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Climate Change Threats to UNESCO-Designated World Heritage Sites: Empirical Evidence from Konso Cultural Landscape, Ethiopia

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Abstract: The purpose of this study was to investigate temperature and rainfall variations and their effects on the UNESCO World Heritage Sites of Konso cultural landscape, Ethiopia, using dense merged satellite–gauge-station rainfall data (1981–2020) with a spatial resolution of 4 km-by-4 km and observed maximum and min temperature data (1987–2020), together with qualitative data gathered from cultural leaders, local administrators and religious leaders. The Climate Data tool (CDT) software version 8 was used for rainfall- and temperature-data analysis. The results showed that the north and northeastern regions of Konso had significant increases in rainfall. However, it was highly variable and erratic, resulting in extreme droughts and floods. The study confirmed that there were significant ($p < 0.05$) increasing trends in the number of days with heavy rainfall, very-heavy rainfall days, and annual total wet-day rainfall (R10 mm, 20 mm, and PRCPTOT). The highest daily minimum temperature, lowest and highest daily maximum-temperature number of warm days and nights, and number of cold days and nights all showed significant rising trends. The increasing trends in rainfall and temperature extremes have resulted in flooding and warming of the study area, respectively. These have led to the destruction of terraces, soil erosion, loss of life and damage of properties, loss of grasses, food insecurity, migration, loss of biodiversity, and commodification of stones. The continuous decline in farmland productivity is affecting the livelihood and traditional ceremonies of the Konso people, which are helpful for the transfer of traditional resource-management knowledge to the next generation. It is therefore necessary to implement local-scale climate change adaptation and mitigation strategies in order to safeguard the Konso cultural landscapes as a worldwide cultural asset and to bolster the resilience of smallholder farmers.

Keywords: cultural landscape; extremes indices; drought; adaptation; mitigation

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1. Introduction

The way ecosystems function in various landscapes has changed and will continue to change, due to the change in climate [1]. In recent years, the occurrences of extreme weather events became very common, and their impacts on the Earth have become worse [2,3]. Therefore, in order to properly explain how rainfall and temperature variations pose serious risks to both natural ecosystems and societies, a thorough understanding of these variations is required. In recent times, annual rainfall over tropical land areas has decreased and its variability has increased significantly [4,5]. Cultural landscapes are highly disturbed by climate change and variability, as these factors have profound effects on farmlands, water availability, food security, and livelihood [6].

In this paper, the concept of cultural landscapes, as defined by [6], is used to describe the connection that exists between society, environment, and culture. Cultural landscapes are a reflection of the long-term interaction between local communities and their biophysical environments. Cultural landscape is a shared experience among individuals and communities and is entwined with notions of social interactions, cultural identity, and cultural cohesion vis-a-vis the biophysical environment.

Climate change disrupts multiple environmental factors, which may consequently modify cultural landscapes and bring ecological complications [7]. Extreme weather events brought on by climate change could endanger both the material and non-material aspects of the cultural landscape [8,9].

Although climate change poses severe threats to many cultural landscapes of UNESCO World Heritage sites, it will not have the same physical effects temporally or spatially. While some regions might be more prone to seasonal flooding, others might face increased aridity and drought. Climate change-related environmental factors, like variations in temperature and rainfall, endanger natural systems, exacerbate the loss and degradation of cultural landscapes, and pose a threat to traditional cultural practices [10]. The frequency and degree to which cultural landscapes are vulnerable to erosion and flooding will certainly increase due to one of the most notable effects of the extreme weather—heavy rains [7]. These destroy physical features (structures) constructed across the landscapes.

The Konso [11] and Ifugaos Rice terraces of the Philippine Cordilleras [12–15] living cultural landscapes are the UNESCO World Heritage sites that can be taken as an example of those threatened by the changing climate. The latter was listed as World Heritage in Danger in 2001 by UNESCO, as a result of modernization and the effects of climate change [12]. But, later, it was removed from the endangered list in 2012. Prolonged droughts and aridity can also worsen the loss of biodiversity and ecosystems, which drives people to migrate elsewhere, and the cultural landscape is degraded due to the absence of maintenance.

The drought, temperature rise, and flooding posed a threat to cultural landscapes, as noted in the UNESCO state of conservation (SOC) reports [12]. The Bangladeshi Sundarbans forests and the stone town of Zanzibar were affected by flooding and sea level rise [16]. Similarly, drought becomes a threat to the well-known natural World Heritage Sites, such as the Serengeti National Park in Tanzania, the Mosi-oa-Tunya/Victoria Falls in Zambia and Zimbabwe, the Niokolo-Koba National Park in Senegal, and the Keoladeo National Park in India [16]. Climate change risks, in particular rain events and related flooding, pose a severe danger to the management and conservation of China's UNESCO-registered cultural heritage [12].

According to [17,18], variations in extreme rainfall and temperature events may have a greater impact on society and the environment [19,20] than changes in their averages. Over half of the recorded natural disasters that have occurred worldwide in the past 50 years (1970–2019) are related to climate extremes, with 15% occurring in Africa [21,22].

The two most significant variables in hydroclimatology that are commonly used to examine the extent and intensity of climate change are temperature and rainfall. Numerous studies, both domestically and abroad, have focused on the analysis of extreme temperature and rainfall events [23–29]. According to these studies, the frequency of extreme weather phenomena such as heat waves, droughts, torrential rains, floods, and tropical cyclones has increased recently. In comparison to 1850–1900, the average global temperature of the last few decades of the twenty-first century (2001–2020) was higher by 0.99 °C, with fast increases over land [27].

Despite regional variations, there has been a noticeable global rising trend for temperatures. The patterns of rainfall, however, differ from those of temperature [7,17,27,28]. Studies have shown that Africa is negatively affected by the high incidence and severity of extreme events [30–32]. Due to its reliance on a climate-sensitive economy, limited capacity for climate change adaptation, and lack of understanding of the climate system, Ethiopia is particularly vulnerable to the effects of climate change and variability [20,33,34].

Ethiopia exhibits varying rising and falling patterns of seasonal and annual rainfall and temperature extremes. In the northeast Ethiopian highlands, for example [35], reported increasing trends for consecutive wet days (CWD) and decreasing trends for consecutive dry days (CDD), while the simple daily intensity index (SDII) and the annual total wet days' rainfall PRCPTOT showed insignificant trends. In southeastern Ethiopia during the main rainy season (spring), declining trends in the number of dry days and length of dry spells were reported [33].

On the contrary, Ref. [32] found that, in 75% of the study stations in the Meki watershed, in Ethiopia's central rift valley basin, the majority of the rainfall indices showed significant declining trends. Rising trends in SDII and PRCPTOT were also documented by [17] in the upper Blue Nile basin headwaters. In addition, Ref. [28] reported negligible negative trends in the number of consecutive wet days (CWD) and the SDII in the majority of stations in the upper Blue Nile basin. Ref. [36], on the other hand, found notable upward trends in the number of consecutive dry days (CDD) in the central rift valley at over 50% of the locations (14 stations) during the belg season.

Studies on rainfall that are currently available did not show clear trends; instead, they displayed mixed patterns. This is likely due to three factors: (1) the topography, which has a significant influence on rainfall; (2) the fact that the trends are highly sensitive to the quality of the data, the selection and span of study periods, and station types considered for the analysis; and (3) the spatial extent of the previous studies [33,37–39]. Regarding temperature, however, [17,28,39–43] reported comparable warming trends in Ethiopia's hot extremes and decreasing trends in its cold extremes.

Because of the substantial spatial variation in rainfall over Ethiopia within short distances, the results of previous studies did not show completely clear pictures on the spatial variability and trends of extreme events. This indicates that different places have different responses to the changing climate. This suggests the necessity of additional local-level research to enhance our understanding of rainfall and temperature changes at grass-root level using long time-series data from multiple stations. Moreover, there is no detailed study which assesses the impacts of rainfall and temperature changes on the cultural landscapes of UNESCO World Heritage sites in Ethiopia.

This study set out to investigate changes and variations in rainfall and temperature, including extreme events, and their effects on Konso cultural landscape, southern Ethiopia. This helps understand the local dynamics and develop pertinent and useful location-specific adaptation and mitigation works. It also helps develop scenario planning for disaster risk reduction and response.

2. Materials and Methods

2.1. Study Area

The Konso cultural landscape is found in the Konso zone, Ethiopia, roughly 580 km south of Addis Ababa [44]. The Konso Zone is located from 5°09′ N to 5°39′ N latitude and 37°01′ E to 37°43′ E longitude (Figure 1). The zone has an area of 2337.81 km^2. It is one of the 12 zones that make up the new south Ethiopia regional state. It borders with Woito river to the west, Segen river to the east and south, Ale and Derashe to the north and Burji to the east. The Konso zone's topography is made up of rolling hills and mountains with valleys and ravines slicing through them [45]. The terrain of the area is complex, featuring large lowland plains in the north and northeast and rocky mountains in the center. Its defining characteristics are its vast drystone terraces, semi-arid climate, and rocky terrain. The Konso people construct terraces on the hillside to prevent soils from erosion, collect rainwater, release excess water, create agricultural terraces, and prevent erosion of the land beneath the structure [46]. The Konso people have survived for generations, despite living in such a harsh environment, because of their traditional methods of managing their land to preserve their valuable soils, moisture, and biodiversity [47].

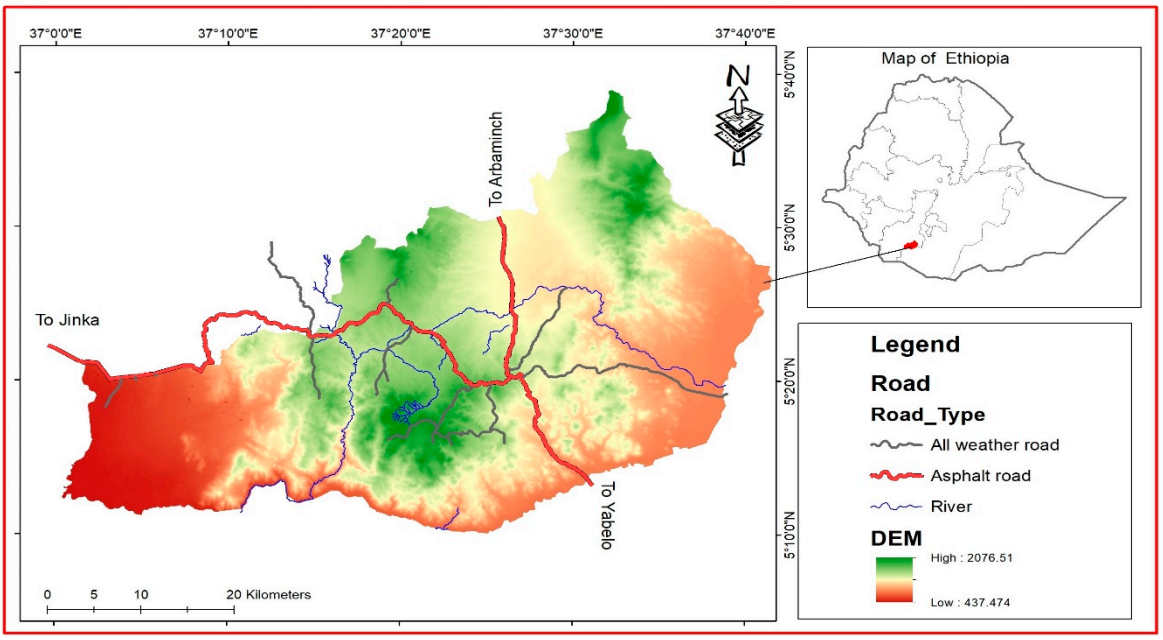


Figure 1. Study area map.

