

Assessment of Extreme Heat Wave Magnitude in Present Climate in the Pastoral Region of Afar, Ethiopia

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Abstract
Heatwaves have been a prominent issue in climate change studies due to the extreme heatwaves that have occurred globally over the past few decades. Extreme heat waves are hitting Ethiopia, which has led to higher rates of death and morbidity as well as higher water and energy needs. This study presents for the first time a climatological analysis of heatwave magnitude for a pastoral region of Afar using the heatwave magnitude index daily (HWMId) index. The study analyzed the intensity of heatwave for the period 1981-2020, as well as for the heatwave event in 2015 using gauged dataset. The findings showed that each year, the proportion of hot days and hot nights increased by 0.3 and 0.3 days per year. The areal aggregated temperature anomaly indicated increasing each year by +0.07 and +0.05 ^{0} C for maximum and minimum temperature respectively. 2015, 2016, and 2015 were considered as the hottest years in the last 40 years, with 2015 being one of the warmest years on record with an anomaly of +1.8 °C for maximum temperature and 1.3 °C for minimum temperature. The finding also clearly indicated that most parts of the study area recorded severe to very extreme heatwaves scored from 4 to 16. The increase in a heatwave may have a negative impact on health, water availability and food security. Therefore, the finding of this study is very important to develop early warning systems that could manage the risk of anomalously extreme weather events.
Keywords: Afar Region, Extreme climate indices, Heatwave, Heatwave magnitude index, Pastoralists, Temperature.
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1. Introduction
1.1 Background
The frequency of extreme weather phenomena like heatwaves, droughts, floods, and wildfires has increased as a result of global warming. Heat waves have been a popular issue in climate change studies as a result of some particularly catastrophic heatwaves in recent decades. According to Intergovernmental Panel on Climate Change (IPCC) reports, the earth's surface and troposphere are heated by an increase in the atmospheric concentration of greenhouse gases. Warmer temperatures are caused by this direct thermodynamic impact, which also results in an increase in the frequency and intensity of warm extremes and a decrease in the frequency and intensity of cold extremes (IPCC a, 2014, Seneviratne et al., 2021). The United States Environmental Protection Agency (USEPA) claims that as the global mean temperature rises, it is almost certain that there will be more frequent hot temperatures and fewer cold temperature extremes over most of the world on daily and seasonal timescales (USEPA, 2016).

Scientists and managers are interested in extreme events because of their potential to cause significant impact on people, infrastructure, nature, and the way of life in a particular community. Examples of these events include heat waves, widespread flooding, very strong storms, and droughts. As a result of climate change, these events are more likely to occur, thus we must comprehend how and when they might take place as well as how to better react to them in order to avoid effects. The criteria that should be used to define a heatwave are hotly contested, and there is no single definition that applies to all cases. McPhillips et al., (2018) defined heatwave as an event that has at least two consecutive days with minimum and maximum daily temperatures greater than the 90th percentiles of the historical minimum and maximum daily temperatures (thresholds), respectively.

Heatwaves are defined as a sustained periods of high temperatures that decrease productivity and increase morbidity and mortality. According to the World Meteorological Organization (WMO), a heat wave is a period of marked unusual hot weather over a specific area persisting at least two consecutive days during the hot periods of the year based on local climatological conditions, with thermal conditions recorded above given thresholds. As defined by International Federation of Red Cross and Red Crescent Societies (IFRC) heat waves are an extended period of time, typically period, with excessive heat (IFRC, 2021).

Previous researchers only addressed the length of a heatwave, not its intensity or magnitude, and are unable to compare the size of heatwaves over location and time, just their length. Using a novel Heat Wave Magnitude Index (HWMI) that can be compared over both location and time, Russo et al., (2016) introduced the concept. The maximum magnitude of heatwaves in a year is measured by the heatwave magnitude index, where a heat wave is defined as a period of three consecutive days where the maximum temperature exceeds the daily threshold for the reference period. The threshold is the 90th percentile of daily maxima, centered on a 31-day window (Russo et al., 2016).

