Spatiotemporal trends in mean and extreme climate variables over 1981–2020 in Meki watershed of central rift valley basin, Ethiopia

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ABSTRACT

Understanding the spatiotemporal changes of climate extremes is essential for managing climatic risk. In the present study, trends of annual and seasonal climate variables along with extreme temperature and precipitation were examined in eight climatic stations of Meki watershed, the Central Rift Valley Basin, Ethiopia during the period 1981 to 2020. A set of 20 precipitation and temperature extreme indices were selected and computed in R Climate package of the R program to detect climate extreme events. The recent method of Innovative trend analysis, the non-parametric Mann–Kendall trend test, and Sen's slope estimator were applied to evaluate trends of the annual and seasonal precipitation and temperature. The result indicates that the annual precipitation has been decreasing in 71% of climatic stations and 43% of these stations showed a significant trend. The annual minimum temperature declined in 75% of the stations, whereas all stations indicated a significant increasing trend in annual mean maximum temperature. The Mann–Kendall test detected a significant increasing and decreasing trend in most of the temperature and precipitation extreme indices respectively. For the temperature extremes, more frequent warm and fewer cold temperature extremes were observed. In more than 75% of the climatic stations, a considerable drying trend was found for the precipitation extreme indices. Besides, stations with significant warming and drying trends were located in the downstream areas of the watershed. Overall, this study proved that the observed warming trend in mean annual temperature contributed to changes in the normal thresholds of extremes. The change in precipitation and temperature extremes have increased the frequency, intensity, and duration of extreme events in most of the stations. Likewise, climate extreme events that occur more frequently with high intensity are likely to exacerbate climatic risks, which require proper planning of risk management strategies in Meki watershed.

1. Introduction

The IPCC sixth assessment report has clearly indicated that the increasing well-mixed greenhouse gas (GHG) concentrations since 1850 have been continuing due to human-induced factors (IPCC, 2021). At the same time, the intensity and frequency of climate extreme events have been extremely increasing due to the changing climate (IPCC, 2019, 2021; Kirchmeier-young, 2020). International coordination and cooperation in governance are critical components in the fight against climate change (IPCC, 2014a,b; Williamson et al., 2018). In 2015,195 nations agreed to pursue efforts to limit the global temperature increase to 1.5 °C above pre-industrial levels (IPCC, 2018). In 2015,195 nations agreed to pursue efforts to limit the global temperature increase to 1.5 °C above pre-industrial levels (IPCC, 2018). However, greenhouse gas concentrations hit a high record in recent years (Cheng et al., 2021; WMO, 2021b). Climate extremes will continue occurring irreversibly if the world fails to keep global warming below 2 °C, and it remains to impact the poorest and the most vulnerable ones (IPCC, 2014a,b).

The high frequency and intensity of climate-related extremes pose an enormous impact on the poorest continents like Africa (IPCC, 2019a; Nangombe et al., 2018; WMO, 2020). The impact of extreme events ranges from food security to social, economic & health threats (Gebrechorkos et al., 2019; Serdeczny et al., 2017; WMO, 2021a). Changes in the temperature and precipitation extremes are observed in various areas of Africa. For example, annual temperature extremes with a magnitude of 1.05 were reported in 2015 and estimated to be higher than the previous year's record over the continent (Nangombe et al., 2018). Eastern and Southern Africa are the most affected regions by extreme precipitation events and sequential droughts (Gebrechorkos et al., 2019; Rowell et al., 2015; Weber et al., 2020). Likewise, risks associated with extreme climate events are

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exacerbated in Ethiopia which poses a significant challenge for agricultural activities, which are the backbone of the Ethiopian economy (Aghakouchak et al., 2020; Erenë and Worku, 2018; Suryabhagavan, 2017). High dependence on agriculture makes the country vulnerable to climatic risks, which urges to prepare a risk management plan and strategy (Geremew et al., 2020).

It is well documented that climate extreme events have already impacted certain parts of the country, particularly the southeastern, eastern lowlands, northeastern, and Central Rift Valley (CRV), which have received significantly less rainfall and are drier during the main rainy seasons (Suryabhagavan, 2017). Most importantly, Ethiopia has been preparing various policies and strategies to tackle the adverse impacts of climate change (Echeverría and Terton, 2016). Nevertheless, climate change policies and strategies have been framed in light of the observed and projected climate extremes to choose locally feasible climate risk management in different agro-ecological setups of the country. However, the observed trends of precipitation extremes across different areas of the country are not conclusive and this has been a challenge for planning and implementing climate risk management strategies (Worku et al., 2019). In this regard, understanding the frequency and extent of climate extremes is a crucial first step to managing the present and future climate risks at local and regional scales (Grebichkos et al., 2019).

Previously, climate extremes were studied in different parts of Ethiopia and reported increasing trends in temperature extremes and mixed results for precipitation extremes. For instance, Grebichkos et al. (2019), studied climate extreme indices in Ethiopia based on the gridded data, and a significant positive trend was observed in temperature extremes over the period from 1979 to 2010. In particular, Consecutive dry days, warm days, and nights showed a significant positive trend in eastern parts of the country. Beyene et al. (2021) have found an increasing trend in extreme precipitation indices over the south and southwest regions whereas a significant decreasing trend was observed in the southeastern parts of Ethiopia for seasonal precipitation extreme indices. On the other hand, Worku et al. (2019) have reported downward and upward trends in annual precipitation and temperature extremes respectively in southeastern parts of the Upper Blue Nile basin, central highlands of Ethiopia. Besides, Shawul and Chakma (2020) analyzed precipitation extreme trends in the Upper Awash basin found irregular distribution in annual precipitation and positive and negative trends of precipitation extremes mainly in the downstream and highland parts of the Upper Awash basin respectively.

