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Air temperature trends, variability and extremes across the Solomon Islands: 1951-2011

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Abstract

Past climatological studies .use only one or two local stations to describe the full climate of Solomon Islands. In this paper, we examined all available daily minimum and maximum surface air temperature data between 1951 and 2011 for all seven weather stations operated by the Solomon Islands Meteorological Service. Taro has the highest mean temperature (Tmean) at 27.5°C, owing its warmer climate to its proximity to the equator than other stations. Henderson at the central region averaged the least at 26.9°C during the same period. Honiara has the warmest Tmean on average from June through October due to its elevation. The overall annual Tmean for the country was 27.3°C with the maximum at 30.8°C and the minimum at 23.7°C. All seven stations show significant trend in Tmean, ranging from 0.14 to 0.39 °C/decade. Over three decades, the frequency of warm days (warm nights) increased by 2.2 days/decade (0.8 nights/decade) with a corresponding decrease of cool days (cool nights) by 0.4 days/decade (1.4 nights/decade). The climate of the Solomon Islands has warmed significantly between 1951 and 2011 with more warm days and nights, and fewer cool days and nights.

Keywords: Solomon Islands, climate change, surface air temperature, extreme temperature

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Introduction

Solomon Islands is located in the Western Pacific Warm Pool region, east of Papua New Guinea and comprises a scattered archipelago of approximately 1000 islands including volcanic mountainous islands and low lying coral atolls with a total land area of 28,785 km^2 and a maritime Economic Exclusive Zone (EEZ) of 1.34 million km^2 (MECDM 2012). The Solomon Islands is in a region vulnerable to geological and hydro-meteorological hazards. There are two seasons in the country; the warm wet season from November to April and the cool dry season from May to October. The local names for these seasons, *Komburu* and *Ara* are based on the prevailing direction of the trade winds (BoM & CSIRO 2011b). This seasonal difference is largely associated with the south-north shifting of the South Pacific Convergence Zone (SPCZ), the main feature of surface convergence and a major influence on climate in the region (BoM & CSIRO 2011a). Solomon Islands' climate is generally humid and warm throughout the year with weak seasonal variations.

The IPCC 5^{th} Assessment (IPCC 2013) reported that globally the combined land and ocean surface temperature was warming around 0.85 [0.65 to 1.06] °C, over the period 1880 to 2012. Changes in the surface temperature over 1901-2012 around the Solomon Islands region ranged between 0.6-1.0°C.

There is growing consensus that the changes in the equatorial Pacific influences temperatures globally as underscored by the 1997-1998 and 2015-2016 El Niño events (Alonk et al. 2012; Held 2013; England et al. 2014). Climate model simulations also suggest that slowing of the warming trend in the recent decades was linked to negative phases of the Interdecadal Pacific Oscillation (IPO; Alonk et al. 2012), which is the low-frequency manifestation of the El Niño-like pattern of climate variability (Power & Colman 2006). The underlying fact remains that oceans, predominantly in the Pacific, have increasingly taken up a substantial proportion of heat (Balmaseda et al. 2013; Watanabe et al. 2013).

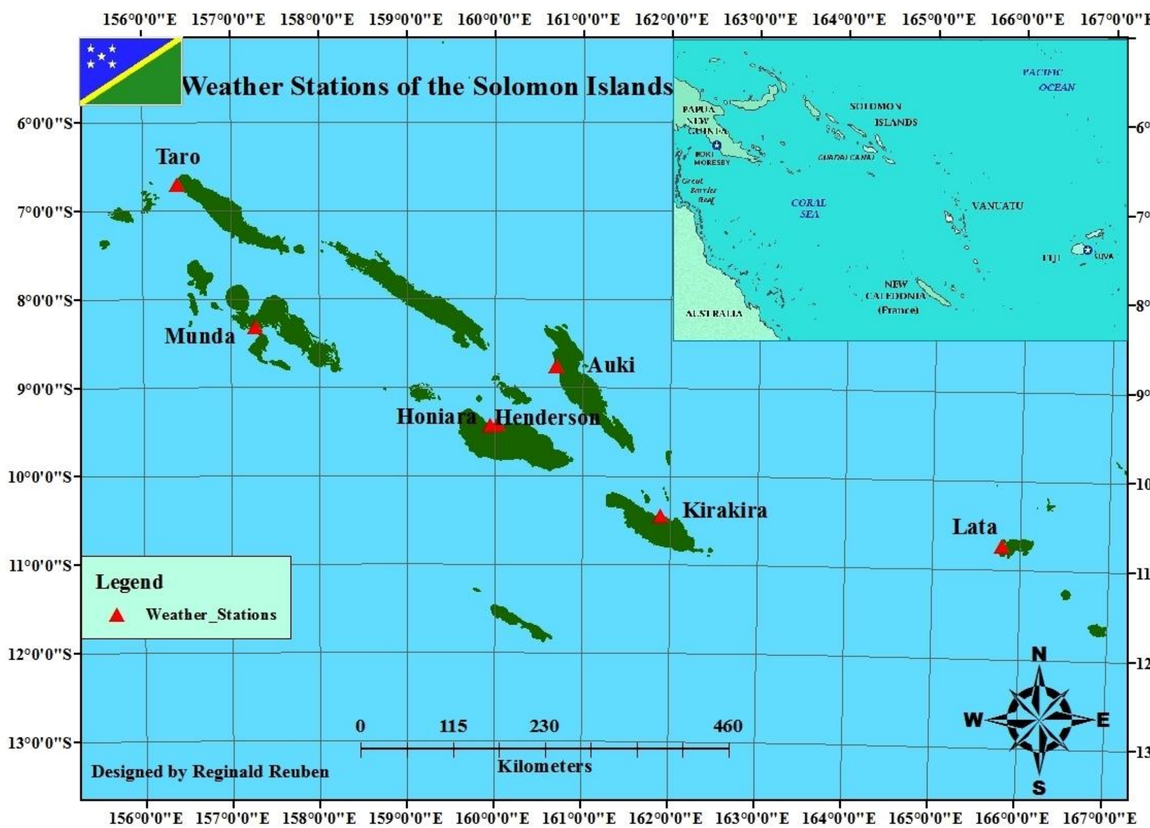
The increase in the mean global temperature was accompanied by the increase in the frequency of extreme events worldwide (Solomon et al. 2007). Even small changes in the mean could produce substantial changes in the frequency of extreme events (Karl et al. 1984; Mearns et al. 1984), as seen in the overall increase in hot days and warm nights with associated decreases in cool days and cold nights on global scale (Alexander et al. 2006; IPCC 2012) and regional scale (Manton et al. 2001; Mataki et al. 2006; Nandintsetseg et al. 2007; BoM & CSIRO 2014). Whatever the changes in mean temperature, it is the extreme climate events that have the biggest negative impacts on human society and the natural environment (Manton et al. 2001; Choi et al. 2009).

