The Trends in Climate and Determination of Climate-Yield Relationships in Different Tea-Growing Regions of Sri Lanka during the Period from 2010 to 2024

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Abstract. This work determined the temporal trends in key climatic variables in different tea-growing regions of Sri Lanka during 2010-2024 and determined climate-yield relationships. Daily meteorological data from Talawakelle, Ratnapura, Hantana, Kottawa and Passara, were computed into monthly means of maximum (T_{Max}), minimum (T_{Min}) and mean (T_{Mean}) temperatures and monthly totals of rainfall (R_F) and pan evaporation (E_T). Primary water balance (W_B) was computed as the difference between monthly totals of R_F and E_T. Change in each climatic variable was computed as the difference (i.e. anomaly) in its monthly value from the respective monthly mean during the reference period 2010-2014. Anomalies of climatic variables showed different temporal trends at different locations. Talawakelle, Hantana and Kottawa showed increasing trends in T_{Max} whereas Ratnapura and Hantana showed increasing trends in T_{Min}. All locations except Passara showed increasing trends in T_{Mean}. Ratnapura and Kottawa showed increasing trends in R_F whereas the rest did not show significant temporal trends. Best-fitting multiple regression models for climate-yield relationships included the second-order polynomials of a temperature-related variable (T_{Max} or T_{Min}) and a water-related variable (R_F or W_B). Estimated temperature thresholds showed that current monthly temperatures in Ratnapura and Kottawa have already exceeded the thresholds beyond which yields begin to decline. In contrast, current temperatures in Talawakelle are close to the threshold while those in Hantana and Passara are still below the threshold. Estimated water-related thresholds show that increasing R_F or W_B will have positive impacts on tea yields in Ratnapura and Hantana, but negative impacts in other locations.

Keywords: Climate change, tea yield, temperature, rainfall, water balance.

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1 Introduction

Tea is a highly climate sensitive crop (Wijeratne, 1996; FAO, 2016). This is because the processes of shoot initiation and leaf growth which determine the yield of tea are directly controlled by temperature and water availability (Carr and Stephens, 1992; Wijeratne, 2004; De Costa et al., 2010). Significant increasing trends in air temperature is the principal feature of global climate change caused by the enhanced greenhouse effect due to increased concentrations of greenhouse gases in the atmosphere (IPCC, 2021). Long-term analyses of air temperature at selected locations in Sri Lanka have shown increasing trends that are similar to or greater in magnitude than the corresponding global trends (De Costa, 2008). In contrast to the clear increasing trend of air temperature, the long-term trend of rainfall has been less clear, both globally and locally (De Costa, 2008; IPCC, 2021). At the global scale, increasing or decreasing trends as well as the absence of a significant trend in the long-term annual rainfall has been shown for different regions. Similarly, analyses across different time scales have shown varying trends for rainfall in different regions of Sri Lanka as well (Chandrapala, 1996; Malmgren et al., 2003; Jayawardene et al., 2005; Wickramagamage, 2015; Nisansala et al., 2020).

In Sri Lanka, tea is grown across a wide range of elevations from near sea level in the low-country up to *ca.* 2000 m above sea level in the up-country. As temperature decreases with elevation, the above range of elevations creates different temperature regimes for tea grown at different elevations. Furthermore, tea is grown on the south-western plains of Sri Lanka as well as on the western and eastern slopes of its central highlands. These regions of Sri Lanka experience different rainfall regimes because of the differential influence of the south-west and north-east monsoons. For example, the low-country tea grown in the south-western plains and the mid- and up-country teas grown on the western slope of the central highlands receive rainfall from both monsoons and the two inter-monsoons. Consequently, these tea crops grow under a high rainfall regime (> 1800 mm y^{-1}) which is well-distributed throughout the year. In contrast, the mid- and up-country teas that are grown on the eastern slope of the central highlands and the mid-country teas on its northern edge (e.g. Matale District) experience a lower (< 1800 mm y^{-1}) and more seasonal rainfall regime. When these different rainfall regimes are superimposed on the temperature variation brought about by elevation, a complex spectrum of climates is created in the tea-growing regions of Sri Lanka. Variations in local topography adds a further layer of complexity to the climate experienced by tea crops in Sri Lanka. Moreover, the global-scale atmospheric phenomenon, the El-Niño Southern Oscillation (ENSO), imposes further variability into the rainfall received in Sri Lanka (Suppiah, 1996; Malmgren et al., 2003; Zubair et al., 2008).

The above-described complexity in the climate of tea-growing regions of Sri Lanka means that the global trends of climate change (i.e. increasing trend in temperature and differential trends in rainfall) may not necessarily be reflected in the changes in climate experienced by the tea crops in Sri Lanka. Therefore, there is a need to characterize the direction and magnitude of change in temperature and rainfall in the different tea-growing regions of Sri Lanka.

Changes in the two key climatic variables, temperature and rainfall, combine to cause changes in the water balance of a tea-growing environment. Increasing air temperatures generally increase evapotranspiration from a crop-soil system and thereby influence the system water balance (Penman, 1948; Monteith, 1965). However, whether the water balance increases or decreases with long-term climate change would be determined by concurrent changes in rainfall, which determines the water input, and in solar irradiance, which determines the energy availability for evapotranspiration. Therefore, the water balance of different tea-growing regions of Sri Lanka may have undergone directional changes depending on the temporal trends of air temperature, rainfall and solar irradiance. Alternatively, there is a possibility that increasing evapotranspiration rates induced by increasing air temperatures may have been compensated by increasing rainfall so that the system water balance could remain unchanged.

Impacts of changes in temperature, rainfall and water balance on tea yield are determined by their respective impacts on the two yield components of tea, *viz.* the number of shoots per unit land area and the mean individual shoot weight (De Costa et al., 2007). Shoot initiation is controlled primarily by temperature where a genetically fixed thermal duration is required to initiate each successive shoot (Burgess and Carr, 1996a; Jayasinghe et al., 2014; Jayasinghe et al., 2018). Therefore, increasing temperatures are expected to increase the rate of shoot initiation as the required thermal duration would be completed within a shorter period of time. However, an increase in temperature beyond the optimum temperature for shoot initiation could reduce the rate of leaf initiation. Mean individual shoot weight is determined by the rates of shoot expansion and accumulation of biomass in the expanding shoot (Wijeratne, 2004). These two processes are controlled by both temperature and water availability, both of which have positive effects on shoot weight (Burgess and Carr, 1997; Burgess and Carr, 1996b). However, supra-optimal temperatures could reduce shoot weight by reducing shoot expansion rate while reduced solar irradiance and excessive water due to high rainfall could reduce shoot weight via decreased photosynthesis and increased disease incidence such as blister blight (De Silva et al., 1974; Mahadevan et al., 2024). Therefore, the complex array of possible changes in climate via different combinations of temporal trends in temperature, rainfall and water balance could impact tea yield in different tea-growing regions in different magnitudes and directions. Therefore, the principal objectives of this study were: (a) to determine the directions and magnitudes of changes in key climatic variables in the different tea-growing regions of Sri Lanka and (b) to determine the impacts of the above changes in climate on tea yields in the respective regions.

2 Materials and Methods

2.1 Meteorological Data

This study was done using the daily meteorological data collected at the stations maintained by the Tea Research Institute (TRI) of Sri Lanka and its Research and Extension Centres, at St. Coombs, Talawakelle (Latitude 6˚54' N; Longitude 80˚42 E; 1394 above mean sea level), St. Joachim, Ratnapura (Lat. 6˚43′ N ; Long. 80˚ 21' E; 29 m amsl), Hantana, Kandy (Lat. 7˚16' N; Long. 80˚38' E; 762 m amsl), Kottawa, Galle (Lat. 6˚06' N; Long. 80˚19' E; 30 m amsl) and Passara (Lat. 6˚57' N; Long. 81˚07 E; 1120 m amsl). The meteorological data had been recorded manually on a daily basis using standard procedures. Data were available from 2010 onwards at all locations except Ratnapura, where they were available only from 2012 onwards. Monthly means of maximum (T_{Max}), minimum (T_{Min}) and mean (T_{Mean}) temperatures and the diurnal temperature range (DTR) (ºC) and monthly totals of rainfall (R_F) (mm), pan evaporation rate (E_T) (mm) and sunshine hours (SSH) (h) were extracted. Daily mean temperature (T_{Mean}) had been calculated as the arithmetic mean of T_{Max} and T_{Min} on a daily basis while DTR was calculated similarly as the difference between T_{Max} and T_{Min}. The respective grand means of T_{Mean} and DTR over a month were calculated as the monthly mean T_{Mean} and DTR. A primary system water balance (W_B) was computed on a monthly basis as the difference between monthly totals of R_F and E_T.