In particular, an inconsistent trend was presented for annual and seasonal precipitation in different parts of the country which suggested the need for a further local level study that takes into account the country’s agro-ecological setups (Gemeda et al., 2021; Geremew et al., 2020). Despite the fact that trends in extreme temperature and precipitation studies have been carried out in various areas of the country, very little is explored particularly in the CRV of Ethiopia.

Changes in climate variables and climate extremities are studied separately in a few parts of CRV (Ademe et al., 2020; Feyisa, 2017; Shawul and Chakma, 2020). However, no local evidence has explored the possible changes in the intensity and duration of extreme precipitation and temperature linked with changing climate variables. As a change in climate is most likely to be perceived by experiencing new extreme records, this study identified key information gaps in the previous climate change studies that overemphasized assessing trends of mean climate variables of the CRV while it is vital to analyze the change in extremities parallel to the mean change which helps to draw how a very small shift in the mean of climate variables influences the normal extreme threshold or exacerbates the frequency and intensity of its occurrence (Kirchmeier-young, 2020). Therefore, this study will try to narrow the identified key research gap found in the previous studies by indicating how the changing climate variables make a change in the probability of occurrences of temperature and precipitation extremes in terms of their frequency, intensity, and duration in Meki watershed.

The main objective of this study was to detect trends of extreme indices and mean annual and seasonal temperature and precipitation in the selected climatic stations based on daily data during 1981–2020 in Meki watershed of the CRV basin. Meki watershed is one of the areas where Enset-based land use system is dominantly practiced (Woldesenbet et al., 2020). The livelihoods of a rural community are highly dependent on agriculture and hence vulnerable to climate extremes. Besides, the watershed is characterized by severe land degradation and soil loss more than any other area of CRV (Bunta and Abate, 2021; Woldesenbet et al., 2020). Furthermore, very high stream flow and water imbalance were documented following annual mean precipitation and temperature variability in Meki watershed (Musie et al., 2020).

It is, thus, crucial to study the intensity, frequency, and duration of extreme temperature and precipitation at a fine spatial scale to detect the extent of climatic shocks which needs for planning proper climate risk responses in the watershed. To the best of our knowledge, no evidence of extreme precipitation and temperature trends along with long-term changing climate have been investigated in Meki watershed. Thus, the findings of this study will serve as input in developing suitable climate risk management plans and strategies for agricultural activities (crops, vegetables, cereals, and Enset production) in the watershed.

2. Material and methods

2.1. Description of the study area

Meki river catchment, a major tributary of Western Ziway-Abjihata sub-basin located in the CRV basin, Ethiopia (JICA, 2012; Kebede Balcha et al., 2021). Meki River drains to the northwest parts of Lake Ziway. The drainage pattern started from Zebedar Mountain (the Gurage highlands) and extends to the central rift floor, Ziway Lake (Desta and Lemma, 2017). The Central Main Ethiopian Rift (CMER) is part of the eastern branch of the East African rift (Corti, 2009). It encompasses three distinct physiographic features: highland, escarpment, and rift floor (Mesele and Mechel, 2020). Most of the Lake Region of Ethiopia lies in the CRV of Ethiopia, up to Lake Awassa (Bonini et al., 2005).

Meki watershed covers 2049 km² and the topography varies from highly faulted plains of the rift floor with an elevation of 1640–3614 m above sea level at the western Gurage highland (Figure 1). The upper basin is mountainous and steep, whereas the lower basin is plane and has a vast valley. Geographically, Meki watershed bounded between 30°20′0″E–38°50′0″E and 7°50′0″N–8°20′0″N. Based on the Köppen-Geiger climate classification, the watershed falls under the ‘cwfb’ warm temperate climate zone with a dry winter and warm summer. Based on altitude, rainfall, and temperature, Meki watershed is represented by tepid to cool sub-humid mid highland agro-ecological zone. The mean annual rainfall and temperature vary at different topography in Meki watershed, climatic stations in the higher altitude received 1011.1 mm whereas, 740.3 mm was recorded in the areas with lower altitude. The annual mean temperature in the watershed ranges from 22 °C in the mountainous and plateaus to 27 °C in the lowland parts of the rift floor. The rainy seasons have similar characteristics to the wide regions of Ethiopia, a small rainy season persists between March to May (spring or locally called Belg) and the main rainy season occurs from June to September (summer or locally called Kiremt). The watershed is characterized by quasi-double maxima (semi-bimodal) rainfall pattern, with a small peak in April and a maximum peak in August.

Meki watershed is home to important indigenous farming practices, such as (Ensete ventricosum) locally called Enset. Enset contributes to food security for about 1/4th of the population in Ethiopia (Olango et al., 2014). It is cultivated as the main food crop in the mountainous parts of the watershed.

1 https://climateknowledgeportal.worldbank.org/country/ethiopia
Teff is a leading cereal crop in the high-altitude areas which are dominated by deep soils and higher rainfall while maize and wheat are more predominant on the valley floor. Likewise, Enset is a unique indigenous food crop widely grown throughout the southern highlands of Ethiopia including Meki watershed. The upper parts of the watershed have been covered by natural forest lands, and the Enset-based land use system is dominantly practiced in highly sensitive ecological setups (Woldesenbet et al., 2020).

2.2. Climate data and data quality control

2.2.1. Climate data

Time series daily maximum and minimum temperature and precipitation data were the main input for this study to analyze the observed precipitation and temperature extremes during the period 1981 to 2020. The climate data were collected from the National Meteorological Agency of Ethiopia for the sixteen climatic stations located in Meki watershed. However, stations with less than 30 years of data and that have several missing values (more than 15%) for the entire duration were excluded from the analysis.

Eight stations were selected based on the lowest proportion of missing data, long-term record span, and completeness of data as well as the representativeness of the agro-ecological settings of Meki watershed. Temperature data is available only for four stations and precipitation data is available for eight climatic stations located in Meki watershed (Table 1).