Extreme temperature affects both human being and livestock. For example, heat affects the body's temperature-regulating mechanism of sweeting and breathing. As sweating struggles to compensate for higher ambient temperature it pushes the regulatory mechanism, such as heart rate and function, harder to release internal heat. Dehydration, cramping, heat exhaustion or heat stroke, and heat stress are frequently the main health effects of heat waves (Mcgregor et al., 2010). According to the World Health Organization (WHO), heat waves can have an immediate impact on huge populations, cause public health catastrophes, and have cascading socioeconomic effects (Arbuthnott & Hajat, 2017). The research finding indicated that the rise in daily temperature corresponds with an increase in the number of hospital admissions. For example, there is a maximum daily temperature of 30 ^{o}C at which Parkinson's diseases admission are minimum. Similarly to this, a temperature of 34 ^{o}C corresponds with an increase in the number Parkinson's diseases admission of cases (Linares et al., 2016).

When climate-sensitive infectious diseases (CSID) increase as a result of extreme climatic events like floods, droughts, and heatwaves, the public is very concerned. For instance, numerous studies (Cheng et al., 2020, Gómez Gómez et al., 2022, Seah et al., 2021) have demonstrated the relationship between increasing temperature and dengue illness. The results are confirmed that the increment of temperature is more likely impact and magnifying the size of dengue outbreaks (Cheng et al., 2020). An epidemiological outbreak investigation involving confirmed malaria-negative individuals who presented with suspected and confirmed dengue fever at both public and private health facilities is conducted from September to November 2019. The outcomes revealed that a total of 1185 dengue fever case are recorded at six health facilities in Gewane District, Afar Region, Ethiopia (Mekuriaw et al., 2022).

The livestock is one of the food security for the world's expanding population, according to the Food and Agricultural Organization (FAO) of the United Nations (Molina-flores et al., 2020). In the prevalence of disease, and a reduction in the availability of feed, fodder, and water are some of the effects of climate change on livestock output and production. The productivity and output of cattle are reduced as a result. Human population largely depend on animal products like milk, meat, eggs, fibers, wool and feather. These products, are adversely affected by various events of extreme climatic conditions. The health of cattle is greatly impacted by heat stress, metabolic dysfunction, oxidative stress, and immunological suppression as a result of increasingly frequent extreme weather events, notably higher temperatures. This makes sickness occurrence and mortality more likely to increase (Ali et al., 2020).

1.2 Objectives

The main objective of this study is to investigate spatio-temporal characteristics of heatwave in the pastoral region of Afar, Ethiopia, using heatwave magnitude index (HWMI) during the last 40 years and to compare 2015 heatwave with respect to reference period (1981-2020).

1.3 Problem statement

Two main livelihoods—pastoral and agro-pastoral—dominate in the Afar region, according to research by the Ethiopian Economic Association (EEA). Agro-pastoral livelihoods provide a living for 15% of the rural population, whereas pastoral livelihoods support about 85% of them (EEA, 2021). Previous studies emphasized examining extreme temperature event on the highland areas of the country, particularly in crop producing areas. Study related to extreme temperature in lowland area of pastoralist is rare. Assessing extreme temperature event is very important to develop sectoral specific early warning system. These presumptions serve as the foundation for the current investigation, which uses an observed climate dataset to examine the spatio-temporal pattern of heatwave in the pastoral region of Afar, Ethiopia, using HWMI for 1981-2020 period.

2. Materials and Methodology

2.1 Study Area Description

The Afar Region is placed in northeastern Ethiopia (Figure 2-1), with geographic coordinates between 8° 51' and 14° 34' North and between 39° 47' and 42° 24' East. The Region is divided into five administrative zones, namely Awsi Rasu (Administrative Zone 1), Kilbet Rasu (Administrative Zone 2), Gabi Rasu (Administrative Zone 3), Fanti Rasu (Administrative Zone 4) and Hari Rasu (Administrative Zone 5), in that order (EEA, 2021).

