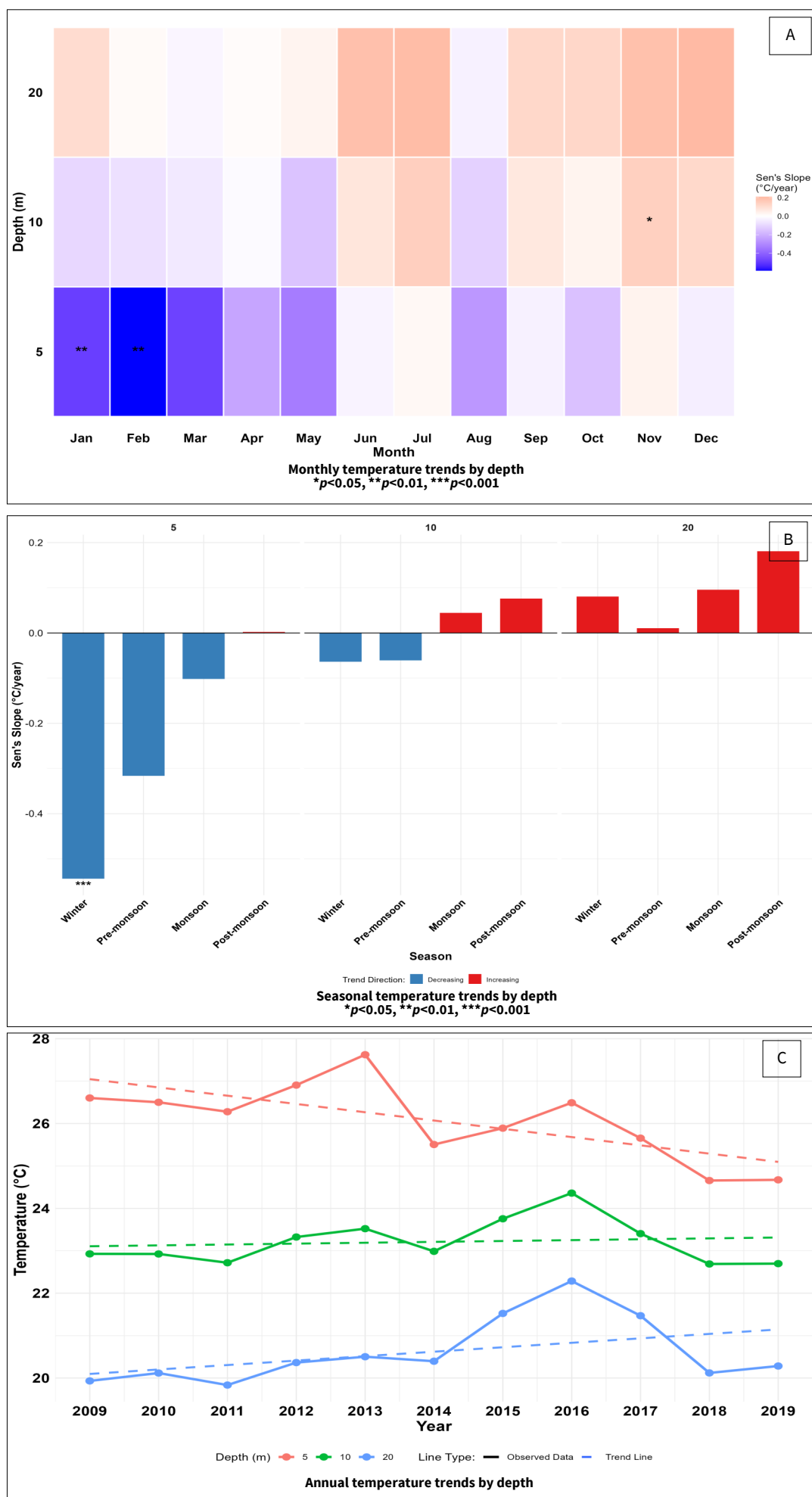


Fig. 2. Soil temperature trends for Ooty during the afternoon hours.