2.2.2. Quality control

Some of the missing data in the studied stations were filled using Multivariate Imputation by Chained Equations (MICE) algorithm prediction in R software. MICE algorithm has been reported in several studies as a well-performed technique to estimate the missing value of the target station compared to the other missing value imputation methods (Badoo et al., 2021; Cao et al., 2018; de Carvalho et al., 2017; Espinosa et al., 2019; Kebede Balcha et al., 2021). Data quality control was undertaken using RClimDex in R software. It has been widely used by the previous researchers to compute climate extreme indices (Berhane et al., 2020; Nie et al., 2019; Saddique et al., 2020; Toure Halimatou et al., 2017; Worku et al., 2019). The quality control performs unusual values in the temperature and precipitation data such as extremely high values of daily precipitation, daily maximum temperature less than daily minimum temperature, and identifies outliers which are values plus or minus four times standard deviation in daily maximum and minimum temperature. Based on the quality control performance, a correction has been made in the wrong values of maximum and minimum temperature, was adjusted by the average values of two days (before and after the outlier’s day), whereas the precipitation values were treated as missing values to be filled in MICE.

2.3. Annual and seasonal precipitation and temperature trend analysis

In this study, a non-parametric Mann–Kendall (MK) trend test and Sen’s slope estimator (SSE) were used to detect monotonic trends and the

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**Figure 1.** Location map of the climatic stations in Meki Watershed.

**Table 1.** Selected climatic stations in Meki watershed.

| Stations | Geographical coordinates | Elevation (m) | Observation Year | Annual mean rainfall (mm) |
|----------|--------------------------|--------------|------------------|--------------------------|
| Butajira | 8°09’00" 38°22’01" | 2000 | 1981-2020 | 1099.3 |
| Wulbareg | 7°44’09" 38°07’13" | 1992 | 1981-2020 | 1182.7 |
| Koshe | 8°36’21" 38°31’31" | 1878 | 1981-2020 | 897.7 |
| Ejersalele | 8°14’35" 38°41’09" | 1797 | 1981-2020 | 831.8 |
| Ziway | 7°55’59" 38°42’00" | 1640 | 1981-2020 | 823.4 |
| Meki | 8°12’00" 38°48’00" | 1662 | 1984-2020 | 740.3 |
| Bui | 8°21’00" 38°33’00" | 2054 | 1987-2020 | 1011.1 |
| Tora | 7°51’19" 38°25’14" | 1640 | 1981-2018 | 832.5 |

**Source:** Computed based on the raw data obtained from NMA.
magnitude of the trend in time series annual and seasonal temperature and precipitation (Kendall, 1975; Mann, 1945; Sen, 1968). Mann–Kendall (MK) test was first proposed by Mann (1945) as a non-parametric statistical tool to identify a trend using Kendall’s tau, it is free from the normality distribution assumption of data. Trends of temperature and precipitation extreme indices have been also examined separately using the same trend test procedure. Statistically, significant value was considered when the p-value is less than or equal to 0.05 (p < 0.05).

The MK test is employed whether to reject or accept the null hypothesis (H0) and the alternative hypothesis (H1). Where (H0) assumes that there is no monotonic trend in the distribution-free data while (H1) would present an increasing or decreasing trend in the observed data.

The Mann–Kendall test S is described by as:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)
\]

(1)

\[
\text{sgn}(x_j - x_i) = \begin{cases} 
1 & \text{if } (x_j - x_i) > 0; \\
0 & \text{if } (x_j - x_i) = 0; \\
-1 & \text{if } (x_j - x_i) < 0.
\end{cases}
\]

(2)

where \(x_j\) and \(x_i\) are the annual values in years \(j\) and \(i\), a positive and negative value of \(S\) indicates an increasing and decreasing trend respectively Eq. (1). The trend test is applied to two time series: \(x_i\), which is ranked from \(i = 1, 2, ..., n - 1\), and \(x_j\), which is ranked from \(j = i + 1, 2, ..., n\). Each data point \(x_i\) is used as a benchmark for comparison with the remaining data points \(x_j\) Eq. (2). For independent and identically distributed data without tied data, the variance statistic, \(\text{Var}(S)\) of the distribution are computed using Eq. (3)

\[
\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} - \frac{\sum_{i=1}^{n} t_i (t_i - 1)}{2} \frac{(2p+5)}{18}
\]

(3)

where \(q\) is the number of ties of extent \(i\), \(t_i\) is the number of observations in the \(p\)th group. Where samples, \(n > 10\), a normal distribution approximation will be used to test the null hypothesis. Once calculating the variance \(\text{Var}(S)\), statistically significant trend was estimated using the (ZMK) value, and the standardized test statistic (ZMK) is given as Eq. (4)

\[
Z_{\text{MK}} = \begin{cases} 
\frac{S + 1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0; \\
\frac{S - 1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0; \\
0 & \text{if } S = 0.
\end{cases}
\]

(4)

2.3.1. Innovative trend analysis (ITA) method

Innovative Trend Analysis (ITA) method was used to analyze long-term trends of annual and seasonal precipitation in Meki watershed. ITA is a recent approach which is introduced by Sen (2012) to characterize the patterns of the trend in time series data. ITA and the MK test computed similar trend results but the ITA approach outperformed the MK trend test due to its detection of monotonic and non-monotonic trends without any conditions of the serial correlation, size of the dataset, and distributions that the MK method could not estimate (See and Jayakumar, 2021).

From the ITA method, the observed time series precipitation data are equally separated and sorted in ascending order and plotted along the 1:1 (45°) straight line on the Cartesian coordinate system by considering the trend identification procedure suggested in Sen (2012) to test whether the time series precipitation data shows monotonic trends or trend free (Figure 2). When the annual precipitation data points are plotted in the Cartesian coordinate system, the result could be displayed in three ways of interpretation. There is no trend in the time-series annual precipitation plot if the data points fall exactly on the 1:1 (45°) straight line. Hence, if the time series precipitation data falls above or below the 1:1 (45°) straight line, a monotonic increasing or decreasing trend will be demonstrated.

