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Climate Trends in the Afro-Alpine Region of Ethiopia: Evidence from Dinsho Meteorological Records

Chirotaw Ayele [1], Gezahegn Degefe [2*]

Department of Biology, Hawassa University, Ethiopia[1]
Department of Biology, Debre Berhan University, Ethiopia[2*]

Abstract

Climate change, largely resulting from greenhouse gasses, caused mainly by anthropogenic activities has a significant effect on mountains' ecosystem. The Bale Mountains National Park (BMNP) represents one of Africa's largest Afro-alpine ecosystems and contains distinct endemic biodiversity. This study investigated long-term patterns and variation in rain fall and temperature at Dinsho (3072 m a.s.l.), an important location in BMNP, utilizing climate data spanning from 1983 to 2014 provided by the Ethiopian Meteorological Agency. Climate data on Temperature and precipitation were examined across three decades to evaluate long term trends and fluctuations. Results indicated a notable increase in temperature throughout the study period. The maximum recorded temperature, 26.4^{0}c, occurred in March 2004 and the lowest minimum temperature, -0.7^{0}c was noted in January 1989 and 1991. The average annual temperature rose by 1.35± 0.45^{0}c between 2004-2014 compared to 1983-1992. The increase in minimum temperature (2.02 ± 0.22^{0}c) exceeded that of maximum temperature, suggesting a reduction in the diurnal temperature range. Rain fall, in contrary, varied greatly between years and demonstrated a significant declining trend. Compared with 1983-1992, mean monthly rainfall fell by 43.6 ± 11.1mm in 2003-2014 equating to an annual reduction of 523.2mm(174.4mm per decade). Dinsho maintained its characteristic bimodal pattern, with pick rainfall, in April and august. Over the past three decades, BMNP has showed significant warming and a decline in rainfall. Elevation related temperature increases, could worsen the impact. These trends may threaten afro alpine habitats, biodiversity, and downstream water supplies.

Keywords: Climate change, Maximum temperature, Mean rainfall

1. Introduction

The Earth's climate has changed naturally over millions of years. However, the changes occurring today and those expected in the future are mainly caused by human activities rather than natural processes [1,2]. Human activities, such as burning fossil fuels and deforestation, have increased the amount of carbon dioxide and other greenhouse gases in the atmosphere. This has led to global warming, which is the long-term increase in the average temperature of the Earth's atmosphere and oceans [3]. Scientists agree that greenhouse gas emissions from human activities are the primary cause of this warming. Over the past century, the global average temperature has increased by about 0.6 °C, and even greater increases are projected in the coming decades if greenhouse gas continues to rise[4].

Mountain ecosystems have gained increasing attention because they are highly vulnerable to climate change, which can cause serious and irreversible impacts on both physical and biological systems [5,6]. Climate warming is generally stronger at higher elevations than at lower elevations, particularly during winter and spring, and this trend is expected to continue under future climate change scenarios [7]. Although most climate models predict faster warming in high mountain regions,

*Corresponding author: gezdeg2017@gmail.com
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observational evidence is less consistent [8,9]. Mountains cover nearly 25% of the Earth's land surface [10], and snow-covered mountains provide water resources that support about 25% of the world's gross domestic product [6]. In addition, around 40% of the global population depends on rivers that originate in mountain regions [11]. Because mountain climates and ecosystems respond quickly to changing climatic conditions, they provide valuable evidence of the early effects of global climate change. Therefore, studying climate trends in high-elevation regions is an effective way to understand the impacts of climate change [7,6].

The Bale Mountains have a unique endemic flora and fauna, resulting from a combination of large area, isolation from the rest of the Ethiopian Highlands, and climatic history [12–14]. Protection of these mountains of immense national and global importance requires consideration of the effects of climate change on this ecosystem in general and on its biodiversity in particular. Therefore, this study examined long-term variability and trends in temperature and rainfall at Dinsho, a key site located in the central part of the Bale Mountains region, using climate data spanning the period from 1983 to 2014. By focusing on this climatically and ecologically important area, the study aimed to provide a clearer understanding of historical climate patterns and their implications for the Bale Mountains region.

2. Materials and Methods

2.1. Study Area

The Bale Mountains National Park (BMNP) is located about 400 km southeast of Addis Ababa in the Oromia National Regional State of southeastern Ethiopia. It was established in 1971 by the Ethiopian Wildlife Conservation Organization (EWCO) to protect the area's wildlife and other valuable natural resources (Figure 1). The park covers approximately 2,200 km² and lies between 6°29′–7°10′ N latitude and 39°28′–39°57′ E longitude. It is bordered by five districts (woredas): Adaba to the west, Dinsho to the north, Goba to the northeast, Mana-Angetu to the south, and Berbere to the east [15].