2.2 Yield Data

Monthly tea yield data were obtained from the records maintained at the respective locations. At St. Coombs, Talawakelle and St. Joachim, Ratnapura, yield data were available as ‘Made Tea’ in kg ha^{-1}. In other locations, yield data were available as ‘Green Leaf’ in kg ha^{-1}. Green leaf yield data were converted to Made Tea yields using a Net Outturn (NOT) value of 21.5% for the months of January, February, March, July and August and a NOT value of 21.0% for the rest of the year (SLTB Circular, 2021 TC/CIR(204)-06(6)2021; Ziyad Mohamad, 2003).

The yield data have been obtained from a mixture of cultivars grown at the respective locations during the 15-year period from 2010 to 2024. There were cultivars from 2000, 3000 and 4000 series and a few estate cultivars.

2.3 Determination of Changes (i.e. Anomalies) in Climatic and Yield Data over Time

Both the climatic variables and tea yields showed inherent variations across different locations. Furthermore, within a given location, climate and yield varied among different months of the year. Therefore, changes (called ‘anomalies’ in climate change literature) in the climatic variables and the yield were computed relative to their baseline average values of each month at each location. For each climatic variable and yield, the respective arithmetic average during the five-year period from 2010 to 2014 was taken as the baseline average for calculation of anomalies as follows:

$$(aT_{Max})_{ij} = (T_{Max})_{ij} - (bT_{Max})_{ij} \quad (1)$$

where, $(aT_{Max})_{ij}$ is the anomaly (i.e. change) of monthly mean maximum temperature during the i^{th} month at j^{th} location, $(T_{Max})_{ij}$ the monthly mean maximum temperature during the i^{th} month at j^{th} location and $(bT_{Max})_{ij}$ the baseline mean maximum temperature of the i^{th} month at j^{th} location for 2010-2014. Therefore, an increase in T_{Max} in a given month, given year and a given location above the corresponding average baseline T_{Max} for 2010-2014 is shown as a positive anomaly and *vice versa*.

Similarly, anomalies of other climatic variables were computed as,

$$(aT_{Min})_{ij} = (T_{Min})_{ij} - (bT_{Min})_{ij} \tag{2}$$
$$(aT_{Mean})_{ij} = (T_{Mean})_{ij} - (bT_{Mean})_{ij} \tag{3}$$
$$(aDTR)_{ij} = (DTR)_{ij} - (bDTR)_{ij} \tag{4}$$
$$(aR_F)_{ij} = (R_F)_{ij} - (bR_F)_{ij} \tag{5}$$
$$(aE_T)_{ij} = (E_T)_{ij} - (bE_T)_{ij} \tag{6}$$
$$(aW_B)_{ij} = (W_B)_{ij} - (bW_B)_{ij} \tag{7}$$
$$(aSSH)_{ij} = (SSH)_{ij} - (bSSH)_{ij} \tag{8}$$

Anomaly of monthly made tea yield $(aYPH_m)$ was computed similarly as,

$$(aYPH_m)_{ij} = (YPH_m)_{ij} - (bYPH_m)_{ij} \tag{9}$$

When changes in climatic variables and yields are computed as anomalies, they are comparable across months, years and locations.

Annual made tea yield (YPH_a) of each location was computed by summing the respective monthly tea yields.

2.4 Statistical Analysis

Initially, monthly climatic and yield data from the five different locations were analyzed separately. Subsequently, all data were pooled and analyzed. Data sets of anomalies of each climatic variable and yield at each location were tested for conformity to the normal distribution using Proc Univariate in SAS statistical software using four different normality tests (i.e. Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling).

Variation of the anomalies of climatic variables and yield at each location over time during the 2010-2024 period was quantified, first, by linear regression analysis. When the anomaly of a climatic variable or yield at a given location was not normally distributed, the Mann-Kendall test was used to determine the trend of the variable over time. Subsequently, temporal trends of the pooled data sets were also determined using the same procedure.

Initially, for each location, relationships between the anomalies of monthly yield $(aYPH_m)$ and the anomalies of individual climatic variables of the corresponding months were examined by regression analysis using linear and second-order polynomial models. Subsequently, multiple regression models containing the second-order polynomial of the anomaly of a temperature variable (i.e. aT_{Max}, aT_{Min}, T_{Mean} or aDTR) and that of a water-related variable (i.e. aR_F or aW_B) as independent variables were tested for describing the relationship between anomalies of yield and climate at each location. Finally, multiple regression models combining the second-order polynomials of the anomalies of a temperature variable and a water-related variable with their interaction were tested. Out of all tested multiple regression models, the best-fitting model was selected based on four criteria, viz. the R^2, the Adjusted R^2, the Akaike Information Criterion (*AIC*) and the Root Mean Square Error (*RMSE*). The respective models having the highest R^2 and Adjusted R^2 and the lowest AIC and RMSE were selected as the best-fitting climate-yield relationship for each location. The same procedure was adopted to determine the best-fitting climate-yield relationship for the pooled data set. Based on the best-fitting climate-yield relationships, optimum monthly anomalies of different climatic variables beyond which monthly tea yields begin to decrease with increasing anomaly were estimated by differentiating the respective relationships at each location with respect to the anomaly of the climatic variable and equating the first derivative to zero.

3 Results

3.1 Climatic Trends

In Talawakelle, anomalies of monthly mean T_{Max} and T_{Mean} showed significant ($p < 0.05$) positive linear trends with time during the period from 2010 to 2024 (Table 1). However, the anomaly of monthly mean T_{Min} did not show a significant trend whereas that of monthly mean DTR showed a positive trend ($p = 0.0523$). The respective anomalies of monthly total R_F and W_B did not show significant trends. However, the anomaly of monthly total E_T showed a significant negative trend with time. The anomaly of monthly total SSH showed a positive trend ($p = 0.057$). For anomalies of variables that were not normally distributed, the Mann-Kendall τ confirmed the result of linear regression regarding the presence (T_{Mean}, SSH) or absence (T_{Min}, R_F and W_B) of a trend.

In Ratnapura, the anomaly of T_{Max} did not show a significant temporal trend (Table 2). In contrast, the anomalies of T_{Min} and T_{Mean} showed significant positive trends whereas that of DTR showed a significant negative trend. Notably, the anomalies of monthly total R_F and E_T showed significant positive trends. The anomalies of W_B and SSH showed positive and negative trends respectively, which were just below the threshold for statistical significance at $p = 0.05$. In the two variables which did not meet the criterion of normality in their distributions (i.e. R_F and W_B), the Mann-Kendall test results were in accordance with the trends of linear regression.

In Hantana, trends of anomalies of T_{Max}, T_{Min} and T_{Mean} were highly significantly ($p < 0.01$) positive (Table 3). In contrast, none of the anomalies of other climatic variables showed significant trends. Mann-Kendall tests agreed with these results for anomalies of variables which were not normally distributed.

