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The Influence of Major Climatic Elements on the Devastated Geo-Hydrological Disasters: A Case of Hanang Disaster of 3rd December 2023 in Tanzania

Asnath Alberto Malekela[1], Stefan Sieber[2,3*], Jafari Swalehe Chobo[4], Joseph Ndunguru[4]

[1]Department of Geography and History, Mwalimu Nyerere Memorial Academy, Dar es Salaam, Tanzania
[2]Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[3]Department of Agricultural Economics, Humboldt University of Berlin, Berlin, Germany
[4]Department of Climatology and Climate Change, Tanzania Meteorological Authority, Dar es Salaam, Tanzania
Email: *stefan.sieber@zalf.de

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Abstract

Changes in major climatic elements such as temperature, precipitation and wind distribution have triggered weather-related and geophysical disasters. In recent years, the globe has experienced an increased number of floods and landslide events which are said to be the most common among other natural disasters. This study examines the influence of climatic elements on the geo-hydrological disaster which occurred in Hanang district-Tanzania on 3rd December 2023. The study used the primary data collected from 182 respondents. Also, the trend analysis (1981-2023) was conducted using average rainfall from 7 meteorological stations in the study area. Annual and seasonal rainfall as well as a number of rainy days were analyzed. The calculated rainfall data were then used to compute the dimensions of the standardized precipitation anomalies (SPA) which is designated as SPA = $(P - P^*)/\sigma p$. Besides, the temperature was analysed to investigate its trend and trend anomaly. Also, the wind rose statistics for the annual, March to May (MAM) and October to December (OND) for the climatology period of 1991-2020 were analysed so as to examine its contribution to rainfall distribution in Hanang district. The examination of annual rainfall data indicates an upward trend in precipitation levels, accompanied by notable variability in rainfall patterns, including seasonal anomalies and deviations from historical averages. The combination of elevated rainfall, anomalies in rainfall patterns, and potentially unfavourable terrain characteristics may have contributed to devastated geo-hydrological disaster risk. However, future research is recommended that could focus on integrating rainfall and temperature data with comprehensive geo-hydrological susceptibility assessments, considering factors such as terrain stability, land cover and land use practices.

Keywords

Climate Elements, Climate Change, Landslides, Floods, Geo-Hydrological Disasters

1. Introduction

Environmental disasters and climate change are growing challenges in the world today. Various parts of the world have been facing weather-related (floods, drought, storms, landslides, heat waves) and geophysical (earthquakes, volcanic eruption, dry mass movement) disasters [1] [2]. Weather-related (meteorological) disasters gained pace in the 1990s due to increased incidences of climate change and global warming [3]. In recent years, the globe has experienced an increased number of floods and landslide events which are said to be the most common among other natural disasters [4]. Climate change is said to be one of the major causes of weather-related disasters specifically floods and landslides [2]. Different parts of the world experience changes in the major climatic elements specifically rainfall, temperature and wind patterns. Such changes have influenced various environmental disasters such as weather-related (meteorological) and geophysical disasters. For the purpose of the current study, the main focus was on floods and landslides (geo-hydrological) disasters.

Changes in the climatic systems have impacted regional precipitation distribution across the world. Raising air temperature and evaporation rate leads to higher accumulation of water vapour in the air, resulting in more intense rainfall and drought due to extended drying periods [5]-[7]. With drier land surfaces and increased extreme rainfall, the land becomes vulnerable to droughts, floods and even landslides. The meteorological factors influencing precipitation distributions in Africa, including Tanzania, are characterized by interdependencies, the major one being the Inter-tropical convergence zone (ITCZ) [8]. This zone is the most important component of the climatic system and consists of a relatively low-pressure surface belt called an equatorial trough [9]. By increasing air temperature, maximum cloudiness, and convergence of trade winds, it is placed between both Hadley cells which is typically related to the ascending channel of Hadley circulation [10]-[13]. The seasonal position of ITCZ varies in response to the location of the maximum radiation led by solar radiation heating. The region overlaying between 5˚S and 5˚N will normally have two rainfall seasons named short rain between October to December and long rain between March to May given that other factors remain constant. The region lying beyond 5˚N experiences the rainfall season between March and September while below 5˚S have seasons from November to April each year [14] [15]. In addition to ITCZ, another factor is the contribution of El Niño-Southern Oscillation (ENSO) which leads to significant impacts on weather patterns, temperature anomalies and rainfall regimes in Tanzania [14]

[16]. El Niño conditions, associated with warmer Sea Surface Temperature anomalies (SSTA) over the central and eastern Pacific, typically result in wetter short rains from October to December [17], whereas La Niña conditions, associated with cooler SST anomalies, result in drier short rains.