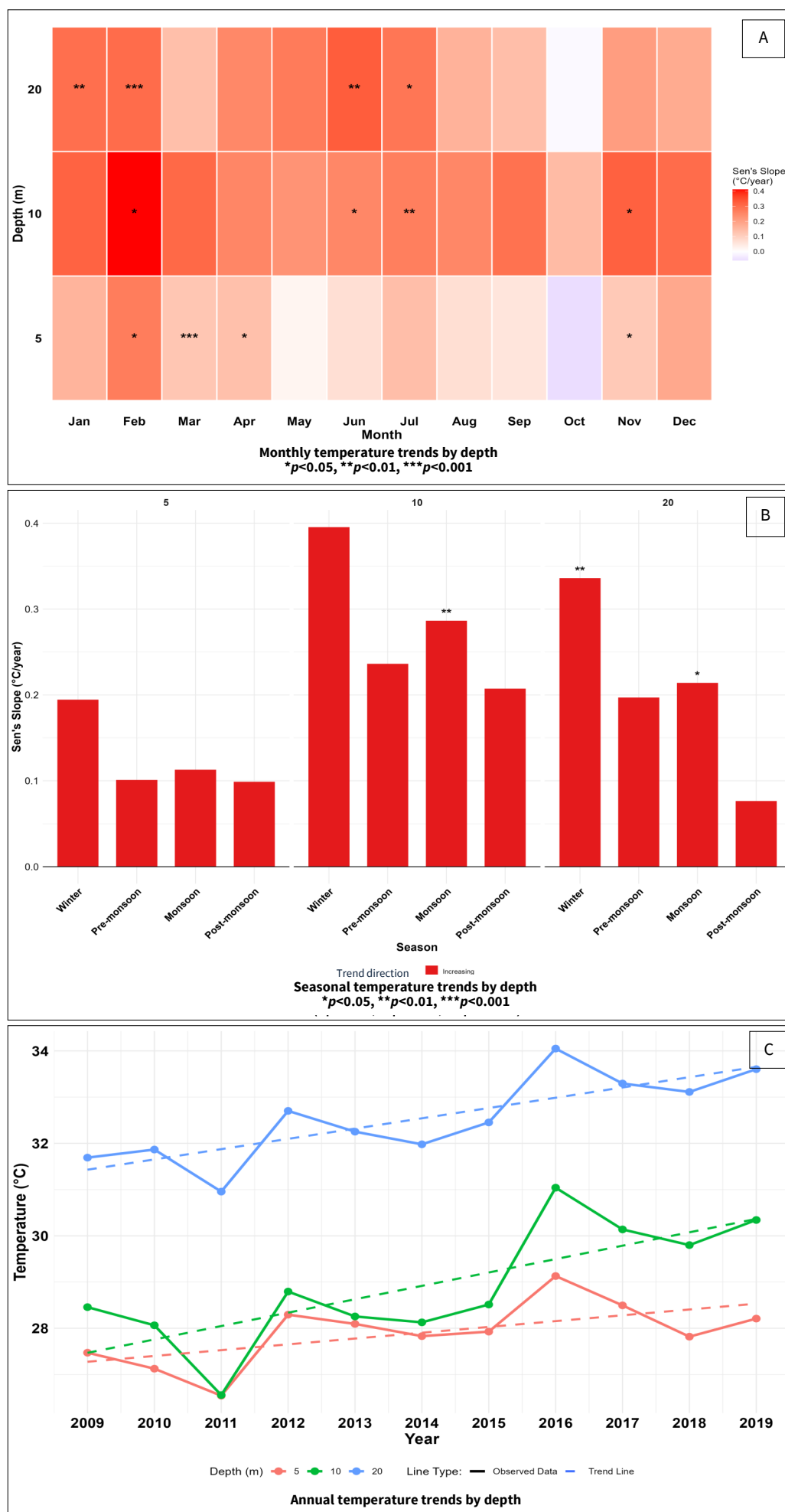


Fig. 3. Soil temperature trends for Kovilpatti during the morning hours.