Special recognition was granted to the Konso people, due to their distinctive ethnic and cultural identity in the region. The Konso cultural landscape has produced unique architecture, modes of land use, space planning and management [48]. The Konso are also renowned for walled towns, ritual forests and man-made ponds (*harda*). The walled towns and rural settlements known as *paletas* are located at the summits of hills and are encircled by one-to-six defensive walls made of dry stone that are constructed from basaltic rock, which is readily available in the area. The spaces inside the walled towns used for cultural ceremonies and other meetings are called *moras*. These play a central role in the life of the Konso people. The *moras* are practical central places for performing various cultural, ritual, public and ceremonial features [44] in the day-to-day life of the Konso people. The cultural landscape serves as an incredible example of human ingenuity in adapting to harsh environments. Consequently, the Konso cultural landscape was inducted as a World Cultural Heritage site by UNESCO in 2011 [45].

Konso is divided into three categories, according to the traditional agroecological zones (AEZs): semi-arid (Kolla, 500–1500 m above sea level, a.s.l.), sub-humid (Woinadega, 1500–2300 m a.s.l.), and arid (Berha, <500 m a.s.l.) which makes up, respectively, 0.01%, 83.1%, and 16.89% of the Konso landscape. In Konso, there are two distinct seasons with high rainfall. The first is known as spring (Katana), which lasts from the middle of February to May. The second is known as autumn (Hageya), and lasts from September to November. The mean annual rainfall (1981–2020) in Konso was 716.3 mm. The average annual mean temperature is also 23 °C.

The people of Konso are known for their special talents in keeping their harsh environment and surviving for many hundred years. Their livelihood is dependent on rainfed-agriculture, which is affected by climate change and variability. Their agricultural system requires continuous conservation of their rugged and sloppy lands. They constructed soil and water conservation structures across their lands. They built terracing to protect flood and retain moisture around the terraces. The terraces are built in small intervals in order to effectively protect from flooding. This makes ploughing the land by oxen difficult, and rather than this, the people use hoes. Every household has an obligation to maintain the terraces on its private farm land after each harvesting season [11]. The main sources of income for the Konso people are cattle and crops. Finger millet and corn, coffee, cotton and soya bean, are among the crops cultivated, with sorghum being the staple food [44]. They are also known for constructing traditional ponds to be used as water

sources in time of drought or dry seasons. Their strong culture of conserving their land from erosion and their efficient use of moisture helped them maximize farm productivity. However, recently, their productivity has been persistently decreasing due to inconsistent and variable rainfall and recurrent drought [11]. Collective social learning is typical in the Konso culture. They have various kinds of mechanisms to transfer environmental knowledge from the elders to young people. For example, blessing speeches by elders, folk dances, and proverbs and tales are part of the ritual ceremonies of the Konso people practiced in Mora [11,44,48]. However, the culture of conserving their environment has been weakening among young people in recent years [11].

2.2. Types and Sources of Data

Daily gridded rainfall (1981–2020) of 4 km-by-4 km and observed max and min temperature (1987–2018) data were obtained from Ethiopian National Meteorological Institute (NMI). Due to insufficient observed data available in Ethiopia, NMI reconstructed the gridded data on a daily timescale with a 4 km-by-4 km spatial resolution for the entirety of Ethiopia in partnership with the International Institute for Climate and Society at Columbia University, USA [49]. Reading University in the UK checked the correctness of the reconstructed data [38,49]. The results revealed a strong correlation (r = 0.8) between the station and gridded data [38], indicating that the reconstructed gridded data are of high quality and the best dataset that can be used for climate change analysis [38,50]. This is very important for conducting climate-related research in the south and southeast parts of Ethiopia, where the stations are scarce, with a lot of missing values. Moreover, the observed daily rainfall and max and min temperature of Karat station (Konso) were obtained from NMI for validating the gridded data. In addition, using purposive sampling, qualitative data was gathered from knowledgeable cultural leaders, local administrators and religious leaders from all the walled towns of Konso.

2.3. Data Quality Control

The Pearson correlation coefficient (r) was applied to validate the relationship between the gridded and observed station data. The analysis showed that there was a significant positive correlation (r = 0.87) between the gridded mean rainfall data and meteorological station (observed dataset). However, the correlations between the gridded and observed maximum (r = 0.72) and minimum (r = 0.45) temperature dataset were poor. Therefore, we used observed Tmax and Tmin data (1987–2020) from Konso meteorological station for the analysis of temperature.

A number of quality control activities were carried out before further analysis. The data quality control tasks were performed using a free open-source R package called the Climate Data Tool (CDT). Erroneous observations can be found and, if possible, corrected, using the comprehensive quality check process provided by the CDT [49]. The program displays the results and allows for the detection of numerous errors [49]. The primary step before carrying out any additional analysis was to verify the grid point coordinates. This makes it possible to determine whether any grid points are outside of the study-area shapefile or if there are duplicate and improbable coordinates. Each daily rainfall data point was examined for the presence of outliers, negative values, and false zeros, using CDT.

2.4. Data Analysis

All the necessary computations on daily rainfall and max- and min-temperature time-series data (computing variability, climatologies, anomalies, rainy season characteristics, and climate extreme indices) were performed using CDT Version 8 (see https://github.com/rijaf-iri/CDT, accessed on 20 November 2023) and ClimPact2 software (https://github.com/ARCCSS-extremes/climpact2/ (accessed on 29 January 2024). Ten rainfall and ten temperature extreme indices were selected from the 27 daily rainfall and temperature extremes defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) [51] (Table 1) as those which best suit Ethiopia, and were computed in this study.

Table 1. Explanations of extreme-rainfall and -temperature indices selected for this study.

S/N	Index	Index Name	Definition	Unit
1	RX1 day	Highest one-day rainfall	Highest rainfall amount in one day	mm
2	RX5 day	Highest five-days Rainfall	Highest rainfall amount in five days	mm
3	R10 mm	Number of heavy-rain days	Annual count of days where rainfall $\geq$ 10 mm	Days
4	R20 mm	Number of very-heavy-rain days	Annual count of days where rainfall $\geq$ 20 mm	Days
5	SDII	Simple daily intensity index	Average rainfall amount in wet days	mm day^{-1}
6	PRCP TOT	Annual total wet-day rainfall	Total rainfall in wet days (Rainfall > 1 mm)	mm
7	CDD	Consecutive dry days	Maximum number of consecutive days with rainfall < 1 mm	Days
8	CWD	Consecutive wet days	Maximum number of consecutive days with rainfall $\geq$ 1 mm	Days
9	R95p	Very wet days	The annual total rainfall amount > the 95th percentile of the study period	mm
10	R99p	Extremely wet days	The annual total rainfall amount > the 99th percentile of the study period	mm
11	TXx	Max Tmax	Monthly maximum value of daily max temperature	°C
12	TXn	Min Tmax	Monthly minimum value of daily max temperature	°C
13	TNx	Max Tmin	Monthly maximum value of daily min temperature	°C
14	TNn	Min Tmin	Monthly minimum value of daily min temperature	°C
15	TN10p	Cold nights	The percentage of days when TN < 10th percentile of a base period	%
16	TX10p	Cold days	The percentage of days when TX < 10th percentile value of a base period	%
17	TN90p	Warm nights	The percentage of days when TN > 90th percentile of base period	%
18	TX90p	Warm days	The percentage of days when TX > 10th percentile of base period	%
19	WSDI	Warm-spell duration indicator	Warm-spell duration indicates the annual count of days with at least six consecutive days when TX > 90th percentile	Days
20	CSDI	Cold-spell duration indicator	Annual count of days with at least six consecutive days when TN < 10th percentile	Days

Source: [32,35,51,52].

Once the computations are finalized, trends and magnitudes in seasonal and annual rainfall and temperature changes, including extreme weather events, were detected using ClimDex within the CDT packages, as well as ClimPact2 softwre. A *t*-test was employed to examine whether there are significant differences in the mean scores of maximum and minimum temperatures across the three consecutive decades (1987–2018). The qualitative information gathered from interviews and focus-group discussions were thematically analysed and used for describing the magnitude and impacts of extreme events on the living cultural landscape.

3. Results and Discussions

3.1. Rainfall Characteristics

3.1.1. Spatial Distribution and Variability of Annual and Seasonal Rainfall

The climate of the Konso zone varies from arid to sub-humid. The study area experiences two unique bi-modal wet seasons. The main wet season is Katana (spring), which

begins in mid-February and ends in May, and the second wet season, Hageya (autumn), begins in September and ends in November. However, March–May (spring) is the second rainy season for most parts of the country [33,53]. Unlike other parts of Ethiopia, which receive the highest amount of rain during Kiremt (June–August), the Konso zone received a small amount of rainfall in this season.

The mean annual rainfall (1981–2020) in Konso was 716.3 mm, with the lowest annual rainfall (358.4 mm) recorded in 1984 and the highest annual rainfall (1640 mm) in 2020. During the Katana season, there was an average rainfall of 379.9 mm, with records ranging from 120 mm in 2008 to 685 mm in 2020. Likewise, the mean seasonal rainfall during the Hageya season was 218 mm, spanning from nearly 50 mm recorded in 2003 and 2005 to 730 mm, recorded in 1981. The south lowlands of Segen received 500 mm of rainfall on average per year, while the highlands received 900 mm. Generally, the northern parts received the highest rainfall, while the lowland areas in the southern part received a small amount of rainfall throughout the year (Figure 2a–c).The study area receives its peak average monthly rainfall in April during Katana and in October during Hageya. The study area's north (Woinadega) part experiences higher amounts of rainfall than the south (lowland and arid areas), suggesting that variations in the aspect, elevation, and orientation of the dominant southeastern trade winds and equatorial westerlies have an impact on the distribution of rainfall [45]. The findings of [54,55], on the other hand, showed that topography is a major factor in determining the spatial patterns of rainfall in the majority of Ethiopia.