Table 1 Annual rates of change from the 2010-2014 baseline means of key climatic variables in Talawakelle during the 2010-2024 period

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	24.00 ± 0.21	0.058**	Y	-	175
T_{Min}	14.30 ± 0.23	-0.007^{ns}	N	-0.051^{ns}	179
T_{Mean}	19.02 ± 0.09	0.026*	N	0.131^{ns}	175
DTR	9.98 ± 0.40	0.065†	Y	-	175
R_F	182.4 ± 16.0	0.060^{ns}	N	-0.015^{ns}	180
E_T	68.27 ± 2.58	-1.078***	Y	-	180
W_B	114.2 ± 17.73	1.138^{ns}	N	0.014^{ns}	180
SSH	144.6 ± 7.51	1.790†	N	0.096†	179

Cl. Var. – Climatic variables: T_{Max}, T_{Min}, T_{Mean} and DTR – Monthly means of maximum, minimum, mean temperatures and diurnal temperature range (°C $month^{-1}$); R_F, E_T and W_B – Monthly totals of rainfall, pan evaporation and water balance (mm $month^{-1}$); SSH – Monthly total sunshine hours (h $month^{-1}$). Std. Err. – Standard error of mean; Probability of regression slope and Kendall τ being not significantly different from zero: * <0.05; ** <0.01; *** <0.001; † 0.05-0.10. ns – non-significant at p=0.10. Nm – Normality of distribution of anomalies (Y-yes; N-no). n – Number of observations.

Table 2 Annual rates of change from the 2012-2014 baseline means of key climatic variables in Ratnapura during the 2012-2024 period

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	32.80 ± 0.24	0.014^{ns}	Y	-	144
T_{Min}	22.86 ± 0.13	0.070***	Y	-	144
T_{Mean}	27.83 ± 0.13	0.042**	Y	-	144
DTR	9.94 ± 0.28	-0.056**	Y	-	144
R_F	335.7 ± 29.9	11.491*	N	0.117*	144
E_T	72.25 ± 3.57	2.347^{ns}	Y	-	138
W_B	248.8 ± 35.6	8.340†	N	0.092^{ns}	138
SSH	132.8 ± 6.19	-1.263†	Y	-	139

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations.

In Kottawa, the anomalies of T_{Max} and T_{Mean} showed significantly positive trends whereas that of T_{Min} did not show a trend (Table 4). Anomalies of DTR and R_F showed positive trends, which were just below the threshold for statistical significance. However, the anomaly of E_T showed a highly significant ($p < 0.0001$) negative trend, with those of W_B and SSH not showing trends. For anomalies of T_{Mean}, R_F, W_B and SSH, which were not normally distributed, Mann-Kendall test results agreed with the results of linear regression.

In Passara, anomalies of a majority of climatic variables did not show significant trends (Table 5). The only exceptions were the anomalies of E_T and SSH, both of which showed significant negative temporal trends. For the anomalies of T_{Min}, T_{Mean}, DTR, R_F and E_T which were not normally distributed, Mann-Kendall τ agreed with the linear regression trend.

Table 3 Annual rates of change from the 2010-2014 baseline means of key climatic variables in Hantana during the 2010-2024 period

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	27.55 ± 0.22	0.052**	Y	-	168
T_{Min}	19.67 ± 0.15	0.048***	N	0.213***	137
T_{Mean}	23.58 ± 0.17	0.047**	N	0.173**	135
DTR	7.83 ± 0.33	-0.002^{ns}	Y	-	135
R_F	190.2 ± 18.3	0.917^{ns}	N	-0.028^{ns}	170
E_T	61.20 ± 2.80	-0.223^{ns}	Y	-	169
W_B	129.0 ± 20.1	1.124^{ns}	N	-0.025^{ns}	169
SSH	152.8 ± 6.00	-1.182^{ns}	Y	-	175

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations.

Table 4 Annual rates of change from the 2010-2014 baseline means of key climatic variables in Kottawa during the 2010-2024 period

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	30.85 ± 0.12	0.037**	Y	-	156
T_{Min}	22.99 ± 0.12	0.009^{ns}	Y	-	156
T_{Mean}	26.92 ± 0.07	0.023**	N	0.163**	156
DTR	7.86 ± 0.19	$0.028^{\dagger}$	Y	-	156
R_F	258.3 ± 20.7	$4.759^{\dagger}$	N	0.077^{ns}	156
E_T	86.60 ± 1.80	-2.403***	Y	-	143
W_B	171.7 ± 21.4	2.759^{ns}	N	0.061^{ns}	143
SSH	179.7 ± 4.37	-0.634^{ns}	N	-0.022^{ns}	168

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations.

When the respective anomalies of all five locations were pooled, all three temperature parameters (i.e. T_{Max}, T_{Min} and T_{Mean}) showed highly significant ($p < 0.01$) linear increasing trends during the period from 2010 to 2024 (Figs. 1.a-c). However, the pooled anomalies of DTR did not show a significant trend (Fig. 1.d). It can be observed that the anomalies tend to be greater in T_{Min} and DTR in comparison to T_{Max} and T_{Mean}. Furthermore, months with higher anomalies (i.e. climate extremes) are more frequent in Talawakelle than in other locations. This is especially true for DTR and T_{Min}. The pooled R_F anomalies showed a significant linear increasing trend whereas the pooled E_T anomalies showed a significant linear decreasing trend (Figs. 2.a and b). However, the pooled anomalies of W_B and SSH did not show significant linear trends (Figs. 2.c and d). Yet, it is notable that the pooled anomalies of SSH showed a second-order polynomial temporal trend ($p = 0.0859$) with a peak in 2015 (Fig. 2.d). It can be observed that higher anomalies of R_F (i.e. months with extremely high rainfall) tended to be more frequent in Ratnapura than in other locations (Fig. 2.a). Furthermore, Ratnapura showed more lower R_F anomalies (i.e. months with drought episodes) and a greater frequency of higher E_T anomalies (Fig. 2.b). As a result, greater frequencies of both higher and lower anomalies of W_B are shown in Ratnapura than in the other locations (Fig. 2.c). Talawakelle showed a greater frequency of both higher and lower anomalies of SSH (i.e. extremely sunny days and extremely cloudy days respectively) in comparison to other locations (Fig. 2.d).

Table 5 Annual rates of change from the 2010-2014 baseline means of key climatic variables in Passara during the 2010-2024 period

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	25.71 ± 0.21	0.012^{ns}	Y	-	171
T_{Min}	18.15 ± 0.15	-0.005^{ns}	N	-0.072^{ns}	171
T_{Mean}	21.93 ± 0.17	0.004^{ns}	N	0.006^{ns}	171
DTR	7.56 ± 0.12	0.016^{ns}	N	0.055^{ns}	171
R_F	177.5 ± 16.6	1.150^{ns}	N	0.001^{ns}	171
E_T	65.17 ± 2.43	-0.971***	N	-0.162**	165
W_B	112.3 ± 19.2	0.163^{ns}	Y	-	165
SSH	134.2 ± 4.51	-1.233*	Y	-	179

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations.

Distributions of the pooled anomalies of all climatic variables except that of E_T did not satisfy the criterion of normality (Table 6). Results of the Mann-Kendall test agreed with those of regression analysis in all climatic variables except the anomaly of R_F. Here, the Mann-Kendall τ was not significant ($p > 0.05$) despite the regression slope being significant ($p = 0.0181$).

Table 6 Annual rates of change from 2010-2014 baseline means of key climatic variables during the 2010-2024 period when the data from all five locations are pooled

Cl. Var.	Baseline (Mean ± Std. Err.)	Change (y^{-1})	Nm	Kendall τ	n
T_{Max}	27.84 ± 0.21	0.036***	N	0.110***	814
T_{Min}	19.24 ± 0.24	0.018**	N	0.067**	787
T_{Mean}	23.56 ± 0.22	0.026***	N	0.128***	781
DTR	8.62 ± 0.15	0.017^{ns}	N	0.033^{ns}	781
R_F	220.8 ± 9.36	2.706*	N	0.023^{ns}	821
E_T	70.77 ± 1.28	-0.491**	Y	-	795
W_B	146.6 ± 9.98	1.844	N	0.018^{ns}	795
SSH	150.5 ± 2.82	-0.821*	N	-0.024^{ns}	829

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations.