The Small Island States of the South Pacific region contributed less than 1% of the global GHG (Mimura et al. 2007). Yet, they comprised of some of the most vulnerable states to the effects of climate change. The small Island States of the South Pacific share many common characteristics that increase their vulnerability to the effects of climate change (Tompkins et al. 2005). As such, they are the ones exposed at the frontlines of global climate change (Maclellan et al. 2009). A comprehensive analysis of Solomon Islands climate is still lacking. The three-volume study of climate change in Pacific published by the Australian Bureau of Meteorology and CSIRO under the Pacific Climate Change Science Program (PCCSP; BoM & CSIRO 2011b) and Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP; BoM & CSIRO 2014) programs relied on only a few stations for the country reports. For the Solomon Islands, only data for Honiara and Santa Cruz (referred here as Lata) were used in the second volume (BoM & CSIRO 2011b) whilst Honiara and Munda data were used in the third volume (BoM & CSIRO 2014), which is an updated country report for the region. Other regional studies (Manton et al. 2001; Griffiths et al. 2005; Nicholls et al. 2005; Choi et al. 2009; Whan et al. 2014) also used 1 or 2 local stations for each country. In this study, we expand the coverage by examining all the available temperature data of seven weather stations operated by the Solomon Islands Meteorological Service (SIMS) between 1951 and 2011 to establish trends, variability, and extremes for all 7 stations.

Methodology

Data source and analysis

We examined all available daily digitized minimum and maximum surface air temperature data between 1951 and 2011 for the seven weather stations shown in Map 1. Table 1 shows the respective periods of digitized data for each station, site elevation, provincial jurisdiction and the geographic coordinates of the stations. The Honiara and Munda stations are part of the World Meteorological Organization's (WMO) Global Surface Network (GSN). All the stations' operational procedures are regularly monitored by qualified SIMS personnel in compliance with WMO standards.



Map 1 The map of Solomon Islands showing locations of the 7 weather stations operated by the Solomon Islands Meteorological Service (SIMS).

Table 1 The Solomon Islands Meteorological Services has maintained seven weather stations that operate to WMO standards. The coordinates, elevation and data years available for each stations are shown.

		Geographic coordinates			
Stations	**Province**	**Latitude**	**Longitude**	**Elevation**	**Data years**
Taro	Choiseul	06°42'S	156°24'E	1.2m	1976-2011
Munda	Western	08°20'S	157°16'E	2.7m	1962-2011
Honiara	Honiara City Council	09°25'S	159°58'E	55m	1951-2011
Henderson	Guadalcanal	09°25'S	160°03'E	7.9m	1975-2011
Auki	Malaita	08°47'S	160°44'E	11m	1962-2011
Kirakira	Makira/Ulawa	10°25'S	161°55'E	5.5m	1965-2000
Lata	Temotu	10°42'S	165°48'E	22.8m	1971-2011

For statistical analysis, standard diagnostic measures and inferential tests were done using R stats version 3.4.0 (www.r-project.org). Significance thresholds for all analyses were set at the 95% confidence level.

A combination of linear regression and time series analysis was used to establish trends. The seasonal and irregular erratic components of the time series were removed through data decomposition in R prior to determining the trends (Example in Figure 1). Daily data was used to calculate the trends in surface air temperature. Monthly values were averaged to obtain annual values.

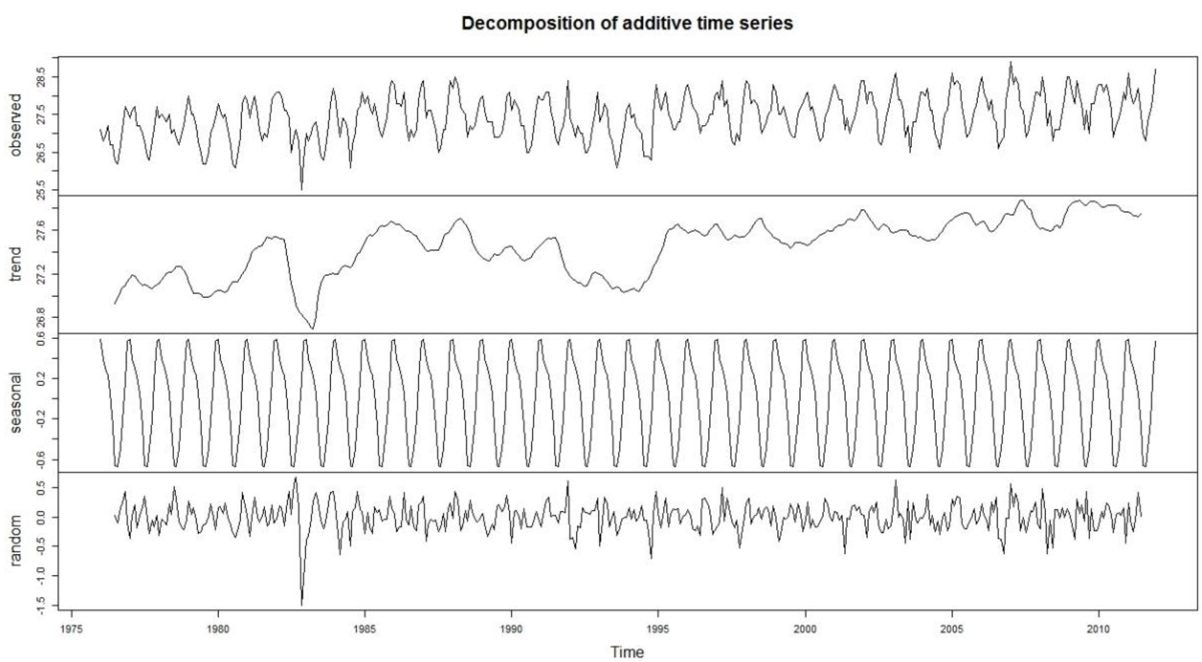


Figure 1 Decomposition of the Tmean of Taro between 1976 and 2011. The time series has 4 components: observed, trend, seasonal, and random component. The seasonal and random components were removed before the trends were determined.

The 30-year average of the period 1961–1990 was set as the normal period by the World Meteorological Organization (WMO), however, a "provisional normal" may apply to stations with insufficient data (WMO 1984, 2011). Hence, in this study, the 1981-2010 normal period, the only period with sufficient data for most of the stations, was used to calculate the temperature anomalies, except for Kirakira, which has data only up to 2000, the year it was decommissioned from further operation due to land issues (MECDM 2011).

Extreme temperature thresholds for respective stations were defined as those daily temperatures exceeding the 1st and 99th percentiles for the period 1981-2010. Any missing values in the daily records can lead only to extreme days or nights being undercounted rather than overcounted. The daily data was a total of 10,957 days (incl. 7 leap years between 1981 and 2010) was ranked in descending order from highest daily temperature to lowest for the 30-year data. Thus, the 1st percentile was determined as the 110th lowest value, and the 99th percentile was the 110th highest value. A warm-day threshold was determined from the 99th percentile, and a cool-day threshold was determined from the 1st percentile of the ranked 30-year data of the daily maximum temperature records. A warm-night threshold was determined from the 99th percentile, and a cool-night threshold was determined from the 1st percentile of the ranked 30-year data of the daily minimum temperature records. Hence, any two stations may not necessarily have had the same extreme temperature threshold as shown in Table 2.