Environmental disasters resulting from climate change have affected the natural and socio-economic systems across the globe. However, communities which are highly affected by disasters live in the low developed countries of the world [18] [19]. This is essentially due to the nature of geographical location where a majority of people live specifically in vulnerable conditions, such as on flood plains, in urban slums or in poor quality housing. Risk to disasters results from the interaction of three features namely; the hazard itself, the population exposure to the hazard, and the community's ability to withstand its impact (vulnerability) [2] [20]. In recent years, hazards have increased in number, intensity and variability [18] [21]. Various environmental threats such as land degradation, deforestation, and erosion have contributed to the increase in disasters. The occurrence and impacts of disasters are a twofold phenomenon, though, most of the studies have focused on the adverse effects of disaster events on the environment, and much less consideration has been focused on the consequences of poor environmental management practices and ecological degradation, which exacerbates a disaster's impact [22]. These disasters affect the environment and communities' livelihoods. However, the severity of the impacts is determined by communities' resilience and the level of preparedness [22]-[24].

In developing countries, communities' vulnerability to disasters depends on their geographical location, socioeconomic status, household composition, minority status, and access to various infrastructures. Such factors can affect communities' or persons' capacity to anticipate, confront, repair, and recover from the effects of a disaster [24] [25]. Africa has been extensively affected by the increased number of natural disaster incidences, and there is a possibility of an increase in severity and frequency [26].

Tanzania as in many other African countries experiences climate change. Various disasters associated with climate change have been happening in recent years. On 3rd December 2023, Tanzania specifically Katesh in Hanang District, Manyara region experienced an environmental disaster which can be termed as a geo-hydrological disaster combining both geophysical and hydrological disaster. This term has been used for the purpose of this study due to the nature of the disaster which is composed of the flow of muds, soils and other liquid and solid materials. The disaster affected the environment and socio-economic systems. The purpose of this study was to examine the influence of changes in the major climatic elements specifically rainfall, temperature and wind on landslides and floods (geo-hydrological) disasters.

2. Materials and Methods

2.1. The Study Area

Hanang district is located between latitudes 3.56˚S and 5.87˚S and longitudes

34.16˚S and 39.25˚E, at an altitude of about 1700 m above the sea level. The district is found in Manyara region within north-eastern highlands of Tanzania and has tropical type of climate modulated by the warm tropical Indian Ocean [27]. Manyara region experience two distinct seasonal rainfall-the short rainfall season (Vuli) that starts in October and continues through December (OND) and the long rain season (Masika) that starts in March and continues through May (MAM) [28]-[30]. The seasonal rainfall over Manyara varies in space and time. The variation is higher during short rains (Vuli) than the long rains (Masika) seasons. The area was purposely selected due to floods and landslide disaster which happened on 3rd December, 2023.

2.2. Data Collection

Both primary and secondary data were collected, secondary data were collected from relevant written sources. Primary data were collected using survey and participatory rural appraisal (PRA). A total of 182 respondents were randomly selected in Hanang-Katesh. Also, the study involved the collection and analysis of rainfall, temperature and wind data of Hanang district spanning the period from 1981 to 2023. The Climate Hazards Group Infrared Precipitation with Station (CHIRPS) version 2.0 with global coverage of 50˚S - 50˚N latitude and spatial resolution at 0.05˚ - 0.05˚ latitude–longitude grid from 1981 to 2023 was used. CHIRPS is blended gauge-satellite rainfall estimates covering most land regions and has high resolution, moderately low latency, low bias, and a long period of record. The low bias of CHIRPS is in reference to the Global Precipitation Climatology Centre dataset [14] [31].

Daily rainfall data from seven meteorological stations were obtained from the Tanzania Meteorological Authority. These data were aggregated to compute annual rainfall totals and to calculate relevant statistical measures, including mean (P*), maximum, minimum, and standard deviation (σ_p) [32] for the period of 1981-2023. The equations for these statistical measures are:

$$P^* = \frac{1}{N}\sum_{i=1}^{N} P_i \tag{1}$$

$$\sigma_p = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(P_i - P^*\right)^2} \tag{2}$$

where:

P_i = individual precipitation values.

N = total number of observations.