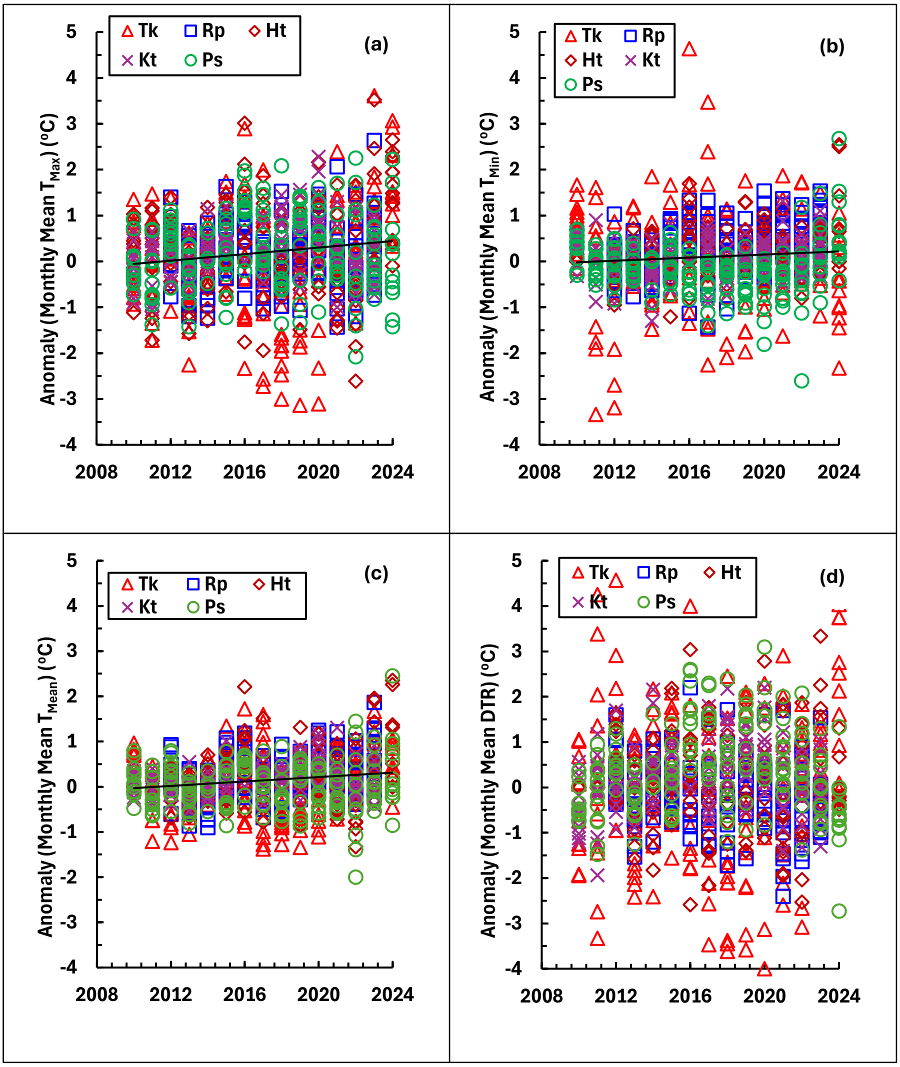

Fig. 1 Differences (Anomalies) of monthly means of temperature from the respective baseline monthly means: (a) Maximum temperature (T_{Max}); (b) Minimum temperature (T_{Min}); (c) Mean temperature (T_{Mean}); (d) Diurnal temperature range (DTR). Tk – Talawakelle; Rp – Ratnapura; Ht – Hantana; Kt – Kottawa; Ps – Passara. Trend lines show the significant trends for the pooled dataset. See text for further explanations.

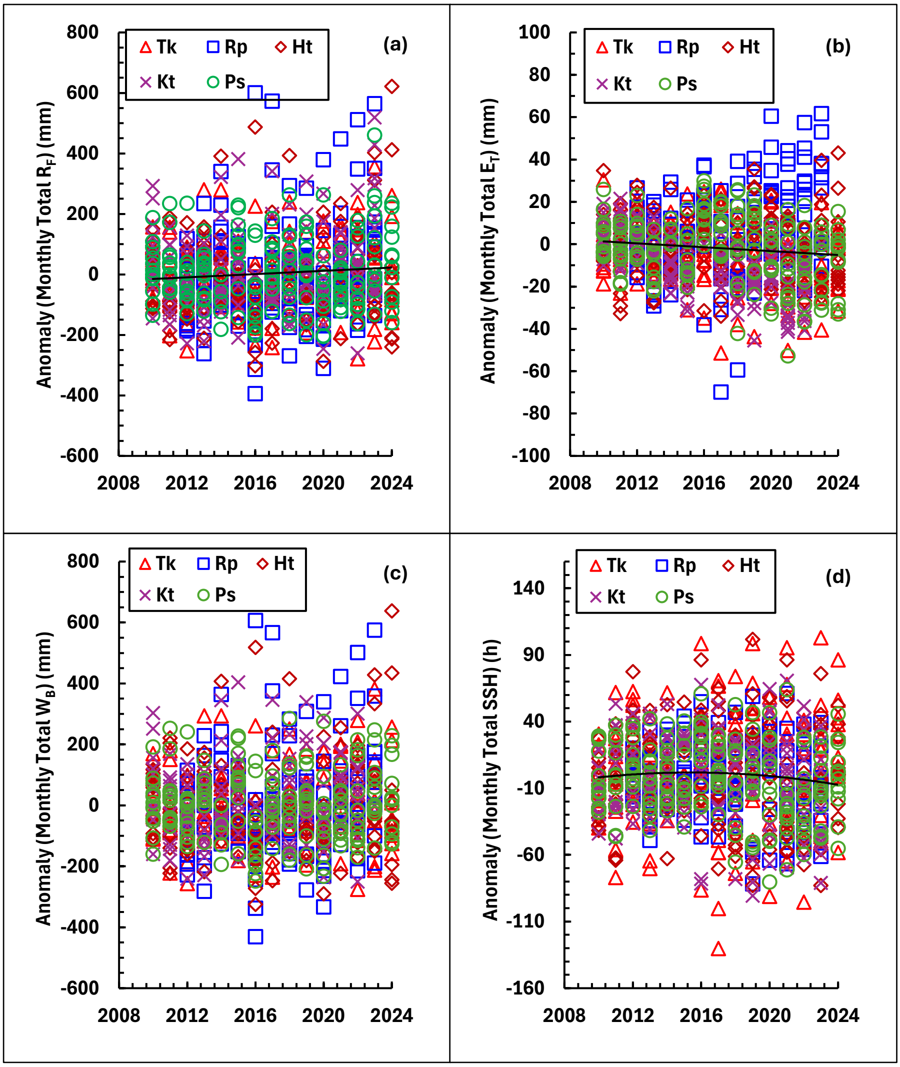

Fig. 2 Differences (Anomalies) of monthly totals of rainfall, pan evaporation, water balance and sunshine hours from the respective baseline monthly totals: (a) Rainfall (R_F); (b) Pan evaporation (E_T); (c) Water balance (W_B); (d) Sunshine hours (SSH). Tk – Talawakelle; Rp – Ratnapura; Ht – Hantana; Kt – Kottawa; Ps – Passara. Trend lines show the significant trends for the pooled dataset. See text for further explanations.

3.2 Yield trends

The annual total made tea yield (YPH_{an}) of Talawakelle, Ratnapura and Passara showed highly significant ($p < 0.01$) linear declining trends during the period from 2010 to 2024

(Fig. 3). In contrast, YPH_{an} of Kottawa showed a highly significant ($p = 0.0001$) increasing trend during the same period. On the other hand, YPH_{an} of Hantana showed a significant ($p < 0.05$) second-order polynomial trend, with YPH_{an} increasing with time until 2016 and then showing a decreasing trend.