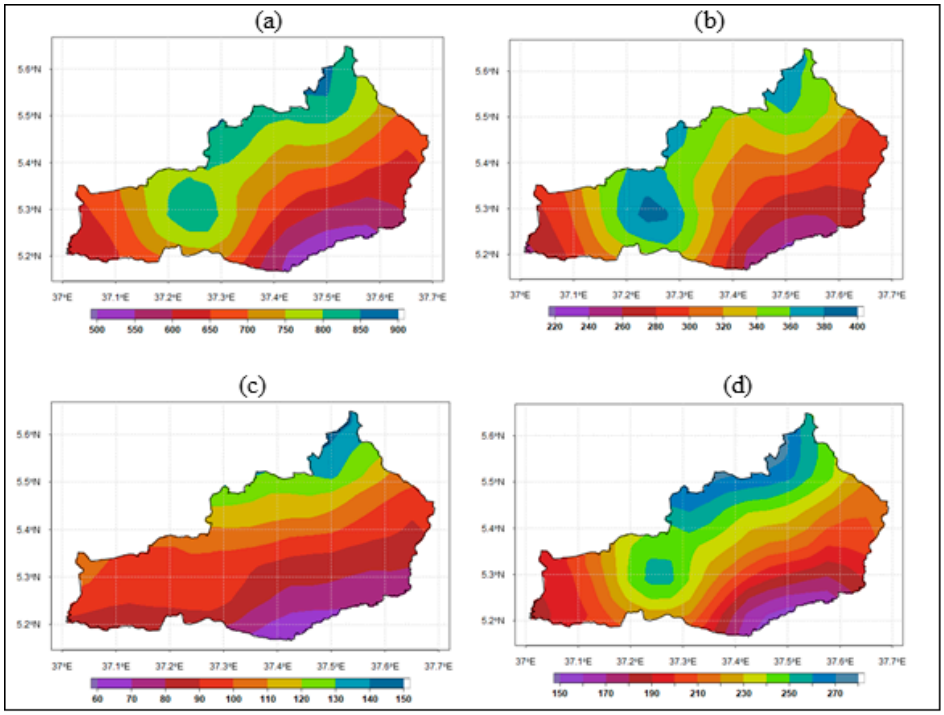


Figure 2. (**a**–**d**): the spatial distribution of rainfall in the Konso zone (**a**) annually, and during (**b**) Katana, (**c**) Kiremt and (**d**) Hageya seasons(1981–2020).

Although the rainfall amount on an annual and seasonal timescale is not adequate for agricultural activities, the northern part of the study area received the highest rainfall. On the other hand, the lowest was observed in the south and southeastern lowlands of the study area. Specifically, on the annual timescale, all parts of the northern and central part of the study area received more than the mean annual rainfall (716 mm) while the southern kebeles (Gesergiyo, Kashile, Sew geme, Gera, Abaroba, Naliya segen and Jarso) and the western parts of the Tebalana quchele, Masoya and Gelgelena qolmale kebeles received less than the mean annual rainfall (Figure 2a) and become arid throughout the year. Apart

from the magnitude of rain they received, similar rainfall patterns were observed in the study area during both the Katana and Hageya seasons.

Rainfall during the Katana season ranges from 200 mm in the Aba roba and Naliya kebeles to 400 mm in the eastern part of the Gelegelena qolmale, Tebelana quchele, and maderiyana gizaba kebeles as well as the whole parts of Borqara, Gelebo, Segenet, Garicha, and Ayilota doketu kebeles (Figure 2b). Although the magnitude was less, the study area also received rainfall during Kiremt (Figure 2c).

A coefficient of variation (CV) [52,53] was used to quantify the variability of rainfall for annual and seasonal timesteps. There are no systematic patterns of rainfall variability throughout the study area (Figure 3a–d). On an annual timescale, the south-central part had low rainfall variability (<20%) whereas the northern, north-central and southeast parts of the study area had moderate rainfall variability (20–30%). Kebeles found at the western periphery of the zone (lowland areas) had high rainfall variability (CV > 30%). On a seasonal timescale, the rainfall variability became stronger in the Hageya than in the Katana season. During the Hageya season, almost all areas had a value of CV greater than 40%, which indicates the occurrences of high rainfall variability. In comparison, some pocket areas in the northern lowland areas had the highest rainfall variability compared to the others in this season. During the Katana season, the southeast parts of the Konso zone and some kebeles on the western border of Konso had high rainfall variability, with a CV value ranging from 35 to 45%. However, the central part had a CV of 30–35%. The high rainfall variability, both in the primary and secondary rain seasons in the study area, has significant impacts on agricultural activities in the Konso zone. In the majority of the study area, the rainfall variability during Kiremt was exceptionally high (>50%). Seasonal timescales showed more variability in rainfall than annual timescales.

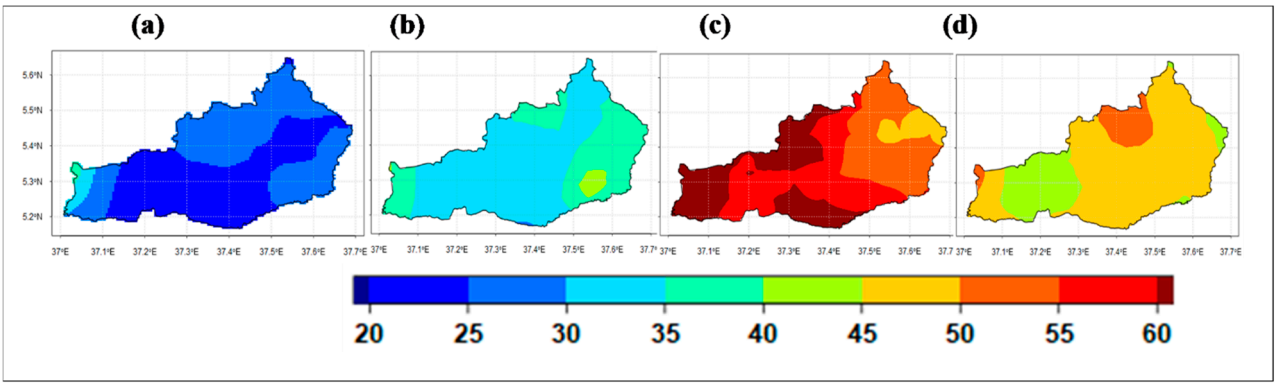


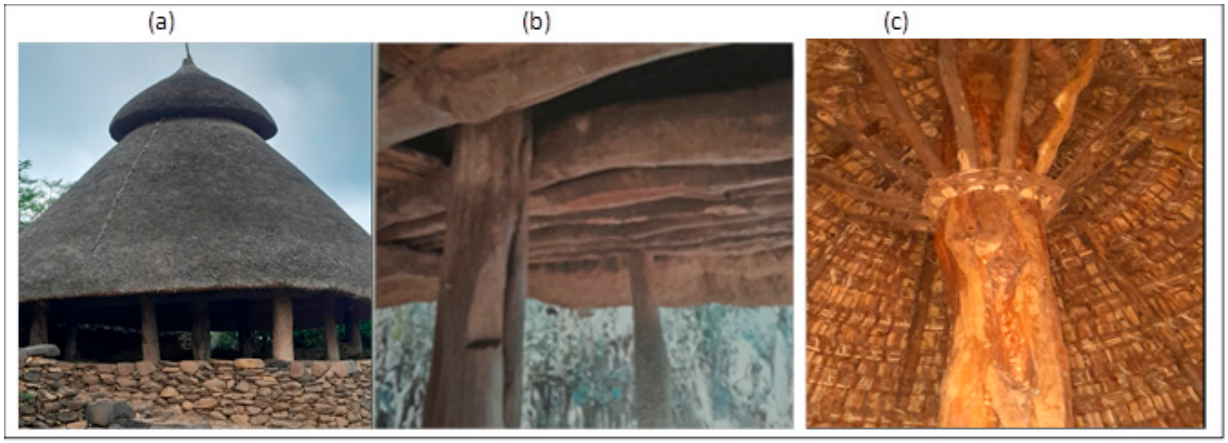
Figure 3. (**a**–**d**): spatial distribution of CV (in %) of rainfall in Konso (**a**) annually, and during the (**b**) Katana, (**c**) Kiremt and (**d**) Hageya seasons (1981–2020).

In a nutshell, the southern and southeast lowland parts of the study area, which received a comparatively little amount of rainfall, showed high CV on both annual and seasonal timescales. The comparison of rainfall variation on temporal scales indicated that seasonal rainfall variability is higher than annual variability. On seasonal time scales, inter-annual rainfall variability is higher in Hageya (SON) than in Katana (main rainy season: MAM). The findings of recent studies in Ethiopia [20,33,56,57] reported that higher variability of rainfall was seen during the Hageya season than the Katana season and compared with the annual rainfall. Other studies [54,58,59] reported that high rainfall variability over Ethiopia with respect to annual and seasonal time steps can be attributed to topography, sea surface temperature and the pressure of the equatorial Pacific, south-westerly moisture from the Southern Indian Ocean, and the seasonal forward movement and retreat of the inter-tropical convergence zone (ICTZ), which persists over Ethiopia. Generally, high rainfall variability indicates uncertainty of the rainy season in the study area, which might have implications for food insecurity, livelihood and landscape change.

Rainfall is erratic, insufficient, and seldom falls when it is supposed to [48]. Flooding is a major issue in the lowland areas of the study area during periods of heavy rain [48]. One of the main obstacles to crop production, according to the elders in the walled towns, is erratic rainfall. Rainfall typically occurs either very late or very early in every cropping season, which prevents the crop from maturing. Crop failures in Konso are primarily caused by heat stress and a lack of moisture [45,47]. There is typically a severe scarcity of water for both humans and animals, because of the fluctuations and lack of rainfall. Women are compelled to travel great distances in search of water during the dry season.

The elders in the walled towns also added that long grasses which have been used for making thatch houses are no longer available because of the change in climate, as well as the conversion of grasslands to agricultural lands. The discussion held with elders indicate that the community have preferred constructing a modern house corrugated with iron sheet to using grasses, in recent years. As a result, the traditional houses are being changed, which questions the sustainability of the Konso cultural landscape [45] as a UNESCO World Heritage site.

The *Mora*, which comprises an open-sided sitting area beneath a huge thatched roof with a heavy wooden ceiling (Pafta) [44], is made entirely from traditional materials available in Konso (Scheme 1). As per the discussion held with elders, it becomes exhausting to construct new pafta and maintain the existing ones because of the absence of local materials needed for construction. due to climate change and variability. The local community cleared forests for their survival and livelihood. As a result, obtaining a variety of hardwoods and grasses for the construction of paftas is a challenge repeatedly mentioned by discussants. Generally, the absence of these traditional materials might be a challenge for the sustainability of the Konso UNESCO-registered landscape.



Scheme 1. A typical pafta and its internal features, in a mora in Konso; (**a**) pafta, (**b**) sleeping floor under the roof of the pafta (**c**) roof of pafta from inside. Photo credit: the authors (2023).