Table 2 The extreme temperature thresholds for seven stations of the Solomon Islands for the period 1981-2010 (except for Kirakira 1971-2000).

	Extreme temperature thresholds			
	Tmax		**Tmin**	
Stations	**Warm day (≥)**	**Cool day (≤)**	**Warm night (≥)**	**Cool night (≤)**
Taro	33.7°C	26.9°C	25.3°C	20.8°C
Munda	33.2°C	26.8°C	26.4°C	21.2°C
Honiara	33.7°C	26.9°C	25.3°C	20.8°C
Henderson	34.0°C	27.0°C	24.7°C	18.9°C
Auki	33.5°C	26.7°C	25.8°C	20.5°C
Lata	33.0°C	26.5°C	26.4°C	22.0°C
Kirakira	33.3°C	26.5°C	25.0°C	18.9°C

Treatment of missing temperature data

The WMO (2011) recommended for annual analysis only yearly data having at least 80% data availability with no more than three consecutive missing years; and for monthly analysis, series having less than ten missing daily values. In this study, the reference verses candidate station technique to impute missing values was applied. A reference station is usually a neighboring station with complete data, which is the basis to impute missing data of a candidate station. The PCCSP report used the neighboring Henderson data to impute missing Honiara data, forming a Honiara-Henderson composite (BoM & CSIRO 2011b). In this study, we expanded on this idea by correlating the partially complete daily data of a particular month of a candidate station with the complete data of all other stations (reference stations) for the same month. The highly correlated variables were used as predictors to impute missing values for the candidate dataset using the mice (Multivariate Imputation by Chained Equation) package in R by which the predictive mean matching (pmm) method was used. Sampled examples given in Figs. 2 and 3. The mice, as its acronym states is often used for multivariate imputation, however, it is also capable of using univariate imputation techniques including overall mean, linear regression, stochastic regression, random sample, and predictive mean matching (Van-Buuren & Groothuis-Oudshoorn 2011; Moritz et al. no date). Such coverage makes this package an appropriate tool for filling missing data for the Solomon Islands' case.

```
              O_T O_M O_H O_A O_L O_K
Oct_Taro       1
Oct_Munda          1
Oct_Henderson .    ,   1
Oct_Auki      .    .   ,   1
Oct_Lata           .       .   1
Oct_Kirakira  .    +   .   .   .   1
attr(,"legend")
[1] 0 ' ' 0.3 '.' 0.6 ',' 0.8 '+' 0.9 '*' 0.95 'B' 1
```

Figure 2 A correlation matrix output in R showing October 1982 Tmin (O_T) data for Henderson, Auki, and Kirakira to be the most correlated to the October 1982 Tmin data for Taro (Oct_Taro) at 0.6 correlation coefficient. Taro is the candidate station with incomplete data in this example.

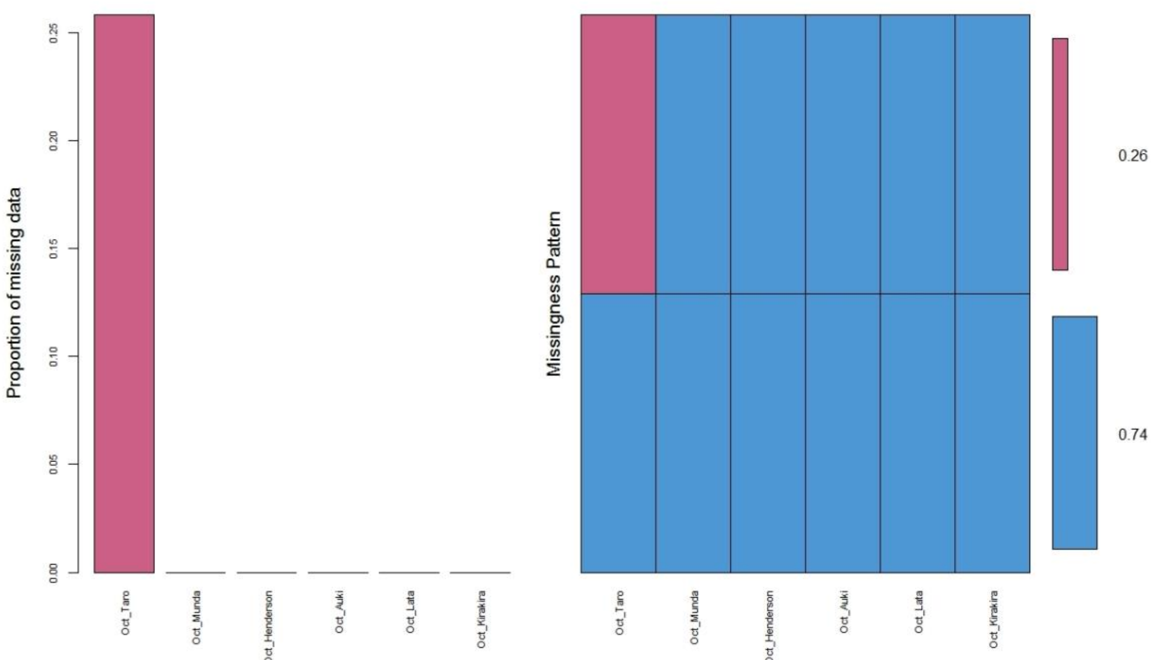


Figure 3 A graphical output in R showing the missing data pattern, revealing 26% missing with 74% complete values from Taro's October 1982 Tmin dataset. The complete data of the same period from Munda, Henderson, Auki, Lata, and Kirakira were comparatively shown but only the most correlated sets from Henderson, Auki, and Kirakira as previously determined (in Fig. 2 above) were used as predictors by the mice package to impute for Taro's missing values.

Results and discussion

Mean surface air temperature

The mean monthly surface air temperatures for the seven weather stations of the Solomon Islands during the 30-year period from 1981 to 2010 (except Kirakira, 1971-2000) are depicted in Figure 4. Typically, within a 12-month period, the monthly surface temperature distribution is a V-like pattern as portrayed in this figure. Generally, the months of November through April (Nov-Apr) have relatively higher average surface temperatures than those of May through October (May-Oct). This distinct seasonal pattern corresponds with the wet (Nov-Apr) and dry (May-Oct) seasons of the Solomon Islands, where the wet season is generally warmer than the dry season (BoM & CSIRO 2011b). The pattern is uniform throughout the country with typically warmer temperatures around January and December and least warm around July-September (Figure 4).

