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ORIGINAL PAPER

Variability of diurnal temperature range over Pacific Island countries, a case study of Fiji

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Abstract

Diurnal temperature range (DTR) is an important index in climate change studies in addition to its influence upon environment and thermal comfort. Understanding variability in DTR at regional scales is, thus, important. In Fiji and other Pacific Island countries, DTR information is important in forecasting thermal comfort. This work is based on Fiji using gauge-based gridded mean monthly DTR data from the Climatic Research Unit (CRU). Annual and monthly DTR for the second half of the twentieth century to the present day are analyzed to establish temporal trends and spatial patterns. A combination of parametric and non-parametric tests was applied to investigate trend, correlation, simple linear regression, and interannual variability in the datasets. Findings show that DTR increases with an increase in latitude over Fiji. The mean monthly DTR between 6.58 and 7.37 °C in June and January coincide with winter and summer, respectively. Cumulative annual mean (CAM) of T, T_{mx}, and DTR showed increasing trends during the study period while the CAM of T_{mn} depicted a decreasing trend. Results suggest that DTR has a positive significant (insignificant) correlation with T_{mx} (T), but shows an opposing significant relationship with T_{mn} at 5% significance level. Each of DTR, T_{mx}, T_{mn}, and T experienced a general increase in values across the timeframe provided by the data. Records show an overall increase of 0.05 °C/decade in DTR. However, since the early 1990s, DTR has been characterized by a downward trend. Nonetheless, the overall trend of increasing DTR is explained by a greater increase in maximum temperatures over minimum temperatures. The observed rate of increase in DTR in warm months exceeds that in cold months. The findings form a baseline for further studies investigating the factors influencing DTR variability, and how the variability is affecting human thermal comfort.

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1 Introduction

Climate variability and change pose a great threat to most Pacific Island nations owing to their vulnerability to the various consequences of these phenomena (Albert et al. 2018; IPCC 2018). Fiji is one such country. Unfortunately, the contributions of these countries to factors that cause climate change are negligible yet they are left at the mercy of the 'major polluters' of the environment which are, predominantly, developed nations (Ritchie and Roser 2019). Despite the creation of various treaties intended to safeguard the welfare of the more vulnerable countries, little has been achieved so far. As a result, Pacific Island countries are left with few options. One such course is adaptation to the observed and projected changes. For this to be effective, policy-makers require information on the observed climate trends as well as projected changes. This facilitates more informed decisions for short- and long-term planning. The earth has been characterized by an overall increase in temperature as a result of the increase in anthropogenic greenhouse gases (GHGs) (Ritchie and Roser 2019). Consequently, there is need for continuous monitoring of the changes that are occurring in climate.

Diurnal temperature range (DTR), the difference between maximum and minimum daily temperatures in a given place, is a standard employed to examine local climate characteristics. It is commonly used as an indicator of climate change, owing to its sensitivity to variations in radiative energy balance (Braganza et al. 2004), and is also used to infer thermal stress in a given area (Paaijmans et al. 2010). The datasets produced provide more in-depth information when compared with mean temperature alone. This insight into variability of DTR is central to the understanding of climate change (Giorgi and Lionello 2008). It also increases our understanding of some of the contributors to variations in DTR, namely rainfall, soil moisture, and cloud cover since each alters hydrological balance and surface energy (Karl et al. 1993; Dai et al. 1999; Xia 2013; Thorne et al. 2016; Bilbao et al. 2019).

According to the IPCC (2013), each of the last three decades has surpassed each other in recording the warmest temperatures. The report further showed that the Earth has warmed by between 0.69 and 1.08 °C, producing an average of 0.89 °C, between 1901 and 2012.

Many studies around the globe have reported an increase in maximum, minimum, and mean temperatures, but a decrease in DTR, over the last six decades (Karl et al. 1991; Easterling et al. 1997; Dai et al. 1999; Liu et al. 2004; Wang and Shilenje 2017; Ongoma et al. 2018; Sun et al. 2019). These studies suggest that, although temperatures are rising, minimum temperatures are increasing at a faster rate than maximum temperatures. However, other studies have revealed no change in DTR in some areas, while further studies still indicate increasing and decreasing DTR (Qu et al. 2014; Vinnarasi et al. 2017; Sun et al. 2019). Given that, despite the ongoing warming trend, temperature variability is not uniform globally (IPCC 2018), there is a need for exclusive regional and/or localized studies that will increase our understanding of, and provide updates on, the spatiotemporal variability of the DTR.

Scant definitive quantitative studies exist where the climatology, climate variability or DTR of Fiji, or indeed any South Pacific nation, are the focus. Kumar et al. (2013) attributed the limited climate research in Fiji to the lack of quality of observed data in both length and reliability. Despite the fact that this challenge can be overcome today using the multiple reanalyzed datasets, most of which are freely available online from various research centers, there is no extensive study that looks at the variability of DTR over Fiji.

Of the studies that have taken place, Mataki et al. (2006) investigated rainfall and temperature trends over Viti Levu (Fiji), relying on observed data from 1961 to 1990 sourced from two weather stations, in Nadi and Suva. The study reported a steady increase in temperature in both locations but no significant change in annual rainfall was identified. The study observed an annual average surface temperature of 25.4 °C at both stations. The months of January and February experience the highest temperatures while July stood out as the coolest month. The findings of the study are similar to observations made by Folland et al. (2003), where a longer time span was examined. Folland et al. (2003) considered data from ten stations across Fiji, spanning between 52 and 78 years. Here, statistically significant changes in both maximum and minimum temperatures were observed with increases ranging from 0.08 to 0.23 °C per decade (Kumar et al. 2013).