Additionally, seasonal rainfall anomalies were determined by comparing observed rainfall (P) with long-term averages for specific time periods [33], such as March to May (MAM) and October to December (OND). Rain days, defined as days with rainfall exceeding 1 mm, were analyzed alongside rainfall anomalies to assess variations in precipitation frequency. The standardized precipitation anomaly (SPA) was computed using the following equation:

$$\text{SPA} = \frac{P - P^*}{\sigma_p} \tag{3}$$

where:

P = observed precipitation.

P^* = mean precipitation.

σ_p = standard deviation of precipitation [34].

To analyze trends in both rainfall and temperature, Sen's slope estimator was applied to determine the magnitude of trends, calculated as follows:

$$\text{Sen's Slope} = \frac{P_j - P_i}{j - i} \tag{4}$$

where:

P_j and P_i are the data points at times j and i respectively [35].

The Mann-Kendall test was applied to assess the significance of trends, with the test statistic (S) defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\left(x_j - x_i\right) \tag{5}$$

where:

sgn is the sign function, returning +1, 0, or −1 [36] [37].

The coefficient of determination (R-squared) was calculated to evaluate the goodness of fit of the linear regression model:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)}{\sum_{i=1}^{N}\left(y_i - \bar{y}\right)} \tag{6}$$

where:

y_i = observed values.

$\hat{y}_i$ = predicted values.

$\bar{y}$ = mean of observed values [38].

Graphical representations, including plots and figures, were utilized to visually depict the temporal patterns of rainfall variability. This methodology enabled a comprehensive assessment of rainfall dynamics in the study area, providing insights into long-term trends, seasonal variations, and potential impacts on local hydrological systems and hazards, such as landslides [39]. The trend analysis (1981-2023) was conducted using average rainfall from the seven meteorological stations within the Hanang district in the Manyara region, where annual and seasonal rainfall as well as the number of rainy days were analyzed to identify whether heavy rainfall was a source of landslides in that area. Additionally, temperature and wind trends were analyzed using linear regression to determine their impact on rainfall patterns.

3. Results and Discussion

3.1. Perceived Indicators of Climate Change

Figure 1 designates the locally based indicators of climate change in Hanang district. The study observed that, majority (92%) of the respondents appealed to have experienced changes in the climatic elements. Such changes included rainfall and temperature variations, floods, drought and changes in the onset and cessation of rainfall. Respondent's perceptions on climate change based on their experiences with the climatic situation of their areas over several years. The analysis of locally based perceptions formed a substantial basis in associating with meteorological data. Similar observation has also been reported by other scholars confirming that local communities have been reporting to have observed changes in the climatic elements [40]-[43].