2.4. Analysis of spatial distribution of precipitation

Accurate estimation of rainfall distribution in different geographical setups important to develop a proper climate risk management strategy for a particular area. Information on the spatial correlation between neighbouring climate stations allows to mapping predictable climatic risk across the area. In this study, long-term spatial distribution of annual and seasonal precipitation, and extreme precipitation indices anomalies was mapped using stochastic algorithms of spatial interpolation technique (i.e. kriging). Ordinary Kriging (OK) has been frequently used interpolation techniques in various studies to predict spatial rainfall distribution and validated as it is an effective interpolation tool in accuracy prediction (Das and Islam, 2021; István Kocsis et al., 2022; Tadesse et al., 2022). Instead of weighting neighbouring points by factors of their inverted distance, OK allows the localized pattern produced by the sample points define the weights (Caloiero et al., 2021). It considers distance and degree of spatial correlation between the known station points when estimating the values of unknown points (Pellicone et al., 2018). The advantage of OK is that it showed small error for the estimation of the related error variance at any point within a study location (Tekleyohannes et al., 2021). Thus, the geostatistical interpolation method of OK has been chosen to produce distribution of mean annual precipitation and extreme precipitation indices map over Meki watershed as it showed the smallest error of estimation.

2.5. Trend, magnitude and intensity of precipitation and temperature extreme indices

Developing statistically robust climate extreme indices which are representative of a wide area of the world, is an important step in detecting climate extreme changes (Zhang et al., 2011). ETCCDI (Expert Team on Climate Change Detection and Indices) of the World Meteorological Organization (WMO) has recommended 27 core indices of temperature and precipitation extremes. The indices describe the intensity, duration, and frequency of extremes (Klein Tank and Zwiers, 2009). For this study, 10 precipitation and 10 temperature extreme indices were chosen based on their compatibility with the agro climatological characteristics of Meki watershed. A total of 20 essential extreme indices are downloaded from http://etccdi.pacificclimate.org and computed using the Rctidm package in R-software. The selected indices for this study are presented as follows in (Table 2).

3. Results

3.1. Trends in mean annual & seasonal precipitation, maximum & minimum temperature

For this study, the eight climatic stations were analyzed in terms of the data recording period. Except for Meki and Tora, all of the climatic stations have a similar periodic pattern of records.
In Ethiopia, the main two crop growing seasons are the extended from June to September (summer) and March to May (spring) locally called *kiremt* & *belg* respectively. Based on Sen's slope values, both decreasing and increasing trends have been manifested in all climatic stations of Meki watershed for the annual and seasonal time series of precipitation and temperature during the period 1981 to 2020.

A decreasing annual rainfall trend was detected in 72% of climatic stations (namely: Wulbareg, Meki, Koshe, Butajira, and Tora) (Figure 3). As presented in (Table 3), the MK test revealed that the trend was significant at all stations except Meki and Koshe (p > 0.05). In contrast, a non-significant increasing trend was found in Bui and Ejersalele climatic stations.

The summer (*kiremt*) season rainfall exhibited a non-significant negative trend in 57% of the climatic stations while a positive trend was observed in Bui, Butajira and Ejersalele, but the trend was significant only at Ejersalele (Figure 4b). Decreasing trend of spring (*belg*) rainfall was observed mainly in Wulbareg, Butajira, Koshe, and Tora climatic stations but significant at Wulbareg and Tora (Figure 4a). Besides, non-significant positive trends were observed in Bui, Ejersalele and Meki stations. Both ITA and MK trend test revealed that a significant trend was not detected in the annual and seasonal rainfall though the remarkable decreasing trend were observed in most of the climatic stations.

Similar findings were detected in the previous studies in annual and seasonal precipitation series in various areas of Ethiopia (Alemayehu and Bewket, 2017; Asfaw et al., 2018; Gummadi et al., 2018; Shewul and Chakma, 2020; Tabari et al., 2015).

Table 4 shows a significant increasing trend in the observed mean annual maximum temperature for Butajira, Bui, and Wulbareg stations whereas a negative trend was detected for annual mean minimum temperature in Butajira, Bui, and Wulbareg but significant at only Butajira. On the contrary, a significant increasing trend was shown in Ziway for both annual maximum and minimum temperature. Most of the previous studies conducted in different parts of Ethiopia have found that there was a noticeable increasing trend in the minimum temperature over the maximum temperature (Alemayehu and Bewket, 2017). However, in this study, except for Ziway, the minimum temperature has been declining in most of the observed stations.

As a result of ordinary kriging (OK) interpolation, higher annual rainfall values were observed in the climatic stations found in the highest elevation areas of the watershed whereas minimum values are detected in the lowest altitude of the watershed. Among the stations in Meki watershed, Butajira and Wulbareg received higher annual total rainfall while Ejersalele and Koshe received lower values during the period 1981–2020 as shown in Figure 5b. Besides, Wulbareg and Bui recorded high amounts of rainfall distributions in the summer (*kiremt*) season while a lower amount of rainfall was reported for Meki and Torra stations (Figure 5c). During the spring (*belg*) season, the maximum values of rainfall were recorded in Butajira and Wulbareg, and Meki and Ejersalele received the minimum amount of rainfall. The highest annual and spring (*belg*) season rainfall was found at Wulbareg which is found to be 1182.54 and 347.74 mm respectively (Figure 5a). Whereas the lowest value was obtained in Meki located near Lake Ziway. The highest amount (656.25 and 640.8) of long rainy (*kiremt*) season was reported in Wulbareg and Bui. At the same time, lower (432.4 and 430.4 mm) rainfall values were reported for Torra and Meki stations. Overall, the two seasonal precipitation trends indicate that there is a rainfall variation across the watershed.