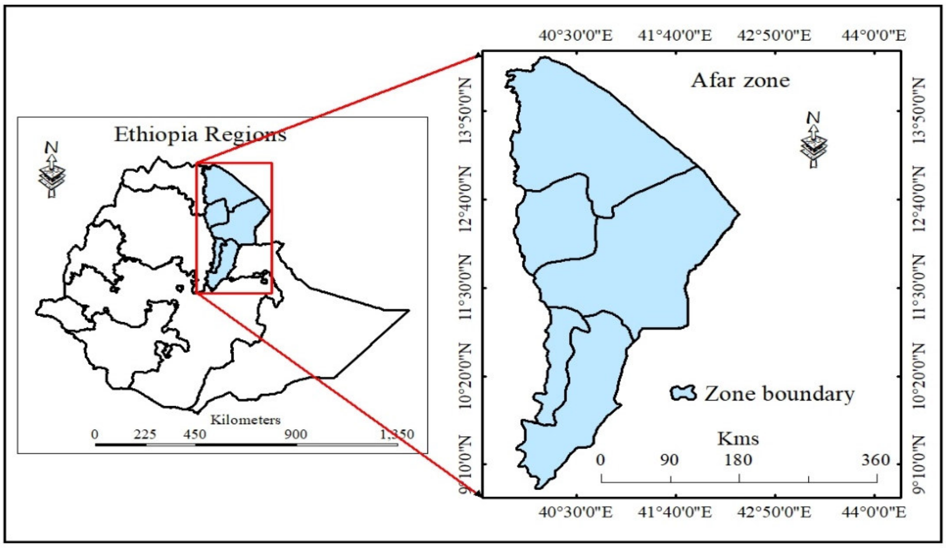

Figure 2-1 Location of study area

2.2 Data Types and Source

2.2.1 Observation Data

For the 1981–2020 study period, the Ethiopian Meteorological Institute (EMI) provided daily maximum and minimum temperature data for 44 gauge sites. The range of data in % for minimum temperature is 2%–83% and for maximum temperature is 2%–84%.

2.2.2 AgERA5 Dataset

Since there are gaps in the gauge data, the European Center for Medium Weather Forecast's (ECMWF) fifth generation atmospheric reanalysis (ERA5) dataset, which has a resolution of 10 by 10 km and covers the years 1981 to 2020, is downloaded [1] and utilized to fill those gaps. The strength of ERA5 dataset are evaluated over East African countries, the results revealed that the climatological bias in temperature is clearly reduced and the representation of inter-annual variability is improved (Gleixner et al., 2020)

2.3 Methodology

2.3.1 Homogeneity Test

From the initial weather observation, long-term climate datasets have been constructed using the Standard Normal Homogeneity Test (SNHT) technique (Alexandersson, 1986). Given that y_i the testing variable in a time series for which (i is the year from 1 to n) is a time series and where Y is the mean and s is the standard deviation (Dorfman, 2019). A test statistic, T(y), is expressed as follows and compares the means of the first Y years with the last (n-y) years:

$$\mathbf{T_y = y\overline{Z}_1 + (n - y)\overline{Z}_2}, \text{ y=1, 2...n} \qquad \text{Eqn 2-1}$$

where

$$\overline{Z}_1 = \frac{1}{y}\sum_{i=1}^{n}\frac{(y_i - \bar{y})}{s} \quad and \quad \overline{Z}_2 = \frac{1}{n-y}\sum_{i=y+1}^{n}\frac{(y_i-\bar{y})}{s} \qquad \text{Eqn 2-2}$$

The year y consisted of break if value of T is maximum, the test statistic given as the following equation and greater than the critical value, which depends on the sample size.

$$\mathbf{T_o = \max_{1 \le y \le n} T_y} \qquad \text{Eqn 2-3}$$

2.3.2 Inhomogeneity Adjustment

The inhomogeneity found in observed dataset are adjusted using Quantile Mapping (QM) technique. The research finding revealed that the Quantile Mapping (QM) techniques performed relatively better correcting in the inhomogeneity of temperature variable in diverse topography (Enayati et al., 2021).