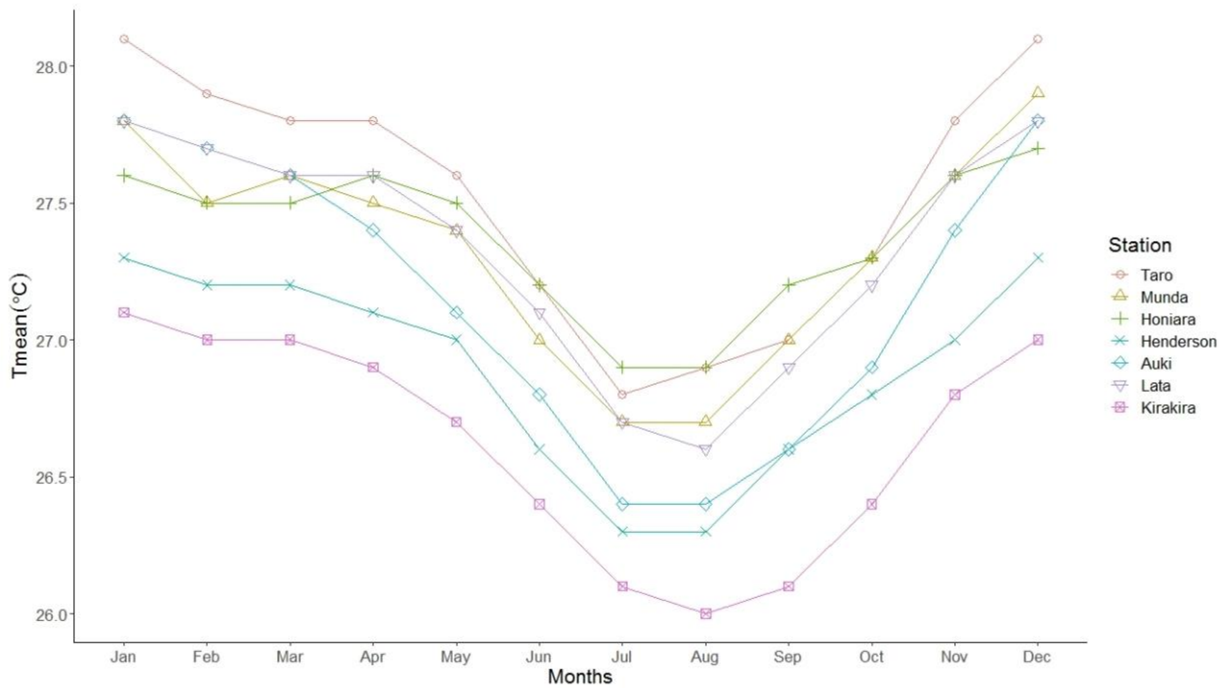


Figure 4 Monthly mean surface air temperatures at 7 weather stations of the Solomon Islands during 1981-2010 (except Kirakira 1971-2000).

Overall, December and January averaged around 27.8°C and 27.7°C respectively, while July and August both averaged around 26.6°C. This corresponds respectively to the summer and winter seasons in the southern hemisphere. Taro station located at the northwesternmost part of the country averaged the highest at 28.1°C during the months of December and January while Henderson located at the central region averaged as the least warm at 26.3°C during July and August. The close proximity of Taro to the equator relative to the other stations of the country may have attributed to its warmer climate. Meanwhile, in Figure 5, Kirakira, located in the east of the country, was depicted as the least warm of all the stations; however, the relatively early period (1971-2000) used in the analysis of Kirakira data here may have also been an attributive factor. Kirakira station located on Makira Island was decommissioned in 2000 due to land lease issue regarding the site location; hence, data beyond 2000 is not available (MECDM 2011).

Honiara showed the warmest on average from June through October; and was significantly higher than its closest neighbor, Henderson, which is about 15km to the east. The elevated temperature was due to Honiara's higher elevation relative to the rest (see Table 1). Topography may be a significant factor on the site temperature around June through October. However, this study does not quantitatively measure the influence of topography as such undertaking is outside its objective. The average elevation of the majority of the stations studied here is 6.7m when Lata (22.8m) and Honiara (55m) elevations were considered as outliers. A study by Giambelluca et al. (2008) on temperature changes in Hawaii found stronger warming at the higher elevations in the last 30 years of a 85 year-based data of 21 stations. This current study, however, could not replicate such long-term data analysis that clearly determined the role of topography over a longer period due to the relatively short observed station data available to us.

Temperature variability

Figure 5 shows the time series of mean surface air temperature for all seven weather stations of the Solomon Islands between 1951 and 2011. It reveals that the mean temperature for all the stations portrays steeper increasing trends prior to the 1990s and then tends to level off a bit during the recent decade. This is consistent with the recent global warming hiatus (Easterling & Wehner 2009). The causes of the hiatus are still an area of debate in the academic sphere; however, some points of common agreement also exist. These include the fact that recent atmospheric circulation patterns over the Pacific have tended to favor La Niña conditions over El Niño ones, with an overall trend towards a stronger, La Niña-like Walker Circulation (L'Heureux et al. 2013). According to Linsley et al. (2006) the increased frequency of La Niña- like mean conditions in recent decades relates to the expansion of the SPCZ. Consequently, the increased cloud cover reduces solar radiation, as a result, it reduces the maximum surface temperature (Dai et al. 1999; Stone & Weaver 2002; Solomon et al. 2007). This dragged down the rate of warming during the day. England et al. (2014) associated the recent global hiatus to the accelerated trade winds, which they said have increased equatorial upwelling in the central and eastern Pacific, which lowers the SST there and drives further cooling in other regions, even to the southwestern Pacific.

El Niño events tend to bring drier conditions in the wet season with above normal maximum and minimum air temperatures due to increased solar radiation as a result of reduced cloud cover; whilst during La Niña temperatures are usually lower (BoM & CSIRO 2011b). Thus, the peaks typically depict warming and this has been the iconic feature that distinctly marks an El Niño-dominated period from others (Folland et al. 2002). The warming influence of El Niño on global temperature is empirically well attested (Folland et al. 2002). But the majority of the observed station data used on global temperature analysis are based on the northern hemisphere, where they are surrounded by vast continental land mass rather than the ocean. In this study, it appears that the prominent El Niño years were marked by significant troughs rather than peaks. This seemed to indicate that during El Niño the temperatures in this island state tend to drop.