In a change from existing studies, this present study examines the long-term changes in DTR in relation to other aspects of temperature over Fiji by introducing the following novelties: first, it is the first coherent study that investigates DTR variability over Fiji; second, it covers the entire country, and third, it covers a longer timeframe. The findings of this work will be important in assigning confidence in the few existing quantitative studies on climate variability and change in Fiji. The outputs will form a basis for further studies of cloudiness, humidity, precipitation, wind, and vegetation among other factors that influence DTR variability over Fiji and Pacific Island Countries. The outcome of this work will be useful in operationalization of human thermal comfort forecasting, which is long overdue in Fiji's case as a country whose economy heavily relies on tourism.

2 Data and methodology

2.1 Area of study

Fiji consists of over 300 islands totaling around 18,300 km^2 of land. The country lies between longitudes 175° E and 178° W, and latitudes 15° S and 22° S. Viti Levu, the country's largest island, is characterized by relatively high topography (Fig. 1). Vanua Levu and Kadavu are located to the northeast and south of Viti Levu, respectively. The mountainous topography of the larger islands is known to influence rainfall over the country, explaining why orographic rainfall is the dominant form of precipitation in Fiji (Chattopadhyay and Katzfey 2015).

Fiji's position in low latitudes sees it experience a tropical climate with warm temperatures and, generally, an abundance of rainfall throughout the year. Given the influence of the Pacific Ocean, the DTR is small while topography and proximity to the ocean play central roles in the spatial variability of temperatures in Fiji. The leeward side of the mountains record higher temperatures when compared to

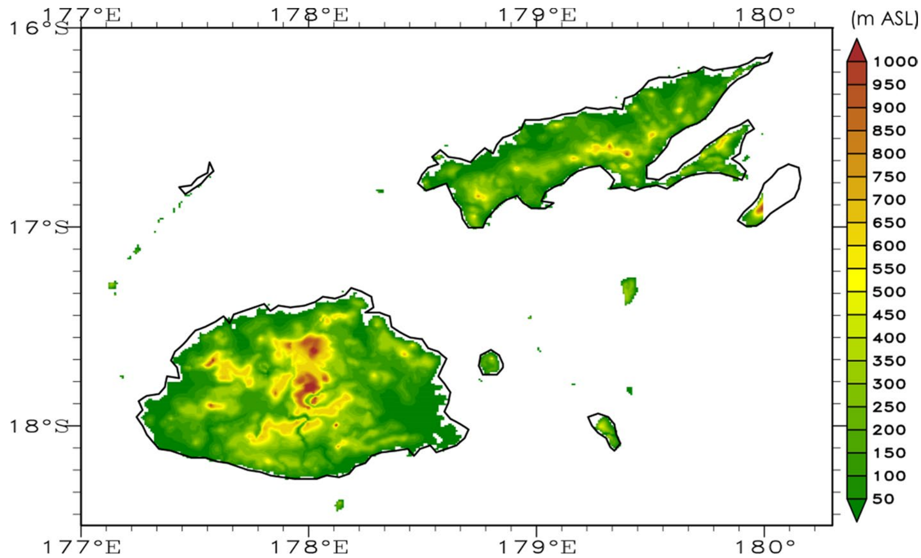

Fig. 1 Map of Fiji showing the topography (mASL). *ASL* above sea level. Data Source: Hastings and Dunbar (1999)

the windward sides (Kumar et al. 2013). The South Pacific Convergence Zone (SPCZ) is the main influence upon the seasonality of Fiji's rainfall (Irving et al. 2011). Given the country's location in the South Pacific trade-wind belt, the prevailing wind is from the southeast. The country experiences a unimodal rainfall pattern during the austral summer months (November to April). The months of May to October are regarded as the winter months and are characterized by relatively strong southeasterlies.

On the other hand, inter-annual variability of rainfall is influenced by synoptic features such as El Niño and La Niña (ENSO) (Kumar et al. 2006). La Niña is associated with above normal rainfall that results in floods, particularly in low-lying areas (Glantz 2001; Zebiak et al. 2015). Moreover, strong cyclones can be observed during the same period. In El Niño years, severe droughts that adversely affect agriculture and, in turn, cause food shortages, can be experienced.

2.2 Data

The analysis is based on widely used reanalyzed mean monthly DTR data from the Climatic Research Unit (CRU TS4.03). The same center provides other datasets such as precipitation, mean temperature, maximum and minimum temperature, wet day counts, and cloud cover. The data run from 1901 to 2018, with a spatial horizontal resolution of 0.5°. However, the timeframe used for the data considered in this study is 1951–2018. This period (1951–2018) is characterized by relatively high increase in surface temperature as a result of global forcing from carbon dioxide (CO_2) that was reported to have increased at a relatively high rate since the 1960s (IPCC 2013). Other variables employed in this study include monthly maximum air temperature (T_{max}), minimum air temperature (T_{min}), and mean temperature (T). The construction and update of the CRU data is discussed at length by Harris et al. (2014). DTR data from the CRU have been used to understand DTR variability in other places (Wang and Shilenje 2017; Libanda et al. 2019).

Although Fiji's Exclusive Economic Zone covers an area of around 1.29 million km^2, it should be noted that this study limits its examination of DTR data to land areas only, where it varies more dynamically when compared with oceanic areas. For that reason, data for some grid points in the vicinity of the ocean are not included or are missing. In addition, it is important to note that our study is somewhat limited by the temporal resolution of the data; here, DTR values are based on mean monthly temperature data.