Similar to YPH_{an}, anomalies of monthly made tea yields (YPH_m) of Talawakelle, Ratnapura and Passara showed highly significant ($p < 0.0001$) negative linear trends from 2010 to 2024 (Table 7). In contrast, the anomaly of YPH_m of Kottawa showed a highly significant ($p < 0.0001$) increasing trend, whereas the anomaly of YPH_m of Hantana showed a highly significant ($p < 0.0001$) second-order polynomial trend with a peak in 2016.

Table 7 Annual rates of change of monthly made tea yields during the 2010-2024 period relative to the 2010-2014 baseline means (i.e. anomalies) at different locations

Loc.	Baseline (Mean ± Std. Err.) (kg ha^{-1} month^{-1})	Change (kg ha^{-1} month^{-1} y^{-1})	Nm	Kendall τ	n
Talawakelle	185.6 ± 6.55	-4.527***	Y	-	180
Ratnapura	76.6 ± 1.83	-4.831***	N	-0.733***	180
Hantana	39.5 ± 2.03	-0.394^{ns}	Y	-	180
Kottawa	98.8 ± 3.15	9.610***	N	0.506***	180
Passara	180.5 ± 8.22	-3.962***	Y	-	180
Pooled[1]	116.2 ± 4.03	-0.821*	N	-0.146***	900
Pooled[2]	102.2 ± 2.61	-3.429***	N	-0.290***	720

Refer to the footnote of Table 1 for an explanation of abbreviations and interpretations. [1]Regression with data from all locations. [2]Regression with data from all locations except Kottawa.

When the anomalies of YPH_m of all locations were pooled, it showed a significant ($p < 0.05$) negative linear temporal trend. A steeper negative linear trend ($p < 0.0001$) was observed for the anomalies of YPH_m when the data from Kottawa were excluded. Anomalies of YPH_m of Talawakelle, Hantana and Passara were normally distributed. In Ratnapura and Kottawa where the distributions of anomalies of YPH_m deviated from normality, results of the Mann-Kendall test were in accordance with the temporal trends of regression analysis. A similar result was obtained for the pooled anomalies of YPH_m (both including and excluding Kottawa) as well. Kottawa showed substantially higher YPH_m anomalies than the rest of the locations, especially from 2018 onwards (Fig. 4). On the other hand, Talawakelle and Passara showed a greater frequency of lower YPH_m anomalies.

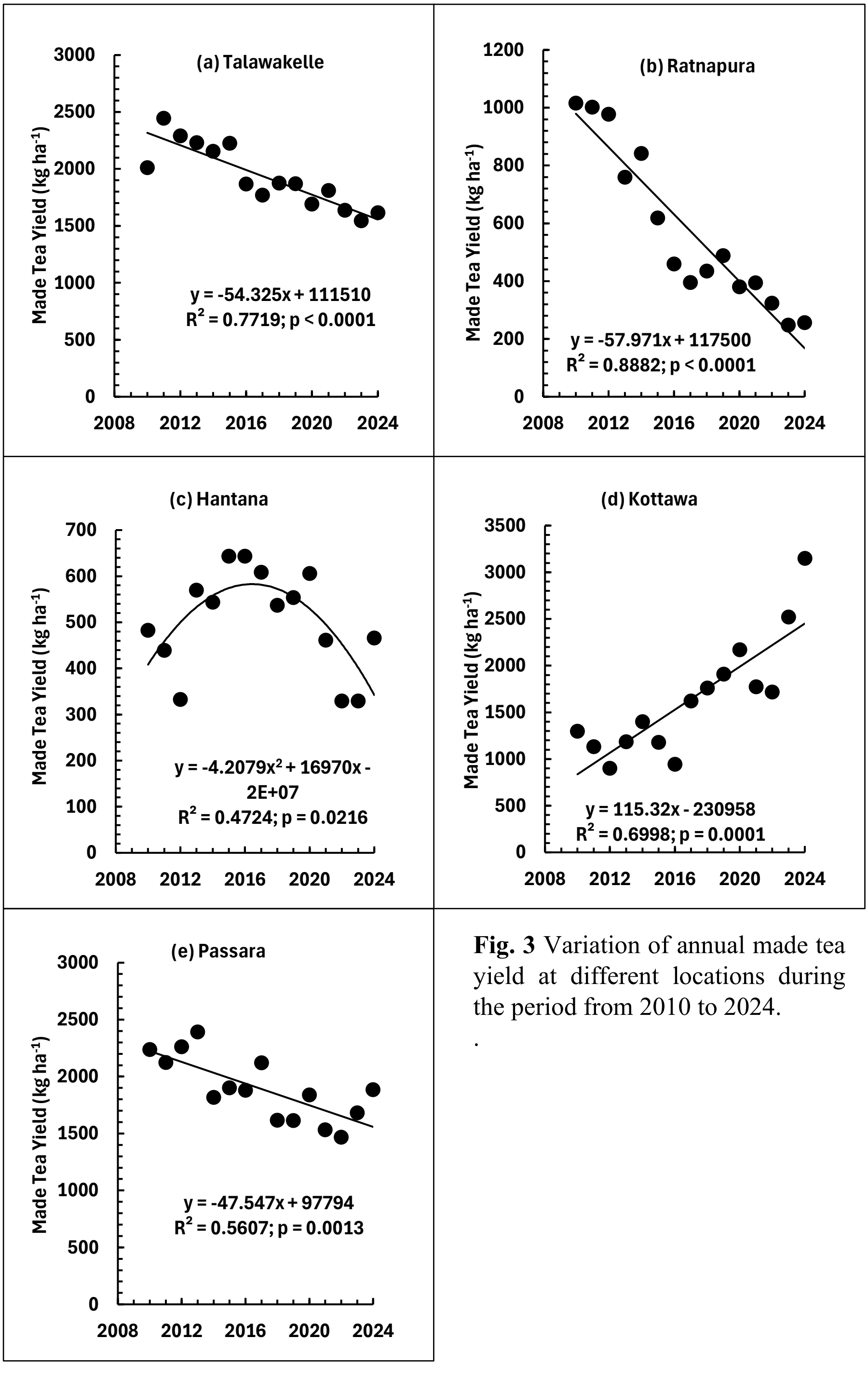

Fig. 3 Variation of annual made tea yield at different locations during the period from 2010 to 2024.

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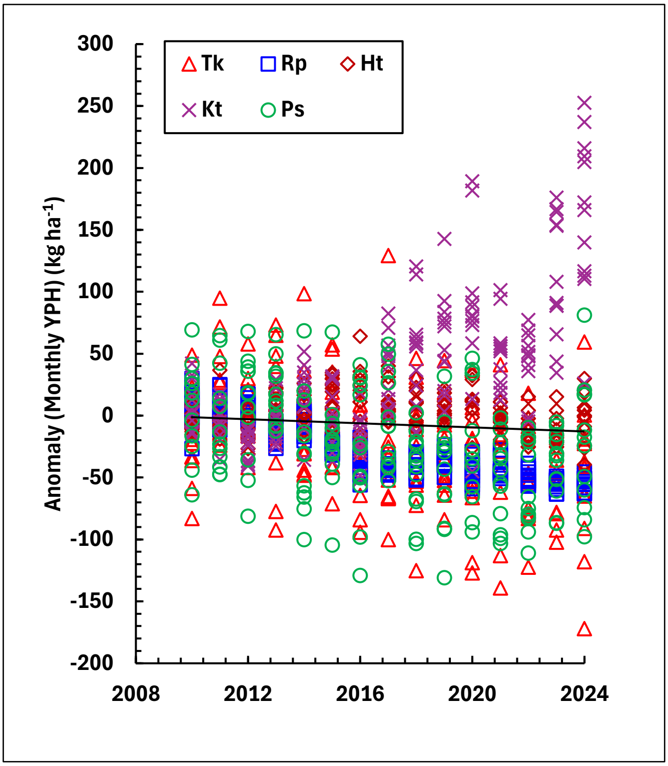

Fig. 4 Differences (Anomalies) of monthly made tea yield of different locations during 2010-2024 from the respective monthly baselines during 2010-2014. The trend line is for the pooled dataset.