BMNP is part of the Bale-Arsi massif, which forms the western section of the southeastern Ethiopian Highlands. The park contains several high mountain peaks, including Tullu Dimtu (4,377 m above sea level), the second-highest mountain in Ethiopia, and Mount Batu (4,307 m above sea level). Nearly 1,000 km² of the park lies above 3,000 m, making it the largest Afro-alpine ecosystem in Africa [16]. The Afro-alpine region includes the high mountains of Ethiopia as well as those of Kenya, Tanzania, and Uganda, often referred to as "islands in the sky" because of their isolated high-elevation habitats [17]. The Bale Mountains are also part of the Eastern Afromontane and Afroalpine Biodiversity Hotspot, one of the world's important biodiversity hotspots identified by Conservation International [18].

Dinsho, a town in the Bale Zone of Oromia, is located at the northern entrance of the park. It serves as the headquarters of Bale Mountains National Park and is the main gateway for visitors and researchers accessing the park.

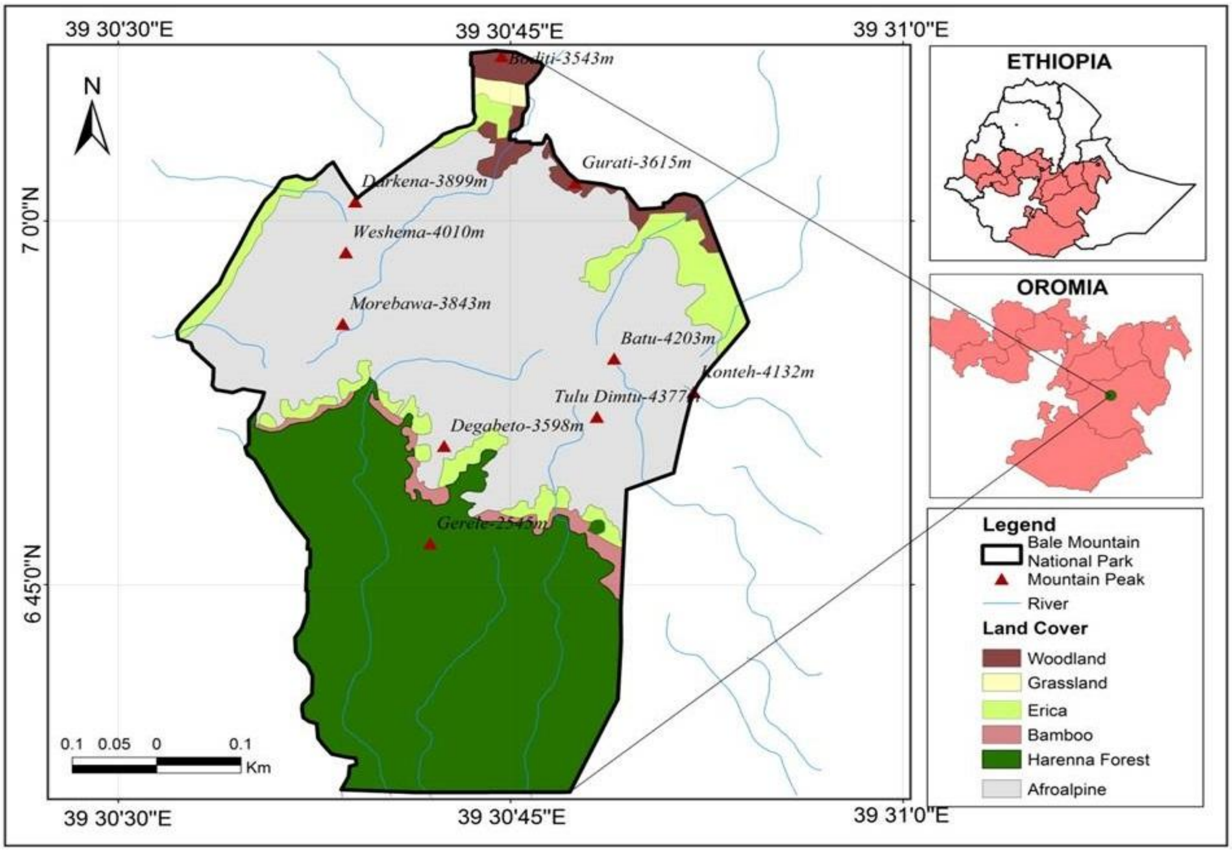


Figure 1. BMNP with its major habitat types and mountain peaks (Modified from OARDB, 2007).

2.2. Temperature and Rainfall Analysis

Temperature and rainfall data for Dinsho were obtained from the Ethiopian Meteorological Agency (EMA), Addis Ababa, Ethiopia. Dinsho meteorological station is located in Oromia Regional State at an elevation of 3,072 m above sea level (7.1° N, 39.766667° E). The station is situated adjacent to the Gaysay Grassland, approximately 1 km southeast of the grassland and about 2 km northwest of the BMNP headquarters. The northern woodland is located about 500 m southwest of the station. Data were unavailable for maximum temperature during 2003, 2008, and 2009, and for minimum temperature during 1994, 2003, 2008, and 2009. Rainfall data were also unavailable for 2007–2009 and 2011. Trends in maximum, minimum, and mean temperatures were analyzed for the periods 1983–1992, 1993–2002, and 2004–2014. Rainfall trends were analyzed for the periods 1983–1992, 1993–2002, and 2003–2014. Years with missing observations were excluded from the analysis.

