Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 3, 1297 doi: 10.2166/wcc.2022.357

# Projection of extreme climatic events related to frequency over different regions of Tanzania

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## ABSTRACT

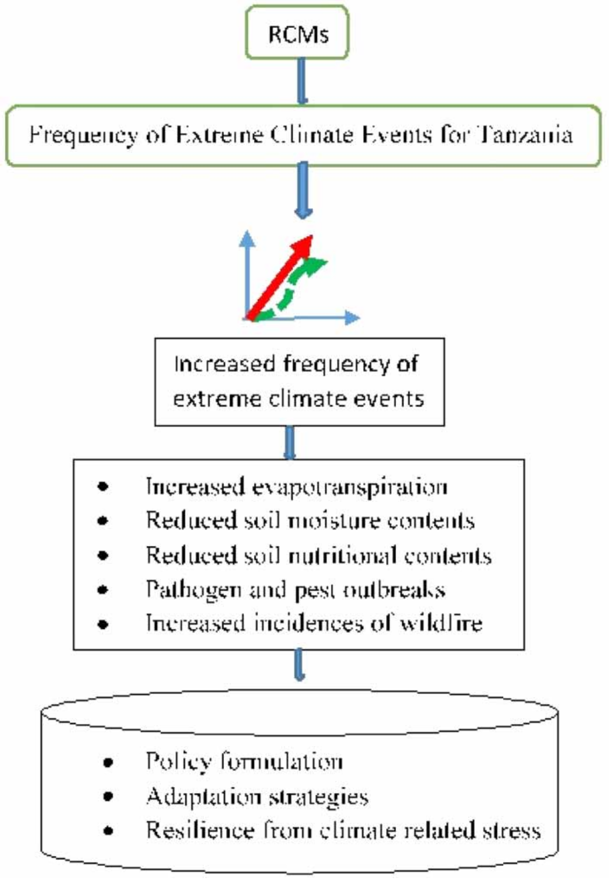
In recent years, extreme climatic events such as heavy rainfall and droughts are common and have contributed to the loss of lives, damage of properties, destruction of the environment and socio-economic livelihood of people predominantly in many developing countries. Characterizing these events to understand their temporal and spatial evolution is of great considerable benefit to different sectors; for instance, energy, agriculture, health and water resource sectors. In this study, we use the outputs of regional climate models to characterize the temporal and spatial evolution of extreme climatic events over Tanzania. Results reveal that all regions across Tanzania are projected to experience a statistically significant increased frequency of extreme climatic events related to temperatures. However, the frequency of extreme climatic events related to rainfall is projected to increase at a non-significant level across most regions. The presented increase in extreme climatic events is likely to pose significant damage to the agriculture sector, water sector and other socio-economic livelihoods of people over many regions in Tanzania. It is therefore recommended that appropriate policies should be put in place to help different sectors and communities at large to adapt to the projected increase in extreme climatic events, especially on the projected warming of near-surface temperatures.

**Key words:** CORDEX, extreme climatic indices, Mann–Kendall trend, regional climate models

## HIGHLIGHTS

- For the first time in Tanzania, this paper analyzes the future extreme climatic events using outputs from the high-resolution regional climate model.
- The paper analyzes the trends in an extreme event to discover the statistical significance of the extremes.
- The observed results could help the agriculture sector in Tanzania, which is challenged by severe increased changes in temperatures.
- The output could help postharvest.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

In recent years, due to climate change, the intensity, duration, severity and frequency of extreme climatic events have increased to pose damage to properties, destruction of the environment and infrastructure in many regions of the world (Climate Communication 2011). Furthermore, damage to infrastructure and socio-economic livelihood of people from climate-related extremes are predicted to increase in the future climate (IPCC 2018). This is expected to present significant challenges to efforts of achieving sustainable development goals (SDGs) in many countries of the world.

Developing countries are particularly more vulnerable to the impacts of increased frequency and intensity of extreme climatic events. This is due to their high dependence on rain-fed agriculture and natural resources for their livelihood, limited resources and technology for adaptation, and weak institutional capacity to adapt and mitigate the impacts (Freeman & Warner 2001; Ahmed *et al.* 2009; Rataj *et al.* 2016; Ampaire *et al.* 2017; Eckstein *et al.* 2017).

To reduce the impacts of extreme climatic events, developing countries are required to start taking necessary steps to develop adaptation and mitigation policies and mainstream into all development projects. However, before devising the adaptation and mitigation policies, it is necessary to characterize and understand the future extreme climatic events at temporal and spatial scales to provide evidence that would guide the policy formulation process.

The Intergovernmental Panel on Climate Change (IPCC) has played a leading role in providing reports that assess the past and future global climate. In these reports, however, the projections of extreme climatic events are at a coarse spatial resolution that is inadequate to be used for impact assessment at a regional and sectoral level. Therefore, there is an urgent need to undertake detailed studies on the projection of extreme climatic events at regional or local levels that would guide the formulation and planning of adaptation strategies at a specific region or location.

In Tanzania, several studies (e.g. Kijazi & Reason 2009a, 2009b; Tumbo *et al.* 2010; Chang'a *et al.* 2017) have characterized the extreme climatic events in the historical climate. Chang'a *et al.* (2017) analyzed extreme climatic indices in Tanzania for the period of 1961–2015 using observed daily rainfall, minimum and maximum temperatures and found that the mean temperature anomaly in the country has increased by 0.69 °C. Furthermore, the mean percentages of warm days and nights have increased by 9.37 and 12.05%, respectively, whereas the mean percentages of cold days and nights have decreased by 7.64 and 10%, respectively. Kijazi & Reason (2009a, 2009b) characterized the prolonged drought events that occurred over the northeastern part of Tanzania from 1998 to 2005 and wet days that occurred over the northern parts of Tanzania in 2006 during the October–December (OND) rainfall season. They indicated that the prolonged drought was related to a low-level moisture divergence and subsidence of the westerly winds over Tanzania and the eastward shift of the country of the ascending arm of the Walker cell. The wet days during the OND season were associated with increased warming over the Indian Ocean coupled with strengthened convective zones over the western Indian Ocean and East African region.

Few studies have focused on the projection of extreme climatic events in Tanzania. The study by Tadross & Johnston (2012) used outputs from the general circulation model (GCM) and statistically downscaled GCM outputs to characterize future climate extremes over Dar Es Salaam. They found that warmer temperatures exceeding 35 °C are expected during the mid-(2046–2065) and end (2081–2100) centuries with the probability of occurrence of 18 and 36%, respectively, under an A2 (business as usual) emission scenario. Unfortunately, these findings contain several uncertainties. The major source of uncertainty comes from the GCM outputs, which have coarse spatial resolution and cannot represent many drivers of climate at local or regional scales. Moreover, statistically downscaled GCM output does not take into account the dynamics of the local climate forcing such as feedback from orography or heterogeneous land surface cover or coastline in the climate systems (Fung *et al.* 2011). The applicable method to obtain reliable high-resolution climate simulation that takes into account regional patterns and fine-scale details that characterize the climate in regions with complex orography is the use of dynamical downscaling (Denis *et al.* 2002). This method is based on nesting a high-resolution regional climate model (RCM) within the GCM and driving it using boundary conditions from the GCMs.

There is no study that has characterized future extreme climatic events in Tanzania using reliable high-resolution climate simulations. This has been the concern that increases the vulnerability of national and local communities to extreme climatic events (Tumbo *et al.* 2010). One of the strategies to reduce vulnerability from extreme climatic events is to characterize the future extreme climatic events to help in the decision planning of adaptation strategies. In this study, the analysis of future extreme climatic events over different regions of Tanzania using a high resolution of climate simulations derived from the Coordinated Regional Climate Downscaling Experiment Program (CORDEX) is carried out.

## 2. DATA AND METHODOLOGY

### 2.1. Study region

The study area is Tanzania, which is located in East Africa between longitudes 29–41°E and latitudes 1–12°S (Figure 1). The country shares borders with Uganda and Kenya in the North; Burundi, Rwanda and the Democratic Republic of Congo in the West; Malawi and Zambia in the South-West; Mozambique in the South and the Indian Ocean in the East.

The country has complex topographic terrain that plays a significant role in influencing heterogeneity in the region's climate. Regions in the north, northern coast, the Island of Zanzibar (Pemba and Unguja) and the northeastern highlands receive bimodal rainfall patterns, whereas regions in the central, southern coast, southern, western and southwestern highlands receive unimodal rainfall patterns (Luhunga *et al.* 2016). These rainfall patterns are mainly driven by the movement of the Inter-Tropical Convergence Zone (ITCZ) (Borhara *et al.* 2020). This zone moves from North to South of Tanzania from October to February and from South to North of Tanzania from March to May.