### 3.2 Trends in climate extremes (temperature and precipitation extreme indices)

#### 3.2.1. Trends in temperature extreme indices

Values of each temperature and precipitation extreme indices at each meteorological station were analyzed using the Mann Kendall test and Sen's slope estimator to detect the time series trends of extreme indices and their magnitude. Table 5 shows the trends of temperature extreme indices in Meki watershed from 1981 to 2020.

#### 3.2.1.1. Cool days (TX10p) and cool nights (TN10p)

As can be seen from (Table 5), TX10p showed a significant negative trend in Butajira, Bui, and Ziway stations whereas a non-significant decreasing trend was observed in Wulbareg. Likewise, a significant negative trend was observed in the

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### Table 2. Precipitation & temperature extreme indices selected for this study.

| Indices   | ID  | Indicator name               | Definitions                                      | Units          |
|-----------|-----|------------------------------|--------------------------------------------------|----------------|
| **Temperature** |     | CTDI | Cold spell duration         | Number of days contributing to a cold period     | Days           |
|           |     | TN90p | Warm nights                | Percentage of days when TN > 90th percentile     | %              |
|           |     | TX90p | Warm days                  | Percentage of days when TX > 90th percentile     | %              |
|           |     | TN10p | Cold nights                | Percentage of days when TN < 10th percentile     | %              |
|           |     | TX10p | Cool days                  | Percentage of days when TX < 10th percentile     | %              |
|           |     | WSDU | Warm spell duration indicator | Number of days contributing to a warm period | Days           |
|           |     | T9x  | Max Tmax                   | Monthly maximum value of daily Tmax              | °C             |
|           |     | TNx  | Max Tmin                   | Monthly maximum value of daily Tmin              | °C             |
|           |     | T6n  | Min Tmax                   | Monthly minimum value of daily Tmax              | °C             |
|           |     | TNn  | Min Tmin                   | Monthly minimum value of daily Tmin              | °C             |
| **Precipitation** |     | CDD | Consecutive dry Days       | Maximum number of consecutive days having precipitation<1 mm | Days           |
|           |     | CWD | Consecutive wet Days       | Maximum length of wet spell                      | Days           |
|           |     | R95p | Very wet days              | Annual total PRCP when RR > 95th percentile      | mm             |
|           |     | R99p | Extremely wet Days         | Annual total PRCP when RR > 99th percentile      | mm             |
|           |     | PRCP/TOT | Annual total wet day precipitation | Annual total PRCP in wet days (RR ≥ 1 mm) | mm             |
|           |     | SDII | Simple daily intensity index | Mean precipitation amount on a wet day | mm/day          |
|           |     | RX1/day | maximum one-day precipitation | Monthly maximum 1-day precipitation | Days           |
|           |     | RX5/day | maximum five-day precipitation | Monthly maximum consecutive 5-day precipitation | Days           |
|           |     | R10mm | Number of heavy precipitation days | Annual count of days when PRCP ≥ 10 mm | Days           |
|           |     | R20mm | Number of very heavy precipitation days | Annual count of days when PRCP ≥ 20 m | Days           |
frequency of TN10p at Ziway. However, insignificant decreasing trend was shown in Butajira, Bui and Wulbareg. Most significantly, the frequency of both cold days and nights tended to be declined in Ziway climatic station, which indicates remarkable warming trend for the past 39 years. The decreasing trends in TX10p and TN10p are consistent with the previous studies (Esayas et al., 2018; Worku et al., 2019) which conducted in different parts of Ethiopia.

3.2.1.2. Warm days (TX90p) and warm nights (TN90p). Three of the four temperature-recorded climatic stations showed upward trends in the frequency of warm days (TX90p), except Wulbareg. Warm nights (TN90p) have also increased in Bui and Ziway whereas a downward trend was observed in Wulbareg and Butajira. MK test detected a statistically significant trend at Ziway for both indices. Ziway is the only climatic station where almost all temperature extreme indices such as TN90P, TX90p, TN10P, TX10P, TXn, TXx, SU25 and, WSDI showed a significant upward trend (Table 5). Similarly, warm days and nights have also indicated a significant positive trend during 1979–2010 in Ethiopia (Gebrechorkos et al., 2019).

3.2.1.3. Warmest day (TXx) and coldest day (TXn). A significant upward trend was found in TXx in Butajira and Ziway stations, while a non-significant upward trend was observed in Bui and Wulbareg stations. The TXn was increased during the (1981–2020) periods in all climatic stations but the trend was significant only in Ziway climatic station (P < 0.002) with a magnitude change of 0.025 °C/year (Table 5). This result suggested that the intensity of warmest and coldest days have been increasing in more than 75% of the climatic stations of Meki watershed. Consistently, Mekasha et al. (2014) have found a significant positive trend in TXx for Ziway station over (1967–2008). In addition, Worku et al. (2019) have found a similar result in Jemma Sub-Basin for the period 1981–2014. Besides, statistically significant upward trend (up to 2.4 °C & 1.9 °C) was reported over the period of 1979–2010 in Ethiopia (Gebrechorkos et al., 2019).

Figure 3. Trends of annual precipitation in the seven climatic stations of Meki watershed.