3. Results

3.1. Temperature of Dinsho

The highest maximum temperature recorded was 26.4 °C in March 2004, and the lowest maximum temperature recorded was 14.0 °C in October 1995. The highest minimum temperature recorded in Dinsho was 11.2 °C in July 2014 and lowest minimum temperature recorded was -0.7 °C in January 1989 and 1991. The maximum, minimum and mean temperature (°C) for the years 1983 to 2014 was analyzed (Table 1).

Table 1. Maximum, minimum and mean monthly temperatures (°C) of Dinsho 1983 to 2014

Month	Maximum temperature	Minimum temperature	Mean temperature
January	17.62 ± 0.30	2.55 ± 0.32	10.23 ± 0.65
February	18.33 ± 0.28	2.99 ± 0.32	10.98 ± 0.64
March	18.76 ± 0.27	4.12 ± 0.31	11.73 ± 0.62
April	17.62 ± 0.28	5.52 ± 0.31	11.72 ± 0.62
May	17.46 ± 0.29	5.18 ± 0.32	11.51± 0.64
June	17.68 ± 0.30	4.67 ± 0.32	11.28 ± 0.65
July	17.42 ± 0.28	5.42 ± 0.31	11.51 ± 0.63
August	17.24 ± 0.30	5.18 ± 0.31	11.20 ± 0.64
September	17.06 ± 0.30	4.79 ± 0.32	10.92 ± 0.65
October	16.21 ± 0.29	4.89 ± 0.31	10.53 ± 0.63
November	16.57 ± 0.30	3.14 ± 0.32	9.81 ± 0.65
December	17.09 ± 0.30	2.76 ± 0.32	9.99 ± 0.65

The highest average monthly temperature of Dinsho was recorded during March (18.76 ± 0.27 °C) and the lowest during January (2.55 ± 0.32 °C). The average maximum, minimum and mean temperatures from 1983 to 2014 were 17.40 ± 0.09, 4.18 ± 0.09 °C and 10.80 ± 0.08 °C respectively (Figure 2).

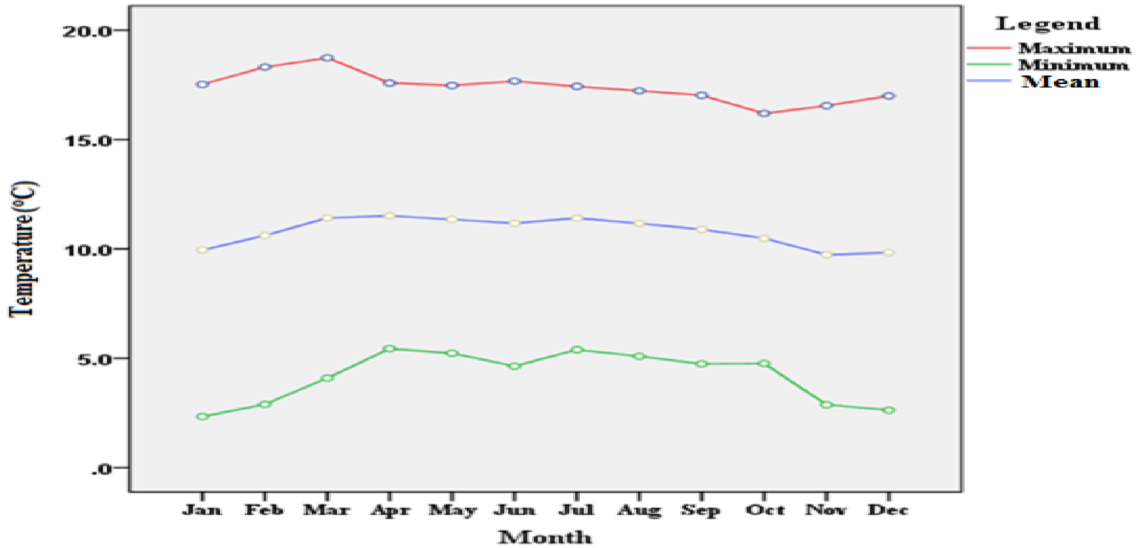


Figure 2. Maximum, minimum and mean temperature of Dinsho 1983 to 2014

Table 2. Maximum, minimum and mean annual temperatures (°C) of Dinsho in three decades

Years	Maximum temperature	Minimum temperature	Mean temperature
1983–1992	17.23 ± 0.13[a]	3.53 ± 0.14[c]	10.38 ± 0.29[e]
1993–2002	17.15 ± 0.15[a]	3.73 ± 0.17[c]	10.74 ± 0.33[ef]
2004–2014	17.88 ± 0.16[b]	5.55 ± 0.17[d]	11.73 ± 0.33[f]

Means with the same letters in the same column are not significantly different (p>0.05)

The maximum and minimum and mean temperature trends were determined within the three decades starting from 1983 to 2014(Table 2). The maximum, minimum and mean annual temperature between the years 2004–2014 were significantly different from the previous two decades. The annual maximum temperature of 2004–2014 (17.88 ± 0.16 °C) was significantly higher than that of the 1983–1992 (17.23 ± 0.13 °C) and the 1993–2002 (17.15 ± 0.15 °C)(Figure 3). In the same way, the minimum annual temperature raised by 2.02 ± 0.22 °C in 2004–2014 as compared with that of 1983–1992 and by 1.82 ± 0.24 °C when compared with 1993–2002.The mean annual temperature of Dinsho significantly increased by 1.35 ± 0.45 °C in the years 2004–2014 as compared with 1983– 1992(Figure 4). But there was no significant difference in mean annual temperature between the years 2004– 2014 and 1993–2002. The maximum, minimum and mean annual temperature from 1983–2014(Figure5).