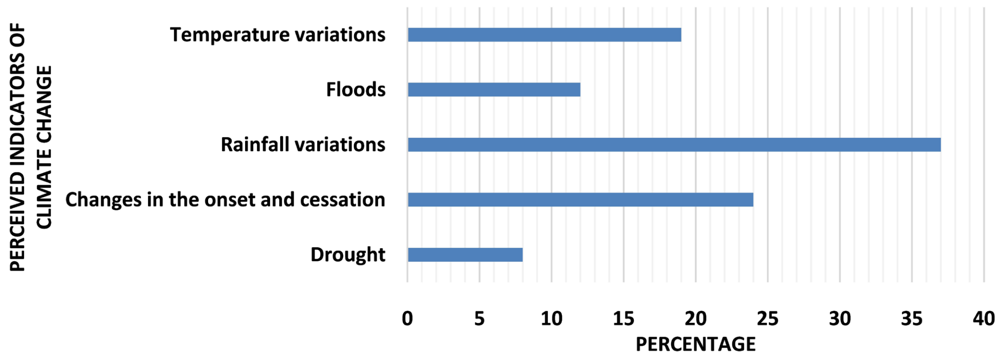


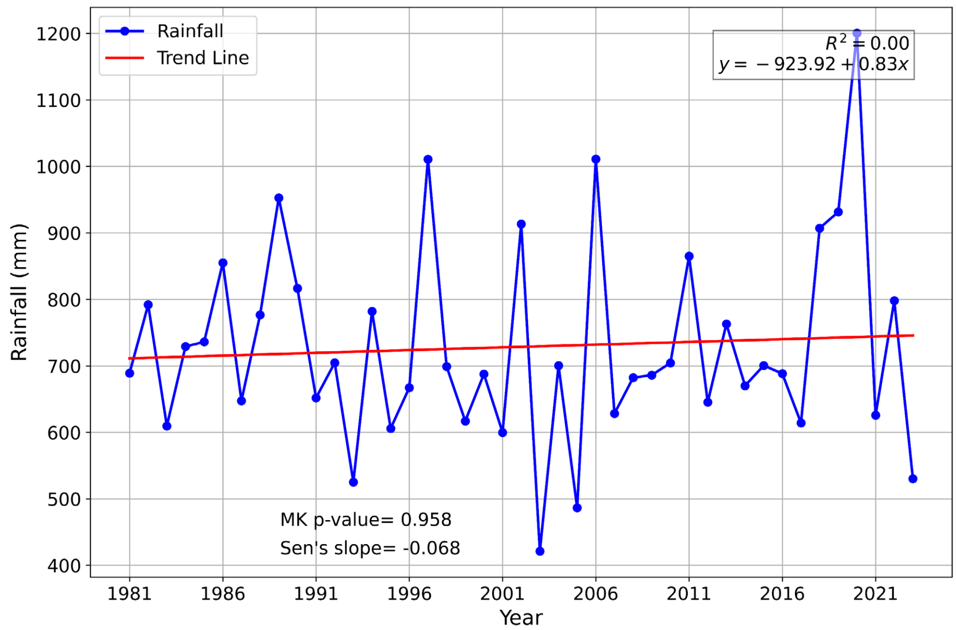
Figure 1. Perceived indicators of climate change. **Source:** Survey data, 2024.

3.2. The Influence of Climate Elements on Geo-Hydrological Disaster in the Study Area

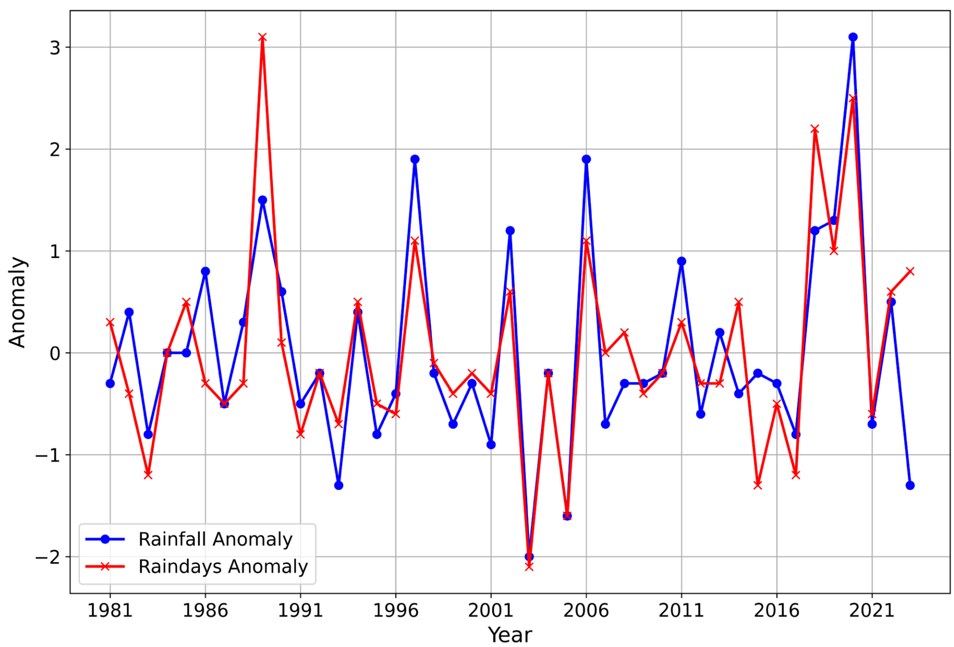
3.2.1. Annual Rainfall Analysis

The study analyzed the rainfall data for the period of 43 years (1981-2023). The annual total rainfall plot (**Figure 2(a)**) exhibits a variability ranging from a minimum of 421.1 mm to a maximum of 1200.5 mm, with a mean value of 728.6 mm and a standard deviation of 151.4 mm. The positive trend line, characterized by a slope of 0.8252 and an R-square value of 0.0047, indicates a slight upward trend in rainfall over the observed period. Despite the low R-square value suggesting a weak explanatory power of the trend line, the positive slope implies a gradual increase in annual rainfall over time. This suggests a potential shift in precipitation patterns, warranting further investigation into underlying climatic factors driving this trend. Increased rainfall, particularly during intense or prolonged precipitation events, can saturate soil and increase the likelihood of geo-hydrological disaster. If the upward trend in annual rainfall leads to more frequent or intense rainfall events surpassing critical thresholds for soil saturation, it could contribute to an increased risk of disasters. The additional results provide valuable insights into the variability of annual rainfall and its potential implications for geo-hydrological disaster events.