2.3 Methodology

Time series analysis was carried out to determine interannual variability of DTR. Mann–Kendall (MK) test was used to investigate trends in DTR variability. The method is discussed in detail by its pioneers, Mann (1945) and Kendall (1938). Modified MK (Hamed and Rao 1998) test was applied to the dataset to address the problem of autocorrelation structures in time series. Statistical significance of each trend was computed at 95% confidence level. Sen's slope estimator (Sen 1968) was used to assess the magnitude of any DTR trends revealed, while investigation of possible abrupt changes in the temperature variables is explored using a sequential MK (SQMK) test (Sneyers 1990).

A Pearson correlation coefficient was applied to establish the relationship between DTR and precipitation in addition to maximum, minimum and mean temperature. Significance of correlation coefficient was tested at 95% confidence level, making use of a table of critical values to make a decision.

Standardized Anomaly Index (SAI) was used to compare the relationships between DTR and the variables. The anomaly helps to minimize the influence of location, making the datasets comparable. Introduced by Katz and Glantz (1986), SAI is outlined as

$$\text{SAI} = \frac{X - \overline{X}}{\sigma}, \tag{1}$$

where the numerator is the anomaly (the difference between the data value and the mean) and the denominator is the standard deviation of the dataset.

Annual and decadal temperature anomalies were investigated by calculating the differences between DTR of the long-term mean (1951–2018) and a given year/decade's mean DTR. The same was also investigated where the long-term mean is replaced by a specific baseline period (1986–2005). The baseline period is in line with the applications of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013). So far, no climate variability and/or change studies have been published using this baseline period for Fiji. Generally, anomalies of various weather parameters are more representative than absolute values (Jones and Hulme 1996). In this case, the anomalies make it easy to compare the changes from one decade or region to another.

Cumulative annual mean (CAM) was utilized to explore variability and any possible regime shifts in T_{mx}, T_{mn}, T, and DTR over time (Pavia and Graef 2002). According to Hasanean and Basset (2006), this approach is able to expeditiously detect the time varying structures within time series that may not be easily recognized in the raw data. Similar to low-pass filters, the cumulative means also have a smoothing effect in the time series (Lozowski et al. 1989). The method was successfully employed by Punia et al. (2015) to analyze temperature variability over northwestern India. The CAMs time series is defined as

$$X_j = \frac{1}{j}\sum_{i=1}^{j} x_i, \quad j = 1, \ldots, N \tag{2}$$

where x_i is the yearly average temperature and N is the number of years of data used. If $j = N$ then, $X_{j=N} = \bar{x}$.

The analyses of DTR and the related weather variables are performed on seasonal, annual, and decadal scales.

3 Results and discussion

3.1 Temperature climatology

The mean annual temperature recorded over Fiji within the study period is 24.51 °C. As expected, DTR is generally low (7.04 °C) given that Fiji is an island country. Making use of observed station data for Nadi, Labasa, and Suva in Fiji over timelines ranging from 1930 and 2008, Kumar et al. (2013) reported a DTR of ~ 10 °C. The low DTR over Fiji and other island countries that experience an oceanic climate is expected owing to contrasts in heat capacity and moisture supply between land and ocean. Table 1 highlights the fact that mean temperature has low temporal variability, a phenomenon supported by the lowest standard deviation (0.26).

The mean temperature difference between the warmest month (February) and the coolest month (July) is 3.61 °C, a result that supports the temperature climatology as reported by Fiji Meteorological Service (FMS 2006). According to FMS (2006), the approximate variation in temperatures from the warmest months (January to February) to the coolest months (July and August) is 2–4 °C. The present study indicates that, as the year progresses into the summer months, there will be an increase in DTR (Fig. 2). The warmer months, December and January, are categorized by warm and humid northerly air mass from the tropics. The two months record the highest DTR values. On the other hand, the cooler months, May to July, experience the lowest DTR.

DTR climatology over Fiji is shown in Fig. 3. Vanua Levu, the more northern of the two main islands, experiences a greater range in maximum daytime temperatures and minimum nighttime temperatures. It is likely that this greater proximity to the Equator is seeing maximum temperatures increase at a faster rate than minimum temperatures, thus producing the more pronounced DTR seen here.

3.2 Relationships between DTR and other temperature variables

Table 2 shows an expected relationships between DTR and other thermometric variables. DTR correlates positively with mean and maximum temperatures. The relationship between DTR and minimum temperature is significantly negative at 5% significance level. On the other hand, DTR exhibits significant positive correlation with $T_{mx\,(r=0.498)}$ at 5% significance level.

The relationship between DTR and these thermometric variables is further displayed in Fig. 4. Here, the Standardized Anomaly Index highlights the negative relationship between DTR and T_{mn}. The year 1992 recorded the highest and lowest values for DTR and T_{mn}, respectively. From early

Table 1 Mean, average maximum and minimum, and standard deviation of mean temperature, minimum and maximum temperature, and DTR (°C) for Fiji (1951–2018)

	T	T_{mn}	T_{mx}	DTR
Mean	24.513	21.017	28.060	7.042
Max	25.097	21.603	28.680	8.076
Min	23.795	20.183	27.244	6.573
SD	0.263	0.303	0.304	0.301