3.3 Relationships between yield trends and climatic trends

In Talawakelle, there were no significant linear relationships between the anomaly of YPH_m and the anomalies of any temperature-related variable (i.e. T_{Max}, T_{Min}, T_{Mean} or DTR) or those of any water-related variable (i.e. R_F, E_T or W_B). However, the anomaly of YPH_m showed significant second-order polynomial relationships with anomalies of T_{Max} ($p = 0.0042$) and T_{Mean} ($p = 0.0214$). Highly significant relationships with the anomaly of YPH_m were shown when the second-order polynomials of T_{Max} were combined with those of R_F ($p = 0.0095$) and W_B ($p = 0.0091$). Significance of the respective multiple regression models were further improved when the respective interaction effects between T_{Max} and R_F and between T_{Max} and W_B were added as an independent variable to the respective models. The multiple regression model containing the second-order polynomials of T_{Max} and W_B plus the $T_{Max} \times W_B$ interaction was selected as the best-fitting model (Table 8) based on its higher R^2 and adjusted R^2 and lower AIC and RMSE values.

Table 8 Best-fitting multiple regression models of the relationship between the anomaly of monthly made tea yield ($aYPH_m$) and the respective anomalies of climatic variables

Location	Best-fitting model	p	Adjusted R^2	n
Talawakelle	$aYPH_m = 12.10 + (0.112\ aT_{Max}) - (7.084\ aT_{Max}^2) - (0.018\ aW_B) - (2.965 \times 10^{-4}\ aW_B^2) - (0.030\ aT_{Max}\ aW_B)$	0.005	0.066	175
Ratnapura	$aYPH_m = -24.955 - (8.933\ aT_{Min}) - (6.007\ aT_{Min}^2) + (4.86 \times 10^{-3}\ aR_F) - (3.799 \times 10^{-5}\ aR_F^2) - (0.030\ aT_{Min}\ aR_F)$	0.000	0.197	144
Hantana	$aYPH_m = 0.965 + (0.721\ aT_{Max}) - (1.746\ aT_{Max}^2) + (7.050 \times 10^{-3}\ aR_F) + (2.822 \times 10^{-5}\ aR_F^2) - (0.033\ aT_{Max}\ aR_F)$	0.009	0.062	168
Kottawa	$aYPH_m = 21.237 + (12.362\ aT_{Max}) + (5.400\ aT_{Max}^2) + (0.067\ aR_F) + (2.688 \times 10^{-5}\ aR_F^2)$	0.001	0.101	156
Passara	$aYPH_m = -13.400 + (5.407\ aT_{Min}) - (10.801\ aT_{Min}^2) + (0.018\ aW_B) - (3.786 \times 10^{-4}\ aW_B^2)$	0.033	0.039	165
Pooled	$aYPH_m = -6.168 + (6.102\ aT_{Max}) - (5.231\ aT_{Max}^2) + (0.023\ aW_B) - (1.095 \times 10^{-4}\ aW_B^2) - (0.022\ aT_{Max}\ aW_B)$	0.000	0.031	788

In Ratnapura, there were significant negative linear relationships between the anomaly of YPH_m and the anomalies of T_{Min} ($p < 0.0001$) and T_{Mean} ($p = 0.0045$). Precision of these relationships (as indicated by the R^2 values) improved when the respective second-order polynomials were fitted. Further improvements in precision could be obtained by combining the second-order polynomials of the anomalies of T_{Min} and R_F plus their interaction (Table 8).

In Hantana, there were no significant linear or second-order polynomial relationships between the anomaly of YPH_m and the anomaly of any of the temperature- or water-related climatic variables. There were only two significant multiple regression models between the anomaly of YPH_m and anomalies of climatic variables. Both these models included the second-order polynomial of the anomaly of T_{Max}. This was combined with the second-order polynomials of the anomalies of R_F and W_B and their respective interactions with T_{Max} in each of the two models. Based on the four criteria, the model containing the second-order polynomials of T_{Max} and R_F plus their interaction was selected as the best-fitting model (Table 8).

In Kottawa, the anomaly of YPH_m showed significant positive linear relationships with anomalies of T_{Min} ($p = 0.0230$), T_{Mean} ($p = 0.0101$) and R_F ($p = 0.0015$). The precision of the relationship with the anomaly of R_F improved when its second-order polynomial was considered. Out of several multiple regression models which combined the second-order polynomials of the anomalies of temperature and water-related variables, the best-fitting model contained the combination of second-order polynomials of the anomalies of T_{Max} and R_F (Table 8). Inclusion of the $T_{Max} \times R_F$ interaction did not improve the precision of the best-fitting model.

In Passara, none of the linear or second-order polynomial relationships between the anomaly of YPH_m and the anomalies of individual climatic variables were significant. Out of several multiple regression models which contained combinations of the anomalies of second-order polynomials as independent variables, the model containing the combination of the second-order polynomials of T_{Min} and W_B was the only model which achieved statistical significance at $p < 0.05$. Hence, it was selected as the best fitting model (Table 8).

When the anomalies of YPH_m and climatic variables of all five locations were pooled, no significant linear relationship could be observed between the anomaly of YPH_m and the anomaly of any of the climatic variables. On the other hand, significant second-order polynomial relationships were found between the anomaly of YPH_m and the anomalies of T_{Max} ($p < 0.0001$), T_{Min} ($p = 0.0125$), T_{Mean} ($p = 0.0001$) and DTR ($p = 0.0001$). Precision of these relationships increased when the second-order polynomials of the anomalies of R_F and W_B were included in the multiple regression models. The best-fitting model included the second-order polynomials of the anomalies of T_{Max} and W_B plus the $T_{Max} \times W_B$ interaction as independent variables (Table 8).

The estimated optimum anomalies beyond which YPH_m begins to decrease with increasing anomaly are shown in Table 9. At locations where T_{Max} is the temperature variable in the best-fitting model, the lowest optimum anomaly was in Kottawa whereas the highest optimum anomaly was in Hantana. In the two locations where the T_{Min} is the temperature variable in the best-fitting model, the optimum anomaly in Passara is greater than that in Ratnapura. In the pooled data set for which T_{Max} is the temperature variable, an anomaly of 0.58°C was estimated as the threshold for the commencement of YPH_m decline. In the three locations which had R_F as the water-related variable in the best-fitting model, the lowest optimum anomaly was in Kottawa whereas the highest was in Hantana, with Ratnapura having an intermediate value. In the two locations where the anomaly of W_B was identified as the water-related variable in the best-fitting models (i.e. Talawakelle and Passara), the respective optimum anomalies were close to each other (i.e. -30 and -24 mm month^{-1}). In comparison, the estimated optimum anomaly of W_B in the pooled data set was substantially greater (105 mm month^{-1}).

Table 9 Optimum values of the anomalies of temperature and water-related variables estimated based on the best-fitting multiple regression models

Location	Temperature variable	Optimum (°C)	Water-related variable	Optimum (mm month^{-1})
Talawakelle	T_{Max}	0.01	W_B	-30
Ratnapura	T_{Min}	-0.74	R_F	64
Hantana	T_{Max}	0.21	R_F	125
Kottawa	T_{Max}	-1.14	R_F	-126
Passara	T_{Min}	0.25	W_B	-24
Pooled	T_{Max}	0.58	W_B	105

4 Discussion

4.1 Trends in climate in different tea-growing regions of Sri Lanka

The five locations of this study spanned a wide range of elevations (29 m to 1394 m amsl) and agroecological regions. Accordingly, the five locations covered substantial ranges of temperature (19.02°C to 27.83°C in terms of T_{Mean}) and rainfall (177.5 to 335.7 mm month^{-1}) regimes and represented the different tea-growing regions of Sri Lanka (Tables 1 – 5). A key finding of the present study is that the nature of climate change experienced by these different locations has been different, which agrees with the findings of previous analyses of long-term climate change in Sri Lanka (De Costa, 2008). Notably, three locations (Talawakelle, Hantana and Kottawa) have shown significant increasing trends in T_{Max} whereas only two locations (Ratnapura and Hantana) have shown significant increasing trends in T_{Min}. However, all locations except Passara have shown significant increasing trends in T_{Mean}. In terms of R_F, the two low elevation locations (i.e. Ratnapura and Kottawa) which had respectively the highest mean monthly total R_F (335.7 mm month^{-1} and 258.3 mm month^{-1} respectively) showed significant increasing trends, but at different rates (11.49 mm month^{-1} y^{-1} and 4.76 mm month^{-1} y^{-1} respectively). In contrast, the other three locations did not show significant temporal trends in their monthly total R_F. These results demonstrate the different directions and magnitudes of climate change that are likely to be experienced by the tea crops in different tea-growing regions in the future. For example, the two low-country locations Ratnapura and Kottawa have experienced the combination of increased temperature and increased rainfall. In contrast, the mid- and up-country locations, Hantana and Talawakelle respectively, have experienced increased temperatures but no significant trend in rainfall. On the other hand, Passara which represented the uva tea-growing region, has not experienced significant trends in either temperature or rainfall.