$$\mathbf{x^o = f(x^m)} \qquad \text{Eqn 2-4}$$

where x^o is adjusted time series x^m is inhomogenoues time series, and $f(\boldsymbol{x^m})$ is transformation function. The Cumulative Distribution Functions (CDFs) of both observed and adjusted variables time series, their quantile relation can also be determined, as shown below (Ringard et al., 2017).

$$\mathbf{x^o = F_o^{-1}[F_m(x^m)]} \qquad \text{Eqn 2-5}$$

Where $F_m(x^m)$ is CDF of x^m, and $F_o^{-1}[]$ is inverse form of the CDF of x^o, which is technically referred to as the

[1] https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agrometeorological-indicators?tab=overview

quantile function.

2.3.3 Bias Correction of ERA5 daily Temperature

Linear scaling (LS) bias correction method is applied to correct ERA5 dataset. The scaling approach mainly includes linear approaches that adjust the climatic factors based on the differences between observed and model output.

$$\mathbf{T^{cor}\,hst,m,d = T_{hst,m,d} + [u(T_{obs,m}) - u(T_{hst,m})]} \qquad \text{Eqn 2-6}$$

Where T^{cor} hst, m, d denote the corrected temperature on the d^{th} day of the m^{th} month, and $T_{hst,m,d}$ denote the temperature from climate model outputs during the relevant period, the subscripts d and m are specific days and months, respectively and μ denotes the mean value.

2.3.4 Heatwave Magnitude (HWM)

HWM is the average magnitude (average maximum temperature) of all yearly heatwaves, scaled over 40-year reference period (1981-2020), and measured in ◦C. The WMO recommends defining climatological standard normal as averages of climatological data computed for successive 30-year periods, updated every ten years. That is, consecutive 30-year normal including 1981-2010, 1991-2020, and so forth (Baddour & Kontongomde, 2007, WMO, 2017). Therefore, in this study 1981-2020 is used as a reference period. It is important to study in detail different characteristics of the strong heatwave of 2015 occurred over pastoral region of Afar. Therefore, 2015 is chosen for this research because it is a period of abnormally hot weather in Ethiopia, particularly in the pastoral region of Afar (Figure 3-1). The number of heatwaves that prevailed over the pastoral region of Afar in 2015 is compared with the reference period (1981-2020).

2.3.5 Heatwave Magnitude Index daily (HWMId)

The **HWMId is an improvement of the HWMI proposed by** (Russo et al., 2014), which is defined as the maximum magnitude of the heatwaves in a year. Heatwave is defined as a period of three consecutive days with maximum temperature (Tmax) above the daily threshold for a reference period 1981-2020. The threshold is defined as the 90^{th} percentile of daily maximum temperature, centered on 31-day window. Hence, for a given day d, the threshold is the 90^{th} percentile of the set of data A_d denoted by:

$$\mathbf{A_d = U_y \in Y_{ref}\, U_i \in W_d^{-15,15}\; T_{max,\; y,i,}} \qquad \text{Eqn 2-7}$$

Where ∪ denotes the union of sets, Y_{ref} represents the years within reference period, $W_d^{-15,15}$ is the 31-day window entered at day d and $T_{\max,y,i,}$ is the daily maximum temperature of the $day\ i$ in year y. For each day in an identified heat wave the daily magnitude, M_d, is calculated following:

$$\mathbf{M_d} = \begin{cases} \dfrac{T_d - T_{30y25p}}{T_{30y}\,75p - T_{30y25p}}, & \mathbf{if\ T_d > T_{30y25p},} \\ \mathbf{0} & \boldsymbol{otherwise} \end{cases} \qquad \text{Eqn 2-8}$$

Where T_d is the daily maximum temperature of day d, and T_{30y25p} and T_{30y75p} are 25^{th} and 75^{th} percentiles, respectively, of the maximum temperature time series over the reference period.