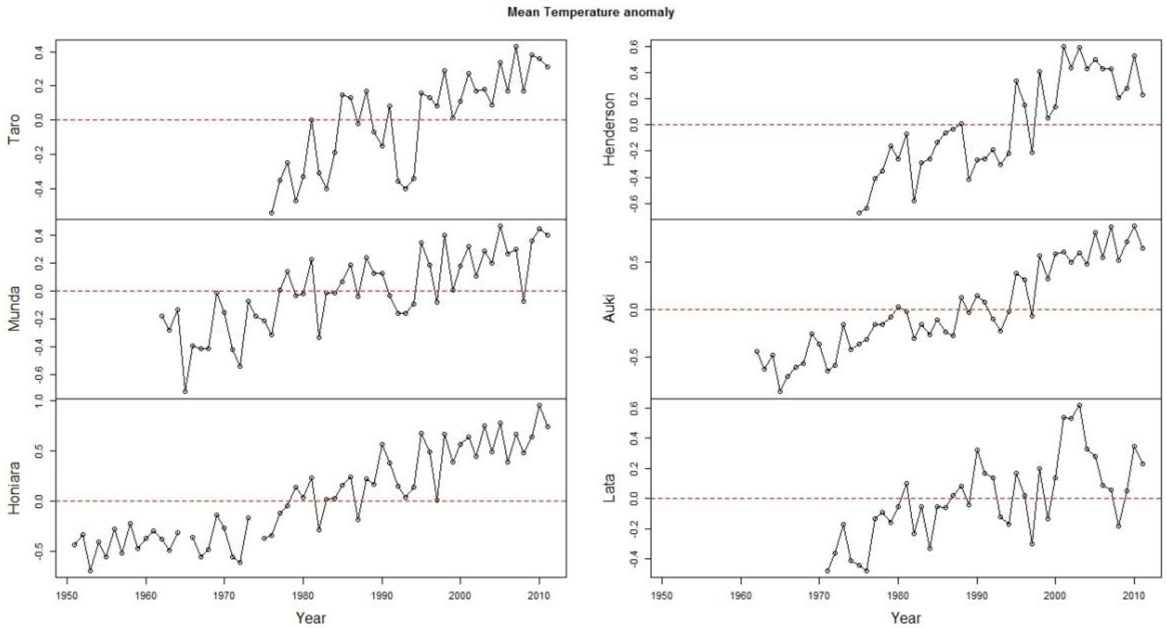


Figure 5 Mean temperature anomalies across 6 weather stations of the Solomon Islands between 1951 and 2011 based on 1981-2010 normal. The dashed lines represent the normal at each station.

For example, the broad trough from 1992 to 1995 is consistently portrayed by all the stations of the Solomon Islands (Figure 5). The 1992-1995 period marks two consecutive periods of El Niño conditions without an intervening cold episode (Salinger 2005). Other prominent years (e.g., 1965, 1982/83, 1997/98 and 2009) that were featured with moderate to strong El Niño conditions also showed significant troughs instead of the peaks. To further illustrate this point, the 1965 El Niño phase began from April of that year and extends through to around May of 1966 (NOAA & National Weather Service 2014); during this period the annual mean temperature of Munda, Honiara, and Auki dropped by 0.8°C, 1.4°C and 1.1°C respectively below the normal.

The Tmax is strongly impacted by the ENSO during the dry season (May-Oct) than during wet season (Nov-Apr) in the Solomon Islands (BoM & CSIRO 2011b). This could mean that whatever the changes that occur to the Tmax during the dry season would definitely have the greatest influence on the climate variability and trends. According to BoM and CSIRO (2011b), both the canonical ENSO and ENSO Modoki affect only maximum air temperatures in the dry season; and that both types of El Niño bring cooler maximum air temperatures in the dry season. This effect is attributed to cooler ocean waters in the region of the Solomon Islands during El Niño events (BoM & CSIRO 2011b). Normally, there is a prevailing onshore flow of southeast trades that commences around May through until October, and these trades were also attributed to the buildup of moist, cloud cover and rain over the windward sides of many high islands of the South Pacific during this period (Mataki et al. 2006).

This study suggests that the likely causes of the recent global hiatus (Easterling & Wehner 2009) appear to link strongly with the variability and trends observed here. A recent study by L'Heureux et al. (2013) suggested that the atmospheric circulation patterns over the Pacific have tended to favor La Niña conditions over El Niño ones, with an overall trend towards a stronger, La Niña-like Walker Circulation. This may correspond directly to the accelerated trade winds, which according to England et al. (2014) is associated with the increased equatorial upwelling in the central and eastern Pacific, which in turn, lowers the SST there, and drives further cooling in other regions, even to the southwestern Pacific. The cooling effect on the surface temperature of the surrounding region as attributed to upwelling was also highlighted previously by Linsley et al. (2006). According to Nicholls (2004), the temperature trends for locations in temperate regions tend to be influenced by changes in the rainfall. However, this effect is not observed in temperature trends in tropical Pacific island sites, which Jones et al. (2013) suggested being greatly influenced by changes in the SST instead. The Jones et al. (2013) study used updated homogeneous temperature data of the Pacific Islands stations including few stations of the Solomon Islands. In this current study, the behavior of the Tmax of the stations in the Solomon Islands during the dry season as described above has shown a consistent evidence that the ocean generally influenced the island temperatures.

Temperature trends

For the analysis of surface air temperature trend, we carry out a regression analysis. Table 3 presents the results of the analysis. It reveals the significant increases in the annual mean temperature trends over 35 to 61 years of respective records of the stations used in this study. This is consistent with the majority of selected regional stations analyzed under the PCCSP (BoM & CSIRO 2011a). The annual mean temperature increased significantly over the 7 stations with rates ranging from 0.14°C to 0.39°C per decade for their respective years of records. This represents an additional increase from 0.02 to 0.29°C per decade higher than the combined South Pacific regional trend of 0.1°C for the past 50 years (Brohan et al. 2006). However, the disparity between the local observations and that of the regional rate may partly due to the model (HadCRUT3v) dataset used by Brohan et al. (2006) that represented an average over a very large geographic region, mostly dominated by the ocean and not at the site level. As such, the relatively lower rate of the increase attributed to the region is due to the domination by ocean temperatures that tend to increase more slowly than land temperatures (Salinger 2005; Bernstein et al. 2007; BoM & CSIRO 2011a). The climate variability of the Solomon Islands is very much influenced by the thermal ocean behavior, particularly during active ENSO events.

The PCCSP report estimated the warming trend over the region from 1960 to 2009 to be around 0.08-0.20°C per decade (BoM & CSIRO 2011a), which is also lower than the local range presented here. But the trends of Honiara and Lata (as Santa Cruz in PCCSP), two local stations covered in the PCCSP report were calculated in this study as 0.22 and 0.15°C per decade respectively fall within the PCCSP range for the region. The slight variations may be attributed to the different length of records used in the different studies (here up to 2011 and PCCSP up to 2009). Further, the use of recent time series is expected to elevate the magnitude of trends because according to Bernstein et al. (2007) decadal increase in temperature is accelerating with time.

Honiara, having the longest data years analyzed in this study, further demonstrated the increased difference in the rate of trends between two 30-year epochs (1951-1980 and 1981-2011) with the latter epoch about doubled the rate of the former as portrayed in Figure 6. That is, the trend in 1951-1980 was about 0.12°C per decade while that of 1981-2011 was 0.23°C per decade (Figure 6). The regressions are both significant at 99% and 99.9% confidence level respectively. An analysis of the temperature trends in Fiji by Kumar et al. (2013) also underscored the higher rate of increase in the more recent years, even to the order of 0.69_{o}C per decade for the Tmax in the 1989-2008 period.