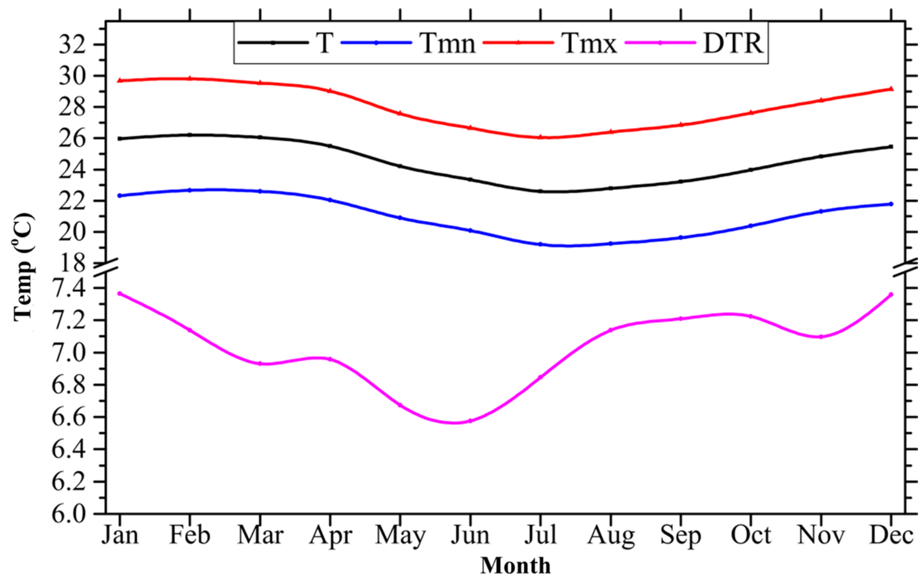

Fig. 2 Annual temperature cycle for Fiji, based on the CRU dataset, 1951–2018

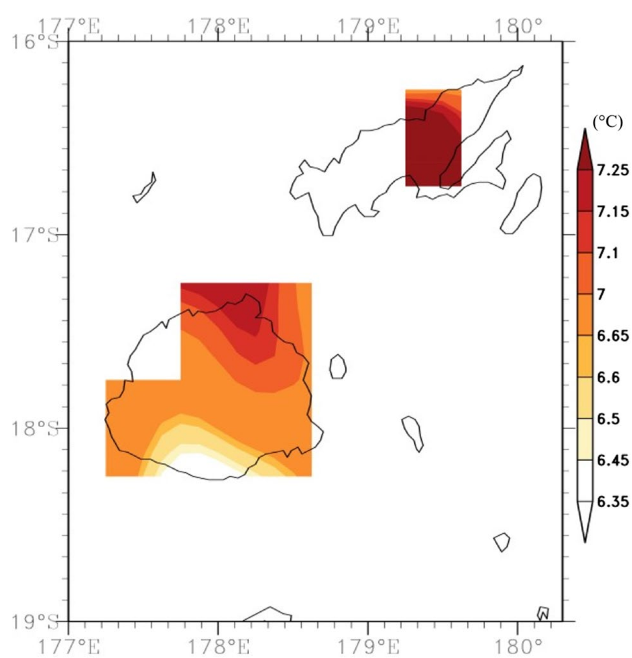

Fig. 3 DTR climatology (°C) over Fiji based on CRU data, 1951–2018

Table 2 Correlation matrices for maximum, minimum and mean temperature, and DTR

	T	T_{mn}	T_{mx}	DTR
T	1	0.868	0.868	0.003
T_{mn}		1	0.507	−0.495
T_{mx}			1	0.498
DTR				1

2000s, the years were dominated by negative DTR anomalies but have tended to become more positive in recent years.

3.3 Decadal variability

The relative decadal contribution of DTR to the long-term mean, 1951–2018, is shown in Fig. 5. The first 10 years recorded the lowest DTR while 1981–1990 and 1991–2000 experienced the second highest and the highest DTR, respectively. Generally, the changes in DTR are of small magnitude.

3.4 Trend analysis

Understanding the observed trends of a given weather variable is important as it forms the basis for predictions. The results from both the Mann–Kendall test (Table 3) and linear regression analyses (Fig. 6) affirm positive trends for all variables under study. The upward trend in temperature is highest in T_{mx} and lowest in T_{mn}, while the rate of change of temperature is approximately 0.4, 0.1, 0.07, and 0.05 °C per decade for T_{mn}, T_{mx}, T, and DTR, respectively.

The ongoing global warming has been characterized by a downward trend in DTR, particularly in the second half of the twentieth century (Braganza et al. 2004). In support, Sun et al. (2019) reported a significant decrease in global land surface DTR at a rate of −0.036 °C per decade for the period 1901–2014, with notable evidence for a large decrease in DTR at −0.054 °C per decade for the period 1951–2014 across the globe. In Fiji, the trend experienced in DTR values is in the opposite direction (Tables 3, 4). In a study focusing on Lautoka, an area in northwest of the main island of Viti Levu, Ghani et al. (2017) employed a relatively

Fig. 4 Standardized Anomaly Index for Fiji based on CRU data (1951–2018)