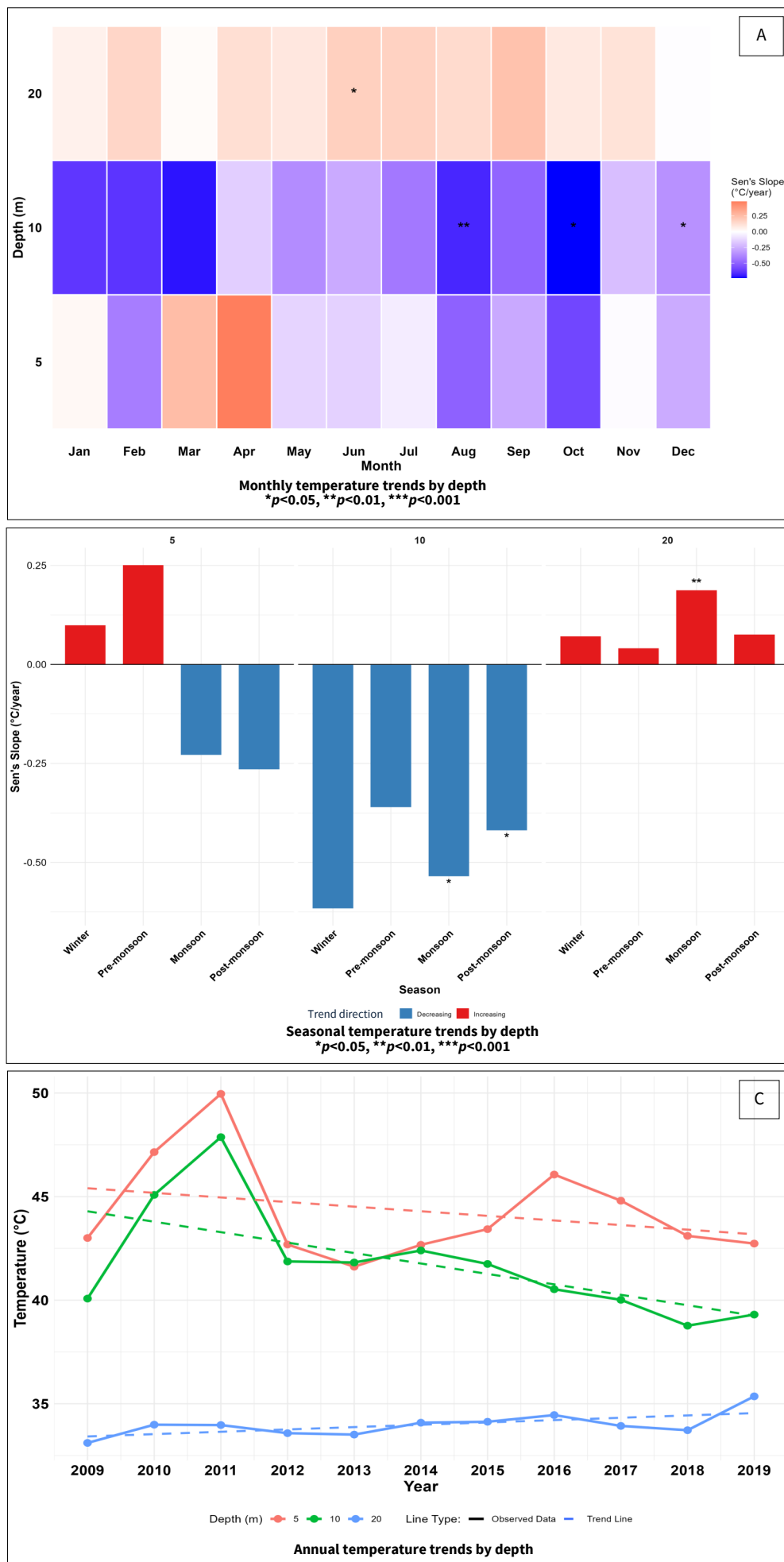


Fig. 4. Soil temperature trends for Kovilpatti during the afternoon hours.