Table 3. Annual and Seasonal precipitation trends in the seven climatic stations.

| Stations | Annual | Spring (belg) | Summer (kiremt) |
|----------|--------|---------------|-----------------|
|          | Z-test | Sen’s slope  | Z-test | Sen’s slope | Z-test | Sen’s slope |
| Bui      | 0.019NS | 0.557        | 0.208NS | 3.240       | 0.011NS | 0.236         |
| Butajira | 0.209** | 6.329        | 0.090NS | 1.266       | 0.258NS | 6.364         |
| Wulbareg | -0.212* | -7.22        | -0.201NS | -3.083      | -0.023NS | -0.65         |
| Ejersalele | 0.209NS | 6.329       | 0.090NS | 1.266       | 0.259* | 6.364         |
| Meki     | -0.020NS | -0.620      | 0.029NS | 0.334       | 0.068NS | -0.712       |
| Koshe    | -0.161NS | -5.392      | -0.199NS | -1.775      | -0.252* | -5.003       |
| Tora     | -0.312** | -10.11      | -0.285** | -5.219      | -0.126NS | -2.356       |

Non-significant = NS; Significant P < 0.05*: p < 0.01**: p < 0.001***.
3.2.1.4. Warmest night (TNx) and coldest night (TNn). Table 5 shows that the intensity of the warmest night (TNx) has increased in 75% of climatic stations during the observation periods whereas a downward trend was reported only in Wulbareg. No significant trend was observed in all precipitation recorded climatic stations. Likewise, the coldest night (TNn) was increased in Wulbareg and Bui while insignificant decreasing trend was observed in Butajira and Ziway climatic stations. Unlike other climatic stations, Bui has been experiencing upward trend in the warmest and coldest indices during 1981–2020. In the previous studies, significant positive trend was also reported on the warmest nights in different areas of Ethiopia (for example Esayas et al., 2018; Gebrechorkos et al., 2019; Worku et al., 2019).

3.2.1.5. Cold Spell Duration Indicator (CSDI) and warm spell duration indicator (WSDI). Duration of warm spell (WSDI) has increased by 2.327 and 0.408 days/year at a significant level of \( p < 0.01 \) & \( p < 0.003 \) in Butajira and Ziway climatic stations respectively (Table 5). Hence, statistically non-significant downward and upward trend was observed in Wulbareg and Bui respectively. A non-significant upward trend was reported for Cold Spell Duration Indicator (CSDI) in Butajira and Bui whereas the non-significant downward trend was demonstrated in Ziway.

| Stations   | Tmax Z-test | Sen’s slope | Tmin Z-test | Sen’s slope |
|------------|-------------|-------------|-------------|-------------|
| Bui        | 0.383**     | 0.038       | –0.023 NS   | –0.005      |
| Butajira   | 0.655***    | 0.061       | –0.331**    | –0.057      |
| wulbareg   | –0.406***   | –0.02       | –0.096 NS   | –0.007      |
| Ziway      | 0.501***    | 0.038       | 0.298*      | 0.027       |

Non-significant = NS; Significant \( P < 0.05 \); \( P < 0.01 \); \( P < 0.001 \).

Figure 4. Box plot showing seasonal precipitation trends over the seven climatic stations.

Figure 5. Spatial patterns of annual and seasonal total precipitation during 1981–2020.
and Wulbareg climatic stations. During 1981–2020, annual mean values of WSDI were larger (2.327 day/39 years) in Butajira than those in Ziway and Bui. In Meki watershed, most of the mean temperature extreme indices showed an increasing trend which is parallel to the reported changes in temperature extremes in Ethiopia (Shuai, 2018).

3.3. Trends in annual precipitation extreme indices

On average, intensity and frequency of precipitation indices exhibited negative trends in most of the climatic stations, in Meki watershed, between 1981 and 2020.

3.3.1. Simple Daily Intensity Index (SDII), Consecutive Dry Days (CDDs), and consecutive wet days (CWDs)

As indicated in (Figure 6), the precipitation extreme indices were analyzed in the seven climatic stations of Meki watershed. The trend analysis of SDII exhibited significant negative values in Butajira, Wulbareg, and Torá stations whereas a positive trend was shown in Ejersalele and Meki with a rate of 0.149mm and 0.108mm per year (p \leq 0.001). The highest SDII was observed in the years 2020 and 2012 (Figure 6b). Likewise, a negative trend for SDII was found in the Jemma sub-basin (Worku et al., 2019). On the other hand, a non-significant positive and negative trend was detected in Bui and Koshe climatic stations respectively. A similar trend was also reported in Meki climatic station, upper Awash Basin (Shawul and Chakma, 2020). Figure 6c shows that CDDs, which implies the absence of precipitation less than 1 mm in consecutive days, decreased in the climatic stations of Butajira, Wulbareg, and Koshe. On contrary, an increasing trend was found in Ejersalele, Meki, Bui and Torá stations. The increasing trend was significant only at Bui (p \leq 0.05). In the same manner, Shawul and Chakma (2020) have found a similar upward trend for CDDs in Meki station over 1980–2015. Length of wet spells that represented by CWDs found to be significantly decreased in Koshe and Meki with a magnitude of 0.06 and 0.07 days per year (p < 0.05). The observed downward trend in Ejersalele and Butajira was not significant. The rest of the stations, Torá, Wulbareg and Bui climatic stations have experienced an insignificant increasing trend over the studied period (see Figure 6e). The highest and lowest annual values of SDII and CDDs were obtained at Meki and Butajira stations. Conversely, the lowest and highest mean annual CWDs value was observed at Meki and Butajira climatic station, indicating stations which were obtained lower value of CDDs showed a complementary higher value of CWDs. The high annual value of CDDs was reported in Bui than those in Ejersalele, Meki and Torá whereas the high mean value for CWDs recorded in Torá than in Bui and Wulbareg.

These results corroborate the findings of Breinl et al. (2020) which reported significant changes in the duration and intensity of extreme dry and wet spells for the US, Europe and Australia.

3.3.2. Number of heavy (R10mm) and very heavy (R20mm) precipitation days

The trend in number of heavy and very heavy precipitation days was increasing in Ejersalele and Torá station at a significant level of (p < 0.006 & 0.013) respectively shown in Figure 6d and f. However, a slight insignificant increment was observed in Meki station in both indices. Some of the previous studies also noted a statistically significant trend in R10mm & R20mm across Ethiopia (Esayas et al., 2018; Shawul and Chakma, 2020; Worku et al., 2019). The remaining stations namely Butajira, Koshe, Wulbareg have experienced insignificant decreasing trend which is similar to the result found by (Berhane et al., 2020). On the contrary, Bui was found to experience decreasing and increasing trends in R10mm and R20mm respectively. The spatial pattern implies, the downstream area of the watershed received a lower value of R10mm and R20mm while the highest values were reported at the upstream parts of the watershed.