The fact that 26 out of 43 years had total rainfall greater than the long-term mean suggests a considerable proportion of years experiencing above-average precipitation. This could indicate periods of heightened geo-hydrological disaster risk during years of elevated rainfall, particularly if accompanied by intense or prolonged precipitation events. Many other scholars have reported that, intense rainfall events can trigger multiple hazards [44]-[46]. Recently, there has been notable rankings of rainfall totals, with 2020 being the highest and 2019 ranking fifth highest. This suggests a recent period of increased rainfall intensity or frequency. These years may have experienced conditions conducive to elevated landslide and floods risks, highlighting the importance of understanding recent trends in precipitation for landslide hazard assessment and mitigation. The variability in annual rainfall totals underscores the dynamic nature of precipitation



(a)



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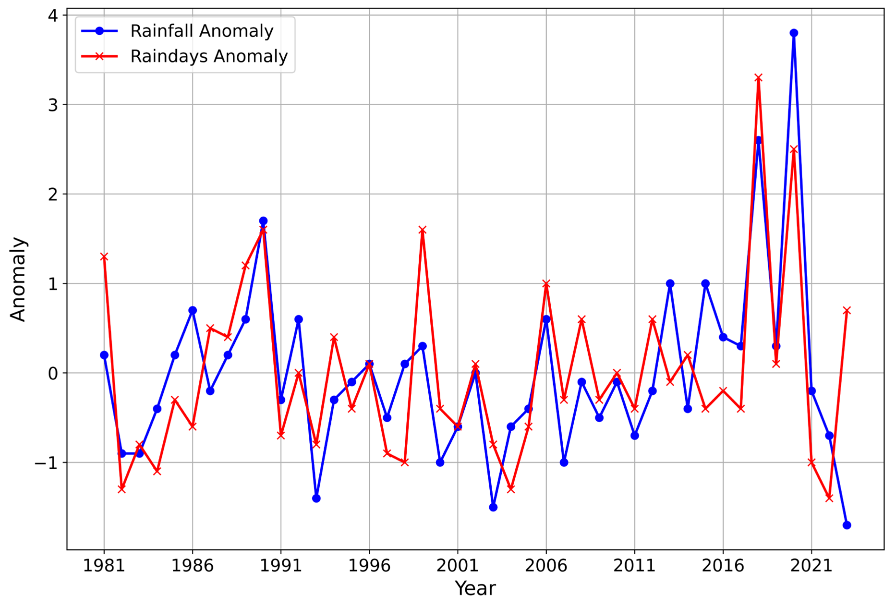

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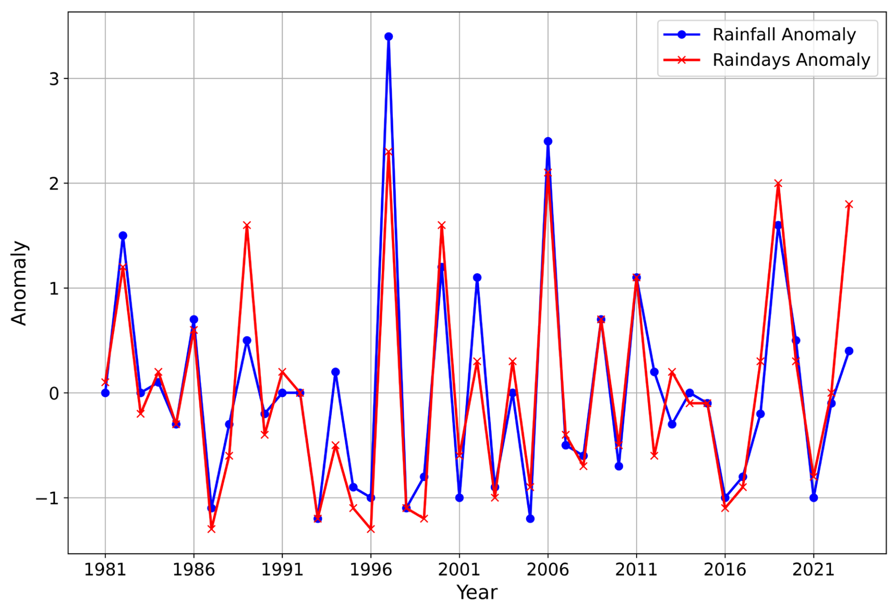