2.3.6 Heatwave magnitude index (HWMI)

The HWMI definition is based on the division of a heatwave to sub-heatwaves. A sub-heatwave is defined as a period of three consecutive days above the daily threshold. The sum of three daily Tmax of a sub-heatwave are transformed in probability values (sub-heatwave magnitude) by means of kernel density function. In the HWMI the magnitude of a heatwave was defined as the sum of magnitude of n sub-heatwaves and the score of the HWMI is given by the maximum magnitude of all heatwave magnitudes for a given year.

2.3.7 Cumulative Density Function Estimation

The kernel density estimator (KDE) is used to estimate the empirical probability distribution function (EPDF) and the associated empirical cumulative density function (ECDF) based on the annual maxima of the sub-heatwave unscaled magnitudes (Silverman, 2018). A nonparametric technique for estimating EPDF and ECDF is the KDE. The general kernel density estimator for f is as follows: Given independent and identically distributed annual maxima of sub-heat wave unscaled magnitudes, $T_1, T_2 \ldots. T_N$, with the common probability density function f(T), where N is the number of years:

$$\widehat{f_h}(T) = \frac{1}{N}\sum_{i=1}^{N} K\,(T - T_i, h)$$

T is the unscaled sub-heat wave magnitude, K is the kernel function, and h is the bandwidth smoothing value. Detailed evaluations of the kernel smoothing technique may be found in (Silverman, 2018). The Gaussian function is computed using the following kernel function, K:

$$K(X,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$

By using the method of (Sheather & Jones, 1991) , h is calculated, and the value of ECDF are obtained by integrating the $\widehat{f_h}(T)$ as follows:

$$ECDF(T) = \frac{1}{N}\sum_{i=1}^{N} K \int_{-\infty}^{T} (T - T_i, h)\, dT$$

Table 1 Classification of heat wave index (HWMI) scale categories

Classification	Normal	Moderate	Severe	Extreme	Very extreme	Supper extreme	Ultra extreme
HWMI	1≤HWMI<2	2≤HWMI<3	3≤HWMI<4	4≤HWMI<8	8≤HWMI<16	16≤HWMI<32	HWMI≥32

3. Results

3.1 Heat Wave Magnitude

This study used an aggregated 44 station temperature data for the entire region from 1981 to 2020 period to investigate the temporal pattern of warm days, warm nights, and maximum and minimum temperature anomaly. The findings showed that the magnitude of heatwaves over the pastoral region of Afar has greatly increased over the past 40 years in terms of hot days (TX90P) and warm nights (TN90P) (Figure 3 1). The hot days increased by 0.3 days per year (Figure 3 1 a) and hot night increased by 0.3 days per year in the last 40 years. Additionally, over the past 10 years, the intensity of heatwaves has more increased with time.

The areal averaged annual maximum and minimum temperature anomalies have risen over the past ten years at an average rate of +0.07 °C for maximum temperature (Figure 3 1 c) and +0.05 °C for lowest temperature, respectively (Figure 3 1 d). The three warmest years were 2015, 2016 and 2017, with 2015 being one of the warmest years on record with an anomaly of +1.8 °C for maximum temperature and 1.3 °C for minimum temperature (Figure 3 1). This is a crucial sign of the severity of climate change and its potential effects on the lives and means of support of Ethiopian pastoralists.