3.3.3. Maximum 1-day (RX1day) and 5-day (RX5day) precipitations

Figure 6g shows negative trends of RX1day in Torá, Koshe, Butajira, Meki and Wulbareg but only a significant trend was observed in Torá and Koshe climatic stations. In contrast, insignificant positive change was shown in Bui and Ejersalele climatic stations. The increase of RX1day in Torá station was higher with a magnitude of 0.669 mm/year. An insignificant positive trend in the RX5day was reported in Bui, Meki and Ejersalele whereas the significant negative trend was found in Torá, Koshe, Butajira and Wulbareg climatic stations (Figure 6h).

For comparison, the negative trends of RX1day and RX5day reported in most of the stations was not in line with the recent findings in Ethiopia (Esayas et al., 2018; Shawul and Chakma, 2020; Worku et al., 2019). However, the negative trends of these two indices shown in the majority of the stations have agreed with the study conducted in Western Tigray, Ethiopia (Berhane et al., 2020). The remarkable positive trend of RX1day and RX5day could magnify the occurrences of floods within the watershed.

3.3.4. Very wet days (R95p) and extremely wet days (R99p)

The upward trend of R95p was found in Bui and Ejersalele while a significant downward trend was detected in Torá, Butajira, and Wulbareg climatic stations. The downward trend was insignificant in Koshe and Meki stations. The upward trend in R95p that reported for Bui and Ejersalele was insignificant with the maximum value of 385.9 mm and 621.6 mm in 1995 and 1996 respectively (Figure 6i). The increasing trends of very wet days exceeding the (R95p) could be a cause of high intensity of flood occurrence in the watershed (Worku et al., 2019). Similarly, the value of R99p in Torá, Koshe, Butajira, Meki, and Wulbareg showed an insignificant downward trend (see Figure 6j). The decreasing trend was higher in Torá and Koshe than in other stations at a significant level of (p \leq 0.05). Unlike the downward trends in all stations, Bui and Ejersalele have
Figure 6. Spatial patterns and trends of the annual precipitation extreme indices. The circles and triangles in the slope legend represent negative and positive trend respectively. The size of the circle and triangle indicates the magnitude of the trend while the dot within the circle and triangle shows a significant level of the trend.
experienced insignificant upward trends for R99p with the higher value of 327.1 and 260.2 in 2019 and 2001 respectively. The trends of R95p and R99p are consistent with the previous studies in different parts of Ethiopia. For instance: Esayas et al. (2018); Worku et al. (2019) found increasing trends of very wet days exceeding the 95th and extremely wet days exceeding the 99th percentile in most climatic stations in Jem ma Sub-Basin and southern Ethiopia. Conversely, decreasing trends in both indices were reported over the Upper Awash basin and Western Tigray respectively (Berhanu et al., 2020; Shawul and Chakma, 2020).

3.3.5. PRECPTOT

The trend in annual total wet-day rainfall (PRECPTOT) was found to be decreasing in 57% of the climatic stations (namely: Tora, Koshe, Butajira, and Wulbarg) but the trend was significant only at Tora station (Figure 6a). Besides, an upward trend was detected in the rest climatic stations (Bui, Meki and Ejersalele), but significant only at Ejersalele. The trend of annual total wet-day rainfall (PRECPTOT) presented in this study agreed with the result in Ethiopia (Nangombe et al., 2018). The value of PRECPTOT displayed a similar spatial pattern with annual and seasonal mean rainfall, results in areas that reported lower annual precipitation received lower PRECPTOT values.

3.3.6. Spatial pattern of trends in climate extremes

Figure 6 depicted the spatial patterns of precipitation extremes which are found to be higher in the higher altitude areas of the watershed than in the lower altitude parts. It is possible to observe the topographic contrasts lead to spatial variation in precipitation extremes in Ethiopia. This implies that the spatial variability of precipitation is highly associated with topography in Ethiopia (Gebrechorkos et al., 2019; Gummadi et al., 2017). A similar study in East Africa reported high spatial variability in annual and seasonal precipitation trends (Ongoma and Chen, 2016). SDII and CDD, the lower values in most of the extreme precipitation were reported in Meki station while Wulbarg and Bui recorded higher values for most of the extremes.