The average seasonal rainfall in Tanzania ranges from 50 to 200 mm/month, with high variations between regions, where during the wettest seasons, some regions may receive as much rainfall as 300 mm/month. The annual average temperature and rainfall across regions of Tanzania range from 14.4 to 26.4 °C and 534 to 1,837 mm, respectively (Luhunga *et al.* 2016; Borhara *et al.* 2020). The western and coastal regions experience higher temperatures in comparison to other regions. The season with high temperatures across the regions starts from October and continues through February or March, whereas the season with low temperatures across the regions starts from May and continues through August or September. The annual average minimum and maximum temperatures across the regions are in the ranges of 9.6–22 and 19.1–30.7 °C, respectively.

**Figure 1** | Map of Tanzania indicating administrative regions.

## 2.2. Data

### 2.2.1. Model and observed data

This study makes use of daily outputs of rainfall, minimum and maximum temperatures from the CORDEX RCMs listed in Table 1. These models run at a spatial resolution of latitude of 0.44° and longitude of 0.44°. The outputs from the RCMs for the reference period (1971–2000) and future climate projections (2011–2100) under two representative concentration pathway (RCP) emission scenarios are used in the computation of extreme climatic event indices.

## 2.3. Methodology

The RCMs simulate climate variables at grids with a spatial resolution of about 50 km×50 km. In facilitation of measuring and monitoring climate extremes, the simulated climate variables are transferred to the location of a meteorological station (Table 2), using the nearest neighbor-interpolation technique. For a detailed description of the nearest neighbor-interpolation technique, the reader may consult Hartkamp *et al.* (1999).

The extreme climatic indices for the reference period (1971–2000) and future climate (2011–2100) are computed using the RClimDex software. This software was developed by Zhang and Yang from the Canadian Meteorological Service

**Table 1** | CORDEX-RCMs and their driving GCMs

| No. | RCM | Model center | Short name of RCM | GCM |
|---|---|---|---|---|
| 1 | DMI HIRHAM5 | Danmarks Meteorologiske Institut (DMI), Danmark | HIRHAM5 | 1. ICHEC |
| 2 | SMHI Rossby Center Regional Atmospheric Model (RCA4) | Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden | RCA4 | 1. MPI<br>2. ICHEC<br>3. CNRM |
| 3 | KNMI Regional Atmospheric Climate Model, version 2.2 (RACMO2.2T) | Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands | RACMO22T | 1. ICHEC |

**Table 2** | Geographic information of weather stations managed by the TMA

| No. | Station name | Latitude (°S) | Longitude (°E) | Alt. (m) |
|---|---|---|---|---|
| 1 | Kigoma | 4.53 | 29.4 | 820 |
| 2 | Same | 0.5 | 37.43 | 860 |
| 3 | Tabora | 5.05 | 32.5 | 1,182 |
| 4 | Tanga | 5.05 | 39.04 | 49 |
| 5 | Dodoma | 6.1 | 35.46 | 1,120 |
| 6 | Ilonga | 6.46 | 37.02 | 503 |
| 7 | Morogoro | 6.5 | 37.39 | 526 |
| 8 | Kibaha | 6.5 | 38.38 | 167 |
| 9 | Zanzibar | 6.13 | 39.13 | 18 |
| 10 | Songea | 10.41 | 35.35 | 1,067 |
| 11 | Mtwara | 10.21 | 40.11 | 113 |
| 12 | Bukoba | 1.2 | 31.49 | 1,144 |
| 13 | Musoma | 1.3 | 33.48 | 1,147 |
| 14 | Mwanza | 2.28 | 32.55 | 1,140 |
| 15 | Arusha | 3.2 | 36.37 | 1,387 |
| 16 | Moshi | 3.21 | 37.2 | 813 |
| 17 | Kilimanjaro | 3.25 | 37.04 | 896 |
| 18 | DaresSalaam | 6.53 | 39.12 | 53 |
| 19 | Iringa | 7.4 | 35.45 | 1,428 |
| 20 | Mbeya | 8.56 | 33.28 | 1,758 |
| 21 | Mlingano | 8.09 | 38.54 | 183 |
| 22 | Igeri | 9.4 | 34.4 | 2,250 |

(Zhang & Yang 2004). The software is easy to use for the calculation of extreme climatic indices for detection and monitoring climate change extremes. The RClimDex software performs a data quality control check and uses the quality-controlled data in the computation of extreme climatic indices. For a detailed description of the RClimDex, the reader may refer to Chang'a *et al.* (2017).

The extreme climatic indices computed in this study are percentile-based indices that are included in the 27 indices suggested by the Expert Team on Climate Change Detection and Indices (ETCCDM) to characterize extreme climatic events over the regions. The percentile-based indices used in this study include the occurrence of cold nights (TNp10), the occurrence of warm nights (TNp90), the occurrence of cold days (TXp10), the occurrence of warm days (TXp90), the occurrence of very wet days (which represent the amount of rainfall falling above the 95th (R95p)) and the occurrence of extreme wet days (which represents the amount of rainfall falling above the 99th (R99p)).

The future changes in extreme climatic event indices are analyzed by calculating the difference between extreme climatic event indices in present (2011–2040), mid- (2041–2070) and end (2071–2100) centuries under two emission scenarios (RCP 4.5 and RCP 8.5) relative to the reference period (1971–2000).

Statistical analysis such as the Mann–Kendall test for trends is used to detect whether there is a trend or not in extreme climatic indices. This test is one of the most widely used non-parametric tests to detect trends in meteorological time series (Ahmad *et al.* 2015). It is a rank-based procedure, which is robust to the influence of outliers and extreme values. According to this test, the null hypothesis $H_0$ states that there is no trend, the data are independent and identically distributed randomly, and this is tested against the alternative hypothesis $H_1$ which assumes that there is a trend. Sen's slope estimator is used to detect the change in extreme climatic indices. This will help to detect if there is a change in extreme climatic indices and by how much. Sen's slope estimator approach provides a more robust slope estimate than the least secure method as it is sensitive to outliers or extreme values.

## 3. RESULTS AND DISCUSSION

The results of extreme events in different regions of Tanzania are presented and analyzed here in two sub-sections. The first sub-section presents the analysis of extreme climatic events in different regions of Tanzania during the historical (1971–2000) climate condition, whereas the second sub-section presents the analysis of extreme events in different regions of Tanzania during the present (2011–2040), mid- (2041–2070) and end (2071–2100) climate conditions under two RCPs (RCP 4.5 and RCP 8.5) emission scenarios.

It is important to note that the analysis of climate events over a particular region using output from an individual climate model is subject to a number of uncertainties that arise from either the driving GCM or RCM (Luhunga *et al.* 2016). To overcome these uncertainties, this study uses outputs from an ensemble average of five RCMs (RACMO22T and HIRHAM5 both driven by ICHEC-EC-EARTH, RCA4 driven by three GCMs: MPI-M-MPI-ESM-LR, CNRM-CERFACS-CNRM-CM5 and ICHEC-EC-EARTH) for analysis. These RCMs and their driving GCMs were obtained from the CORDEX.

The ability of the CORDEX model to simulate the historical climate condition in different regions of Tanzania was evaluated by Luhunga *et al.* (2016) and found reasonable model skills, suggesting their potential use in representing the climate condition in different regions of Tanzania. It is important to understand that although the outputs from climate models are used in this study or were used in previous studies (Tölle *et al.* 2018; Luhunga & Songoro 2020; Putra *et al.* 2020), their results should be interpreted to account for the inability of the models to simulate the small-scale processes including convection processes inside the model grids that play a role in modulating the intensity and magnitude of extreme climatic events.

### 3.1. Analysis of historical (1971–2000) extreme climatic events in different regions of Tanzania

### 3.1.1. Analysis of the frequency of extreme climatic events related to temperature and rainfall in different regions of Tanzania

One of the impacts of climate change is to increase the frequency of extreme climatic events (IPCC 2007). The increased frequency of extreme climatic events related to temperature including droughts and heat-waves has contributed to the damage of crops, crop failures, decreased crop yields and post-harvest loss, whereas the increased frequency of extreme climatic events related to rainfall including floods has contributed to the damage of properties, destruction of environment and infrastructures, and disruptions of food supply chain especially from point of production (farms) to the market places (consumers) (Magehema *et al.* 2014; IPCC 2016; Anande & Luhunga 2019; Luhunga & Songoro 2020; WMO 2020; Msemo *et al.* 2021). Here, the frequencies of extreme climatic events related to temperatures and rainfall over different regions of Tanzania during historical climate conditions (1971–2000) are analyzed.