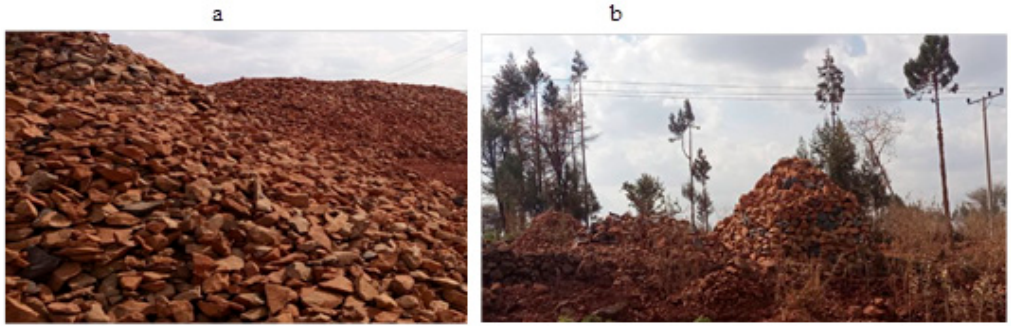
The interview also made clear that climate change forced the local people to migrate to new areas where they could find productive land for cultivation. Several people had abandoned their dwellings which were located in the walled towns, and migrated to Gumaide, kolme, Kemele, etc., as an adaptation strategy. A good example is the case of Tara walled town, where a significant proportion of the outer ring was abandoned (Scheme 2). This could bring a change in the structure and content of the registered walled town.

The key-informant interview and focus-group respondents underlined the fact that the engineering expertise, social cohesiveness, and common values of the local communities who produced Konso's cultural landscape are gradually being degraded, which has resulted in the change in the environment and livelihood of the people (Scheme 2). The stones, for example, have far-reaching implications for the people of Konso. They have a link with their survival in the arid and harsh environment for many hundreds of years. They provide many benefits to them. Stones are used to construct terraces to protect soil erosion; they

are also used to build walls across the crop field to protect from animals, to prepare stages and sitting plains in the moras, and used to construct the high and elongated rings that encircle their villages. However, recently, they have collected and prepared stones for sale from their farmlands, which will definitely contribute to the collapse of their traditional land management through terracing, which in turn means that the cultural landscape deteriorates (Scheme 3). The landscape, as a result of the combined impacts of climate change and population pressure, is not sufficient to provide all the necessary products to sustain the lives of the local community. Due to the change in climate, land productivity is reduced and food insecurity repeatedly occurs in the area. Konso's resilient agricultural techniques, which are centered on extensive terracing and productive indigenous natural-resource management methods [11,47,48], which nurture a web of agrobiodiversity, have been gradually abandoned because of less engagement on the part of the community with environmental conservation works. The young generation seems to disregard the ritual practices and traditional land-management techniques which have been the basis for the designation of the site as a UNESCO World Heritage site. The local community, especially the young, are engaged in non-agricultural activities, leaving the culture of maintaining terraces and participating in ritual ceremonies, which has its own implication for the continuity of the cultural landscape. Off course, engaging in off-farm activities can be considered as one of the adaptation strategies with respect to the impacts of climate change. However, it is undertaken at the expense of landscape conservation and management.



Scheme 2. Demolished traditional houses inside the rings (**a**) and free spaces created as a result of migration (**b**), in Tara walled village. Credit: the authors (2023).



Scheme 3. Stones in quarry site (**a**) and collected from farm lands (**b**) ready for selling in Mechelo Photo credit: Authors (2023).

3.1.2. Standardized Rainfall Anomalies (SRA)

Figure 4 demonstrates the distribution of annual rainfall in the study area, which was above and below the normal average, which resulted in the existence of flood and drought events. The annual rainfall anomalies presented in Figure 4 reveal that there were

spatio-temporal variations in the amount of rainfall in the Konso zone. The entire Konso zone received rainfall lower than the long-term average annual rainfall in 1984, 1987–1988, 1993, 1998–2000, 2004, 2008–2009, and 2016, which coincided with the occurrences of El Nino events of 1987, 1991, 2001, 2004, 2009 and 2015 in Ethiopia [60,61]. Conversely, many areas received rainfall higher than the long-term average annual rainfall in 1981, 1982, 2006, 2010, 2018, 2019, and 2020. The latter years were known for the existence of flood hazards in many parts of Ethiopia. However, the SRA analysis revealed that the years 1984, 1988, 1993, 1999 and 2009 were the driest years recorded in the Konso zone in the study period.

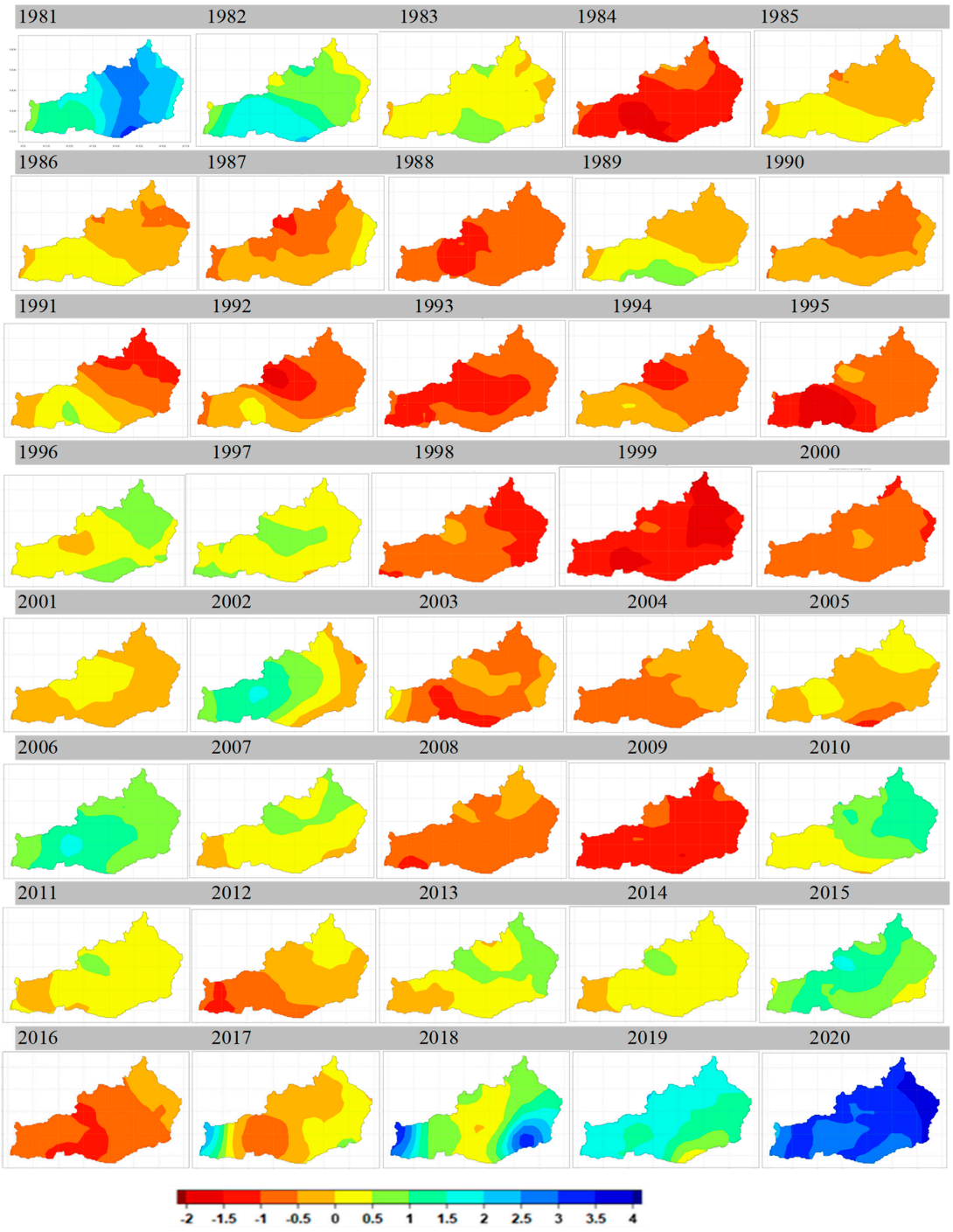


Figure 4. Standardized annual rainfall anomalies in the Konso zone shown as the magnitude of departure from the long-term mean rainfall (1981 to 2020).

In our analysis, we have found that there is a good match between the driest years of the study area and the years in which drought occurs in Ethiopia. The year 1984 was the worst drought year in the history of Ethiopia, and this year was clearly detected in all areas of the study zone. During this year, the annual rainfall reached up to 2 times the standard deviation below the long-term average (Figure 4). The same is true for the year 1999.

The study area received the highest rainfall in 1981, 2006, 2019 and 2020, and these years were the wettest years across the study period. The years 2019 and 2020 were 2 and 3.5 times the standard deviation above the long-term average (1981–2020). All these driest and wettest years were reported in similar findings [4,55,56,62,63].

This alternative dryness and wetness (droughts and floods) has far-reaching implications on the livelihoods of smallholder farmers residing in arid and semi-arid areas [64]. The livelihood of the Konso people is being threatened by high variability and unpredictability of rainfall [45,47]. The variability and unpredictability of rainfall in Konso is resulting in frequent occurrences of drought and floods, which have meant that the livelihood of the people and cultural landscape have deteriorated. For example, the recent 2015/2016 drought reduced annual household consumption by 8%, and this created poor resilience systems among rural communities in Ethiopia [61].

3.1.3. Trends in Annual and Seasonal Rainfall

Figure 5a–d show trends in annual and seasonal rainfall per pixel over the zone, and dots on the plot indicate a significant increasing trend at $p < 0.05$. Except for a few areas in the southern tip of the zone, the mean annual rainfall shows a tendency of increasing trends. Specifically, the north-central, northeastern and western parts of the study area experienced significant increasing trends in annual rainfall, with values ranging from 40.4 to 98.87 mm decade^{-1} during the study period (1981–2020).The highest significant increasing trend was observed at the northern part of the study area, specifically in Gelebo kebele, and the lowest was recorded in the southeast part, specifically in Jarso kebele.