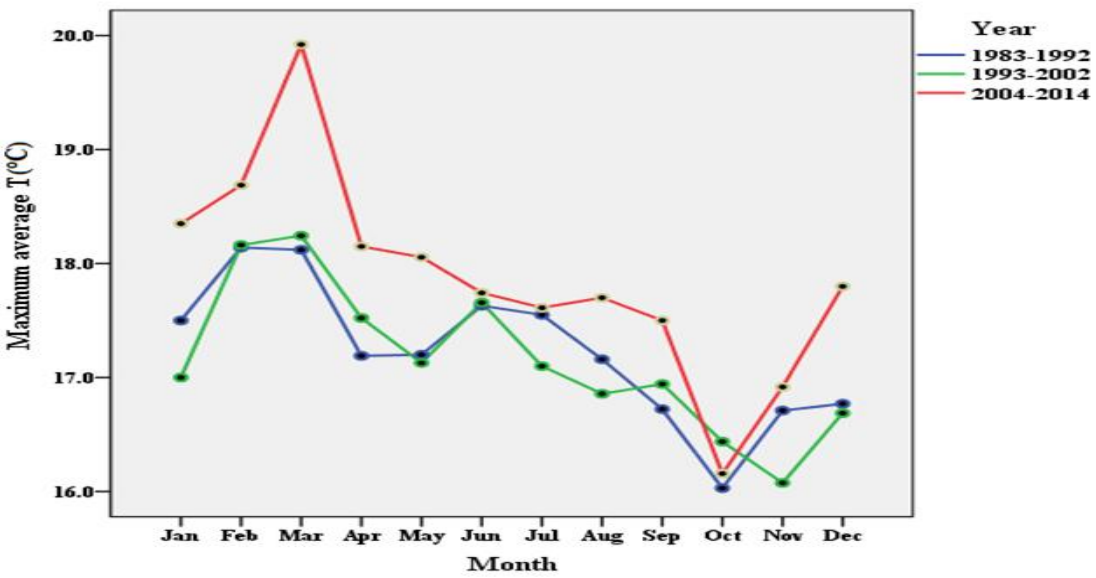


Figure 4. Minimum temperature of Dinsho for the three decades

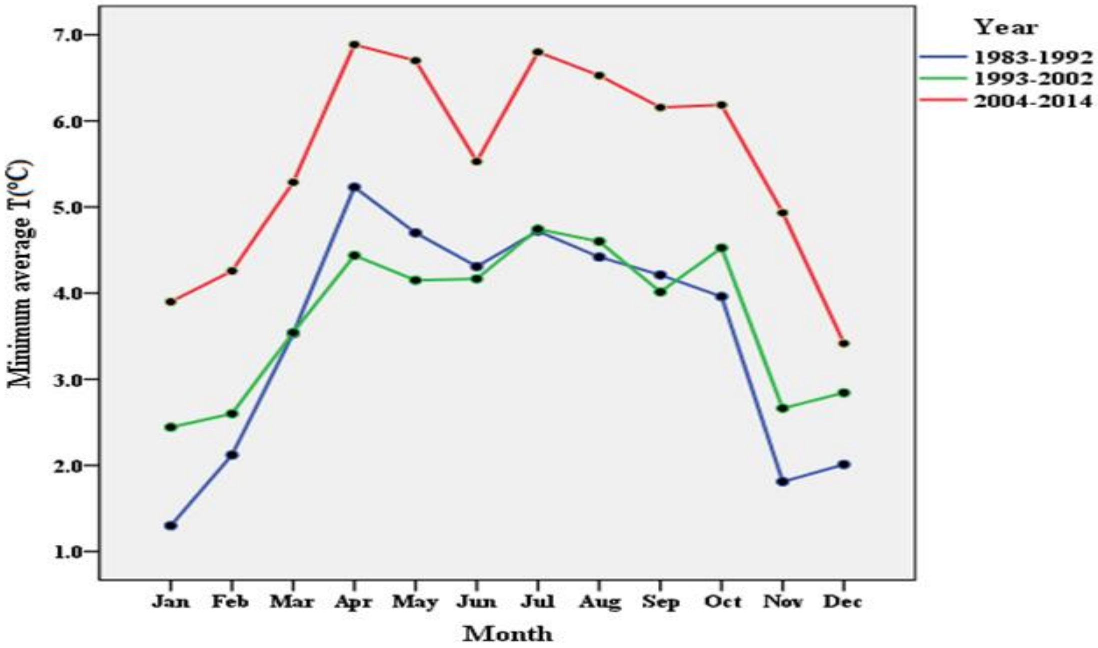
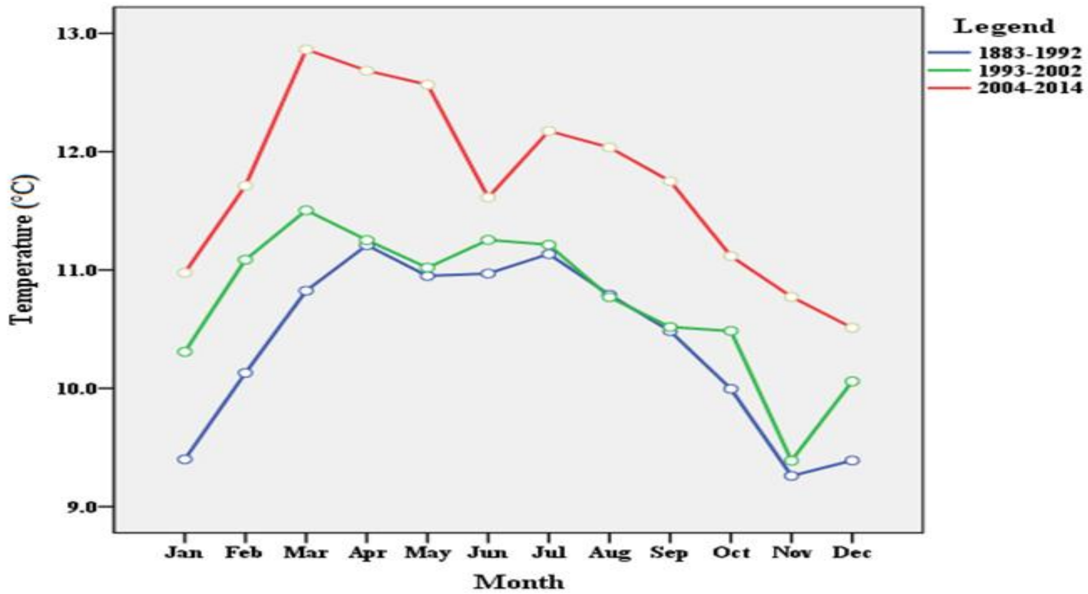


Figure 5. Mean temperature of Dinsho for the three decades



3.2. Rainfall

The mean rainfall of Dinsho from 1983 to 2014 was analyzed (Table 3).

Table 3. Average monthly rainfall of Dinsho (1983 to 2014)

Month	Mean monthly rainfall (mm)

January	20.8±16.3
February	37.8 ± 15.1
March	85.9 ± 15.3
April	208.3 ± 15.3
May	131.8 ± 15.8
June	86.8 ± 15.1
July	190.3 ± 14.9
August	208.9 ± 18.0
September	155.9 ± 15.4