Figure 2 indicates the spatial distributions of the trends in the frequency of extreme climatic indices related to temperatures. It can be seen from Figure 2(a), that there is a statistically significant decreasing trend of the frequency in cold days (TX10p) in the range of 0.09–0.18 days/year, across regions of Tanzania. The northern regions around the Lake Victoria basin (including Bukoba, Mwanza and Musoma), western regions (including Kigoma), the southwestern highlands (including Mbeya and Njombe) and the Northern Coast (including Dar es Salaam, Zanzibar and Tanga) experienced a significantly higher decreasing trend in cold days in the range of 0.12–0.18 days/year at a $\geq$95% significant level. However, a non-significant decreasing trend in cold days (TX10p) in the range of 0–0.06 days/year is depicted over the northeastern highland including areas of Arusha, Kilimanjaro and Same. These declining trends in cold days imply that during the historical climate, daytime temperatures are becoming warmer across all regions of Tanzania and decrease the possibilities of days with cool temperatures. These findings are in agreement with global warming patterns as was projected with a very high confidence (very likely) that the number of cold days in many parts of the world would and will continue to decline (IPCC 2007; Seneviratne *et al.* 2012).

The number of cold nights (TN10p) across regions in Tanzania during the historical climate (1971–2000) indicates a decreasing trend at a $\geq$99.99% significant level. Coastal regions (including Tanga, Dar es Salaam, Morogoro and Mtwara), northeastern highland (including Kilimanjaro), a western region including (Kigoma), southwestern highland (Mbeya and Iringa), central region (Dodoma) and western side of the Lake Victoria basin (Bukoba) experienced a decreasing trend in cold nights (TN10p) in the range of 0.24–0.31 days/year at a 99.99% significant level. It is important to note that the number of cold days and cold nights in different regions of Tanzania have decreased at a very high significant level. However, the decline in cold nights is much higher than cold days (Figure 2(a) and 2(b)). This is a strong evidence that climate change is taking place in different regions of Tanzania as the IPCC (2007, 2013) concluded that the warming of climate systems is

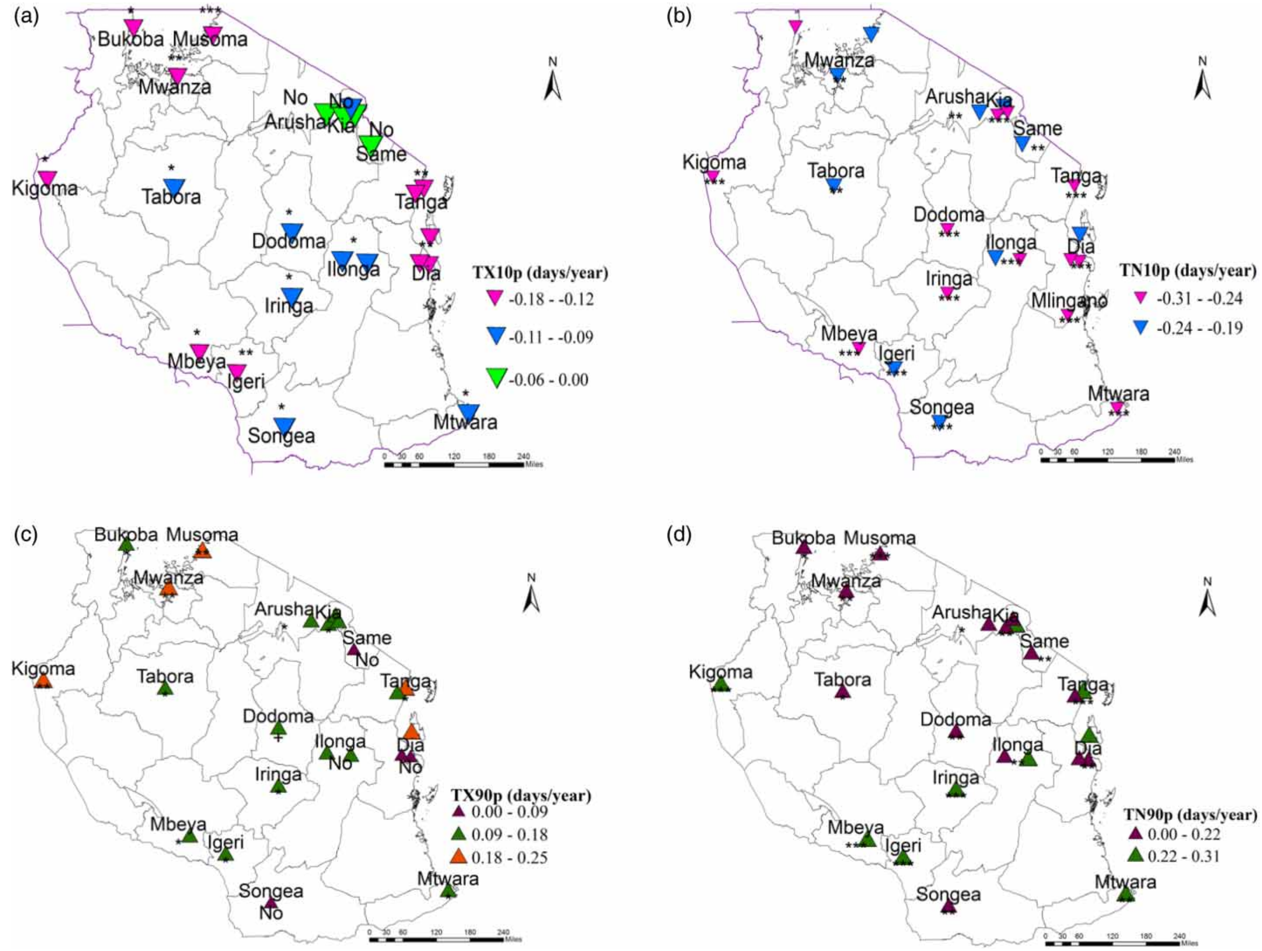


**Figure 2** | Trend in spatial distribution of the number of cold days during the present century (1971–2000): (a) number of cold days, (b) number of cold nights, (c) number of warm days and (d) number of warm nights. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

unequivocal and that the number of cold days and cold nights will decline in many regions of the world. Moreover, the observed higher declines in cold nights than cold days across regions of Tanzania is an indication that the nighttime temperatures are warming faster than the daytime temperatures.

The number of warm days (TX90p) during the historical (1971–2000) climate condition is presented in Figure 2(c). It can be seen that all regions of Tanzania experienced a statistically significant increasing trend in warm days (TX90p) in the range of 0.06–0.25 days/year. However, a non-significant increasing trend in warm days is observed over Ilonga, Songea, Dar es Salaam, Same and Kibaha regions. Moreover, Same and Musoma regions experienced the lowest and the largest increasing trend in warm days of 0.06 and 0.25 days/year, respectively (Figure 2(c)). The number of warm nights (TN90p) has increased significantly in different regions of Tanzania during the historical climate condition (Figure 2(d)).

Kigoma and Lyamungo regions experienced the highest and lowest increasing trend in warm nights of 0.309 and 0.161 days/year, respectively, at a ≥99.99% significant level. These results are crucial, first, to prove or discern that climate change is happening in all regions of Tanzania and, second, to prepare appropriate adaptation strategies and policies as the increase in both nighttime and daytime temperatures affects crop growths, declines crop yields and can influence the development and eruption of new crop diseases.