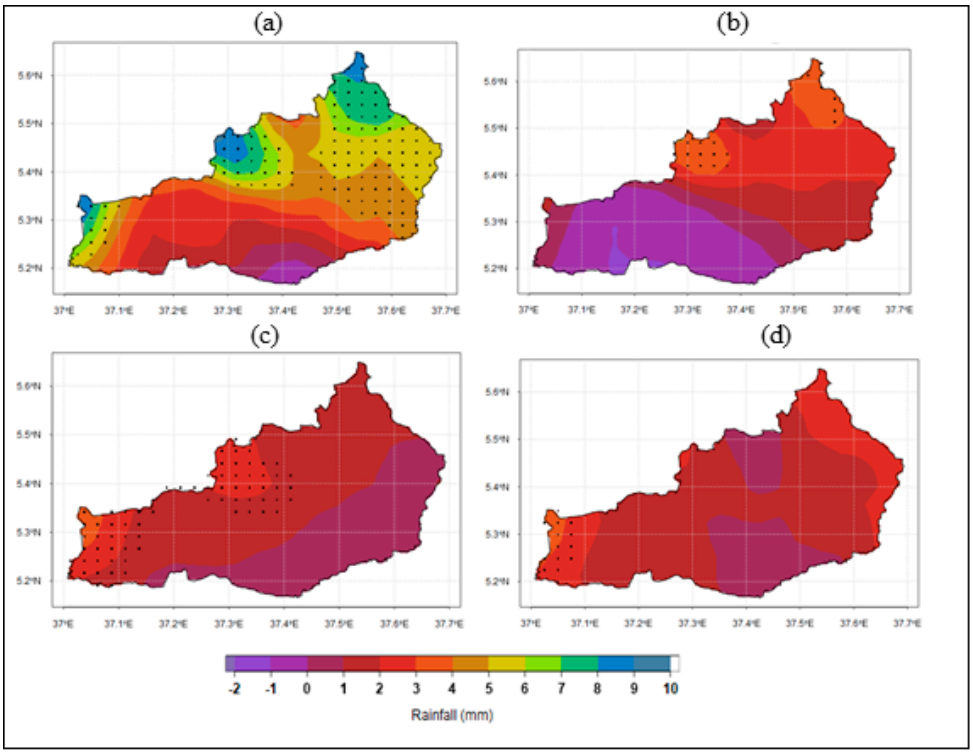


Figure 5. (**a**–**d**): rainfall trends in Konso Zone, (**a**) annually, and during the (**b**) Katana, (**c**) Kiremt and (**d**) Hageya seasons (1981–2020). Dots on the plot indicate a significant increasing trend ($p < 0.05$).

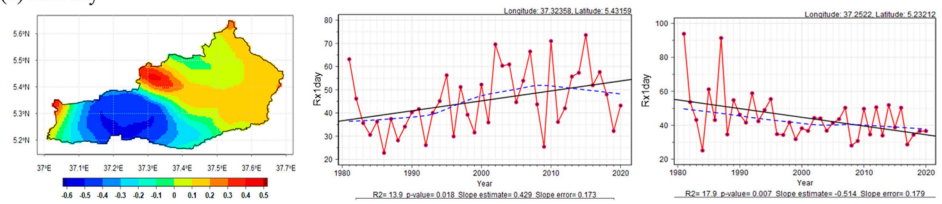
On a seasonal time scale (during Katana), most of the areas experienced mixed non-significant trends. The southern and south-western parts of the study area (almost 30% of the total area) had a decreasing tendency, whereas the north and northeast parts of the study area experienced increasing tendencies. The area coverage that experienced a significant increasing trend in rainfall on an annual timescale decreases during the Katana season. Rainfall during this season was significantly increasing in the northern kebeles (Gelebo, Tish male, and Beayide) and in the north-eastern part of the study area (Segen and Melegana Dugaya kebeles), with a value ranging from 27.56 to 39.57 mm decade^{-1}. However, the areas which showed a significant increasing trend are found in the highlands (a sub-humid agro-ecology). During the Hageya season, all parts of the study area experienced non-significant positive changes. A few kebeles (Masoya, Gelgelena qolmale, and Tebelana quchele) in the western part of the study area showed a significant increasing trend, ranging from 22.5 to 34.44 mm decade^{-1}. We discovered a clear pattern of the positive trends in rainfall on an annual timescale, which increased from the south to the north part of the study area. However, during the Katana and Hageya seasons, the rainfall did not show any consistent patterns and trends.

Our findings (mixed trends for rainfall during the Katana season) are partly consistent with the results of Gashure and Wana (2021) [45], who reported insignificant declining trends of belg rain (Katana season) in Konso. This might be due to the difference in the number of stations used for the study. Their finding is based on two meteorological stations, which might not represent the study area (Konso). However, the present study used 4-by-4 km grid pixels, which covered all the study area. Although the magnitude of rainfall received in Konso during the Kiremt season is negligible, it showed a significant ($p < 0.05$) increasing trend in the western and north-central parts of the study area (Figure 5c). The declining trend in the Katana and Hageya rainfall might be triggered by the atmospheric–oceanic processes that influence the rainfall of south and southeast Ethiopia. A considerable increase in temperature and a decrease in rainfall in east Africa could be significantly created due to ENSO-related global warming dynamics [54,60].

3.1.4. Spatial Patterns and Trends in Extreme Rainfall Indices

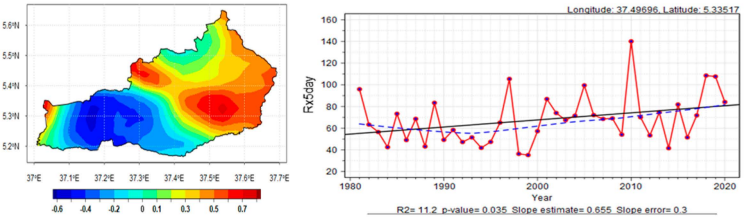
Every socio-economic activity and the natural ecosystem are affected by climate extremes, such as flooding and drought. It is crucial to analyze and understand the severity and frequency of these extreme events [24,32], in parallel with the mean climatic changes. It will help realize how a very small change in the average values of climate variables influences the normal extreme threshold or exacerbates its frequency and intensity [28]. Figure 6a–j present the spatial patterns and trends in extreme rainfall indices. As shown in Figure 6a–j, there was no clear and systematic geographic pattern for most extreme rainfall indices. Mixed increasing and decreasing trends were observed across the study area.

(a) Rx1day



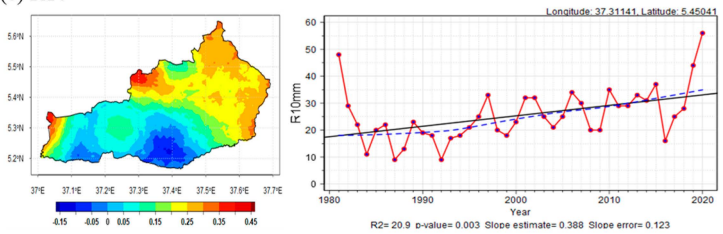
South and western part showed declining trend while some areas in north showed increasing trend (P<0.05)

(b) Rx5



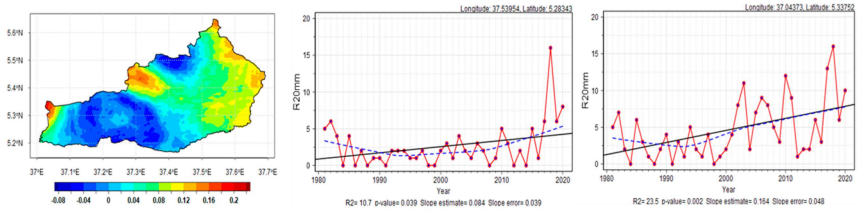
Only south east part shaded in red and dark brown showed significant (P<0.05) increasing trend

(c) R10



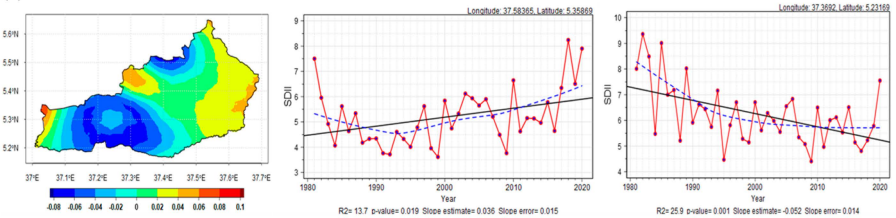
All areas shaded with reddish, brown and yellow exhibited significant increasing trends

(d) R20



Areas shaded with reddish, brown, light green and yellow showed significant rising trend (p<0.05)

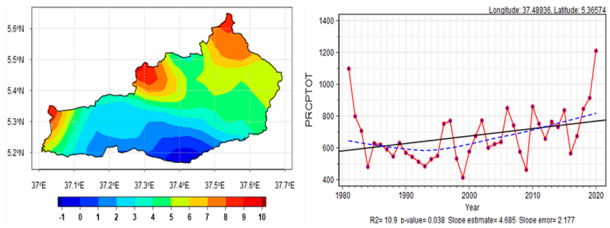
(e) SDII



Yellow, brown and redish showed significant (p<0.05) increasing trend while blue colors significant declining trend (p<0.01)

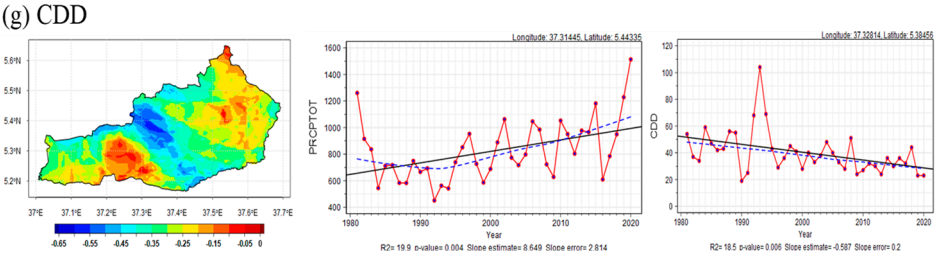
Figure 6. *Cont.*

(f) PRCPTOT



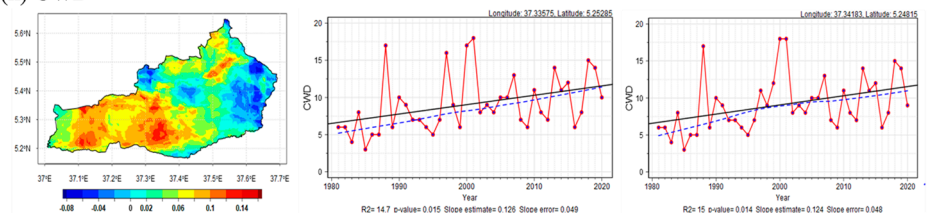
Green, yellow, brown and red color shaded areas showed significant increasing trend ($p<0.05$)

(g) CDD



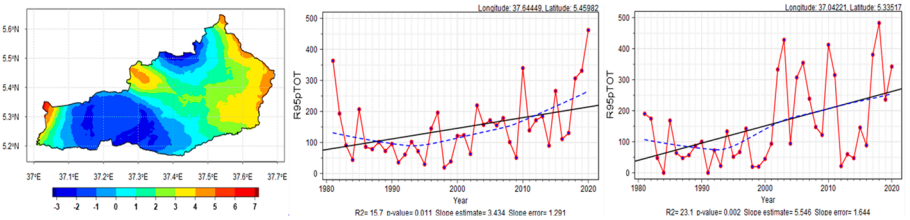
Areas shaded with light green and other blue colors showed significant decreasing trend ($p<0.05$)