Kirakira registered the highest warming rate at 0.39°C per decade in this study even though the time series used only up to 2000 (Table 3). No data for Kirakira is available after 2000 as the station was decommissioned then and is no longer operational to the writing of this paper. Kirakira's relatively high rate could be influenced by the significant decadal increases at Kirakira between 1971 and 2000 (0.6, 0.7 and 0.6 °C/decade during 1971-1980, 1981-1990 and 1991-2000 respectively (Not shown). However, rates over 0.3°C per decade were not rare even in the region (Salinger 2001; Folland et al. 2003; Jones et al. 2013; Whan et al. 2014).

Table 3 Surface air temperature trend analysis at seven weather stations of the Solomon Islands for their respective longest data years available at time of study.

Station (data years)	**Trend in °C per decade**	**Adj. R-squared (R_2)**
Taro (1976-2011)	0.20 [0.15-0.25]***	0.6924
Munda (1962-2011)	0.14 [0.10-0.17]***	0.6045
Honiara (1951-2011)	0.22 [0.19-0.25]***	0.8500
Henderson (1975-2011)	0.28 [0.22-0.34]***	0.7605
Auki (1962-2011)	0.29 [0.26-0.33]***	0.8876
Lata (1971-2011)	0.15 [0.11-0.21]***	0.5562
Kirakira (1965-2000)	0.39 [0.32-0.45]***	0.8665

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '•' 0.1 ' ' 1*

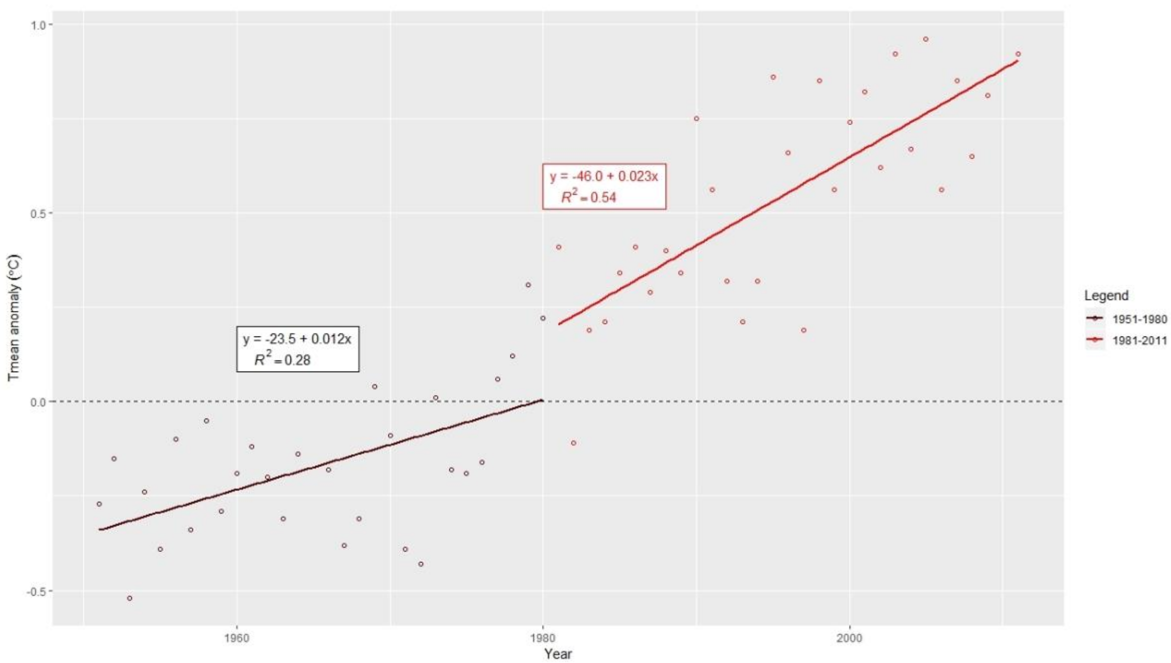


Figure 6 Mean surface temperature trend at Honiara between two 30-year time epochs (1951-1980 and 1981-2011) based on 1961-1990 normal.

Warm and cool days and nights

Figure 7 presents the result of what a typical frequency distribution of warm and cool days and nights for the Solomon Islands look like on monthly basis. January and December normally have the highest occurrence of warm days and nights, which decreases towards the mid-year with the least occurring during July and August. On the other hand, July through September normally have the highest occurrence of cool days and nights, which decreases towards the start and end of each year, with the least number of occurrences around January and December. Hence, there is a relatively higher occurrence of warm days and nights during the wet seasons

(Nov-Apr) than the dry seasons (May-Oct) and vice-versa for the cool days and nights. The occurrences of extreme temperatures may be attributed to the natural seasonal occurrence and the influence of other climate features. To study the shift of the temperature thresholds over the years in terms of seasonality is beyond the scope of this research. According to BoM and CSIRO (2011b), on a seasonal basis, there is usually increased solar radiation and reduced cloud cover during Nov-Apr for the region, which may contribute to the high number of warm days during this period. On the other hand, the increased manifestation of the south-east trade winds (c.f., England et al. 2014) and cloud cover associated with topographical influence of the high islands during May-Oct (Mataki et al. 2006) may likely have resulted in the cooling effect on surface temperature resulting in low number of warm days but high number of cool days during May-Oct.

ENSO plays an important role as well. According to BoM and CSIRO (2011a, b) El Niño episodes normally bring warmer maximum and minimum air temperatures during the wet season (Nov-Apr); and bring cooler air temperatures in the dry season (May-Oct) due to cooler ocean waters in the region of the Solomon Islands. Moist from the cooler ocean are picked up by the prevailing trade winds and blown landward, which in turn cools the maximum and minimum surface temperatures during the dry season, which results in the relatively higher occurrences of cool days and nights during May-Oct.