The number of very wet days (R95p) and extreme wet days (R99p) indicate an increasing trend in most regions of Tanzania (Figure 3). It is important to note here that the trend in very wet days (R95p) during the historical climate condition (1971–2000) has increased in 13 regions and decreased in 10 regions; however, only two regions (Kilimanjaro and Arusha) show a statistically significant increasing trend in very wet days (Figure 3). Dar es Salaam experienced a decreasing trend in extreme

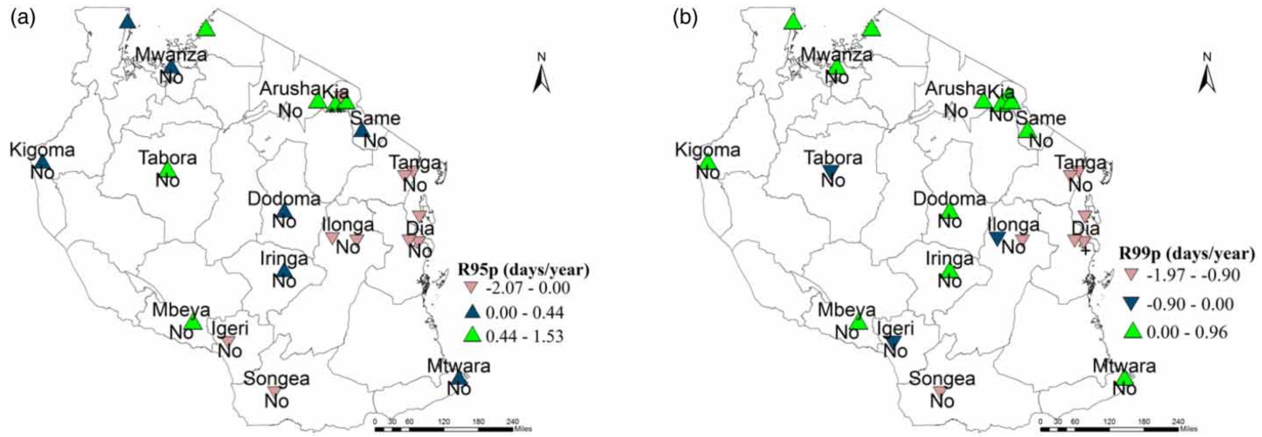


**Figure 3** | Trend in spatial distribution of the number of wet days during the historical (1971–2000) climate condition: (a) number of very wet days and (b) number of extreme wet days. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

wet days (R99p) at a 90% significant level. In general, the number of very wet days and extreme wet days during historical climate conditions in most regions have increased with a non-significant trend, whereas the northern Coast, including Tanga and Morogoro regions, experienced a non-significant decreasing trend in both very wet days and extreme wet days during the historical climate condition.

### 3.2. Analysis of the future (2011–2100) projection of extreme climatic events in different regions of Tanzania

In the previous sub-section, an analysis of the frequency of extreme climatic event over different regions of Tanzania during the historical climate condition was presented; here, the analysis of future (2011–2100) projection of extreme climatic events in different regions of Tanzania is presented. The spatial distributions of the projected trend in cold days (TX10p) during the present century (2011–2040) under RCP 4.5 and RCP 8.5 emission scenarios are presented in Figure 4(a) and 4(b). This figure indicates that during the present century (2011–2040), all regions will experience decreased frequency in cold days (TX10p) in the range of 0.06–0.11 and 0.09–0.14 days/year under RCP 4.5 and RCP 8.5 emission scenarios, respectively. These decreasing trends in cold days are statistically significant in most regions with the exception of Kilimanjaro, Tanga and Moshi regions, which will experience a non-significant decreasing trend in cold days in the range of 0–0.06 days/year under the RCP 4.5 emission scenario. In comparing the number of regions that experienced a significant decreasing trend in cold days during the historical climate (1971–2000) condition and the present (2011–2040) century climate condition, it reveals an increasing number of regions with a statistically significant decreasing trend in cold days from 19–20 regions under the adaptation scenario (RCP 4.5) and from 19–23 regions under the business as usual scenario (RCP 8.5). In comparing the magnitude of the decline in cold days in historical and present century climate conditions, it is found that the trend in cold days will decline faster in the present century under both RCP 4.5 and RCP 8.5 scenarios than in the historical climate condition, with higher rates under the business as usual scenario (RCP 8.5) than under the adaptation scenario (RCP 4.5). These results are important, first to discern that climate change will continue to rise the daytime temperature in the present century and, second, adaptation can help to slow or reduce the risk of extreme climatic events. The number of cold nights (TN10p) in different regions of Tanzania during the present century under both RCP 4.5 and RCP 8.5 emission scenarios is presented in Figure 4(c) and 4(d). It can be seen from Figure 4(c) and 4(d) that all regions of Tanzania will experience a decreasing trend of cold nights in the range of 0.05–0.11 and 0.06–0.12 days/year under RCP 4.5 and RCP 8.5 emission scenarios, respectively, at a 99.99% significant level. These trends in the cold nights are likely to decrease more rapidly in Bukoba and Musoma regions under RCP 4.5 and RCP 8.5 emission scenarios, respectively. It is important to note here that cold days and cold nights over different regions of Tanzania will decline at a very high significant level. This can be used as evidence that climate change will continue to take place over all regions of Tanzania, similar to what was concluded in the IPCC assessment reports that many regions of the world are very likely to experience decreased frequency of cold days and cold nights (IPCC 2007).

The spatial distribution of the number of warm days (TX90p) and warm nights (TN90p) during the present century (2011–2041) under RCP 4.5 and RCP 8.5 emission scenarios are presented in Figure 5(a)–5(d). All regions will experience an

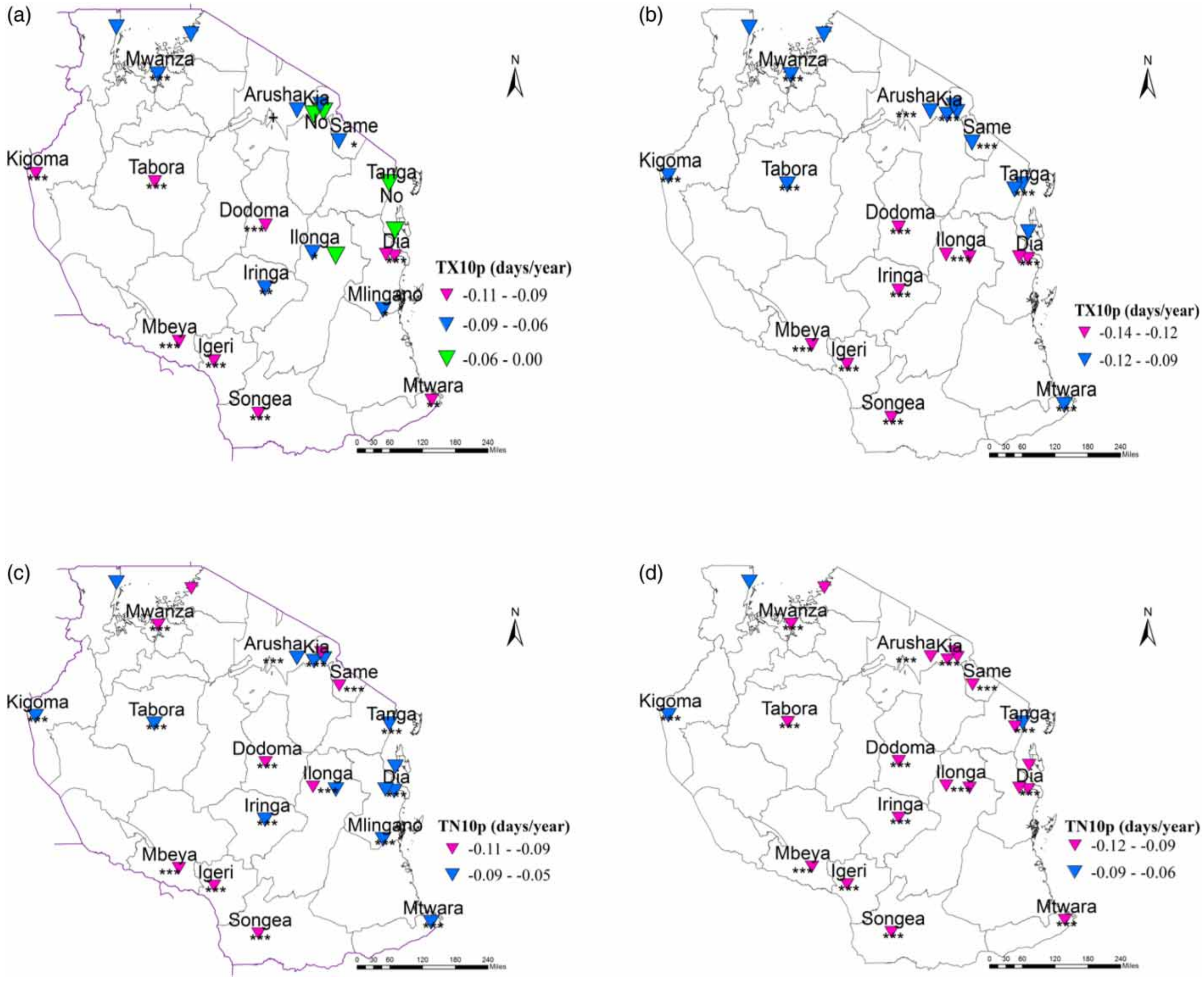


**Figure 4** | Trend in spatial distribution of the number of cold nights during the present century (2011–2040): (a) cold days under RCP 4.5, (b) cold days under RCP 8.5, (c) cold nights under RCP 4.5 and (d) cold nights under RCP 8.5. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

increased trend in warm days and warm nights during the mid-century under both RCP 4.5 and RCP 8.5 emission scenarios. The trend in warm days across regions of Tanzania is likely to increase in the range of 0–0.78 and 0–0.98 days/year under RCP 4.5 and RCP 8.5 emission scenarios, respectively, at a 99.99% significant level, while the trend in warm nights across regions of Tanzania is likely to increase in the range of 0–1.06 and 0–1.10 days/year under RCP 4.5 and RCP 8.5 emission scenarios, respectively, at a 99.99% significant level. These results are important in formulating adaptation strategies and policies.