(d)

Figure 2. Temporal Analysis of Rainfall Trends and Anomalies in Hanang District, Manyara Region, Tanzania (1981-2023): (a) Annual Rainfall Trend: Trend analysis showing the annual precipitation dynamics over time. (b) Annual Rainfall Anomaly vs Rain Days Anomaly: Comparison of annual rainfall anomalies and rain days anomalies, revealing deviations from typical precipitation patterns. (c) March to May (MAM) Rainfall Anomaly vs Rain Days Anomaly: Examination of rainfall anomalies and rain days anomalies during the March to May period, highlighting seasonal variations in precipitation. (d) October to December (OND) Rainfall Anomaly vs Rain Days Anomaly: Analysis of rainfall anomalies and rain days anomalies during the October to December period, providing insights into late-year precipitation dynamics.

patterns and their influence on landslide occurrence. Understanding the temporal variability in rainfall, including both long-term trends and short-term fluctuations, is essential for assessing landslide risk and implementing effective mitigation measures. Based on the observed rainfall anomalies shown in **Figures 2(b)-(d)** both present the relationship between the number of rainy days and seasonal rainfall anomalies, highlighting distinct patterns. During 2019, 2020, and 2023, both metrics exhibited positive anomalies, indicating intensified and prolonged rainfall episodes. This convergence implies frequent with much intense rainfall events, which could have led to persistent soil saturation, reducing slope stability and triggering the landslide. The event in December 2023, characterized by significantly lower total rainfall compared to historical records and ranking as the fourth lowest in history (1981-2023), is noteworthy. While this event may represent a deviation from the recent trend of elevated rainfall (**Figure 2(b)**), it does not necessarily diminish the overall risk of landslides, as other factors such as antecedent soil moisture conditions and terrain characteristics also influence landslide susceptibility in Hanag district.

3.2.2. Rain Days Analysis

The range of rain days observed over the 43-year period, from a minimum of 10 to a maximum of 33 days, highlights a considerable variability in the frequency of rainfall events during the October to December season. The average number of rain days during this period, calculated at 19 days, serves as a baseline for understanding deviations from typical rainfall frequencies. The year 2023 rain days (**Table 1**) as the fourth-ranked highest year for rain days, with 30 rain days recorded during the October to December period, suggests a notable increase in precipitation frequency compared to the long-term average. This elevated number

Table 1. Average daily rainfall (mm) data for Hanang Area (2023).

Day	Oct	Nov	Dec	Day	Oct	Nov	Dec
1	0.0	44.6	6.3	**18**	0.0	0.0	0.0
2	0.0	78.6	14.1	**19**	0.0	0.0	0.0
3	0.0	8.2	10.5	**20**	4.5	31.5	0.0
4	0.0	6.4	28.4	**21**	0.0	7.2	0.0
5	0.0	55.5	8.5	**22**	0.0	5.7	3.6
6	4.0	14.2	25.0	**23**	0.0	13.3	0.4
7	0.0	2.9	34.5	**24**	2.9	4.0	4.6
8	0.0	0.0	8.7	**25**	5.1	1.3	1.1
9	0.0	0.0	16.9	**26**	0.0	4.9	9.1
10	0.0	4.0	8.1	**27**	0.0	17.9	2.1
11	0.0	22.1	4.5	**28**	0.0	15.2	4.2
12	0.0	12.4	0.4	**29**	0.0	4.9	2.5
13	0.0	2.1	3.3	**30**	5.4	4.1	39.7
14	0.0	1.3	54.1	**31**	1.1		3.7
15	0.0	50.6	2.9	**Max**	**5.4**	**78.6**	**54.1**
16	0.0	2.2	17.5	**Rain days**	**7**	**28**	**25**
17	2.2	6.0	0.0				

Source: Tanzania meteorological authority 2024.