October	149.2 ± 15.1
November	53.5 ± 15.3
December	38.2 ± 15.3

The maximum monthly rainfall of Dinsho was during August (208.9 ± 18.0 mm) and April (208.3 ± 15.3 mm) followed by July (190.3 ± 14.9 mm). The minimum monthly rain fall of Dinsho was during January (20.8 ± 16.3 mm) and February. November and December also had small rains. The mean annual rain fall of Dinsho was 1386.46 mm. Figure 14 shows the rainfall patterns in Dinsho during months of the year.

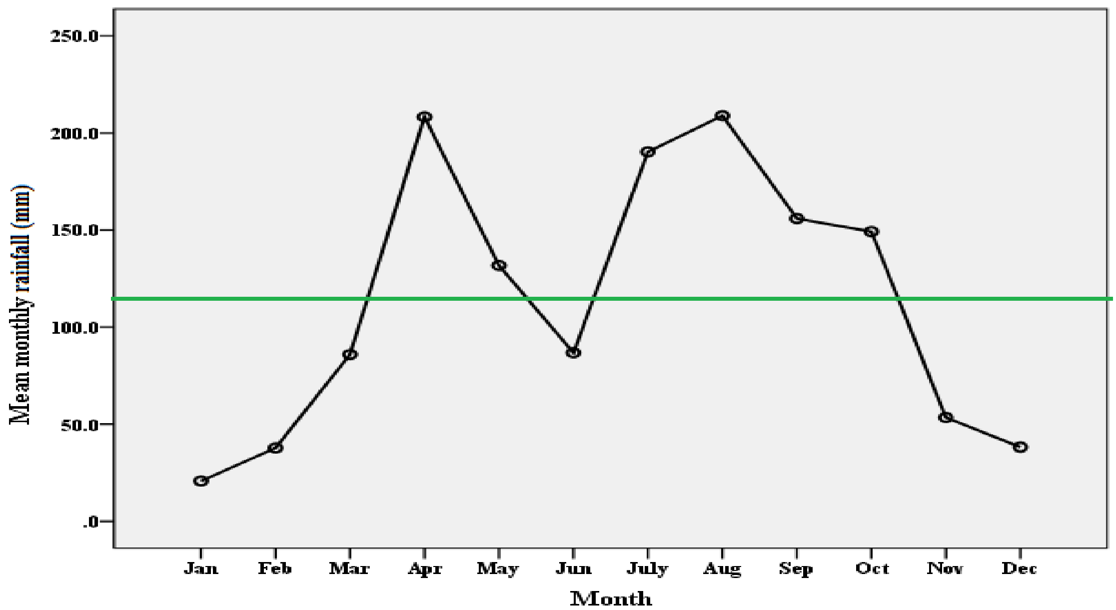


Figure 6. Rainfall in Dinsho during the months of the year (1983 to 2014)