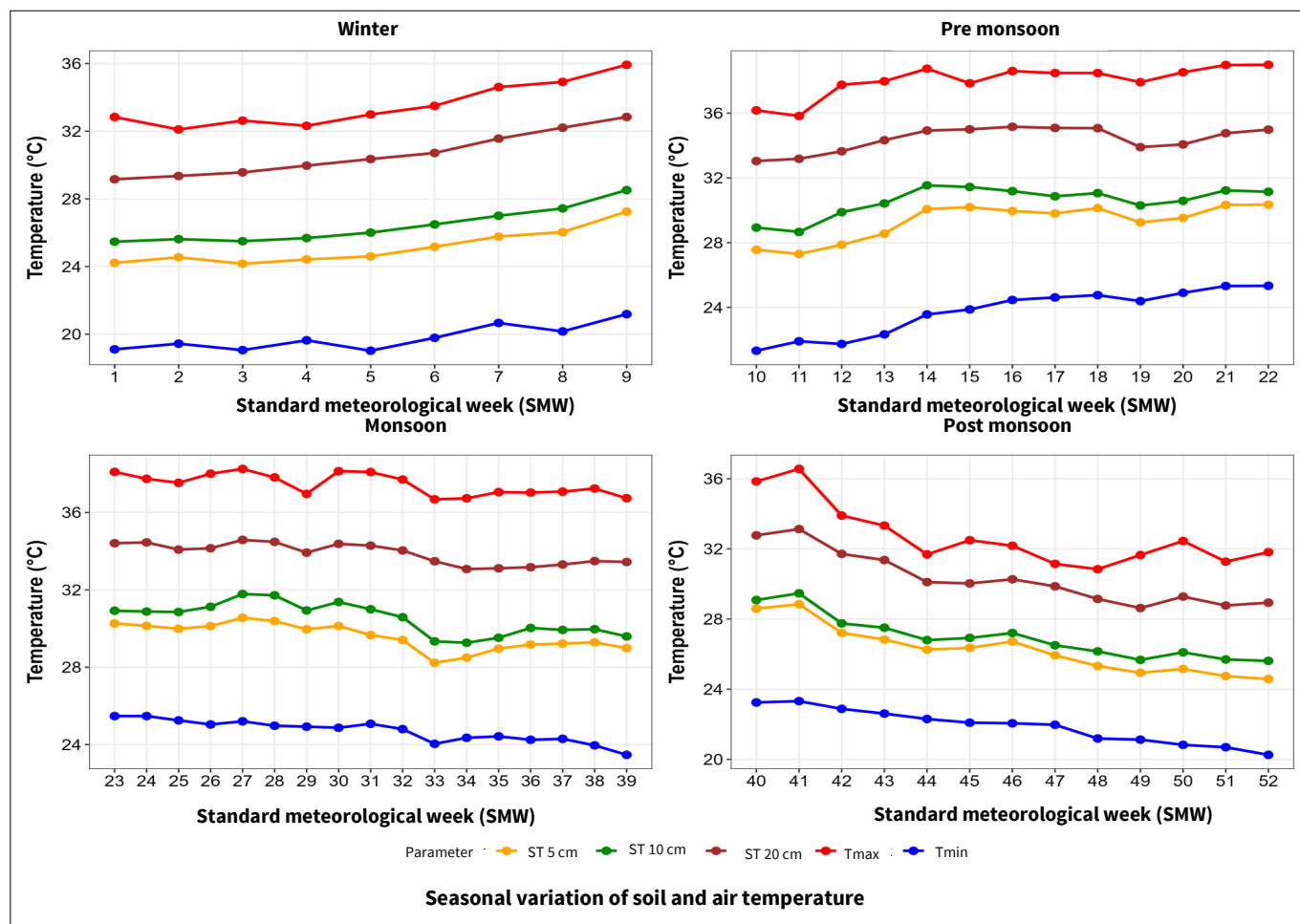


Fig. 5. Seasonal variations in soil and air temperature in the morning at Kovilpatti.