(h) CWD



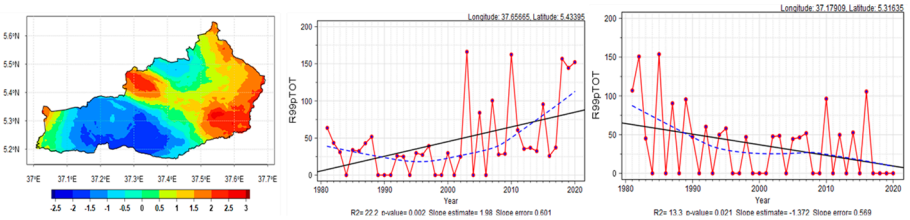
Red and dark brown shaded areas had significant rising trend ($p<0.05$)

(i) R95 p



Areas shaded with yellow, brown and red color exhibited significance rising trends ($P<0.05$)

(j) R99P



Areas shaded with red and brown color showed significant positive trends while dark blue and blue showed significant decreasing trends ($p<0.05$)

Figure 6. Trends of rainfall extreme indices in Konso zone (1981–2020) (**a**) Rx1, (**b**) Rx5, (**c**) R10 mm, (**d**) R20 mm, (**e**) SDII, (**f**) PRCPTOT, (**g**) CDD, (**h**) CWD, (**i**) R95p, (**j**) R99p. Solid red, solid black and dashed blue lines indicate annual extreme values, long-term trends and five years moving average respectively.

i **Absolute indices**

Maximum 1-day (RX1 day) and 5-day (RX5 day) rainfall

Although there were many places in the northeast and southeast part of the study area showing increasing tendencies, only some pocket areas on the north and western periphery, which are shaded in a red color, showed a significant increasing trend ($p < 0.05$) of Rx1day (Figure 6a). The magnitude of change in Rx1 day in the northern part (0.43 mm year^{-1}) is higher than the change on the western periphery (0.3 mm year^{-1}). In contrast, a large part of the south-central parts shaded with dark- and light-blue colors exhibited significant declining trends ($p < 0.05$), with a magnitude ranging from -0.3 mm year^{-1} to -0.5 mm year^{-1}. With regard to Rx5 day rainfall, significant positive change ($p < 0.05$) was observed only in the central part of Jarso kebele, in the southeast part of the study area, with a magnitude of change ranging from 0.62 to 0.73 mm year^{-1}. The south and southwest parts of the study area showed an insignificant decreasing trend, while the north and north-eastern parts showed insignificant increasing trends (Figure 6b). There was no clear pattern in the trends of Rx1 and Rx5 day rainfall.

Simple daily intensity index (SDII) and annual total wet-day rainfall (PRCPTOT)

Mixed results were found in the trends of SDII in the present study. Significant increasing trends in SDII were found in the eastern, and in some portions of the northern and western borders of the study area, which are shaded with yellow and light-brown colors (Figure 6e). In contrast, the southern parts, which are shaded with dark- and light-blue colors, showed significant decreasing trends of SDII, with a value ranging from -0.32 mm year^{-1} to -0.72 mm year^{-1} (Figure 6e). Similar findings on mixed downward and upward trends in SDII were reported by [28]. The studies in [35,65] revealed a declining tendency of SDII at the middle of the Konso zone and Mekaneselam, respectively, whereas [66], identified increasing trends of SDII in Bilate. The increasing trend in annual total wet-day rainfall (PRCPTOT) was found to be significant in the north, northeast and northwest areas of the zone, which are shaded with light-green, green, yellow, brown and red colors (Figure 6f). The magnitude of increment was higher than 4 mm year^{-1} in these areas. The increasing trends of PRCPTOT is consistent with similar findings by [29,65,66], who reported a positive trend in all AEZs off Ethiopia except for a hot arid AEZ in Bilate, and Gayint and Simada, respectively.

ii **Threshold indices**

Number of heavy (R10 mm) and very-heavy rainfall (R20 mm) days

The annual occurrence of a heavy rainfall (R10 mm) event was lowest in the southern part and highest in the northern part of the study area. In areas shaded with yellow, light-brown and red colors on the eastern, northern and western periphery of the zone, the annual number of days with heavy rainfall (R10 mm) exhibited significant ($p < 0.05$) increasing trends (Figure 6c). The altitudinal variation might have contributed to this variation. Our finding is in agreement with similar studies [43,65,66]. A small proportion of the southern parts (lowland areas) shaded in dark blue showed a decreasing tendency in R10 mm. Similar to R10 mm, the highest number of annual R20 mm was observed in the north, east and western areas of the zone. Areas particularly shaded with light-green, yellow, brown and light-red colors revealed significant ($p < 0.05$) increasing trends in R20 (Figure 6d).This finding is also consistent with other studies conducted in rift valley areas [32,43,65] and Lay Gayint and Tach Gayint [29].

The increasing trends in heavy and very-heavy rainfall indicate potential risks related to soil erosion and flooding, which have implications for the livelihood of the local community and the management of the cultural landscape. The decline in agricultural productivity and the increment in the destruction of physical structures (Scheme 4) became common challenges in the study area as a result of the increment in heavy and very-heavy rainfall days. The number of heavy and very-heavy rainfall days are increasing because of unreliable and fluctuating rainfall characteristics in the study area. The increasing trends

in the occurrences of these intense heavy rains cause serious crop damage, which makes smallholder farmers vulnerable to many kinds of shocks, including the inability to prepare the soil and water-conservation structures after heavy rains. This, in turn, contributed to food insecurity, which had a direct impact on the sustainability of the cultural landscape (both tangible and intangible resources).



Scheme 4. (**a**,**b**) Damaged terraces as a result of heavy rainfall in Mechelo. Photo credit: the authors (2023).

iii **Duration indices**

Consecutive dry and wet days (CDDs and CWDs)

Mixed results were found in the trends in CDD in the Konso zone. Significant decreasing trends in CDD were observed in central parts and other pocket areas, with a magnitude of change ranging from −0.38 to −0.58 days year^{-1}, while the southern and north-eastern parts of the study area exhibited insignificant increasing trend. Conversely, significant increasing trends in the maximum number of consecutive wet days (CWD) were observed in the south-central and western part of the zone, with a magnitude ranging from 0.91 to 0.12. These areas are shaded with light-brown, red and dark-brown colors (Figure 6h). The findings of the present study are in agreement with similar findings by [19,29,35], who reported a mixed result showing both decreasing and increasing trends in CDD in the AEZs of the Guraghe zone, the Meki watershed, and south Wollo, respectively. The increasing trends in CWD in lowland areas were also consistent with similar finding [19,35]. However, this is not in line with the findings of [24,65], who reported significant increasing trends in CDD and decreasing trends in CWD over warm semi-arid AEZs of Ethiopia and Lemi (North Shewa), respectively.

The declining trend in the length of dry-spell days indicated that the moisture will be kept for a long period, which has huge implications for the availability of water for both varieties of consumption. Hardas-water wells will not be easily exposed to drying. The community can access water very easily for domestic, as well as agricultural, activities.

iv **Percentile indices**

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

There was no clear patterns in the trends of R95p and R99p in this study. Mixed declining and increasing results were found. A significant declining trend in R95p was observed in a few pocket areas in the south-western part of the zone, which are shaded with a dark-blue color (Figure 6i), while the southeast margins, and the northern- and western-border areas of the zone shaded with yellow, brown and red colors, exhibited significant increasing trends in R95p (Figure 6i), with a magnitude ranging from 3 mm to 6.2 mm year^{-1}. On the other hand, significant increasing trends in R99p were observed in some pocket areas of the Jarso, Tish male, Gelebo, Arfayide and Masoya kebeles, with a magnitude ranging from 2.17 mm to 2.63 mm year^{-1}. In contrast, significant declining trends in R99p were observed in large areas in the southern part of the zone comprising

the Naliya segen, Aba roba, Gera, Shewa geme, Kashile, Gesergiyo, Fasha, Mecheqe, and Doha kebeles. The magnitude of change ranged from −1.1 mm to −1.75 mm year^{-1}. Our finding are consistent with similar findings by [32,33,65,66], who reported increasing trends in R95p and R99p in many parts of Ethiopia.

The significant increasing trends above R95p might cause high intensity of floods, which leads to a degradation of biodiversity and ecosystems, water scarcity, land degradation, and crop damage. Climate change does not only have a direct impact on the cultural landscapes. These direct impacts of climate change also bring indirect consequences, including the loss of agricultural activities, displacement of people, and loss of intangible values, which bring into question the sustainability of the cultural landscape.

3.2. Temperature Characteristics

3.2.1. Trends in Annual Min, Max and Mean Temperature

The mean min temperature of the Konso zone annually and during the Katana and Hageya periods were 17.47, 17.1 and 18 °C, respectively (Table 2). On the other hand, the mean max temperature annually and during the Katana and Hageya periods were 28.32 °C, 28.57 °C, and 27.93 °C, respectively. The maximum and minimum values of the annual maximum and minimum temperature were 29.6 °C and 26.9 °C, as well as 18.47 °C and 16.7 °C, respectively.

Table 2. Trends and means of annual and seasonal temperatures (1987–2020).

Temperature		Annual	Katana	Hageya
Mean minimum (°C)		17.57	17.1	18.0
Mean maximum (°C)		28.32	28.57	27.93
Min T	Trend (Z-test)	2.42	2.28	2.12
	Sen's slope °C/decade	0.31 *	0.42 *	0.3 *
Max T	Trend (Z-test)	4.5	4.14	1.97
	Sen's slope °C/decade	0.57 ***	1.01 ***	0.3 *

*** and * represents significant level at 0.001 and 0.05, respectively.

The trends in minimum and max temperature on an annual timescale are shown in Table 2 and Figure 7. From the table, it can be noted that both the annual min and max temperature showed significant rising trends, with the magnitude of 0.31 (at $p < 0.05$) and 0.57 °C (at $p < 0.001$) decade^{-1}, respectively. However, the increasing trends in Tmax was more pronounced in the first decade of the study period than in the other decades (Figure 7). The *t*-test also confirmed that the Tmax of the first decade was significantly ($p < 0.05$) different from that of recent decades on an annual timescale (Table 3). The seasonal max temperature trend during Katana and Hageya indicates a warming trend at a rate of 1.01 (at $p < 0.001$) and 0.3 °C (at $p < 0.05$) decade^{-1}, respectively. The *t*-test analysis on a seasonal timescale indicated that the change in the first period was significantly more pronounced than in other recent decades during the Katana season (Table 3).

Similar significant ($p < 0.05$) warming trends were also shown in the min temperature during the Katana and Hageya seasons, at the rate of 0.42 and 0.3 °C decade^{-1}, respectively (Table 2). However, a significant increasing change ($p < 0.05$) in Tmin was observed in the recent decade, compared to in the 1990s (Table 4 and Figure 8).