Most importantly, the pooled data set from the five locations of this study which represented all tea-growing regions in Sri Lanka showed a combination of increasing monthly temperatures (0.036, 0.018 and 0.026°C y^{-1} for T_{Max}, T_{Min} and T_{Mean} respectively) and increasing monthly rainfall (2.71 mm month^{-1} y^{-1}) (Table 6). The increasing trends in temperature and the observation that T_{Max} showed a greater rate of increase than T_{Min} are in agreement with the global patterns of increasing temperatures (IPCC,

2021) as well as the local patterns (De Costa, 2008). However, the observed increase in the monthly total R_F in the pooled data set agreed only partly with the global trend of wet regions getting wetter (IPCC, 2021). Notably, it differs from trends shown in previous analyses of rainfall in different regions of Sri Lanka (De Costa, 2008) where no locations showed increasing rainfall trends.

An unexpected result that came out of this analysis was the significant decreasing trend of the monthly total E_T in Talawakelle, Kottawa and Passara (Tables 1, 4 and 5), which are from three different elevations and temperature regimes. In Talawakelle and Kottawa, the significant decreasing trends of E_T have occurred despite the significant increasing trends of temperature. In Talawakelle, an increasing trend in SSH was observed (Table 1), which was just beyond the threshold for statistical significance ($p = 0.057$). The combination of increasing temperatures and SSH in Talawakelle probably increased transpiration from the tea crop and thereby probably increased the relative humidity (RH) in the environment. The higher RH would decrease E_T because of the lower water vapour concentration gradient between the evaporating surface and air (Penman, 1948; Monteith, 1965). The same feedback mechanism probably decreased E_T in Kottawa also where temperature showed an increasing trend, but SSH did not show a significant trend. It is notable that the pooled data set also showed the same combination of trends for temperature and SSH in Kottawa while showing a significant decreasing trend in E_T. In contrast, in Passara, where there were no increasing trends in temperature, the significant decreasing trend of SSH was probably responsible for the observed decreasing trend of E_T. Reduced SSH decreases E_T because of the decreased supply of solar radiation energy for the conversion of liquid water to water vapour during evaporation. The decreasing trend of E_T that has been observed in these locations in the present study could be a more widespread trend, which needs further investigation.

It is notable that none of the locations showed significant trends in the monthly water balance (W_B) despite both Ratnapura and Kottawa having showed significant increasing trends in R_F. In Ratnapura, despite the high rate of increase in R_F, E_T also showed a significant increasing trend and thereby prevented a significant increase in W_B. Despite showing a significant increasing trend in R_F and a significant decreasing trend in E_T, even the pooled data set did not show a significant trend in the W_B. This finding is contrary to the commonly held view that the frequency of droughts is likely to increase with future climate change. It is possible that the high variability in R_F has prevented a significant increasing or decreasing trend in W_B. At the global scale too, a majority of regions of the world, including the South Asian region, do not show a significant trend in the water balance or drought (IPCC, 2021).

4.2 Trends in tea yields

Similar to the climatic trends, the trends of annual and monthly tea yield also were different for the different locations (Fig. 3 and Table 7). However, predominantly declining trends were shown in Talawalakelle, Ratnapura and Passara, which represented three of the four tea-growing regions (i.e. up-country, low-country and uva). Even though these three locations are in three elevational zones, the magnitudes of decline in both annual yields (54, 58 and 48 kg ha^{-1} y^{-1} respectively) and monthly yield anomalies (4.53, 4.83 and 3.96 kg ha^{-1} $month^{-1}$ respectively) varied within a narrow range. Even in Hantana, which represented the mid-country, a declining trend in the annual yield has been shown since 2016. It is notable that despite the increasing trend in Kottawa, the pooled data set of monthly yield anomalies showed a significant declining trend.

It is possible that in addition to the climatic trends during the 15-year period (2010-2024) considered in the present study, many other factors may have contributed to the observed declining trends in tea yield. As all fields from which yield data were obtained are under direct management of the Tea Research Institute of Sri Lanka, it could be assumed that they were maintained under recommended crop and soil management. However, periodic changes in administrative personnel in the estates (Talawakelle and Ratnapura) and stations (Hantana, Passara and Kottawa) may have led to sub-optimum crop- and soil management and could have contributed to the observed declines in yield. Interestingly, Kottawa has shown a significant increasing trend in tea yield, which contrasts with the trends shown at all other locations. Replacement of the TRI 2000 series cultivars with 3000, 4000 and 5000 series cultivars could probably have contributed to this increasing trend. Furthermore, optimum crop management and adherence to good agricultural practices which would have maintained the inherent soil fertility of the location, which also adjoins the natural rainforest in Kottawa, probably allowed the positive impacts of the combined increasing trends of temperature and rainfall to bring about the observed positive yield trend.

The trends of annual yields over the 15-year period showed the typical yield variations within the four-year pruning cycle that has been practiced at all five locations (Fig. 3). However, the longer-term trends over the 15-year period were stronger than the shorter-term trends within the respective pruning cycles.

4.3 Climate-yield relationships

The anomalies of monthly climatic variables showed the direction and magnitude of climate change during the 2010-2024 period while the anomalies of monthly yield reflected the change in monthly yield during the corresponding months. Accordingly, the relationships between the respective anomalies of climatic variables and monthly yields (Table 8) showed the contribution of climate change to the observed yield variation. The best-fitting multiple regression models in all locations included the second-order polynomials of a temperature-related variable (T_{Max} or T_{Min}) and a water-related variable (R_F or W_B). This agrees with the expected climate-yield relationship as all key physiological processes that contribute to yield (e.g. photosynthesis, respiration, shoot initiation and leaf expansion) have optimum-type responses to temperature and water availability (Squire, 1990; Evans, 1993; De Costa, 2000). Accordingly, tea yields in all locations increase until the temperature variable (T_{Max} or T_{Min}) and the water-related variable (R_F or W_B) increases up to a threshold. When the temperature variable and the water-related variable increase beyond the threshold, the tea yields decline in all locations. In the response to temperature increase, the yield increases up to the threshold probably due to the stimulation of key yield-determining processes (i.e. shoot initiation, shoot elongation and photosynthesis) with increasing temperatures. The yield decrease beyond the temperature threshold occurs because of adverse impacts of higher temperatures on the physiology of tea plants such as reduced rate of shoot initiation and reduced photosynthetic rate due to photoinhibition (Mohotti and Lawlor, 2002; De Costa et al., 2007). The increase of tea yields up to the water-related threshold occurs because increased water availability increases the rates of key yield-determining processes (Burgess and Carr, 1996a, b; Wijeratne et al., 1998; Wijeratne, 2004; De Costa et al., 2007). The yield decrease beyond the water-related threshold could be caused by the increased incidence of diseases such as blister blight, which is a key determinant of tea yield in all tea-growing regions in Sri Lanka (De Silva et al., 1974; Mahadevan et al., 2024).