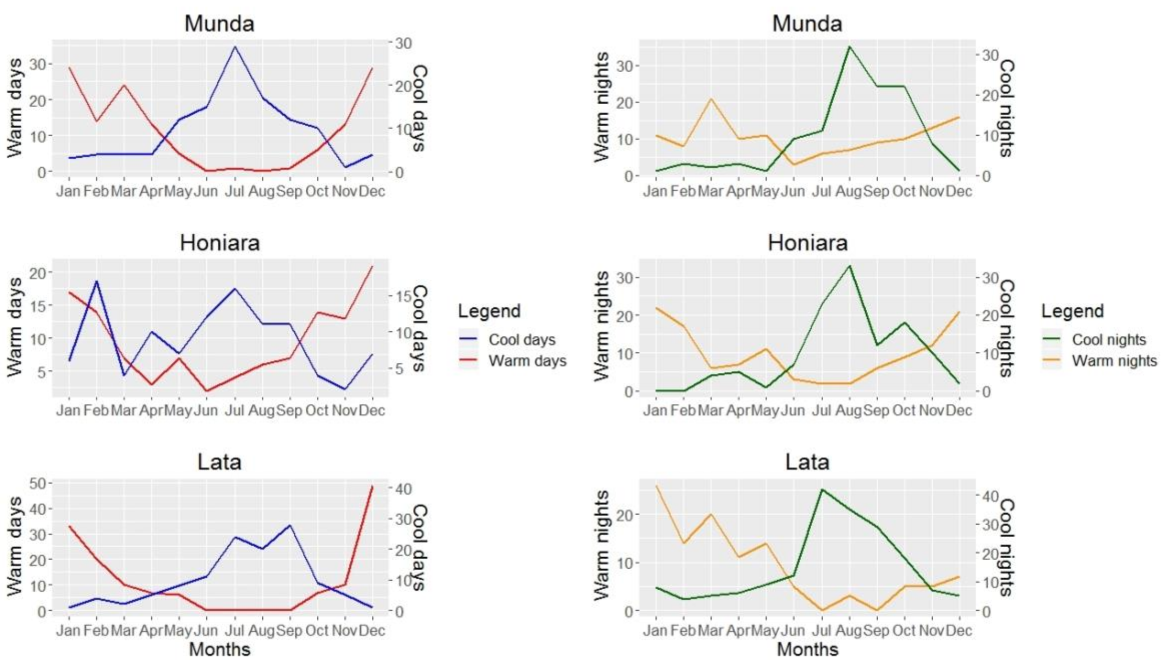


Figure 7 The monthly distribution of warm and cool days and nights at Munda, Honiara and Lata stations from 1981 to 2010.

Extreme temperature trends

Figure 8 presents the visual representation of trends for the warm and cool days and nights over 1981-2010 period at the stations in the Solomon Islands. It typically shows that the annual number of warm days and nights increased while the number of cool days and nights decreased over the 3 decades at most stations in the Solomon Islands. Table 4 presents the results of the regression analysis for the frequency of the extreme temperature thresholds at each station. It reveals that all the stations except Lata displayed significant increases in the number of warm days. Lata, which is located at the south-easternmost part of the country has a very high interannual frequency of warm days, hence, resulted in the insignificant regression. For the warm nights, Auki, Lata, and Kirakira showed significant increases at 90% and 99% confidence level respectively; while Taro, Munda, Honiara, and Henderson displayed an insignificant regression due to the occurrences of the high interannual frequency of warm nights in their data. Further, in this study, the different data years used for Kirakira (1971-2000) than the rest of the stations (1981-2010), could affect the results because according to the IPCC (2013) trends based on very short records are very sensitive to the beginning and end dates due to natural variability. The trends of the extreme temperatures as summarized in Table 4 were consistent in direction but smaller in magnitude with those of a recent study by the Pacific-Australia Climate Change Science and Adaptation Planning Program (PACCSAPP; BoM & CSIRO 2014). This may be due to the different data years analyzed by this study and PACCSAPP. The PACCSAPP study under the country reports analyzed the extreme temperatures on a relatively longer time period for the two stations (Honiara 1953-2011 and Munda 1962-2011) of the Solomon Islands.

For the cool days, all the stations except Lata displayed decreasing trends. Lata is the one station that is located to the farthest south-east of the country (Map 1). However, all the regression are not significant at all (Table 4). Meanwhile, for the cool nights, Honiara, Henderson, Auki, and Lata, displayed significantly decreasing trends whilst those of Taro, Munda and Kirakira are not significant due to high inter-annual variability in their data, making it difficult to establish a significant trend.

The increasing warm days and nights, and decreasing cool days and nights were consistent with other studies in Fiji (Mataki et al. 2006; Kumar et al. 2013), the Asia-Pacific region (Manton et al. 2001; Nicholls et al. 2005; Choi et al. 2009) and for small islands in general (Mimura et al. 2007). On the global scale, similar trends were observed over most land areas during the past 50 years (Alexander et al. 2006; IPCC 2007, 2012).

The opposing trends (i.e. increasing warm days and nights vs. decreasing cool days and nights) observed may also be linked to the change in the mean temperature or variance of the data distribution. When the distribution of data follows the normal or Gaussian distribution principle, the effect of a small shift, corresponding to a small change in the mean or variance of the distribution affects the frequency of extremes at either end of the distribution (Salinger 2005; Solomon et al. 2007). Hence, small shifts in the mean value could produce substantial changes in the frequency of extreme events (Karl et al. 1984; Mearns et al. 1984). So an increase in the frequency of warm days and nights was accompanied by a decline in the number of cool days and nights as the mean shifts to the right of the distribution curve. With very high confidence, the PCCSP projected changes in annual mean surface air temperature for 2030, 2055 and 2090, relative to 1990, under the A2 (high) emission scenario to be around 1°C by 2030, 1.8°C by 2055 and 3.3°C by 2090 for the regions of the Solomon Islands (BoM & CSIRO 2011b). So for example, the observed annual mean temperature of 27.5°C at Taro may increase to a value as high as 28.5°C by 2030, 29.3°C by 2055 and 30.8°C by 2090. Similarly, the minimum and maximum temperatures will also increase coherently over the same periods. At such projected rate, the surface air temperatures over the country will increase over the course of the 21st century and beyond if nothing is done to cut back on greenhouse gas emissions, the fundamental cause of climate change at the global level.

Averaged over all the stations (National avg), the annual frequencies of warm days and nights have increased by 2.2 and 0.8 days per decade respectively, whereas the frequencies of cool days and nights have decreased by 0.4 and 1.4 days per decade respectively over the past decades (1981-2010; Table 4). The frequencies of the warm days and nights, and cool days and nights in the Solomon Islands were lower compared to a study by Choi et al. (2009) on 10 Asia-Pacific Network (APN) countries (Mongolia, China, Republic of Korea, Japan, Vietnam, Thailand, Pakistan, Malaysia, Australia, and New Zealand) for the period, 1955-2007. The trends in the warm days and nights in the APN countries exceeded those of the Solomon Islands by a factor of 2 and 7 respectively, and the cool days and nights exceeded those of the Solomon Islands by a factor of 8 and 5 respectively (c.f., Choi et al. 2009). The disparity in the magnitude of trends may be attributed to various reasons including the different length of records used by this study and that of Choi et al. (2009). Secondly, to the fact that the ten APN countries are industrially advanced than the Solomon Islands, significant urbanization may have given rise to the influence of "heat island effect" on their surface air temperatures (e.g., Ren et al. 2008). Thirdly, the 10 APN countries have a relatively larger land area, so their warming rate would be higher than the oceanic island countries, such as the Solomon Islands (c.f., Salinger 2005; Bernstein et al. 2007).