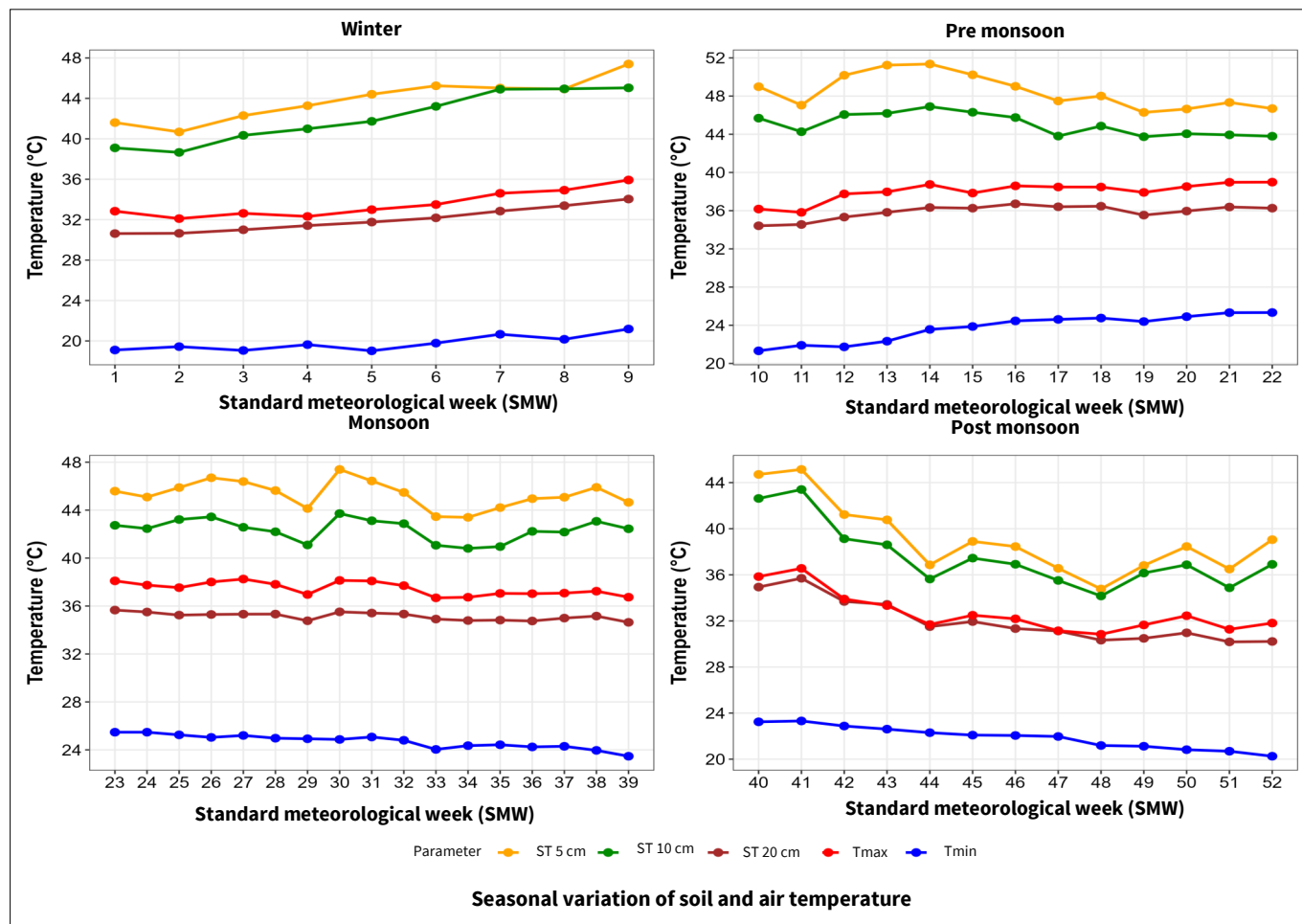


Fig. 6. Seasonal variations in soil and air temperature in the afternoon at Kovilpatti.