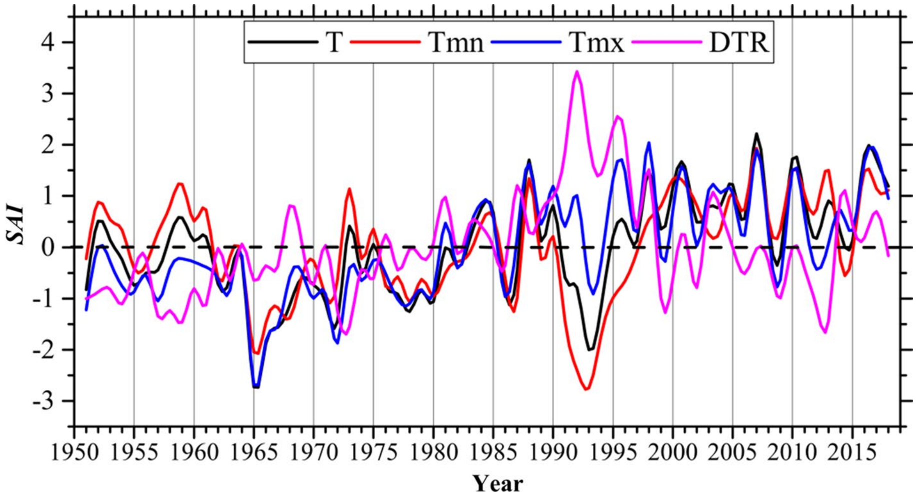

Fig. 5 Decadal DTR anomalies (°C) for **a** 1951–1960, **b** 1961–1970, **c** 1971–1980, **d** 1981–1990, **e** 1991–2000, **f** 2001–2010, **g** 2011–2018 (relative to long-term mean, 1951–2018)

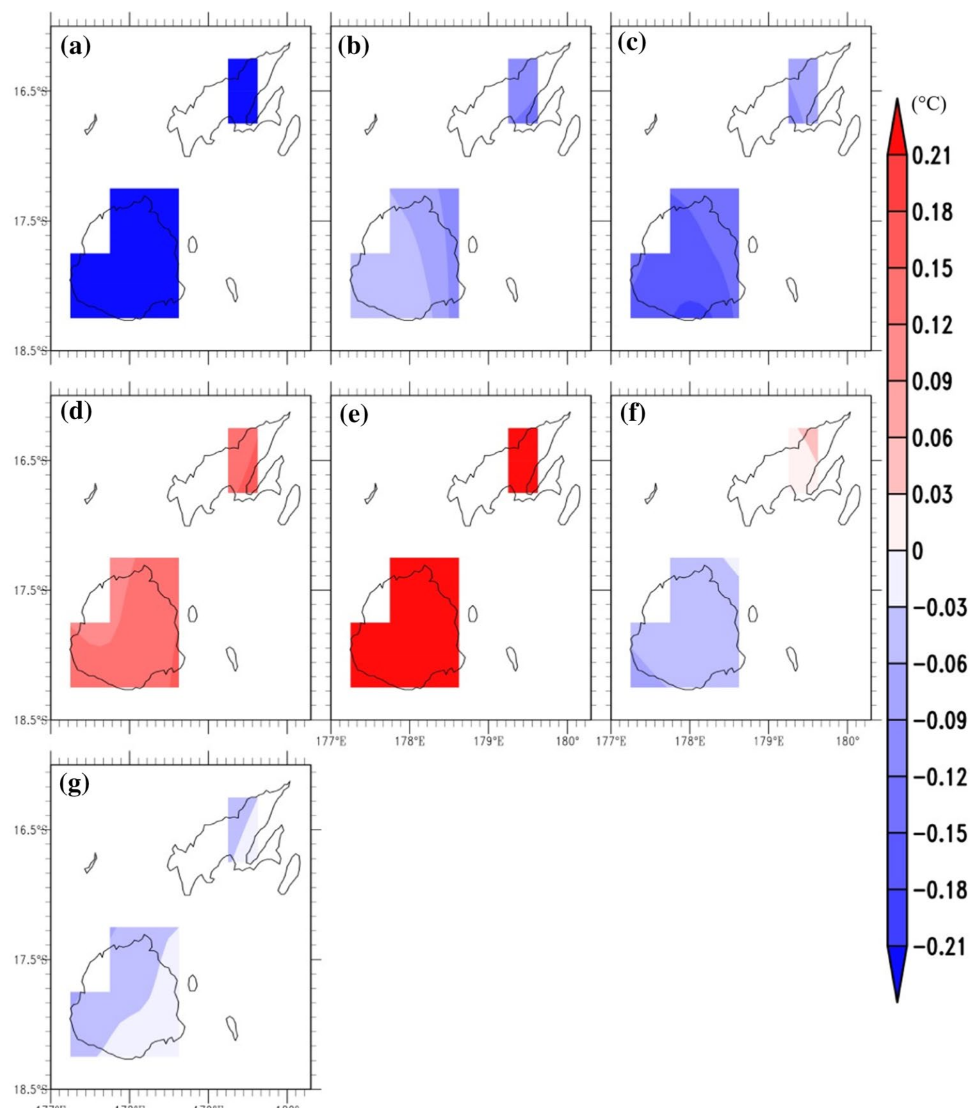

Table 3 Mann–Kendall test for temperatures in Fiji (1951–2018)

	T	T_{mn}	T_{mx}	DTR
Z value	3.5348	1.5587	6.9078	2.0786
p value	0.0004	0.1191	0.0000	0.0377
Variance	59,605.83	106,224.7	21,760.35	98,088.28
Tau	0.3793	0.2234	0.4478	0.2862
Trend	Statistically significant increasing	Statistically significant increasing	Statistically significant increasing	Statistically significant increasing