The smallest rainfall of the year at Dinsho happened in the months of November to February. Rainfall starts to increase and reaches its second highest amount during March followed by a decrease in May and June. Then it rises up sharply in July and reaches its maximum peak during August. Then rainfall starts to decrease slowly during September and October and then sharply decreases back to its lowest values from November – February (Figure 6).

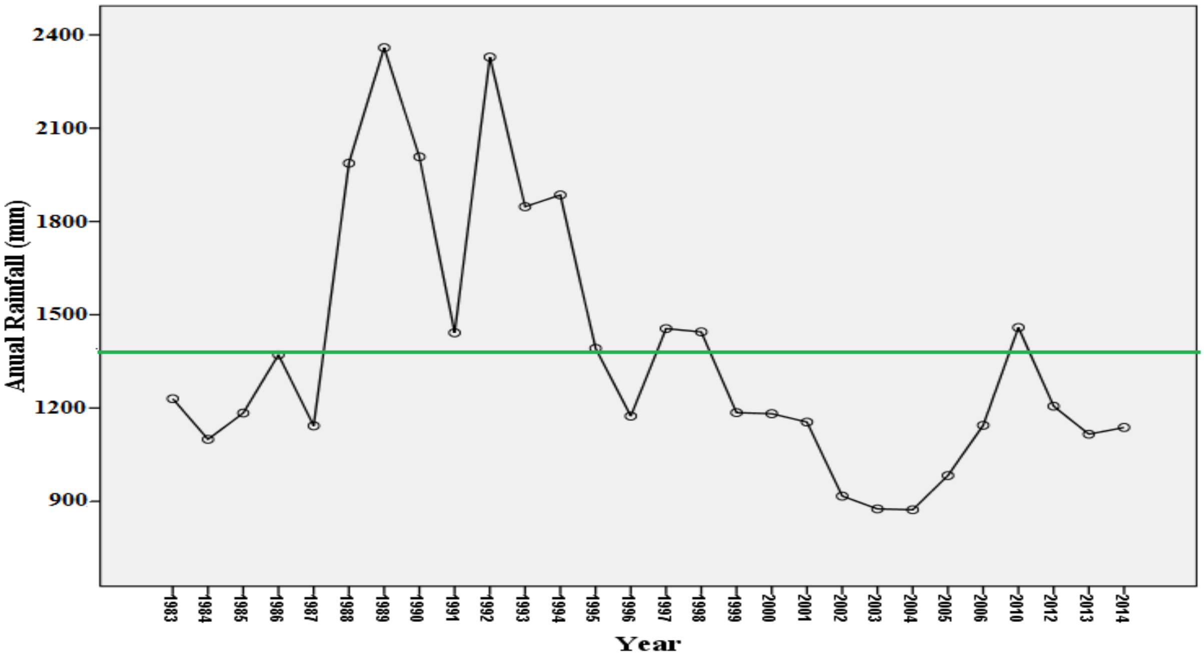


Figure 7. Rainfall variability in Dinsho (1983– 2014)

Annual rainfall in Dinsho showed variability during 1983 to 2014 (Figure 7). Generally, the mean monthly rainfall was below average from 1983 to 1987, and then sharply increased in 1988 reaching its highest amount in the same year. In 1990 rainfall showed a little decrease and further declined in 1991 to nearly a mean value. Then it increased to a second maximum value in 1992 and started to decline to below average 1996. A little increase to above average was seen during 1997 and 1998 and then decreased to a value equivalent to 1996 for the next three years (1999–2001). This was followed by a further decrease from 2002 to 2004 to its lowest amount in the three decades. Afterwards rainfall showed a little rise during 2005, 2006 and then went up to a value average in 2010 (data is lacking for the years 2007– 2009 and 2011), subsequently it decreased during 2012, 2013 and 2014 to a below average value. Analysis was done to see the rainfall pattern of Dinsho from 1983 to 2014(Table 4).

Table 4. Mean monthly rainfall of Dinsho in three decades

Year	Mean monthly rainfall (mm)
1983–1992	134.3 ± 7.2^{a}
1993–2002	114.6 ± 7.4^{ab}
2003–2014	92.9 ± 8.6^{b}

Means with the same letter are not significantly different ($p>0.05$)

The average monthly rainfall was significantly lower during 2003– 2014 compared to 1983– 1992. It decreased by 43.6 ± 11.1 mm during 2003– 2014 compared to 1983– 1992. This was equivalent to a 523.2 mm annual decrease from 1983–2014 at a rate of 174.4 mm per decade. There was no significant difference in rainfall among 1993–2002 and the remaining two decades(Figure 8).