4. Discussion

In this study, more than half of the climatic stations in Meki watershed demonstrated a downward precipitation pattern for both short and long rainy seasons. This result of declining annual and seasonal rainfall was confirmed in regional, and international studies (Adler et al., 2017; Ongoma and Chen, 2016). Since farmers in the CRV of Ethiopia predominantly follow a rain-fed farming system (Ademe et al., 2020; Getnet et al., 2016), the total amount of precipitation and the number of rainy days in both long and short rainy seasons (Kiremt & Belg) have a direct relationship with agricultural productivity (Kassie et al., 2015). In this regard, the downward trends of precipitation would have significant implications for declining crop production over the study area. In contrast, the recent increases in annual and seasonal precipitation in the rest of the stations suggested that there is homogeneity in the temporal distribution of precipitation across the watershed which might be influenced by slow Walker Circulation over the Indian and Pacific oceans, driven by the fastest-warming in the tropical ocean system (Tierney et al., 2015). Furthermore, climatic stations located at higher altitude areas received high intensity of precipitation compared to stations located in the lower altitude area. The precipitation trend for the two seasons exhibited that there is a spatial variation across the watershed. This result corroborates the findings of Cattani et al. (2018); Ongoma and Chen (2016) showed spatial variations of rainfall in East Africa. The prior studies have also confirmed the spatial distribution of areal precipitation is highly correlated with topographic variations in Ethiopia (Gummadi et al., 2017; Harka et al., 2021; Shawul and Chakma, 2020). On the other hand, the observed increase in mean annual temperature in the watershed is in line with the rapid change in the global and regional mean temperature (Henley and King, 2017; IPCC, 2014a,b). Change in the annual mean maximum temperature is more pronounced than the annual minimum temperature in all climatic stations. In 2020, the highest temperature record was observed in all stations. Besides, the global average temperature, the year 2020 was reported as one of the three warmest years on record (WMO, 2021b). The significant rising maximum temperature can emerge human, animal, and crop diseases as well as reduce the length of crop growing season which were confirmed in the previous studies conducted in the CRV (Belay et al., 2017; Feleke, 2015). There is empirical evidence of the slight change in climate leading to severe climate extremes and extreme events in many regions (IPCC, 2014a,b; Kirchmeier-young, 2020). Globally, the number of cold days and nights has decreased while the number of warm days and nights increased (IPCC, 2014a,b). In this study, it is most likely confirmed that there were more frequent warm and fewer cold temperature extremes over the studied climatic stations. During 1981–2020, the warmest days have been significantly increasing in stations (Ziway & Butajira) found in the downstream and upper stream parts of the watershed respectively. This implies that extreme temperature events will become more intense in this area. Likewise, significant change in annual maximum and minimum temperature in Ziway station led to significant extreme records. From the temperature extremes indices analysis, a remarkable warming trend is evident in most of the stations which is consistent with the results of Gebrechorkos et al. (2019); Ongoma and Chen (2016) at national and regional scales. On contrary, frequency of cold temperature extremes tended to be significantly increased in Wulbarg station which indicates cooling trend in the past 39 years.

In most of the stations, the duration of dry spell occurrence has become increased in both dry and rainy seasons but it was not significant. A high probability of long dry spell occurrence was observed in Ziway (in 1986 & 1999), Butajira (in 2020), Bui (in 1999 & 2017). Feyisa (2017) has reported a similar result for the occurrence of dry spell for stations found in the CRV of Ethiopia. The probability of occurrence of an extended dry spell during the crop growing season would cause significant yield reduction by deficit crop water requirement under the rainfed agriculture, it thus requires comparable risk management strategies (e.g. irrigation) to meet the water requirements of crop. Likewise, the highest length of wet spell duration was recorded in Ziway (in 2015), Butajira (in 2020), Bui (in 2009). The significant change in the duration of wet spell occurrence in the three stations results in excessive water in soil and leads to flooding. Both water logging and excessive length of rainy days have impacted crop growing. Thus, a suitable risk management plan has to be prepared to reduce the observed extreme events.

For precipitation extremes, among the four climatic stations, the increase in CDDs over Bui was the most significant (10.9 day/33 years), and CWDs increased (6.7 day/33 year) and reached the maximum of 16 days during the entire study period in 2020. The observed wettest the year of 2020 in Bui climatic station is associated with the warmest years on record as heavy rain and extensive flooding were reported over large parts of Africa in 2020 (WMO, 2021b). The increment of seasonal precipitation trend and high intensity of R95p and R99p in Bui was also an indication of rapid transition from the probability of dry spell occurrence (1999–2005) to wet spell (2006–2012) over the past 39 years. Therefore, an extreme precipitation events i.e. floods (due to frequent heavy precipitation) has been dominantly occurred over the station.

The decrease in intensity of R95p and extremely wet days R99p along with the increases of CDDs in more than 70% of the stations can be an indication of drying and high risk for seasonal drought. High intensity of R10mm and R20mm have occurred frequently in Ejersalele and Bui. The reported positive trend in the amount of annual and seasonal rainfall over the two stations can directly be influenced by the high intensity of R10mm and R20mm. The increase in all precipitation extreme indices over Bui and Ejersalele could indicate the increase in frequency and the intensity of flood occurrence. In contrast, the remarkable decreases in all wet precipitation extreme indices (RX1day, RX5day, SDII, R99p, R95p, R10mm and R20mm) in the rest of the stations confirmed that the high mean intensities of dry days (observable drying trend) during the study period which is consistent with the previous study in
5. Conclusion

This study examined trends of spatiotemporal annual and seasonal precipitation, mean annual maximum and minimum temperature, and precipitation and temperature extremes in eight climatic stations of Meki watershed. During the period 1981 to 2020, a downward trend was recorded in most of the stations but the trend was significant in a few stations. The mean annual maximum temperature has been increasing in all of the stations. Hence, the annual minimum temperature was decreased in more than 75% of the stations. This proved that the watershed has been experiencing a warming trend for the past 3 decades. Besides, stations that are located in the upstream areas (high altitude) of the watershed were found to have higher values for annual and seasonal rainfall compared to the climatic stations located in the downstream area. This indicates rainfall distribution is highly correlated with topography in Meki watershed.

Furthermore, this study observed the intensity and frequency of precipitation extremes decreased while the temperature extremes increased in most of the stations which indicates drying and warming trends respectively. Except for the maximum number of Consecutive Dry Days (CDD) and Simple Daily Intensity Index (SDII), higher values of precipitation extreme indices were noticed in Bui and Butajira which are located near the upstream area whereas the lower value was recorded in Meki (downstream area of the watershed). This implies people located in the downstream areas are more vulnerable to climate extreme events than people that lived in the upstream parts of the watershed.

Overall, extreme events are likely continuing to occur more frequently due to an intensification of temperature extremes across the watershed. The findings of this study confirmed an alarming signal for the probability of occurrences of future climate extremes which calls for further investigation on how future temperature and precipitation extremes will continue to change in Meki watershed. Thus, this paper will recommend to study future climate scenarios and related impacts on the agricultural productivity in the watershed which will help to propose an appropriate anticipatory climate risk management strategy.

Declarations

**Author contribution statement**

Simret Terefe: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; Wrote the paper

Amare Bantider; Ermias Teferi; Meskerem Abi: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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**Data availability statement**

Data will be made available on request.

**Declaration of interest’s statement**

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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