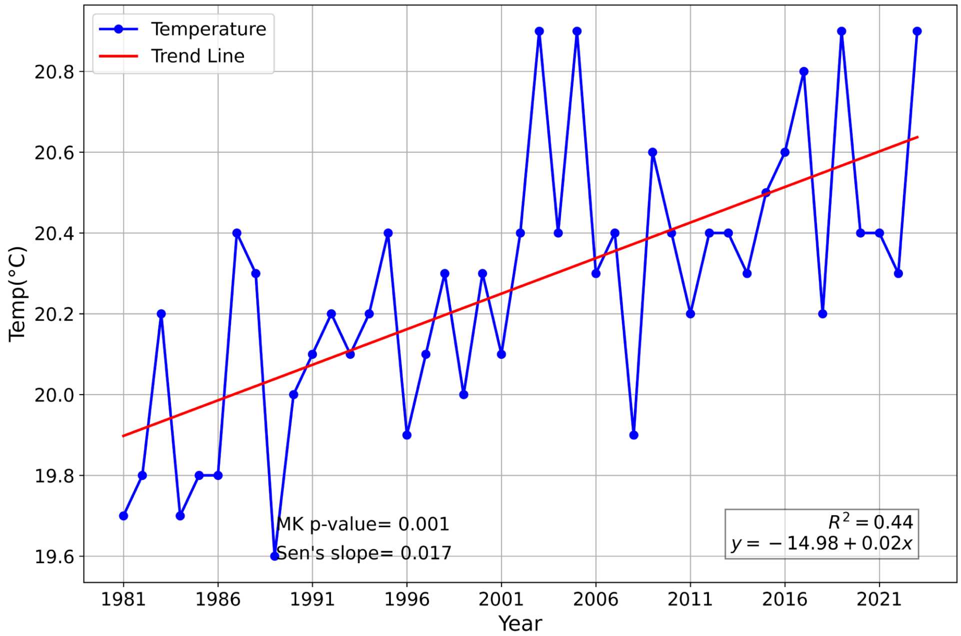
of rain days may indicate a period of enhanced rainfall activity during the season, potentially contributing to heightened landslide risk due to increased soil saturation and runoff. The occurrence of a maximum daily rainfall of 78.6mm on November 2nd, 2023, underscores the intensity of precipitation events experienced during the season. Such high-intensity rainfall events can contribute to rapid soil erosion, runoff, and increased geo-hydrological disaster susceptibility, particularly if they coincide with periods of already elevated soil moisture levels.

Overall, November experienced the highest rainfall among the three months with frequent and intense rainfall events contributing to a substantial cumulative rainfall for the month. December also witnessed significant rainfall, although slightly lower than November, while October had comparatively lower rainfall with sporadic rain events and fewer rainy days. By integrating information on rainfall frequency, intensity, and anomalies (**Figure 2(d)**), over the October to December period, alongside historical rainfall data and geo-hydrological disaster events, a more comprehensive understanding of the relationship between precipitation patterns and geo-hydrological disaster risk can be achieved. This holistic approach facilitates the identification of periods of elevated landslide susceptibility and informs proactive measures to mitigate the associated hazards.

3.3. Temperature Analysis

3.3.1. Annual Mean and Anomaly Temperature

The analysis of the annual mean temperature plot (**Figure 3(a)** and **Figure 3(b)**) reveals several key findings regarding temperature trends over the observed period. The mean annual temperature for the study area is calculated to be 20.3˚C, with fluctuations ranging from a minimum of 19.6˚C to a maximum of 20.9˚C. The positive trend line fitted to the data indicates a gradual increase in mean annual temperatures over time, supported by a moderate R-squared value of 0.4561. This suggests that approximately 45.61% of the variation in annual mean temperatures can be explained by the linear trend observed. The slope of the trend line is calculated to be 0.0178, indicating a steady upward trend in temperatures. While the slope value may seem small, its significance lies in its consistency over the observed period, signifying a persistent warming trend. However, it's essential to note that local factors, such as urbanization, land use changes, and proximity to water bodies, may influence temperature readings and should be considered when interpreting the trend. Overall, the positive trend in annual mean temperatures highlights the importance of continued monitoring and adaptation efforts to address the impacts of climate change in the study area. Further analysis reveals that 23 out of the 43 years in the historical dataset (1981-2023) exhibited mean temperatures exceeding the long-term average of 20.3˚C. Notably, the highest recorded temperature in this dataset, reaching 20.9˚C, occurred in 2023, representing an outlier compared to the historical temperature records. This anomaly underscores the significance of recent temperature variations and their potential implications for climate trends in the study area. The frequency of years with temperatures surpassing the long-term mean suggests a consistent pattern of above-average temperatures, which aligns with broader climate change trends observed globally. These findings highlight the need for ongoing monitoring and assessment of temperature trends, as well as proactive measures to mitigate the impacts of climate variability and change on local ecosystems, communities, and infrastructure. Several studies on climate change have reported that changes in temperature may have imperative hydrological consequences, both indirect and direct, through prompting potential evaporation, total evaporation and soil moisture [6] [7].