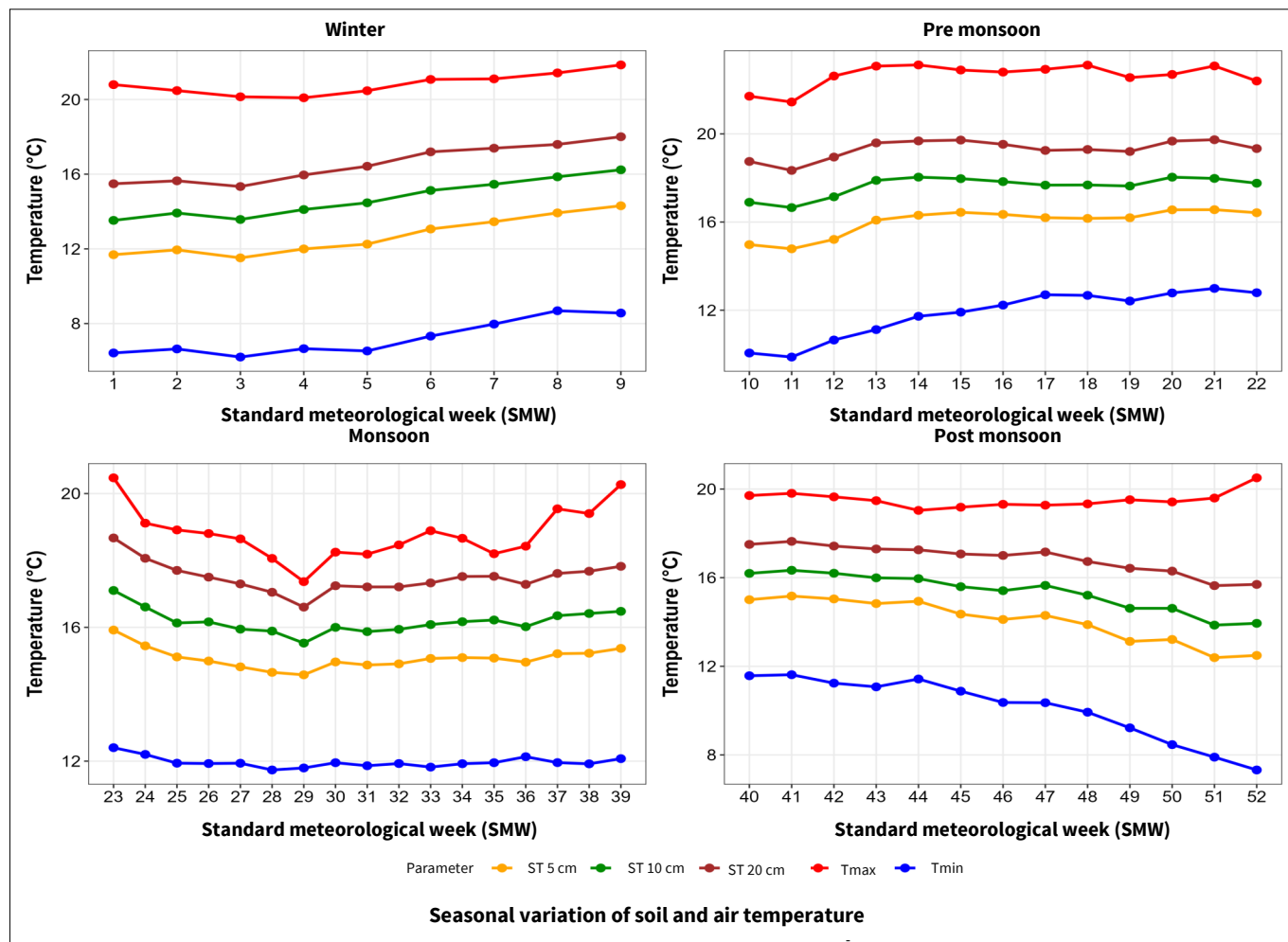


Fig. 7. Seasonal variations in soil and air temperature in the morning at Ooty.

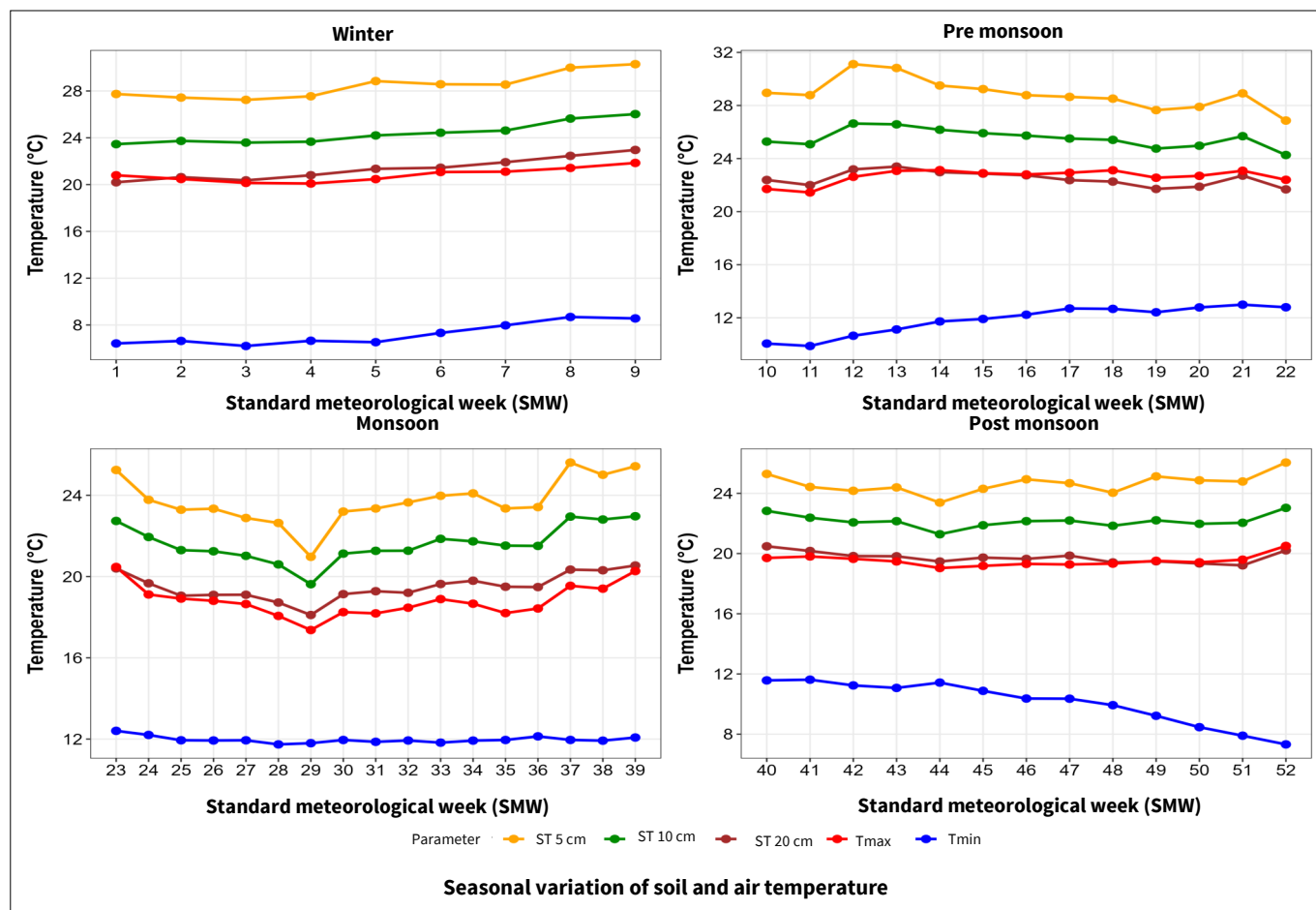


Fig. 8. Seasonal variations in soil and air temperature in the afternoon at Ooty.