The distribution of trends in the frequency of cold days and cold nights during the mid-century (2041–2070) under both RCP 4.5 and RCP 8.5 emission scenarios are presented in Figure 6(a)–6(d). From these figures, it is clear that in the mid-century, most regions will experience a statistically significant decreasing trend in cold days in the range of 0.03–0.059 and 0.04–0.07 days/year under RCP 4.5 and RCP 8.5 emission scenarios, respectively (Figure 6(a) and 6(b)). The analysis further reveals that in the mid-century, under the RCP 4.5 emission scenario, the coastal regions, southwestern highlands, southern regions, western regions, and west and southern parts of Lake Victoria are likely to experience decreasing trends in the frequency of cold days in the range of 0.03–0.05 days/year. However, under the RCP 8.5 emission scenario, the northern coast, northeastern and southwestern highlands, western regions, and west and eastern parts of Lake Victoria are likely to experience a decreasing trend in the frequency of cold days in the range of 0.04–0.07 days/year. It is interesting to find that in mid-century under both RCP 4.5 and RCP 8.5 emission scenarios, the trends in cold days are decreasing more rapidly than those in the

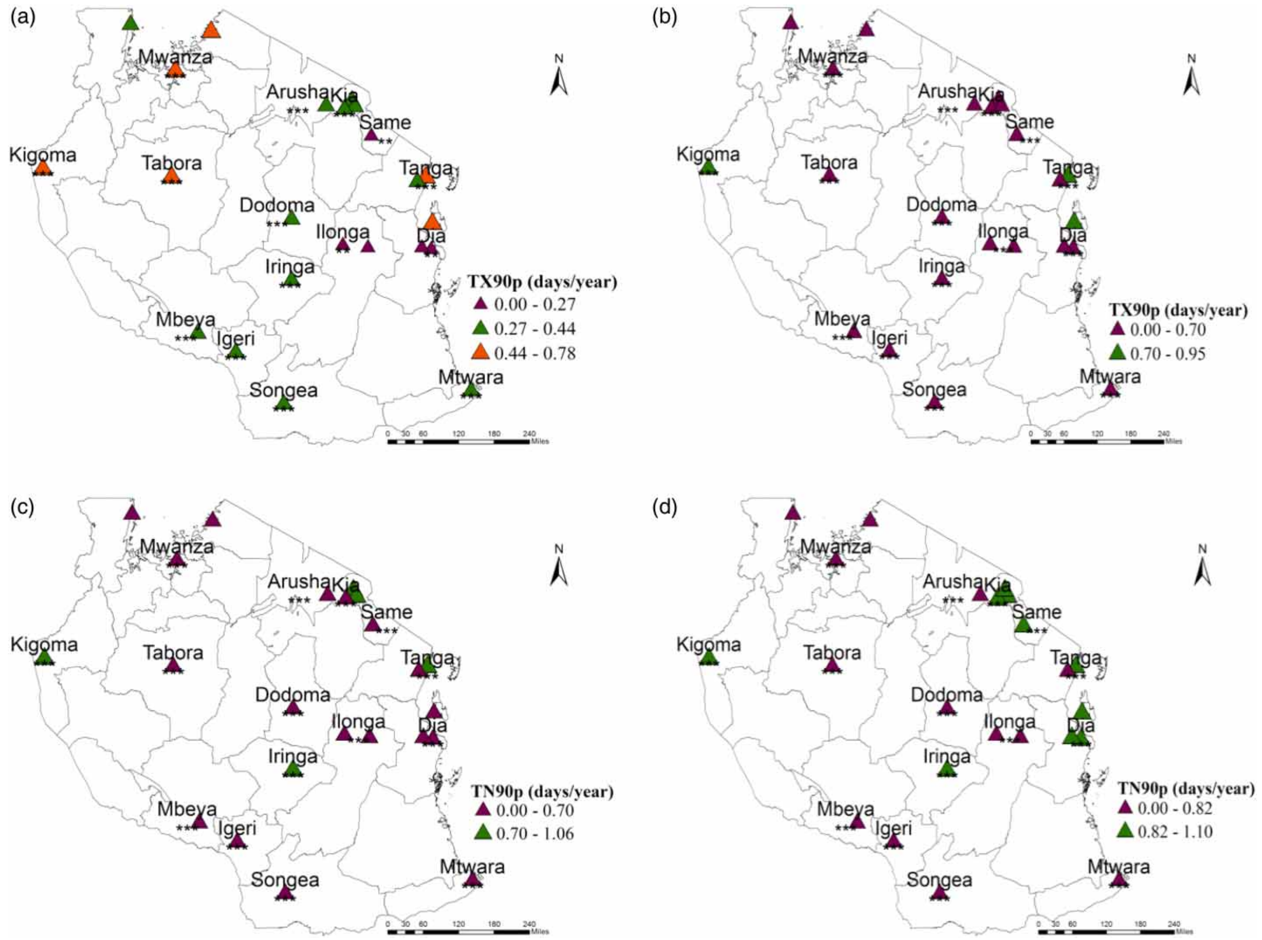


**Figure 5** | Trend in spatial distribution of the number of warm days during the present century (2011–2040): (a) warm days under RCP 4.5, (b) warm days under RCP 8.5, (c) warm nights under RCP 4.5 and (d) warm nights under RCP 8.5. The significant statistics are presented as (***) trend significant at $\alpha=0.001$, (**) trend significant at $\alpha=0.01$, (*) trend significant at $\alpha=0.05$ and (+) trend significant at $\alpha=0.1$.

present century and the historical climate condition. The trend in cold nights indicates that during the mid-century under both RCP 4.5 and RCP 8.5 emission scenarios, most regions in Tanzania are likely to experience a statistically significant decreasing trend in cold nights (Figure 6(c) and 6(d)). However, the Tabora region is likely to experience non-significant decreasing trends in cold nights during the mid-century under the RCP 4.5 emission scenario. The number of warm days (TX90p) and warm nights (TN90p) during the mid-century are likely to increase across all regions of Tanzania (Figure 7(a)–7(d)). These results can be used to formulate adaptation strategies and policies.

The distribution of the trends in cold days during the end (2071–2100) century under both RCP 4.5 and RCP 8.5 emission scenarios are presented in Figure 8(a)–8(c). These figures show that all regions are projected to experience decreasing trends in cold days during the end century under both RCP 4.5 and RCP 8.5 emission scenarios (Figure 8(a) and 8(b)). It is worth here to mention that in most regions, the trends in cold days are projected to decrease more rapidly in the end century when compared to those in the mid, present and historical climate conditions.

Similar to what was observed in the mid-century climate conditions, the trends in cold nights are likely to continue decreasing during the end century under both RCP 4.5 and RCP 8.5 emission scenarios (Figure 8(c)). However, most regions are likely to experience a non-significant decreasing trend in cold nights during the end century under both RCP 4.5 and RCP 8.5 emission scenarios (Figure 8(c)).