Z—MK test statistic result

All experience a statistically significant increase

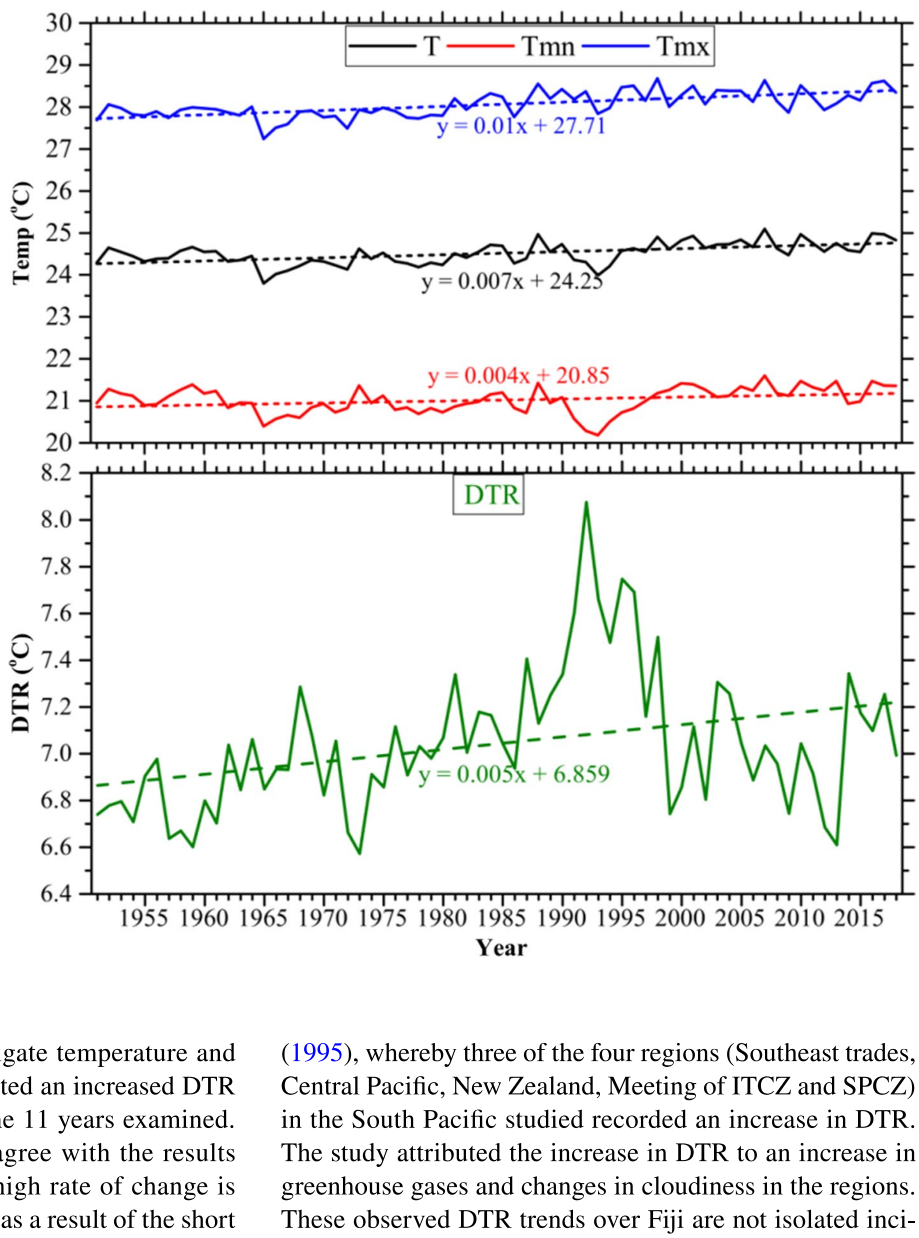

Fig. 6 Annual variation over Fiji based on the CRU data, 1951–2018 including linear regression equation showing overall trends of T, T_{mn}, T_{mx}, and DTR

short (2003–2013) dataset to investigate temperature and humidity variability. The study reported an increased DTR of between 0.21 and 1.01 °C over the 11 years examined. Although these findings generally agree with the results of the present study, the relatively high rate of change is somewhat questionable. This may be as a result of the short temporal distribution of the data, which may not take into consideration long-term climate cycles. The findings of the present study concur with the observations made by Salinger (1995), whereby three of the four regions (Southeast trades, Central Pacific, New Zealand, Meeting of ITCZ and SPCZ) in the South Pacific studied recorded an increase in DTR. The study attributed the increase in DTR to an increase in greenhouse gases and changes in cloudiness in the regions. These observed DTR trends over Fiji are not isolated incidents; despite reporting recent overall reductions in DTR across the globe, Sun et al. (2019) noted that the DTR shows an increasing trend in most parts of Europe.

Table 4 Mean monthly linear regression analysis for DTR, 1951–2018

Months	Regression equation
Jan	$y = 0.007x + 7.091$
Feb	$y = 0.008x + 6.859$
Mar	$y = 0.008x + 6.638$
Apr	$y = 0.009x + 6.633$
May	$y = 0.000x + 6.656$
Jun	$y = 0.002x + 6.494$
Jul	$y = 0.006x + 6.614$
Aug	$y = 0.000x + 7.122$
Sep	$y = 0.004x + 7.060$
Oct	$y = 0.003x + 7.099$
Nov	$y = 0.006x + 6.859$
Dec	$y = 0.005x + 7.183$

A linear regression equation helps to show the overall trends in the thermometric variables studied (Fig. 6). There is an observed increase in all variables with time. The greatest increase in T_{mx} (0.1 °C/decade), followed by T, DTR, and T_{mn} at 0.07, 0.05, and 0.04 °C per decade, respectively. It is worth noting that the rate of increase of mean temperature in Fiji is slightly lower than the global rate of 0.1 °C/decade in the second half of the twentieth century (IPCC 2013). Over the same timeframe, Thorne et al. (2016) reported an increase in maximum and minimum temperatures of 0.19 °C per decade and 0.24 °C per decade, respectively, on a global scale. These changes are greater than the observations made for Fiji in our study.