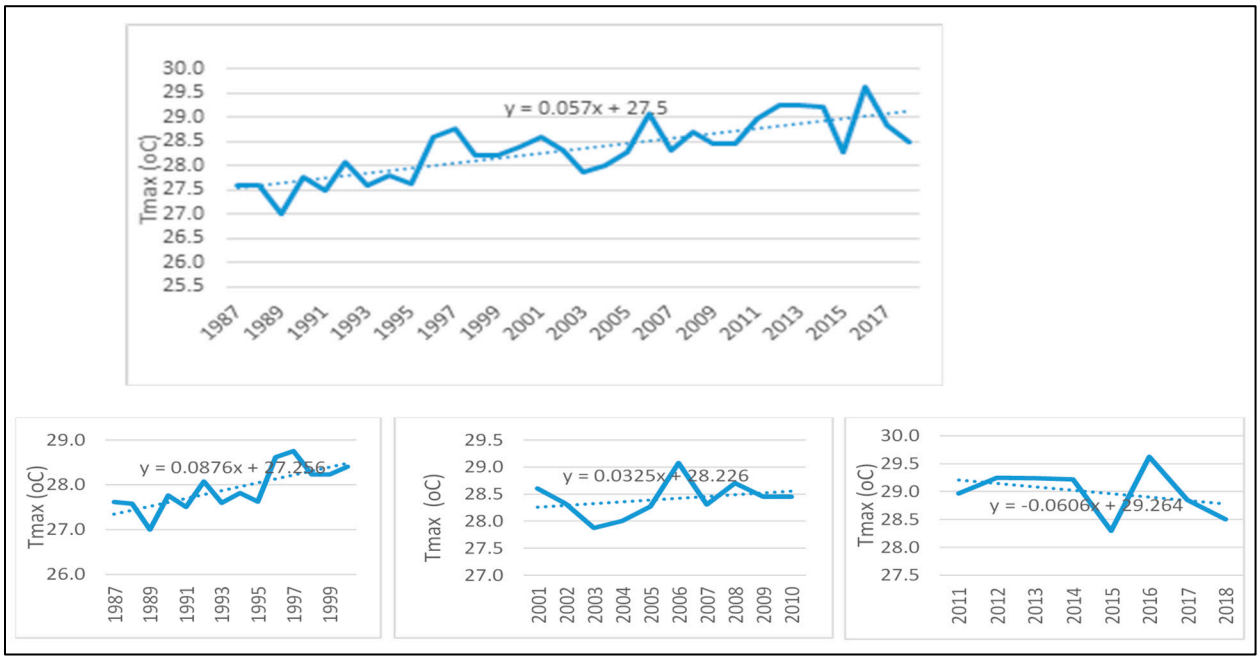


Figure 7. Trends in mean annual Tmax during distinct decades of the study period (1987–2018).

Table 3. *t*-test of Tmax in three consecutive 10-year periods (1987–2018).

		1st Period	2nd Period	2nd Period	3rd Period	1st Period	3rd Period
Annual	Mean	27.717	28.3762	28.37615	28.84961	27.717	28.84961
	Variance	0.17265	0.12473	0.124731	0.222731	0.1727	0.222731
	p value	0.000205558		0.013078232		0.00000196	
Katana	Mean	27.6074	28.6162	28.61615	29.31657	27.607	29.31657
	Variance	0.52663	0.29541	0.295408	1.909649	0.5266	1.909649
	p value	0.002263079		0.090897795		0.001805931	
Hageya	Mean	27.6185	27.8781	27.87806	28.28166	27.618	28.28166
	Variance	0.39706	0.51773	0.517733	0.647616	0.3971	0.647616
	p value	0.218292418		0.17571521		0.013494925	

Table 4. *t*-test of Tmin in three consecutive 10-year periods (1987–2018).

		1st Period	2nd Period	2nd Period	3rd Period	1st Period	3rd Period
Annual	Mean	17.3122	17.3912	17.39115	17.69012	17.3122	17.6901
	Variance	0.101825	0.53015	0.530155	0.363775	0.101825	0.36377
	p value	0.379020293		0.110576866		0.021484279	
Katana	Mean	17.91868	17.6293	17.6293	18.1589	17.91868	18.1589
	Variance	0.319559	1.48063	1.480628	0.670961	0.319559	0.67096
	p value	0.249697503		0.090530474		0.047686485	
Hageya	Mean	16.92352	17.0939	17.09394	17.37075	16.92352	17.3707
	Variance	0.04916	0.77296	0.772957	0.370431	0.04916	0.37043
	p value	0.303665064		0.23497423		0.022242331	

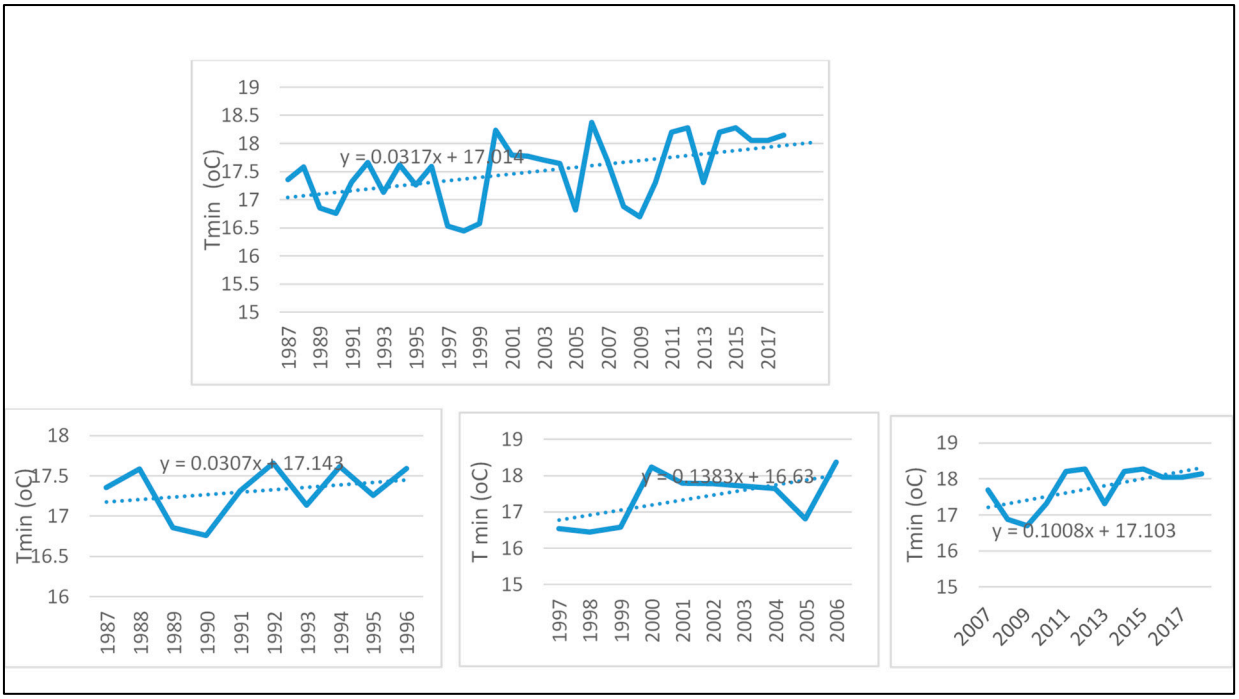


Figure 8. Trends in mean annual Tmin during distinct decades of the study period (1987–2018).

The increasing trends in both minimum and max temperatures were reported in similar findings [32,55,60–62], in studies which were conducted in all of Ethiopia, the Sidama region, the Meki watershed, and southern Ethiopia, respectively. However, it is remarkable that the max temperature has been increasing at a higher rate than the min temperature, on both time scales [35,55].

3.2.2. Anomalies of Min and Max Temperature

Both the min and max temperature anomaly on an annual timescale indicated that the temperature became hotter in recent years, compared to the 1980s and 1990s (Figure 9). However, there was no clear pattern of hotter and colder years during the Katana and Hageya seasons in the study period. Regarding the min temperature, the years 2001 and 1999 were the coldest and 2019 and 2008 were the hottest, during the Katana and Hageya seasons, respectively. On the other hand, the years 1980s and 1990s were the coldest and 2010s were the hottest for max temperature during the Katana and Hageya seasons, in the study period. Generally, the anomaly was highest with respect to min temperature rather than max temperature in both the Katana and Hageya seasons. The analysis of the temperature anomaly indicated that both min and max temperature show a warming trend for all periods (annual, Katana, and Hageya) in the study period. Similar findings [32,35,55,62,65] confirmed increasing tendencies of hotter years with respect to minimum, maximum and mean temperatures in recent years.

3.2.3. Trends in Extreme-Temperature Indices

The trends in extreme-temperature indices are shown in (Table 5). As depicted in the table, all the warming extreme-temperature indices (TXx, TX90p, TN90p, and WSDI), except TNx, showed significant increasing trends of varied magnitude. The rate of increasing trends in the warmest day (TXx) was 1.02 °C decade^{-1}. Similarly, the annual percentage of days with respect to warm days (TX90p) and warm nights (TN90p) showed significant increasing trends, at the rate of 12.2 and 7.29%, respectively. However, the annual warmest day with the min temperature (TNx) showed an insignificant increasing trend.

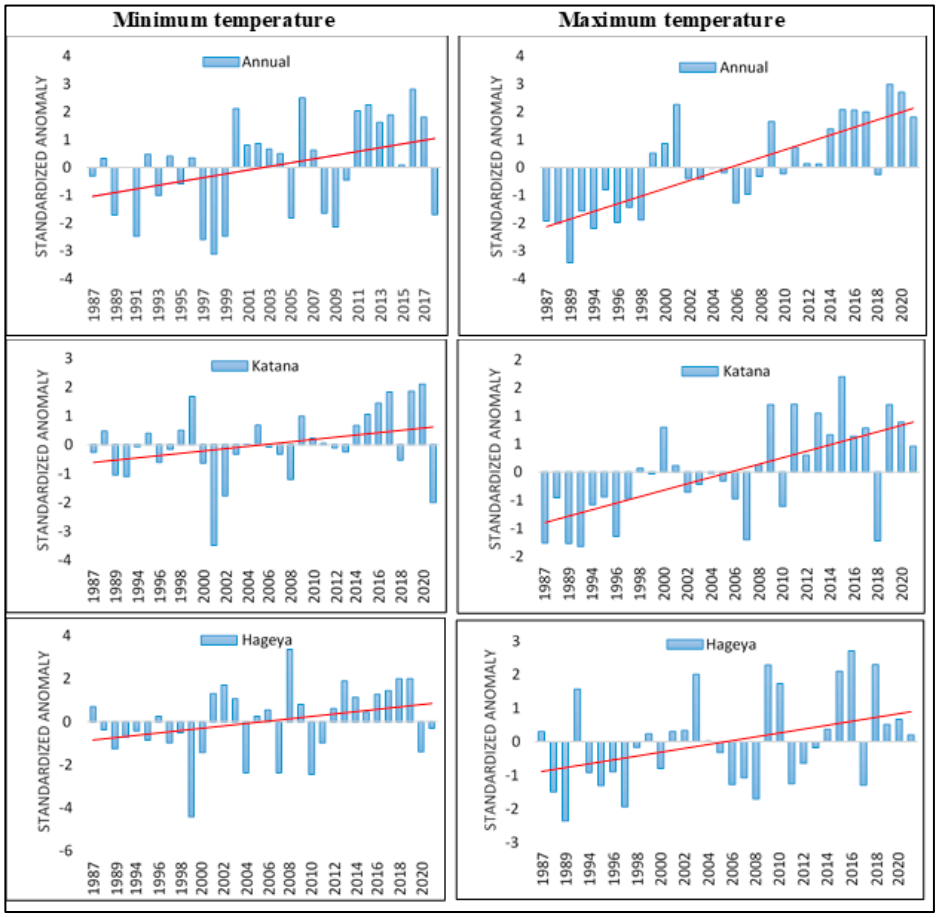


Figure 9. Standardized anomalies of the min and max temperature on different timescales (1987–2020).