The analyses of projected trends in warm days and warm nights during the end (2071–2100) century under both RCP 4.5 and RCP 8.5 emission scenarios are presented in Figure 9(a)–9(d). Analysis from these figures reveals that all regions are likely

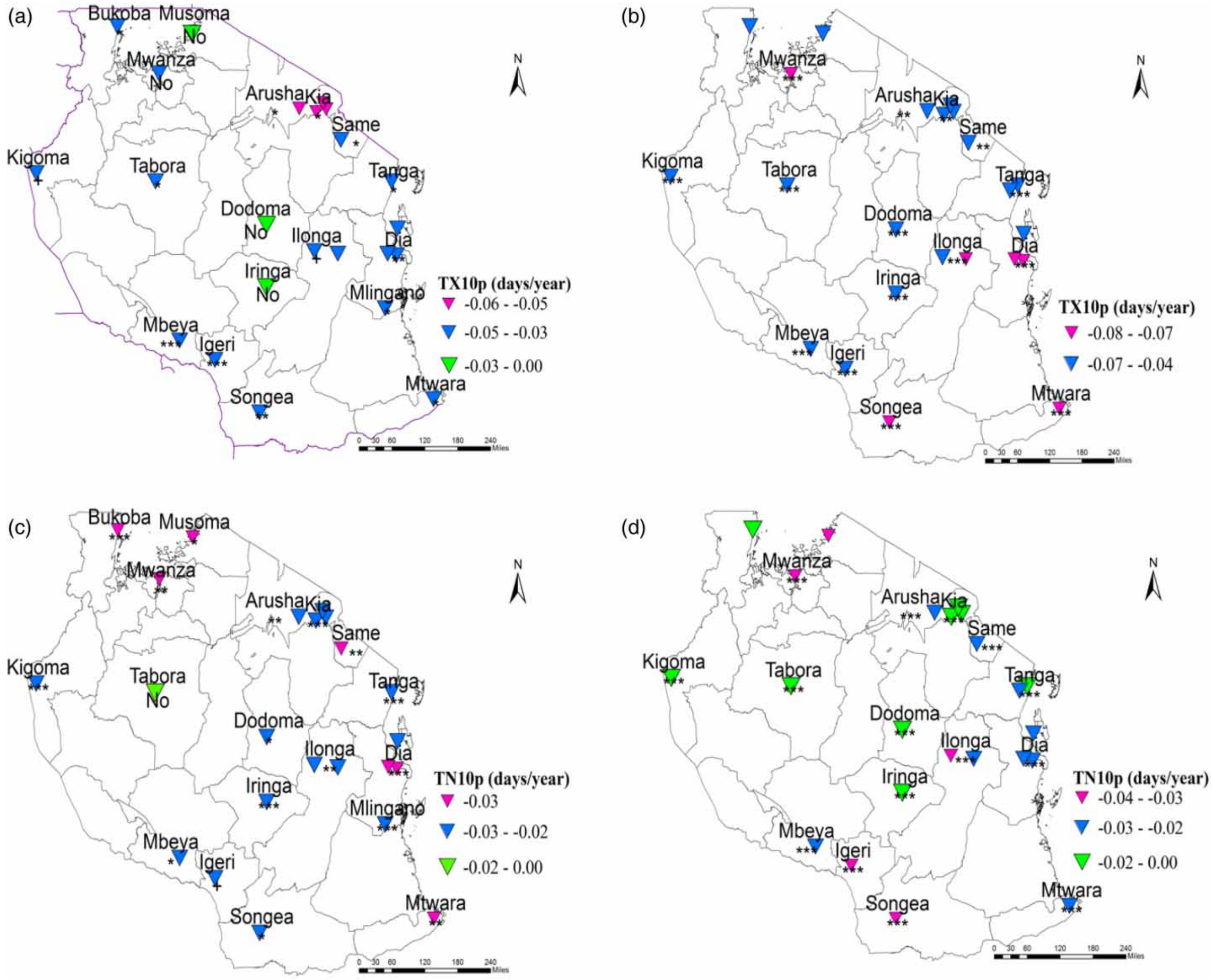


**Figure 6** | Trend in spatial distribution of the number of cold days during the mid-century (2041–2070): (a) cold days under RCP 4.5, (b) cold days under RCP 8.5, (c) cold nights under RCP 4.5 and (d) cold nights under RCP 8.5. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

to experience a very significant increasing trend in warm days during the end centuries under both RCP 4.5 and RCP 8.5 emission scenarios. However, Zanzibar, Tanga and Kigoma are likely to experience very significant increasing trends in warm days of 0.9 days/year during the end century. In general, in most regions, the trends in warm days are likely to increase more rapidly during the end century under RCP 8.5 than RCP 4.5 emission scenarios. This is an indication of the urgent need for developing adaptation strategies and streamlines such strategies into all-development projects.

The analysis of the projected trend in warm nights (TN90p) during the end (2071–2100) century under both RCP 4.5 and RCP 8.5 emission scenarios is presented in Figure 9(c) and 9(d). These figures show that all regions are likely to experience very statistically significant increasing trends in warm nights during the end century under both RCP 4.5 and RCP 8.5 emission scenarios.

### 3.3. Projection of extreme rainfall indices related to frequency

The frequencies of very wet days and extreme wet days in the present century (2011–2040) under RCP 4.5 are expected to increase in the range of 1.53–3.26 days/year in four regions (Zanzibar, Kilimanjaro, Dar es Salaam and Kibaha) at a 99.99% significant level (Figure 10). However, other regions would experience a non-significant increasing trend of very wet days. On the other hand, the extreme wet days during the present century will increase in the range of 0.14–

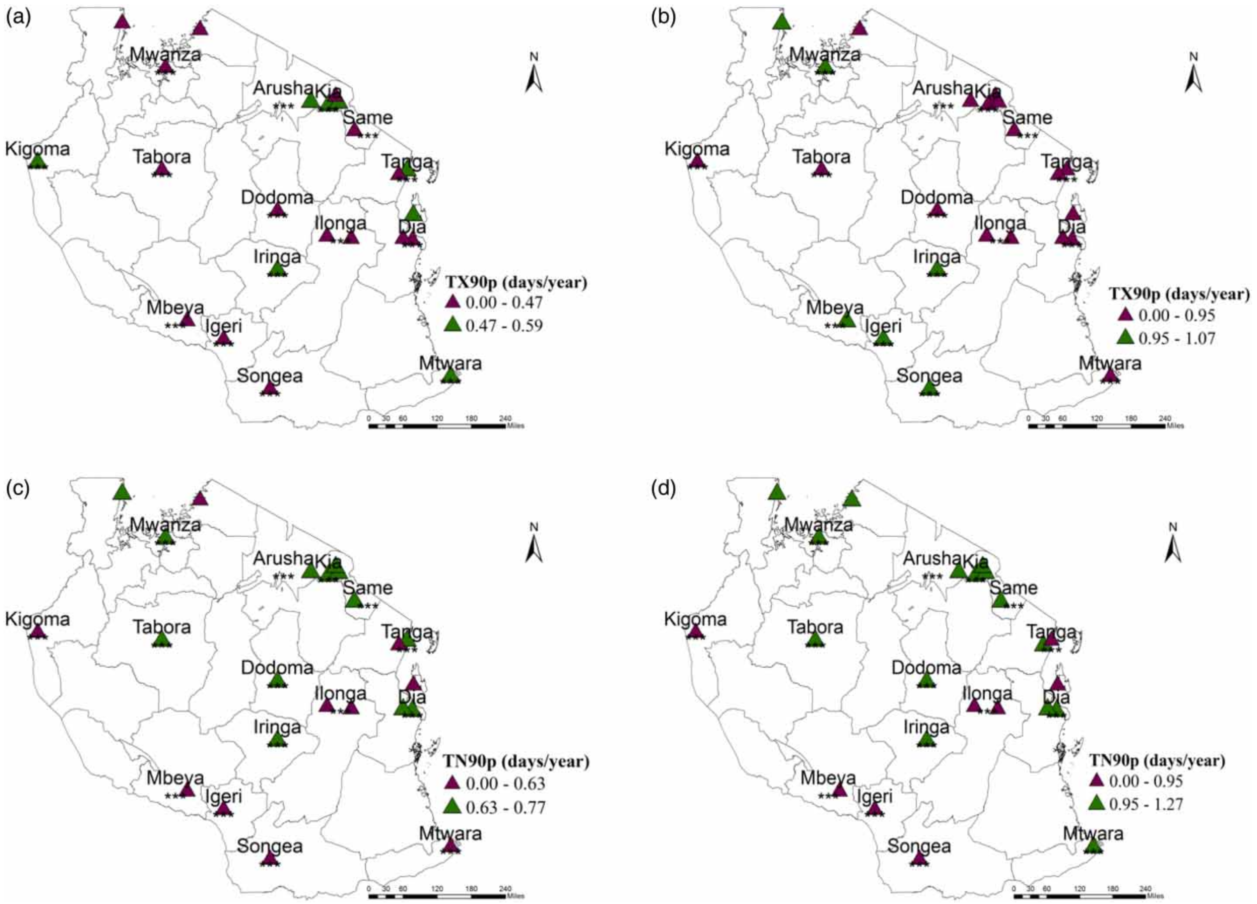


**Figure 7** | Trend in spatial distribution of the number of warm days during the mid-century (2041–2070): (a) warm days under RCP 4.5, (b) warm days under RCP 8.5, (c) warm nights under RCP 4.5 and (d) warm 8.5. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend nights under RCP significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

0.85 days/year in the Iringa region at a 90% significant level (Figure 11). In general, the trend in very wet days and extreme wet days during the mid- and end centuries is projected to increase in most regions with non-significant trends.