Monthly linear trend analysis for the entire timeframe is presented in Table 4. The findings show positive trends for all months examined. In addition, the summer months of November to April exhibit greater increases in DTR in comparison to the winter months (May to October).

3.5 Abrupt changes in temperature variables

Possible abrupt changes in the thermometric variables under study are presented in Fig. 7. The variables followed a similar pattern as revealed in Table 3, with each reaching significant levels at different points in the data. Abrupt changes in DTR, T, T_{mx}, and T_{mn} were observed around 1963, 1996, 1985, and 2003, respectively. It is evident that the variables experienced abrupt change before reaching significant levels at $\alpha = 5\%$. Upper significant levels were reached by T_{mx} in 1989, T_{mn} in 2011, T in 2011, and DTR firstly in 1968, which was followed by a decrease, before picking up again in 1976 and remaining there to the present day. However, it is important to note that there is a decrease in DTR since late 1990s.

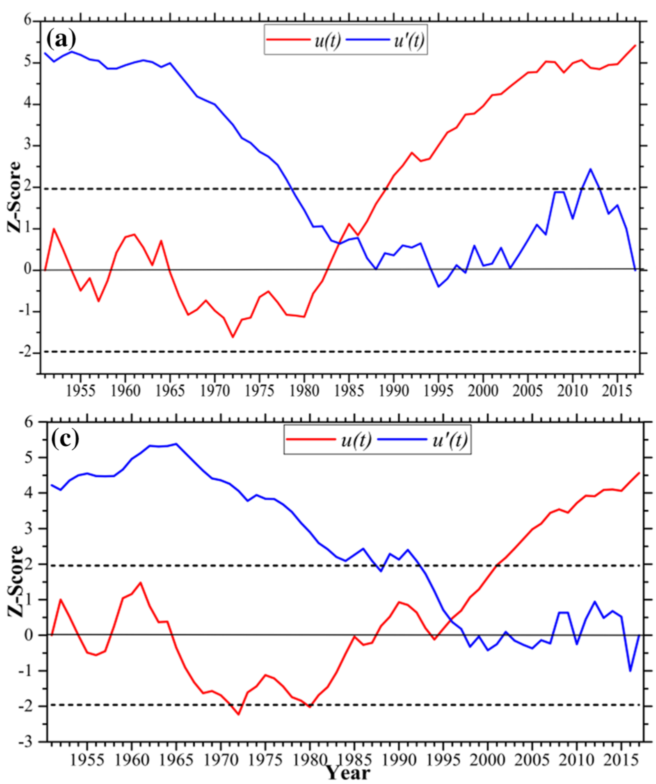

Fig. 7 Mann–Kendall test highlighting abrupt change in **a** T_{mx}, **b** T_{mn}, **c** T, and **d** DTR values for Fiji (1951–2018). $u(t)$ and $u'(t)$ are forward and backward sequential statistics, respectively, while dotted lines indicate upper and lower confidence limits at $\alpha = 5\%$

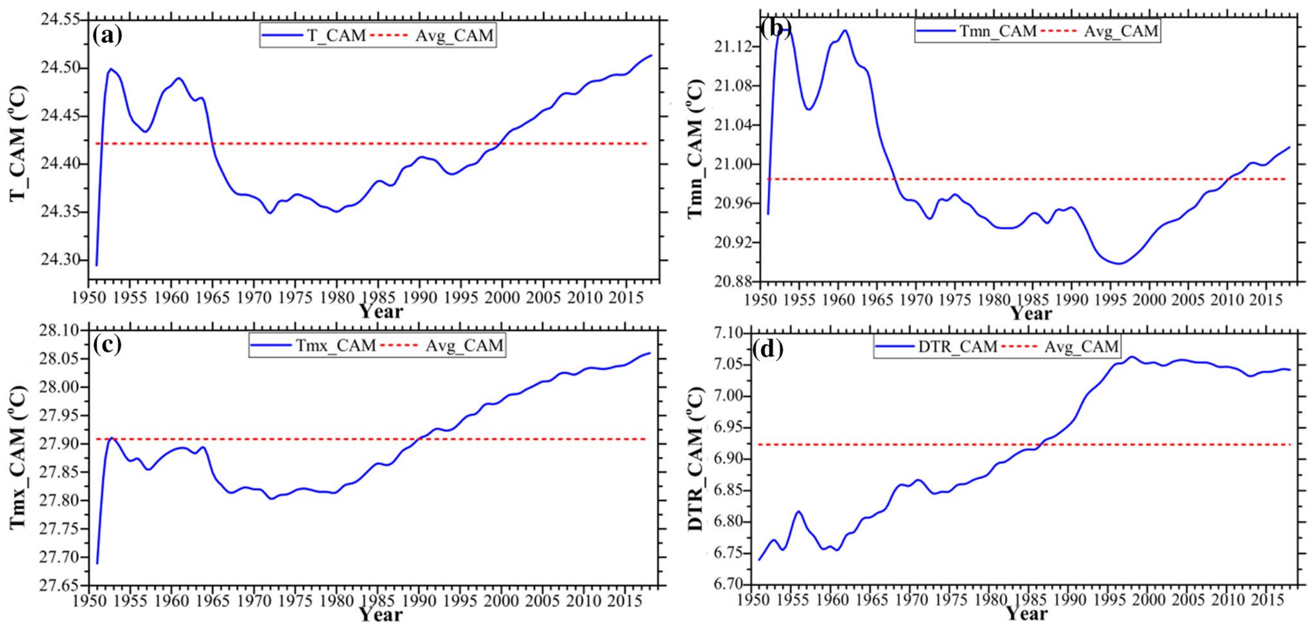

Fig. 8 CAMs of **a** T, **b** T_{mn}, **c** T_{mx}, and **d** DTR of the study area. The blue line is CAM and the dotted line indicates the average of CAM for the period 1951–2018 in °C

The results indicate that there has been an increase in mean temperatures since the early 1980s (Fig. 7c), coinciding with a stable forward trajectory in T_{mx} (Fig. 7a). In comparison, the same increase in T_{mn} was not observed until the late 1990s, thus supporting the earlier argument that the increase in DTR is mainly as a result of a greater rate of increase in T_{mx} values and not T_{mn} values.