The morning and afternoon soil temperature trends over the month (A), season (B) and annual (C) for Kovilpatti are given in Fig. 3 and 4 respectively. In contrast, Kovilpatti showed predominantly increasing morning soil temperatures across all temporal scales. Significant annual warming was observed at 10 cm ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.029$) and 20 cm ($0.2\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.008$). Monthly increase was widespread at 5 cm in February ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.029$), March ($0.1\text{ }^{\circ}\text{C yr}^{-1}$; $p<0.001$), April ($0.1\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.048$) and November ($0.1\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.020$); at 10 cm in February ($0.4\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.043$), June ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.020$), July ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.002$) and November ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.020$); and at 20 cm in January and February ($0.3\text{ }^{\circ}\text{C yr}^{-1}$ each; $p=0.005$ and $p<0.001$, respectively), June ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.008$) and July ($0.3\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.013$). During the morning period, seasonal warming was evident during the monsoon ($0.3\text{ }^{\circ}\text{C yr}^{-1}$ at 10 cm, $p=0.008$; $0.2\text{ }^{\circ}\text{C yr}^{-1}$ at 20 cm, $p=0.029$) and winter ($0.3\text{ }^{\circ}\text{C yr}^{-1}$ at 20 cm, $p=0.005$). Afternoon temperatures at Kovilpatti showed mixed trends. Significant cooling occurred at 10 cm in August ($-0.7\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.008$), October ($-0.7\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.043$) and December ($-0.4\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.029$).

In contrast, warming was observed at 20cm, particularly in June ($0.2\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.035$). Seasonal afternoon trends showed decreases during the monsoon ($-0.5\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.013$) and post-monsoon ($-0.4\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.042$) at 10cm, while 20cm exhibited warming during the monsoon ($0.2\text{ }^{\circ}\text{C yr}^{-1}$; $p=0.002$). These contrasting trends highlight distinct soil thermal dynamics: Ooty shows consistent cooling in surface layers during colder months, whereas Kovilpatti exhibits widespread morning warming and selective afternoon cooling, reflecting site-specific climatic and soil-moisture interactions.

Phase relationship between maximum air temperature and soil temperature

The seasonal variations in soil and air temperature in the morning at Kovilpatti are illustrated in Fig. 5. At Kovilpatti, morning soil temperatures at 5 and 10 cm showed positive lag values of 6 weeks, indicating that peak soil temperatures occurred well after the maximum air temperature (Tmax). This delay reflects the thermal inertia of the soil, which slows the transfer of heat into the upper layers. In contrast, the 20 cm depth exhibited a negative lag of -4 weeks, suggesting that deeper soil layers reached their maximum temperature earlier than the air, likely due to slower but more sustained subsurface heat transfer.

In the afternoon, all depths at Kovilpatti showed negative lags (-8 weeks at 5 and 10 cm and -4 weeks at 20 cm), indicating that soil temperatures peaked before Tmax. This pattern reflects rapid surface heating driven by direct solar radiation, causing the soil to warm earlier in the day relative to the air. The seasonal variations in soil and air temperature in the afternoon at Kovilpatti are given in Fig. 6.

At Ooty, morning lag values were generally small and positive, with 7-week lags at 5 and 20 cm and 1-week lag at 10 cm, indicating a more synchronised soil-air temperature response in the cooler hill environment. Afternoon lags were consistently -2 weeks across all depths, showing that soil temperatures peaked slightly before Tmax, similar to Kovilpatti but with shorter lead times. The seasonal variations in soil and air temperature in the morning and afternoon at Ooty are illustrated in the Fig. 7 and 8 respectively.

Overall, the lag patterns demonstrate that the phase relationship between air and soil temperature varies with depth, time of day and local climate. Positive morning lags reflect the moderating effect of thermal inertia, while negative afternoon lags indicate rapid surface heating. Smaller or negative lags at deeper layers highlight the complex subsurface thermal dynamics influenced by soil properties and climatic conditions.