## 4. CONCLUSION AND RECOMMENDATION

The extreme climatic events influenced by the change of the global climate are affecting several sectors of the economy in many developing countries (IPCC 2018). This is due to the number of factors including the lack of resources and technology for adaptation, weak institutional capacity to adapt and mitigate the impacts, and high dependence on climate-sensitive sector to drive their economy but also limited knowledge on the spatial and temporal evolution of extreme climate-related stresses. These hinder the effort of developing actionable adaptation and mitigation plans. In this study, extreme climatic events over different regions of Tanzania were analyzed using climate data derived from an ensemble of five high-resolution climate simulations from the CORDEX program. The analysis focused on the spatial and temporal evolution of extreme climatic indices that related to frequency to understand how often such events evolved in the historical (1971–2000) climate and how often they are likely to manifest in the future (2011–2100) climate under the adaptation scenario (RCP 4.5) and under the business as usual scenario (RCP 8.5).

Results reveal that the trends of the number of cold days (TX10p) and cold nights (TN10p) have decreased significantly throughout the country during the historical climate (1971–2000). The number of cold days across regions has decreased in the range of 0.09–0.18 days/year (Figure 2(a)), whereas the number of cold nights has decreased in the range of 0.19–0.31 days/year (Figure 2(b)). These results support the findings from other studies (e.g. Chang'a *et al.* 2017, 2021) who

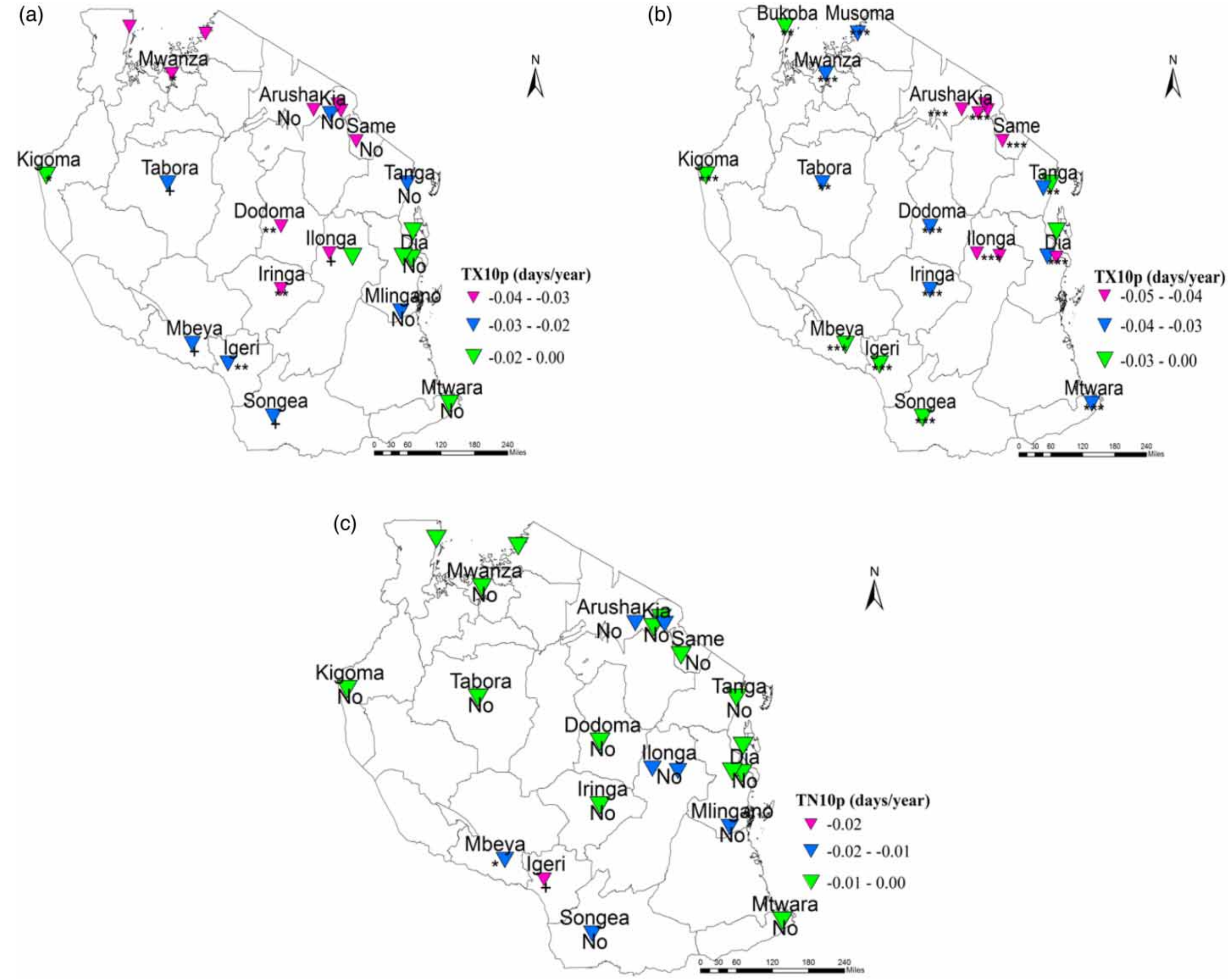


**Figure 8** | Trend in spatial distribution of the number of cold days during the end century (2071–2100): (a) cold days under RCP 4.5, (b) cold days under RCP 8.5 and (c) cold nights under RCP 4.5. The significant statistics are presented as (***) trend significant at $\alpha=0.001$, (**) trend significant at $\alpha=0.01$, (*) trend significant at $\alpha=0.05$ and (+) trend significant at $\alpha=0.1$.

indicated warming of nighttime temperature is higher compared to daytime temperature. Conversely, all regions of Tanzania have experienced a significant increasing trend in the number of warm days (TX90p) and warm nights (TN90p) (Figure 2(c) and 2(d)). The extreme rainfall indices (very wet days (R95p) and the extreme wet days (R99p)) indicated non-statistically significant decreasing and increasing trends throughout the regions.

It is important to note that the decreasing trend in cold days (TX10p) and cold nights (TN10p) and an increasing trend in warm days (TX90p) and warm nights (TN90p) across regions of Tanzania are higher for the present (2011–2040) century under both RCP 4.5 and RCP 8.5 scenarios than that of the historical (1971–2000) climate, but lower than at the mid-(2041–2070) and end centuries under both RCP 4.5 and RCP 8.5 scenarios. This implies that the risks related to increased incidences of extreme temperature events would be higher in the present, mid- and end centuries under both RCP 4.5 and RCP 8.5 scenarios compared to the historical climate condition. The extreme climatic indices related to rainfall are projected to increase the future climate conditions with nonsignificant trends in most regions.