3.6 Cumulative annual mean

Cumulative annual mean (CAM) analyses detect persistent changes in time series by smoothing the structure. Figure 8 shows CAM and average CAM of T, T_{mx}, T_{mn}, and DTR. The red dotted lines reflect the deviation of CAM from the mean values. It is clear that there is an overall increase in T, T_{mx}, and DTR. In contrast, T_{mn} was dominated by a decreasing trend until the mid-1990s, when it changed to an increasing trend, a phenomenon that has persisted ever since. Diverging trends of T_{mn} and T_{mx} show an extending range of temperature variation, peaking in 1992 with a value of 8.076 °C. The results affirm the Standardized Anomaly Index values of Fig. 4.

Figure 9 highlights notable rising trends in T, T_{mx} and T_{mn} when recorded values are compared with CAMs, while DTR displays a less notable rising trend. It is interesting to note that T, T_{mx}, and T_{mn} variations from the CAM were particularly low during mid-1960s.

4 Conclusions

The aim of this work was to identify the long-term (1951–2018) climatology and spatiotemporal variability of DTR over Fiji by examining them in conjunction with other thermometric variables. It is evident that DTR is positively correlated with T_{mx} but negatively correlated with T_{mn}, a consequence of the fact that there was a greater increase in T_{mx} values in comparison to T_{mn}. Overall, DTR is experiencing a positive trend in Fiji over the recent past, a phenomenon that differs from the findings of many studies across the globe. The increase in DTR is more notable in warmer months/seasons in comparison to colder months/season.

The fact that the observed DTR variability is different from what would be expected calls for a comprehensive study to establish robust reasons for the reported changes. Thus, the findings of this study will provide a baseline for follow-up studies examining DTR controlling factors such as cloud cover, soil moisture, humidity, and precipitation. The authors also suggested that future studies investigate the impact of the observed DTR and overall temperature (T) on human comfort.

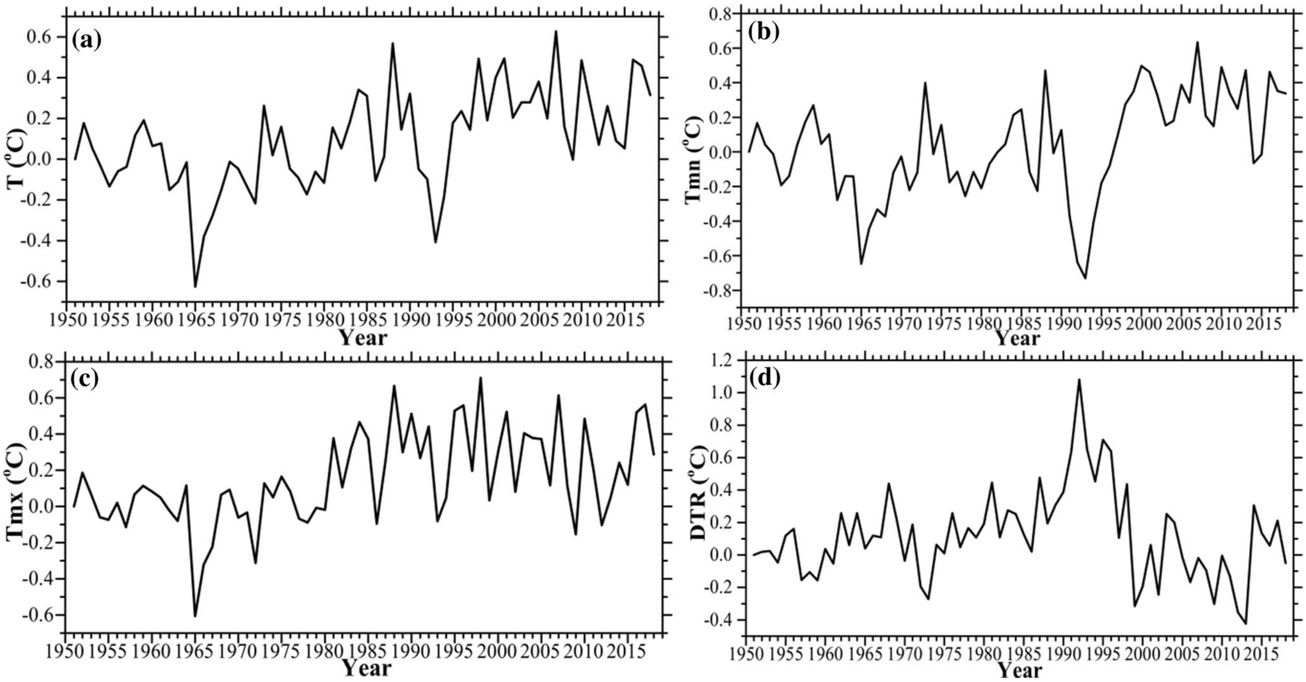

Fig. 9 Difference between CAMs and recorded values for **a** T, **b** T_{mn}, **c** T_{mx}, and **d** DTR (°C) of the study area, 1951–2018

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