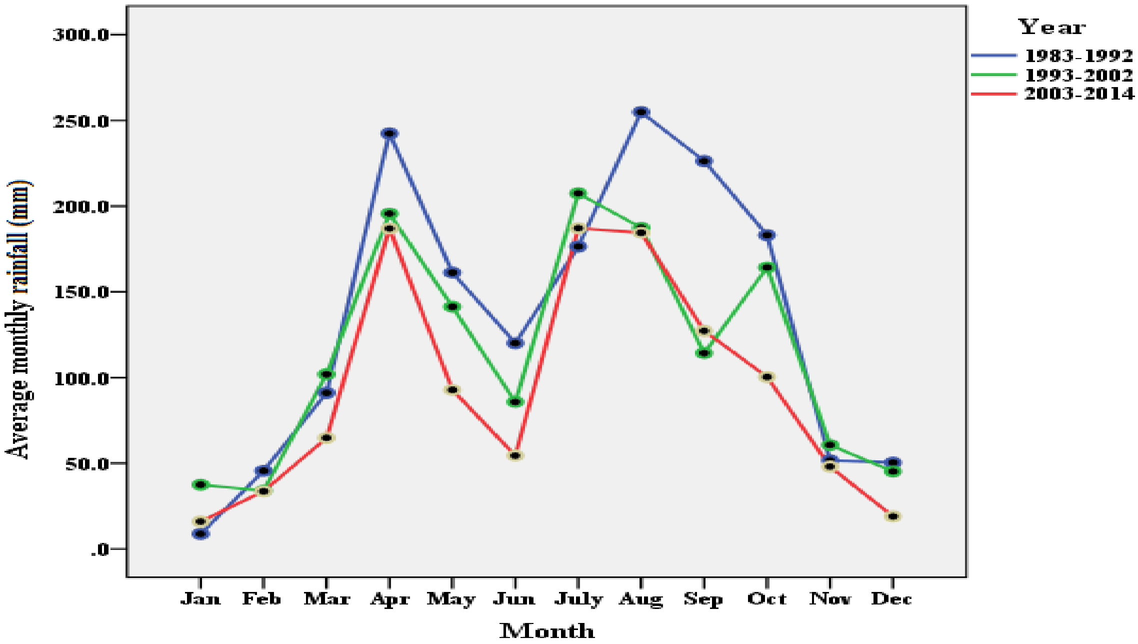


Figure 8. The monthly rainfall of Dinsho in three decades

4. Discussion

The highest temperature recorded in Dinsho (elevation of 3072 m a.s.l.) from 1983 to 2014 was 26.4 °C in March 2004 and the lowest temperature recorded was −0.7 °C in January 1989 and 1991. These values were higher than the highest temperature recorded earlier in BMNP (18.4 °C) and the lowest temperature recorded by Hillman (1986) at the Sanetti Plateau (−15 °C) [19]. The lowest temperature recorded by Hillman (1986) was much lower than the minimum temperature recorded in Dinsho (3072 m) during 1983–2014 (−0.7 °C). Using the standard environmental lapse rate of 0.6 °C per 100 m increase in elevation [20], the expected temperature at Tullu Dimtu (4,377 m), the second-highest peak in Ethiopia, would be approximately −8.53 °C. However, the lowest temperature recorded over the past three decades was 6.47 °C higher than this estimated value, indicating a substantial deviation from earlier records. This agrees with findings that the frequency of cold days and cold nights decreased significantly across Ethiopia between 1960 and 2003 [21].

The mean annual temperature of Dinsho increased by 1.35 ± 0.45 °C during 2004–2014 compared with 1983–1992, at a rate of 0.45 °C per decade. This rate was nearly equivalent to that reported for southeastern Ethiopia (about 0.4 °C per decade during winter and summer) [22]. However, it was higher than the national average increase of 1.3 °C between 1960 and 2006 (0.28 °C per decade) [21,23,24]. This indicates that the mean annual temperature increase observed in Dinsho over 32 years was comparable to the increase experienced across Ethiopia over approximately 46 years. Thus, warming in Dinsho exceeded the national average. This value was also greater than the global warming rate of approximately 0.30 °C per decade between 1975 and 2010. Our findings agree with studies showing that mountain regions have warmed faster than surrounding lowlands [25,26].

The annual maximum temperature during 2004–2014 increased significantly by 0.72 ± 0.20 °C compared with 1983–1992 and by 0.78 ± 0.21 °C compared with 1993–2002. The annual minimum temperature increased even more, by 2.02 ± 0.22 °C and 1.82 ±

0.24 °C, respectively. This indicates that minimum temperatures increased more rapidly than maximum temperatures. Similar patterns have been reported in mountain regions, where warming is often characterized by greater increases in daily minimum temperatures than maximum temperatures [27,28]. Observed land-surface warming has also been associated with larger increases in daily minimum than maximum temperatures [29,30,6]. Consequently, the daily temperature range, commonly referred to as the Diurnal Temperature Range (DTR), has decreased, which is recognized as an important indicator of climate change [31–33].