Discussion

The contrasting soil temperature trends observed between Kovilpatti and Ooty highlight the strong climate control on soil thermal regimes and associated processes. Kovilpatti recorded with higher soil temperatures than Ooty. Other than climatic and environmental factors, these dynamics are further influenced by soil texture. Black soils (Vertisols) of Kovilpatti exhibit significantly higher thermal retention and surface temperatures compared to the clay loam soils of Ooty. The high heat absorption capacity and lower albedo of black soils contribute to the greater thermal stress observed in the semi-arid environment of Kovilpatti. At Ooty, significant decreasing trends in both morning and afternoon soil temperatures, particularly during winter and at shallow depths, indicate a progressive cooling of the surface soil layer. This pattern is consistent with the climatic characteristics of high-altitude ecosystems, where lower ambient temperatures, higher humidity, increased cloud cover and frequent precipitation reduce soil heat accumulation (17, 18). Such cooling may also be influenced by vegetation or land-use changes that enhance surface insulation (19). These sharply differing climatic settings provide an ideal natural gradient for assessing spatial variability in soil thermal regimes.

The pronounced winter cooling at 5 cm in the afternoon suggests that surface soils are highly sensitive to seasonal climatic variability, with potential impacts on microbial activity, nutrient cycling and shallow-rooted plant growth (7, 20). In contrast, slight warming trends at deeper layers (20 cm in the morning and 10 cm in the afternoon) likely reflect thermal inertia and delayed heat transfer, indicating a more complex vertical temperature response to atmospheric forcing (21). Kovilpatti, on the other hand, exhibits predominantly increasing morning soil temperatures across depths and seasons, consistent with warming expected in semi-arid environments exposed to intense solar radiation and limited soil moisture (22). The marked increases during winter and summer point to intensifying thermal stress, which may exacerbate soil moisture deficits and influence crop productivity and soil biological processes. However, the concurrent decreasing trends in afternoon temperatures at 10 cm, especially during monsoon and post-monsoon periods, suggest a more nuanced thermal regime. These declines may be driven by episodic rainfall (23), enhanced soil moisture, or vegetation cover that moderates afternoon heat flux. The warming observed at 20 cm in the afternoon further underscores depth-dependent heat exchange processes unique to semi-arid soils. Together, these findings reveal that soil temperature dynamics are shaped by the interplay of climate, soil moisture, vegetation and depth-specific thermal properties, resulting in distinct thermal signatures across agro-climatic zones.

Ecological and hydrological implications

Soil biogeochemistry and root dynamics

Warming of subsurface layers at Kovilpatti (10–20 cm) may stimulate microbial activity, accelerate organic matter decomposition and enhance nutrient mineralisation, potentially increasing soil respiration and altering carbon cycling. In contrast, winter cooling of surface soils at Ooty may slow microbial processes and influence the growth and functioning of shallow-rooted plants.

Plant stress and agricultural effects

High afternoon temperatures and large diurnal amplitudes in Kovilpatti increase thermal stress on crops, particularly before the monsoon when soil moisture is low. Conversely, winter cooling in Ooty may affect the survival of overwintering crops and delay germination or early growth stages.

Soil moisture interactions

Soil temperature strongly influences moisture dynamics. Warming enhances evaporation and surface drying, which can further amplify soil heating. In contrast, monsoon-driven increases in soil moisture help moderate temperature extremes. The observed seasonal patterns emphasise the importance of soil moisture-temperature interactions, suggesting that future studies should integrate simultaneous monitoring of both variables.

Conclusion

The contrasting soil temperature trends observed between Kovilpatti and Ooty clearly demonstrate how site-specific climatic conditions shape soil thermal regimes. In Ooty, surface soil (0–5 cm) showed significant cooling trends, especially during winter. While such cooling may reduce thermal stress, it can also suppress microbial activity, slow nutrient cycling and affect shallow-rooted crops during winter. In contrast, Kovilpatti showed significant warming trends, particularly at deeper soil layers (10–20 cm). This intensifying heat load heightens thermal stress, accelerates evaporation and may challenge crop resilience in the semi-arid environment. These depth-specific and season-specific responses underscore the dynamic interplay between solar radiation, soil moisture and atmospheric conditions.

Future work should integrate soil moisture, radiation balance and vegetation dynamics to better explain depth-wise thermal contrasts such as the 14.3 °C gradient in Kovilpatti and the 5.5 °C in Ooty. Semi-arid regions may require improved mulching, irrigation scheduling and residue retention to buffer rising soil temperatures, while high-altitude regions should prioritise soil cover and winter moisture conservation. Long-term monitoring of soil temperature-moisture-carbon interactions will support climate-resilient land management and enhance predictive modelling across contrasting agro-climatic zones.

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Authors' contributions

PM was responsible for data collection, conducting statistical analysis and drafting the manuscript. DG conceptualised and designed the study, in addition to reviewing the manuscript. SNK contributed to the review, editing and coordination processes. JD and BK both participated in reviewing and editing. AB assisted with data collection and manuscript review. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the first author used Paperpal by Editage for language assistance. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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