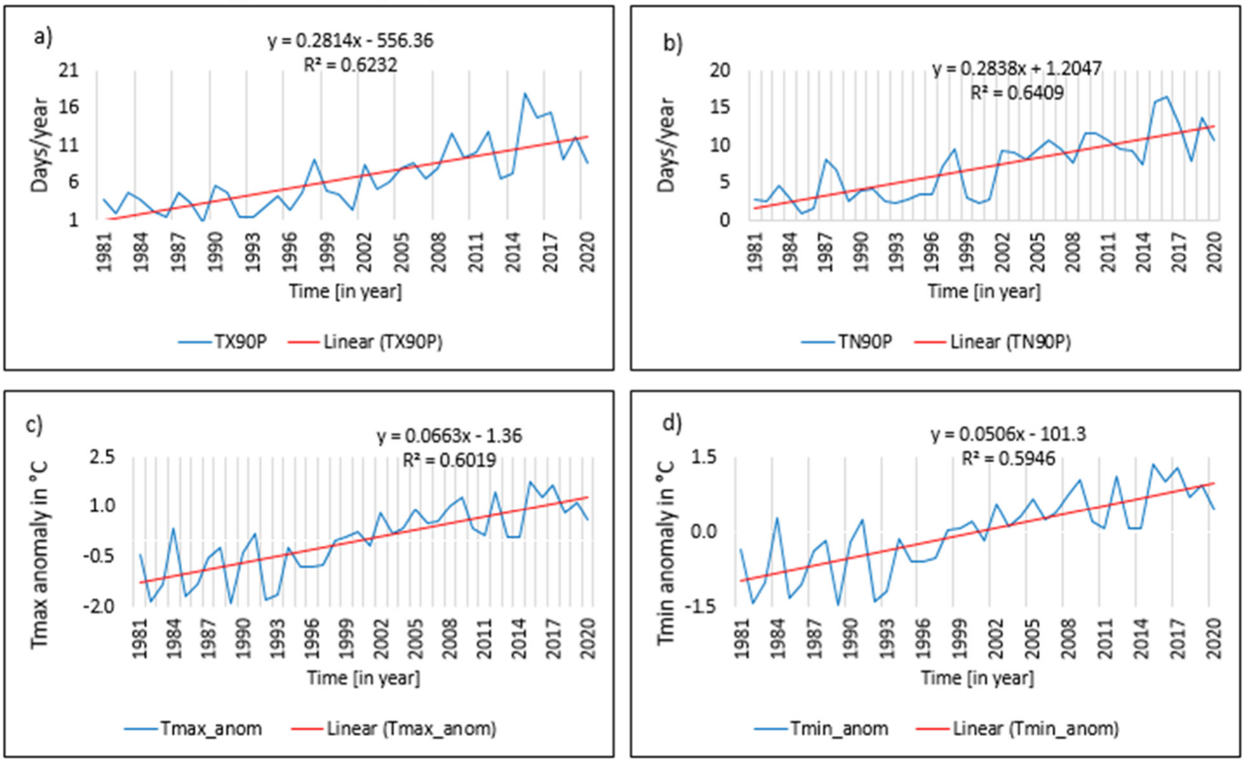

Figure 3-1 Annual averaged warm spell and temperature anomaly over Afar.

3.2 Heatwave Magnitude Index (HWMI)

A heatwave is always a multiple of a whole number of sub-heatwaves, hence the HWMI is considered as the total number of sub-heatwaves, if an event was not a multiple of a sub-heatwave, the sub-heatwave, which is typically a three-day occurrence. The HWMI result revealed that every station indicated that throughout the previous 40 years, there had been at least one heat wave with a HWMI greater than or equal to one. The results also revealed that the majority of zone one and zone two districts had very extreme heatwave with a HWMI of 8 or above(Figure 3 3)