Studies have shown that warming is amplified at high latitudes, and growing evidence indicates that warming is also amplified with elevation (elevation-dependent warming, EDW), particularly in mountain environments [34,6]. In the present study, increases in maximum, minimum, and mean temperatures, together with a decrease in DTR, were observed at an elevation of 3,072 m a.s.l. (Dinsho). Based on the EDW hypothesis, even greater increases in temperature and further reductions in DTR are expected at higher elevations, up to 4,377 m in BMNP. Unfortunately, these elevations include the extensive Afro-alpine habitat, the largest on the African continent. Increased warming and changes in precipitation are likely to have considerable consequences for both mountain ecosystems and downstream human populations [9].

Annual rainfall in Dinsho showed that November to February received the least rainfall. Rainfall increased during March, reached a secondary peak in April, declined in May and June, then increased sharply during July and reached its maximum in August before gradually declining through September and October. This seasonal pattern agrees with previous studies describing the bimodal rainfall regime of BMNP [35,36]. The small rainy season occurs between March and June, while the main rainy season extends from July to October. During the past three decades, rainfall in April (208.3 ± 15.3 mm) was nearly equal to the August maximum (208.9 ± 18.0 mm). The two rainy seasons therefore differed mainly in their cumulative rainfall totals. These findings support previous reports describing the northern BMNP as having eight rainy months (March–October) and four dry months (November–February) [37,38].

Annual rainfall in Dinsho exhibited considerable interannual variability during 1983–2014. This agrees with studies reporting high seasonal rainfall variability across Ethiopia [39, 40]. Analyses of rainfall from 1951–2010 showed that some years experienced above-normal rainfall, whereas others experienced below-normal rainfall [41,42]. Similar variability is expected to continue in the future. Such strong interannual and interdecadal variability makes long-term rainfall trends difficult to detect [21,43]. Rainfall variability is also common across much of Africa, with substantial multidecadal variability in several regions [44]. Several studies have linked Ethiopian rainfall variability to the El Niño–Southern Oscillation (ENSO). During El Niño years, below-average rainfall is commonly observed during the June–September (Kiremt) season over much of Ethiopia [41].

Although uncertainty remains regarding long-term rainfall trends, year-to-year variability remains the dominant characteristic of Ethiopian rainfall [15, 18].

In addition to this variability, rainfall in Dinsho decreased significantly during 2003–2014 compared with 1983–1992. Average monthly rainfall declined by 43.6 ± 11.1 mm, equivalent to an annual reduction of 523.2 mm or 174.4 mm per decade. This agrees with the decreasing rainfall trend reported for southern and southeastern Ethiopian highlands during recent decades, although the decline observed in Dinsho was considerably greater than the reported regional average of approximately 28 mm per decade [22].

Overall, the substantial increase in minimum and maximum temperatures together with the marked decline and high variability in rainfall indicate that significant climatic changes have occurred in Dinsho, the northern woodlands, and the Gaysay Grasslands of Bale Mountains National Park during the past three decades. These changes are likely to be even more pronounced at higher elevations, particularly across the Sanetti Plateau, which contains the largest continuous Afro-alpine ecosystem in Africa.

5. Conclusion

This study provides strong evidence of substential climatic changes in Dinsho, located in Bale Mountains National Park from 1983 and 2014. There has been significant rise in mean, maximum especially minimum temperatures, with the rate of warming surpassing that observed nationally. The relatively considerable increase in minimum temperature implies a reduced difference between day time and night times temperatures, signaling a contraction in the diurnal temperature range associated with the climate change. Rain fall retained its bimodal structure but became highly variable between years and decreased substantially over the most recent decades. The sharp fall in precipitation, alongside rising temperature signals, escalating environmental stress in this elevated ecosystem.

Since climate warming intensifies at higher altitudes, the mountainous zones of BMNP particularly the Sanetti plateau and its afro alpine landscapes are expected to face even stronger temperature rises. Such condition could severely impact endemic species, ecosystem stability, and the fresh water systems that sustain downstream residents. These results underscore the pressing importance of incorporating climate responsive approach in to conservation planning, sustained ecological monitoring, and flexible management practice in the Bale Mountains. Safeguarding this internationally recognized biodiversity hotspot demand embedding climate change considerations in to park governance and broader environmental policies to preserve both ecosystem and community wellbeing.

Recommendations: The findings of this study highlight the need to integrate climate change adaptation into the management and conservation strategies of Bale Mountains National Park to address the increasing temperatures, declining rainfall, and growing climate variability. Long-term climate and ecological monitoring should be strengthened to support informed decision-making and detect ongoing environmental changes. Particular attention should be given to conserving the vulnerable high-altitude ecosystems, including the Sanetti Plateau and Afro-alpine habitats, while improving watershed management to protect freshwater resources. Furthermore, continued research on the impacts of climate change on biodiversity and ecosystem functioning is essential, alongside strengthened collaboration among park managers, researchers, policymakers, and local communities to implement effective climate adaptation and conservation measures.

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