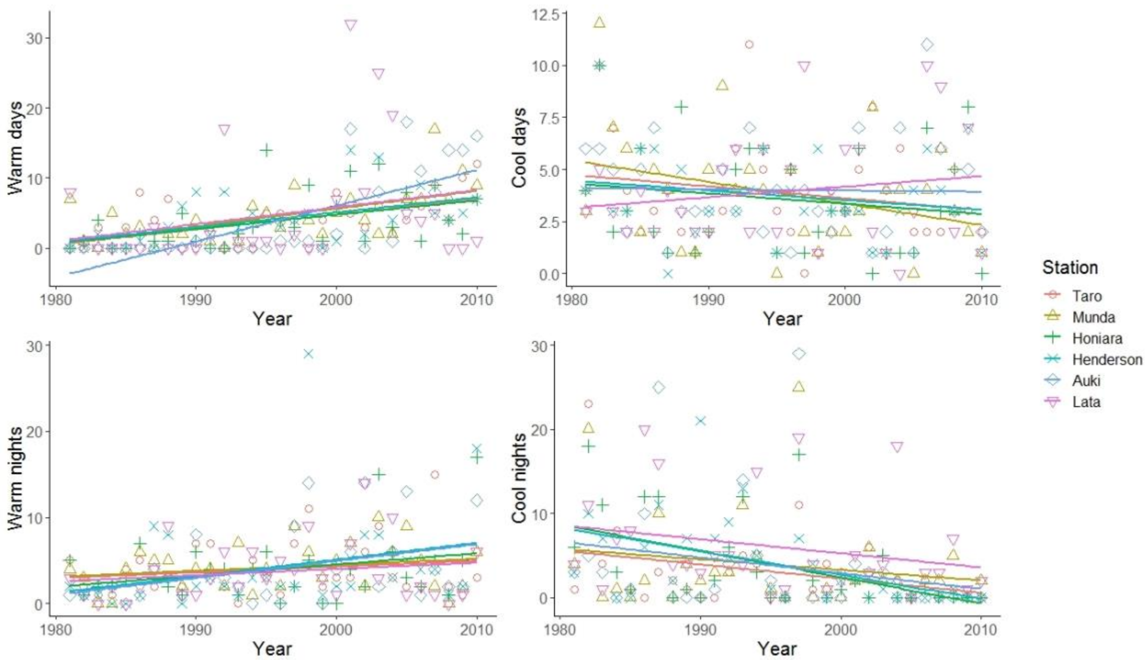


Figure 8 Trend lines of warm and cool days (top panels) and warm and cool nights (bottom panels) at 6 weather stations from 1981 to 2010.

Table 4 Extreme temperature indices trend analysis for the seven stations during 1981-2010 (except Kirakira 1971-2000).

Temperature extreme indices	Taro	Munda	Honiara	Henderson	Auki	Lata	Kirakira	National avg
Warm days/decade	2.1[0.9-3.3]** *R^2 0.317*	1.9[0.8-3.1]** *R^2 0.024*	2.0[0.7-3.3]** *R^2 0.277*	1.6[0.6-2.6]** *R^2 0.286*	4.3[2.8-5.8]*** *R^2 0.582*	1.2[-0.6-3.0] *R^2 0.071*	3.5[2.2-4.8]*** *R^2 0.540*	**2.2**
Cool days/decade	-0.4[-1.4-0.5] *R^2 0.037*	-0.6[-1.6-0.5] *R^2 0.046*	-0.5[-1.6-0.7] *R^2 0.026*	-0.1[-0.9-0.7] *R^2 0.001*	-0.4[-1.3-0.5] *R^2 0.032*	0.5[-0.6-1.6] *R^2 0.028*	-0.4[-1.5-0.7] *R^2 0.019*	**-0.4**
Warm nights/decade	0.7[-0.8-2.1] *R^2 0.031*	0.7[-0.4-1.8] *R^2 0.052*	1.0[-0.4-2.5] *R^2 0.071*	0.7[-0.4-1.8] *R^2 0.061*	1.1[-0.1-2.4]$^{\cdot}$ *R^2 0.125*	0.4[-0.8-1.6]$^{\cdot}$ *R^2 0.017*	1.8[0.6-3.1]** *R^2 0.253*	**0.8**
Cool nights/decade	-0.5[-1.7-0.7] *R^2 0.024*	-0.4[-1.7-0.9] *R^2 0.013*	-2.5[-4.1, -0.9]** *R^2 0.291*	-2.3[-3.6, -1.0]*** *R^2 0.347*	-1.2[-2.6, -0.2]$^{\cdot}$ *R^2 0.109*	-1.7[-3.4, -0.05]* *R^2 0.152*	-0.3[-1.8-1.2] *R^2 0.007*	**-1.4**

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '*

Conclusion

In this paper, we examined all available daily minimum and maximum surface air temperature data between 1951 and 2011 for the seven weather stations operated by the SIMS to produce a comprehensive coverage of the climatology of Solomon Islands.

Taro station averaged the highest average temperature at 27.5°C, owing its warmer climate to its relative proximity to the equator than the rest of the stations. Honiara showed the warmest from June through October due to its higher elevation than the rest of the stations. Henderson at the central region averaged the least at 26.9°C during the same period of time. The overall annual mean temperature for the Solomon Islands based on 1981-2010 average was 27.3°C, the overall annual maximum temperature was 30.8°C and the overall annual minimum was averaged at 23.7°C.

Trend analyses of the surface air temperatures have highlighted increasingly significant trends at all the stations in the Solomon Islands between 1951 and 2011. The mean surface air temperature increased between 0.14 and 0.39°C/decade between the seven stations that give an average temperature increase for the country to be around 0.24°C/decade. Comparing two 30-year epochs for Honiara showed that the rate of trends during the more recent epoch (1981-2011; 0.23°C/decade) has doubled that of a previous epoch (1951-1980; 0.12°C/decade). The magnitude and direction of the local trends are consistent with other studies for the region and global average. The changes observed in the mean surface temperatures for the Solomon Islands are consistent with the observed signals of human-induced climate change.

There have been significant increases in the frequencies of warm days and nights with accompanied decreases in the number of cool days and nights at most of the stations. The national average frequency trend of warm days for the country increased by 2.2 days/decade with station rates ranging from 1.2 to 4.3 days/decade, while the trend of warm nights increased by 0.8 nights/decade with station rates ranging from 0.4 to 1.8 nights/decade. On the other hand, the national average frequency trend of cool days for the country decreased by 0.4 days/decade with station rates ranging from -0.1 to -0.6 days/decade while, the trend of cool nights decreased by 1.4 nights/decade with station rates ranging from -0.3 to -2.5 nights/decade. Meanwhile, the high inter-annual variability of the frequency of the extreme temperature thresholds is also found to influence the significance of the regression in few of the data. However, the trends are typical and consistent with other studies.

Limitations that may influence the robustness of climate analysis in the Solomon Islands include the lack of long-term surface temperature data as well as the lack of complementary data such as wind, solar radiation, evaporation, humidity and cloud coverage. The direction and magnitude of the trends in this study, however, are consistent with previously published conclusions from the region and the globe. Moreover, the findings in this study may be used as a baseline study for Solomon Islands climatology as our coverage is inclusive of all weather stations, which past studies have not covered.

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