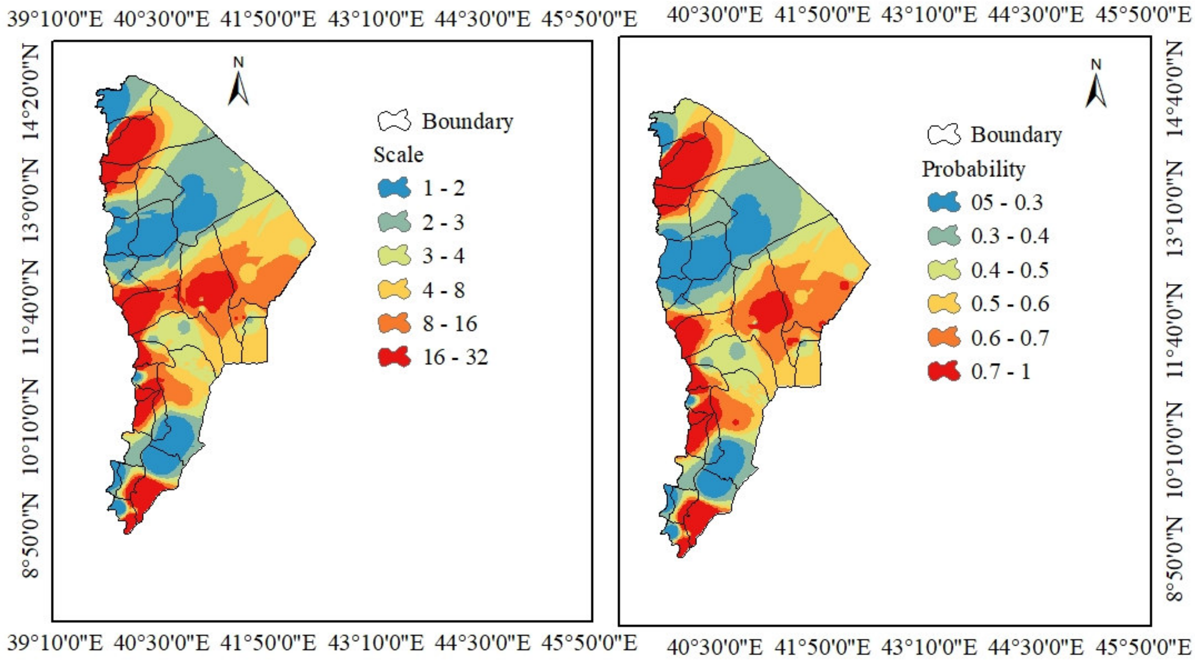

Figure 3-3 Spatial distribution of HWMI values of the strongest heatwave in 40 year period.

3.3 Heatwave Magnitude Index daily (HWMId)

Figure indicates spatial distribution of HWMId score and temperature anomaly given in ^{0}C for 2015 heatwave. It is estimated for a certain day of the heat event that is essential when a heatwave lasts for several days and there are significant temperature fluctuations. In light of the fact that the HWMId index emphasizes the participating days in order to more accurately represent the heat event than the HWMI index. The finding clearly indicated that most part of the study area were recorded severe to very extreme heat waves scored from 4 to 16 (Figure).