Table 5. Annual trends in extreme-temperature indices in Konso (1987–2020).

Names of Indices	Slope/Year	*p*-Value
TXx	0.102	0.007
TXn	0.094	0.03
TNx	0.028	0.48
TNn	−0.164	0.312
TX10p	−0.309	0.25
TN10p	−0.528	0.23
TX90p	1.228	0.001
TN90p	0.729	0.05
WSDI	4.307	0.001
CSDI	−1.361	0.3

Conversely, every cold extreme-temperature index (TNn, TX10p, TN10p, and CSDI), except TXn, indicated a negligible downward trend. The coldest day (TXn), however, exhibited a substantial ($p < 0.05$) rising trend, at the rate of 0.94 °C decade^{-1}. The coldest nights (TNn) also showed an insignificant declining trend, at the rate of 1.64 °C decade^{-1}. The increasing change in temperature for the warmest days (TXx) was more pronounced than the increasing change in the coldest day (TXn). Cool days (TX10p) and cool nights (TN10p) demonstrated negligible declining trends, at the rate of 3.09 and 5.28% decade^{-1}, respectively (Table 5). The hot-temperature indices (TXx, TNx, TX90p, and TN90p), generally, showed a larger magnitude of change than the cold-temperature indices (TXn, TNn, TX10p, and TN10p). From the analysis, it can be concluded that the disparity in the trend among the min temperature indices was stronger than in the indices for max temperature.

The annual number of days with at least 30 consecutive days with a TX > 90 percentile (WSDI) showed significant increasing trends, while the CSDI showed an insignificant downward trend. Generally, it can be concluded that most-warming extreme indices showed significant rising trends, and the cooling extreme indices showed insignificant declining trends.

Based on the analysis, it was determined that there was a greater trend discrepancy between the minimum temperature indices compared to the maximum temperature indices. While the CSDI showed a insignificant downward trend, the WSDI showed significant increasing trends. Overall, significant rising trends were observed in the majority of warming extreme indices, while insignificant declining trends were observed in the cooling extreme indices.

Similar significant warming and cooling trends in TXx, TNx, TX90p, and TN90p were reported in similar findings [17,24,28,32,65]. However, unlike the present increasing trends in cold-temperature indices (TXn, and TNn), many studies [17,24,32,65] reported mixed upward and downward trends. Our finding is consistent with the findings of [43], who disclosed significant increasing trends in absolute-temperature extreme indices (TXx, TNx, and TXn) in studying the trends in extreme climate events over three agro-ecological zones of southern Ethiopia for the period (1983–2014).

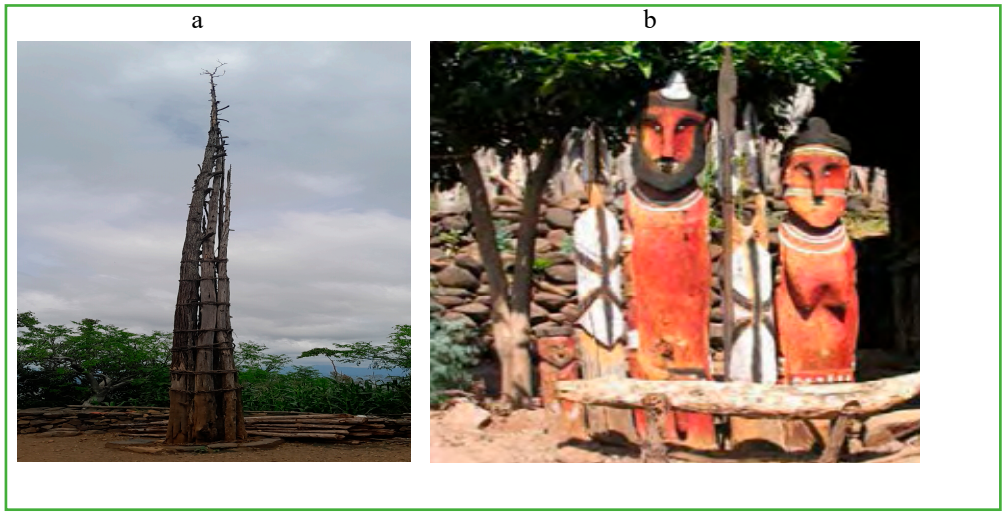
The majority of the temperature extreme indexes are showing increasing trends, which suggests that the study area is warming. Because of the heat stress, Konso's dry land will see an increase in evapotranspiration, which will negatively affect crop production and water availability. Agriculture, water resources, health, and other industries were significantly impacted by changes in the patterns of rainfall and temperature extremes.

Generally, climate change has huge implications for the sustainability of the Konso living cultural landscape. The state of conservation of the Konso cultural landscape is determined by the availability of local materials, which are being reduced due to the change in climate. Primarily, the crop yield, which was becoming worse in recent years, made the local community food-insecure, which has a strong connection with the celebration of the ritual ceremonies.

The ritual ceremonies performed by the poqolas (traditional leaders) were thought to maintain the harmony and balance between nature and man. As per the discussion held with elders, these ritual ceremonies were influential in disseminating indigenous knowledge and community-obligation codes which might help conserve and preserve their cultural landscape. For example, the annual 'thanks for harvest giving' ceremony (Tuta), which requires more food items for its celebration, has been abandoned in most of the walled villages of Konso. Similarly, the traditional power-transition ceremony, which takes place every 18 years (kara) for 2 months was also abandoned because of a shortage of food items.

Although it is fading, the Konso community is known to remember their traditional leaders and heroes who demonstrated outstanding performance for the wellbeing of the Konso landscape (for both the natural and cultural elements). The elders said that the erection of ulahita (Scheme 5) to commemorate a generational grade (khela) is weakening, because of the unavailability of juniper trees. The juniper trees used for ulahita should be cut from sacred forests. However, it is difficult to obtain sacred forests, due to the change in climate and population pressure. The construction and erection of waka (wooden grove) (Scheme 5) for commemorating heroes for the achievement of their leadership was also diminishing, due to the absence of huge trees for its preparation.

The discussants also mentioned that the hardas (traditional ponds) (Scheme 6) are constructed by the Konso people to collect rain water during wet seasons and for use in the dry season. However, today, almost all hardas are dried up, due to high evapotranspiration and insufficient rain water. The community is forced to travel long distances to fetch drinking water.



Scheme 5. Generational marking Ulahita trees (**a**) and Waka for commemorating heroic leaders (**b**) in Konso. Photo credit: the authors (2023).



Scheme 6. Dried-up traditional pond (harda) in Mechelo (**a**) and remote drinking-water sources on the northern border of the Konso zone (**b**). Photo credit: the authors (2023).

4. Conclusions and Implications

The dry-terrace intensive agriculture, the walled towns, and the socio-cultural institutions are the distinctive characters of the Konso cultural landscape inscribed as a World Heritage site. The sustainability of the cultural landscapes is, however, seriously threatened by the hazards associated with climate change. In this research, we looked at how temperature and rainfall patterns changed over time and how they impacted the Konso cultural landscape in southern Ethiopia.

Recently, frequent drought, rainfall variability and changes, temperature increment, and extreme events have been observed in the study area. The climate data analysis revealed that the variability and unpredictability of rainfall, including its extreme events, coupled with heat stress as a result of rising of temperature extremes, negatively affected the cultural landscape. The analysis of the temperature anomaly indicated that both minimum and max temperature have been escalating in the recent decade on all timescales (annually, and during Katana and Hageya), which will activate warm conditions in the study area, thereby making the environment moisture-deficit, which in turn results in the reduction in land productivity.

The changes in rainfall and temperature have negative effects on crop yield and water availability, because they increase evapotranspiration on Konso's dry land. By disrupting the ecosystem services, rising temperatures and erratic rainfall are very likely to make the

situation of the Konso living cultural landscape worse. The various human cultures that are embedded in their natural environments will be significantly impacted by the ways in which the ecosystem is changing. Because of the declined benefits obtained from the cultural landscape, the local community may disregard their culture and reliance on the cultural landscape. As a result, ritualistic traditional practices that are necessary to preserve the living cultural landscape have been abandoned.

Climate change threatens the sustainability of the Konso world heritage cultural landscape by (1) reducing farm productivity, which influences the annual God-thanking cultural ceremonies (*Tuta*) and the ceremony to transfer power and responsibility from older-age groups to younger-age groups (*Kara*), which are believed to be the core ceremonies used to educate and disseminate their strong belief in cultural landscape conservation and management; (2) initiating migration of the local community to relatively productive areas, which contributed to the ruin of the dwellings in the walled town; (3) minimizing the availability of grasses used to construct the traditional individual houses and communal *paftas* in the cultural space called the '*mora'*; (4) minimizing the erection of memorial *wakaa* and *ulahitas*, due to the scarcity of juniper trees; and (5) making the local community engage in off-farm activities, which contributed to the abandonment of their day-to-day engagement in conserving and managing their landscape.

The examination of temperature and rainfall extremes and their relationships with the cultural landscape will provide information for decision-makers, which will help them mitigate risks. If the present trends in rainfall and temperature continue, rain-fed agriculture is likely to be further challenged by future climate change, which will lead the community into impoverishment and which has resulted in the deterioration of the cultural landscape. To ensure the survival of the Konso cultural landscapes as a global cultural treasure and to strengthen the resilience of smallholder farmers, localized adaptation and mitigation approaches to the changing climate are needed. Finally, we recommend carrying out more thorough research to forecast the study area's future rainfall and temperature conditions, as well as assessing the degree of community vulnerability with respect to the effects of climate change, in order to improve and identify the most suitable local and national adaptation strategies.

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