The presented results are important for the preparation of adaptation strategies from the projected increased frequency of extreme temperatures. The IPCC (2018a) indicated that the significant increase in the frequency of extreme temperatures would present serious impacts on biodiversity. For instance, insects, plants and vertebrates would lose over half of their habitats due to increased temperatures. This would present impacts on populations who depend on natural biodiversity for their livelihoods. Other consequences of increased frequencies in extreme temperatures include risks of forest fires and the spread

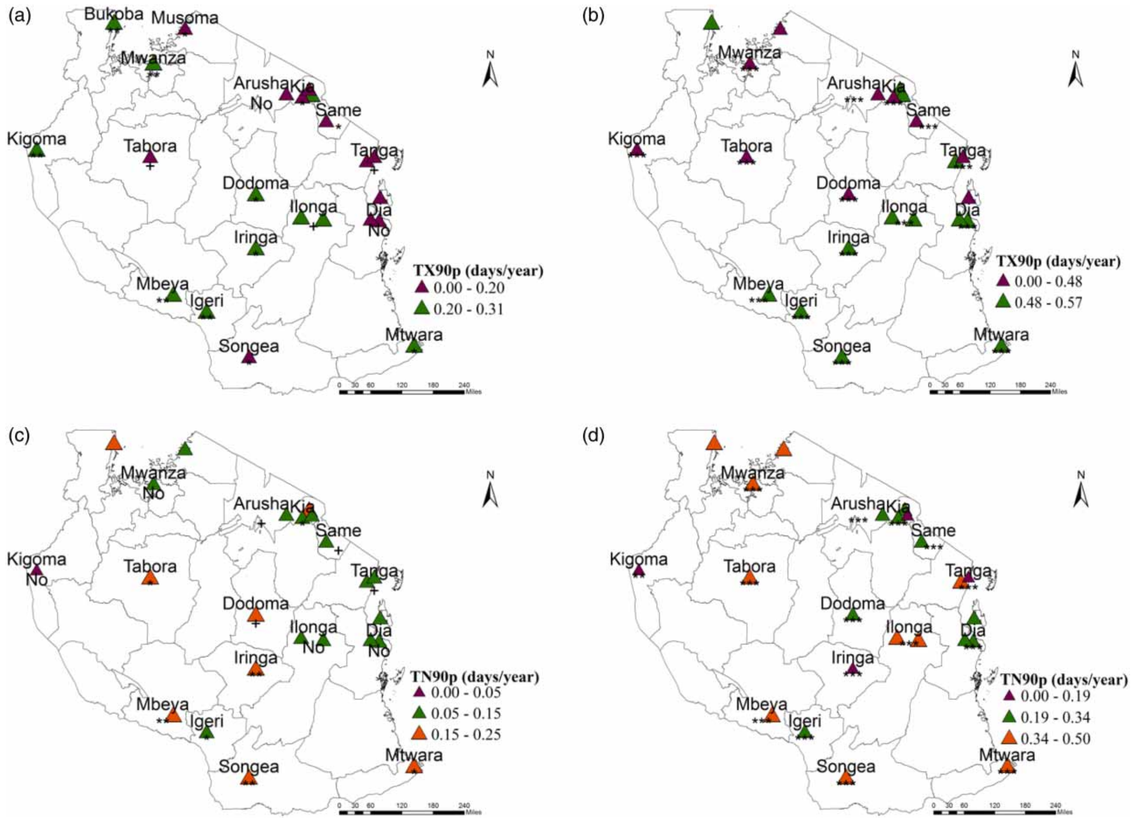


**Figure 9** | Trend in spatial distribution of the number of warm days during the mid-century (2071–2100): (a) warm days under RCP 4.5, (b) warm days under RCP 8.5, (c) warm nights under RCP 4.5 and (d) warm nights under RCP 8.5. The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1.

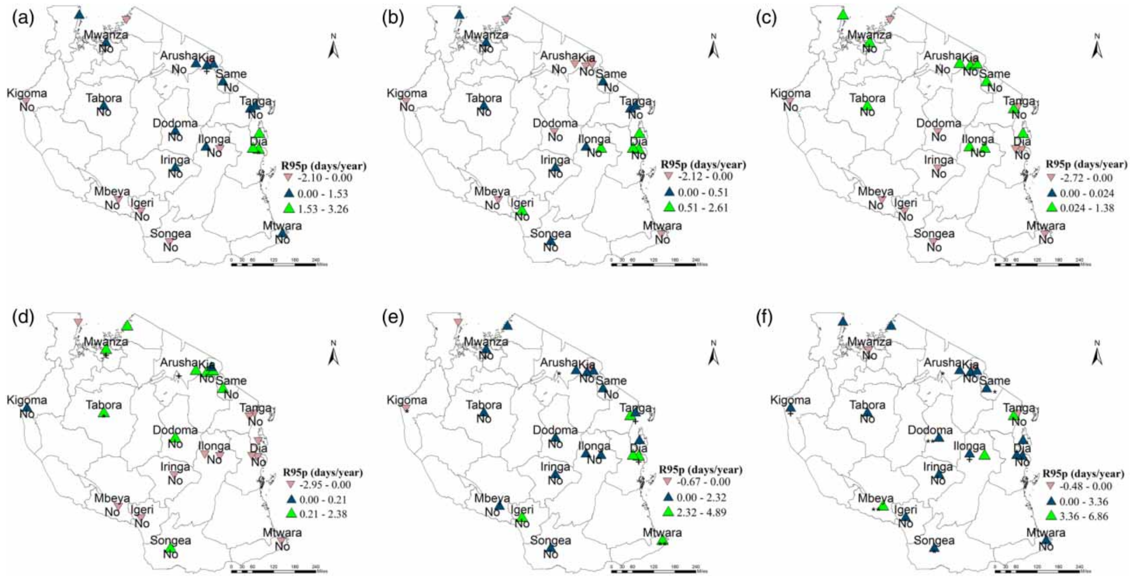


**Figure 10** | Trend in spatial distribution of the number of very wet days: (a,b) during the present century (2011–2040), (c,d) the mid-century (2041–2070) and (e,f) the end century (2071–2100). The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1. (a) very wet days (RCP 4.5) (b) very wet days (8.5) (c) very wet days (RCP 4.5) (d) very wet days (8.5) (e) very wet days (RCP 4.5) (f) very wet days (8.5).

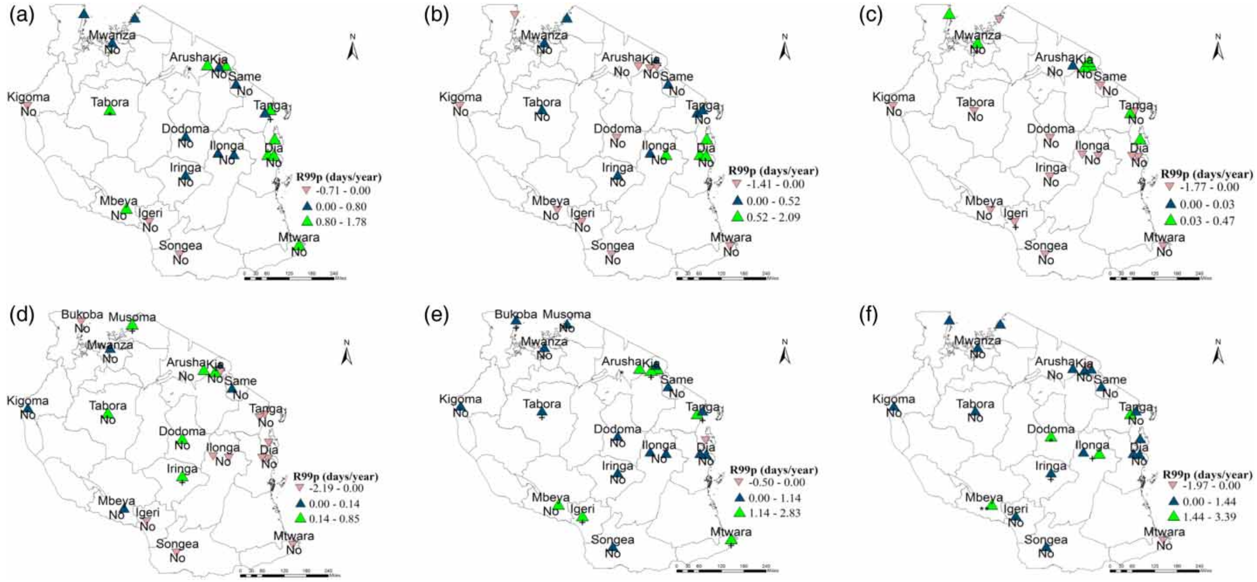


**Figure 11** | Trend in spatial distribution of the number of extreme wet days: (a,b) during the present century (2011–2040), (c,d) the mid-century (2041–2070) and (e,f) the end century (2071–2100). The significant statistics are presented as (***) trend significant at $\alpha$=0.001, (**) trend significant at $\alpha$=0.01, (*) trend significant at $\alpha$=0.05 and (+) trend significant at $\alpha$=0.1. (a) extreme wet days (RCP 4.5) (b) extreme wet days (RCP 8.5) (c) ) extreme wet days (RCP 4.5) (d) extreme wet days (RCP 8.5) (e)  extreme wet days (RCP 4.5) (f) extreme wet days (RCP 8.5).

of invasive species. Indeed, the IPCC (2018a) report summary for policy-makers reveals that marine species would shift from tropical regions to higher latitudes due to an increase in extreme frequency in temperatures. Therefore, it is important to develop policies and strategies to adapt to the significantly increasing temperatures that are projected to occur across regions during the future climate.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 17 September 2021; accepted in revised form 20 January 2022. Available online 9 February 2022