It can be noted that tea yields in Talawakelle, Hantana and Kottawa have a threshold response to T_{Max} whereas the yields in Ratnapura and Passara show a threshold response to T_{Min}. At the three locations which have shown the threshold response to T_{Max}, a greater magnitude of change has been shown in the anomalies of T_{Max} than with the corresponding anomalies of T_{Min} (Tables 1, 3 and 4). Similarly, in Ratnapura where only the anomaly of T_{Min} has shown a significant increasing trend (Table 2), the anomalies of tea yields have shown a threshold response with T_{Min} rather than T_{Max}. It is interesting to note that anomalies of tea yield in Passara also have shown a threshold response to the anomaly of T_{Min} despite none of the temperature variables showing a significant trend (Table 5).

The negative temperature thresholds of the two low-country locations (i.e. Ratnapura and Kottwa) (Table 9) show that the current monthly temperatures have already exceeded the temperature thresholds beyond which yields begin to decline with further increases in temperature. The temperature threshold, which is very close to zero in Talawakelle indicates that the current temperatures are almost at the optimum so that further temperature increases would decrease its tea yield. The positive temperature thresholds in Hantana and Passara indicate that the current temperatures are still below the optimum temperature threshold so that increasing temperatures in the near future would cause an increase in the tea yield until the threshold is exceeded. The lower temperature threshold in the cooler environment in Talawakelle in comparison to the higher temperature thresholds in the relatively warmer environments in Hantana and Passara indicate that the yield-temperature relationship of tea is region-specific and that the relationship shows adaptation to the prevailing temperature regime. Accordingly, tea crops in the lower temperature regimes have a lower temperature threshold due to adaptation of their physiological processes to lower temperatures. In comparison, adaptation to the relatively higher temperature regimes in Hantana and Passara have resulted in higher temperature thresholds for tea crops in these regions. Such temperature adaptation (i.e. acclimation) has been demonstrated for photosynthesis, the principal process responsible for yield determination (Lin et al., 2012; Kumarathunga et al., 2018).

In Hantana, T_{Max} is the temperature variable in the best-fitting model, and its anomaly has shown a significant increasing trend at the rate of 0.052°C y^{-1} (Table 3). At this rate of increase, the threshold T_{Max} will be reached in another four years in Hantana. In Passara, T_{Min} is the temperature variable in the best-fitting model, but it has not shown a significant trend during the past 15 years (Table 5). Therefore, an analysis of the temperature trends over a longer period is required to determine the likelihood of the temperature threshold being exceeded in Passara in future.

Talawakelle and Passara have W_B as the water-related variable in their best-fitting models (Table 9) and both show a negative W_B threshold. This indicates that future increases in W_B, either due to increased R_F or decreased E_T, could decrease tea yield at these two locations. It is notable that both these locations have shown significant decreasing trends in E_T while not showing significant trends in either R_F or W_B (Tables 1 and 5). In Kottawa also, where R_F is the water-related variable in its best-fitting model, the negative R_F threshold indicates that increases in R_F will reduce the tea yields. During the last 15 years, Kottawa has shown an increasing trend in R_F, which is just below the threshold for statistical significance (Table 4). This means that there is a possibility of the currently increasing trend of yields in Kottawa being reversed due to excessive rainfall. Both Ratnapura and Hantana have R_F as the water-related variable in their best-fitting models. In contrast to other locations, both these locations show positive R_F thresholds, thus indicating that the current rainfall regimes are sub-optimal so that future increases in R_F could bring about yield increases in these locations. However, the best-fitting model for Ratnapura shows a negative $aT_{Min} \times aR_F$ interaction, which means that increasing T_{Min} will have a stronger negative impact on tea yields and will negate the positive impact of increasing R_F. Similarly, the best-fitting model for Hantana shows a negative $aT_{Max} \times aR_F$ interaction so that the positive impact of increasing R_F will be negated by the negative impact of increasing T_{Max}.

The pooled data set shows a positive temperature threshold (i.e. 0.58°C for T_{Max}) and a positive water-related threshold (105 mm $month^{-1}$ for W_B) (Table 9). This means that overall, the current temperature and water balance thresholds are still sub-optimal and there is a likelihood for the tea yields to increase with increasing temperature and water balance. However, the negative $aT_{Max} \times aW_B$ interaction in the best-fitting model indicates the possibility of negative impacts on future yields when the increases of both T_{Max} and W_B occur simultaneously. At the rate of overall T_{Max} increase shown during the last 15 years (i.e. 0.036°C y^{-1}), the T_{Max} threshold will be exceeded in another 17 years. In contrast, the overall W_B has not shown a significant trend during the last 15 years so that an analysis of W_B over a longer period is required to determine when the water balance threshold will be exceeded.

4.4 Strengths and weaknesses of the present analysis and directions for further analysis

A key strength of the present analysis is its selection of locations which represents all tea-growing regions. The use of climatic data collected at the same site from which yield data have been collected is a further strength as it avoids errors due to spatial averaging and mismatching. However, a weakness is the relatively short period of 15 years to determine the trends in climate and yield. This was due to the non-availability of reliable yield and climatic data, especially at locations other than Talawakelle. Therefore, this analysis should be repeated with yield and climatic data over a longer period.

Use of monthly climatic data is a strength of this study as the commonly used annual climatic data do not reflect within-year variations in climate. Furthermore, the present study used anomalies (i.e. deviations from the mean climate relative to a reference period) to quantify changes in climate that have occurred. This method has several advantages over the use of monthly or annual means. Firstly, use of anomalies overcomes the inherent variations in climate that occur due to location-specific factors such as elevation and time-specific factors such as the month of the year. This is because the anomaly is calculated relative to the existing climate. Therefore, the anomaly specifically calculates the change in climate that has occurred relative to the mean climate that has prevailed during the reference period. Secondly, quantification of the temporal trends in anomalies provides an indication of how the change in climate has progressed over time.

This analysis has the underlying assumption that the observed yield variations are solely due to climatic variations and therefore, does not take into account the possible contributions from non-climatic factors such as sub-optimal crop- and soil management. For example, during the 2020-2021 period, nutrient management was sub-optimal because of the unavailability of adequate quantities of fertilizer. Quantification of the respective contributions from non-climatic factors to the variation of tea yield in different tea-growing regions is difficult because of the complexity of their effects and interactions on the yield-determining physiological processes. However, statistical significance in the climate-yield relationships established demonstrate that this analysis has succeeded in identifying and quantifying the influence of climate in determining tea yield in the different tea-growing regions in Sri Lanka.

Yield data that have been used in this analysis have come from a mixture of cultivars which represent the TRI 2000, 3000, 4000 and 5000 series as well as estate cultivars. Therefore, the climate-yield relationships established in this work are non-specific to cultivars and as such, are generally applicable across the whole range of tea-growing regions and cultivars. This can be considered as a strength of this study. As the cultivar profile gradually shifts from TRI 2000 series cultivars to 3000, 4000 and 5000 series, the climate-yield relationships will also shift because the higher series cultivars have incorporated traits of greater climate resilience (e.g. moderate resistance to drought, high temperature and blister blight).

5 Conclusions

Based on this analysis, it is concluded that climate of different tea-growing regions has changed differently, in terms of the direction and the magnitude. The specific combination of climatic variables that show significant trends also changes from region to region. However, the climate-yield relationships show a common form and consist of threshold-type relationships of a temperature-related and a water-related variable. It is recommended that measures of increasing climate resilience of the tea crops in different tea-growing regions of Sri Lanka should be based on the specific trends of climate change observed in those specific regions. Such measures should include the breeding of climate-resilient cultivars and the introduction of crop management practices to minimize adverse impacts of climate change.

Author contributions. W.A.J.M. De Costa: Conceptualization, data analysis, interpretation of results and writing of the manuscript; B.L.D.S.M. Fernando: Collection and compilation of data for analysis, preparation of the manuscript; N.P.S.N. Bandara, A.L.R.U. Kumara, P.D. De Alwis, G.S. Pradeep, K.G.N.M. Gamage, U.C. Oliver and S.B. Edirisinghe: Collection and supply of climatic and yield data.

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