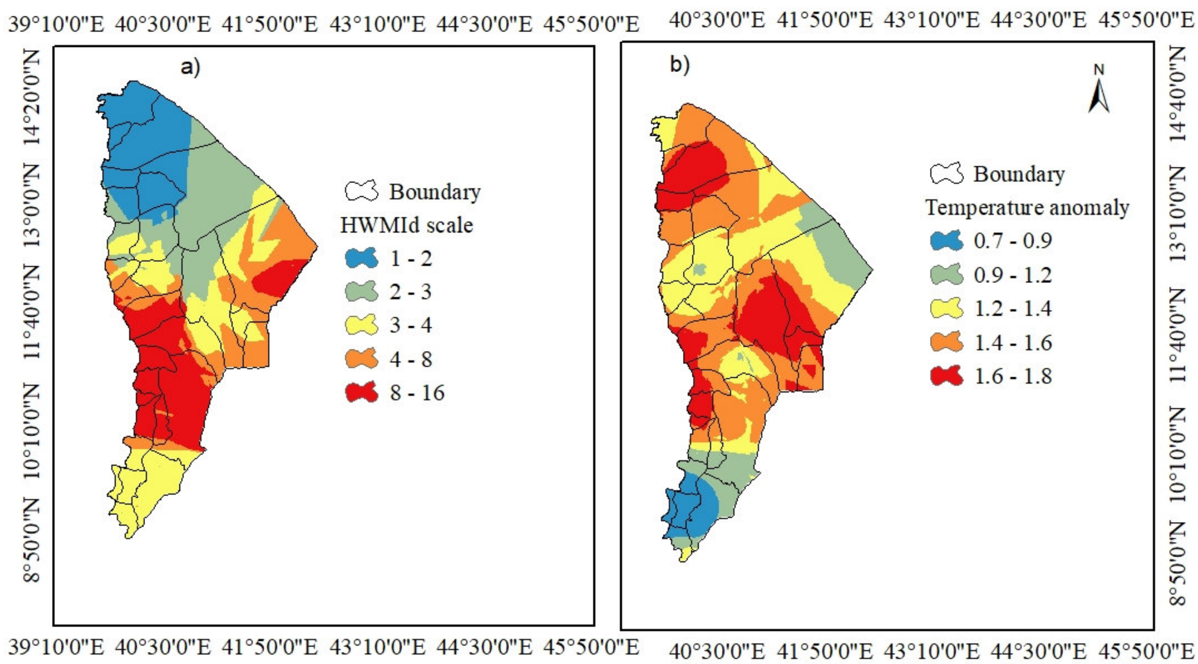

Figure 3-4 Spatial distribution of HWMId (a), temperature anomaly in ^{0}C (b) for 2015 heatwave.

4. Discussion

This work is based on the observed daily climate dataset for 1981-2020 period and the reanalysis data used to fill gap in gauge. The data quality was carried out using SNHT for homogeneity test in gauged dataset and LS for bias correction in reanalysis time series. The finding is clearly indicated that the spatial distribution of HWMId (Figure

a) was quite noticeable compared to temperature anomaly (Figure b). There are similarities between heatwave intensity and temperature anomaly in many locations. Therefore, it is clearly indicated that the likelihood of an increase in the intensity of heatwave, when temperature anomaly is positive for a particular year and location.

In Ethiopia, similar works also agreed with this finding that an increase in warm nights and hot days ranging from 0.31 to 0.62 and 0.38 to 0.71 days per year, respectively (Berhane et al., 2020). Teshome & Zhang, (2019) noted that the observed temperature extremes of the warm duration spell indicator, daily maximum temperature, summer days and tropical nights showed an increasing trend. The Famine Early Warning System Network (FEWSNET) report indicated that Ethiopia has experienced the devastating drought in more than 50 years which is triggered by 2015 El Nino. As a result, a severe food insecurity and shortage of water for both livestock and human being in many districts announced by Ethiopian government and humanitarian aid organization. The situation was most horrible in the pastoral areas due to their easily exposed livelihood of the community (FEWSNET, 2016).

The research finding revealed that an increased in intensity and frequency of heat waves, especially in the last 10 years (Ceccherini et al., 2016). Ceccherini et al., (2016) also noted that no significant changes detected for cold waves and significant increasing of annual temperature ranges (the difference between yearly mean of Tmax and year mean of Tmin). The global surface temperature in 2015 was +0.9 ^{0}C above the 20th century average, making 2015 the warmest year in the period of instrumental data (Hansen et al., 2016). Hansen et al., (2016) also noted that climate change was the major factor in driving the record-breaking heat and the late 2015 record warmth was stimulated by strong El Nino.

5. Conclusion

This study presents for the first time a climatological analysis of heatwaves for pastoral region of Afar using HWMId index. The study analyzed the intensity of heatwave for the period 1981-2020, as well as for the heatwave event in 2015 using gauged dataset. The finding is clearly indicated that the heatwave intensity was greater in the west, central and eastern part of the region. The results also revealed that significantly increased in hot days and warm nights over the study area during the last 40 years, particularly the warming is more increased in the last 10 years. 2015 was the warmest year in the last 40-year period.

Warming over the study area have increasing water loss through evaporation rate from water bodies and transpiration rate from plant stomata, subsequent decrease in the availability of water for human being and livestock, agriculture and industry. Extreme temperature leads to hotter days, and more frequent and longer heatwaves also may have increased the severity of climate sensitive diseases and severe food insecurity over pastoral areas of the country.

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Author contribution

The author conceptualized this study, collect necessary data, quality control, analyze and interpreted the result, and wrote the manuscript.

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Competing interests

The author declares that there are no opposing interests in publishing this manuscript

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