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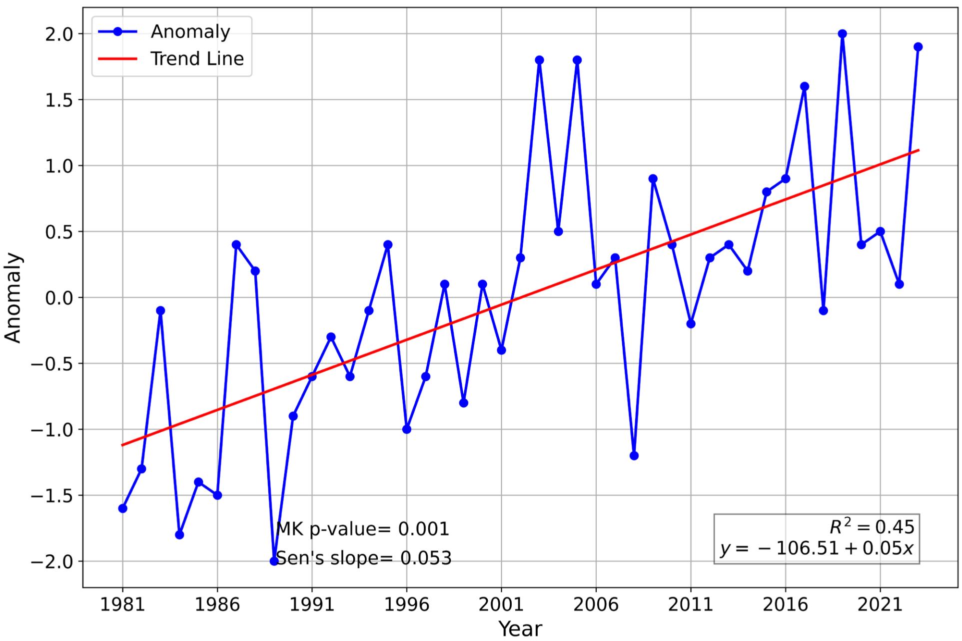

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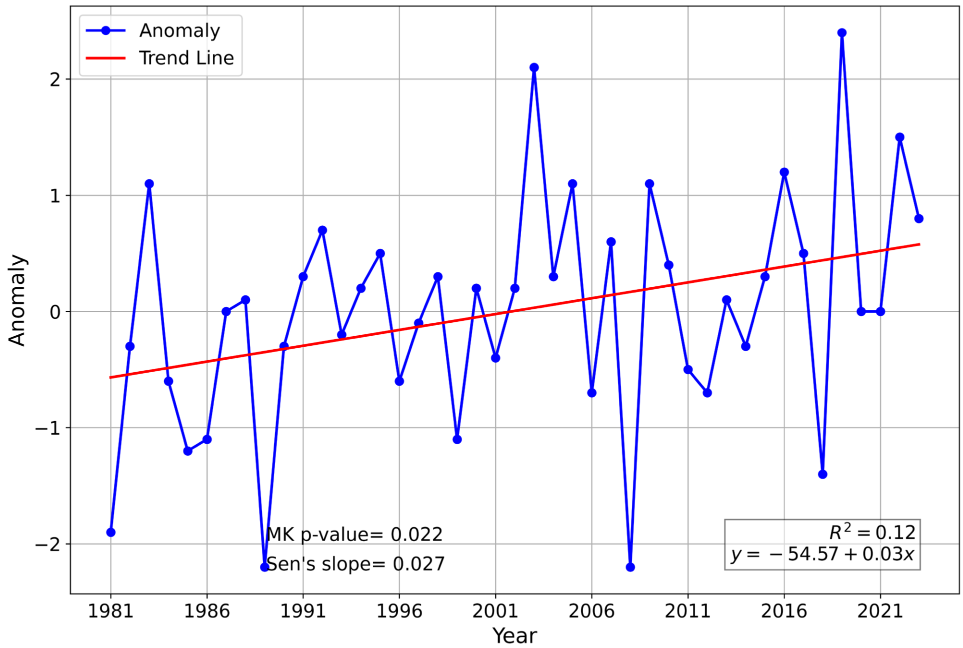

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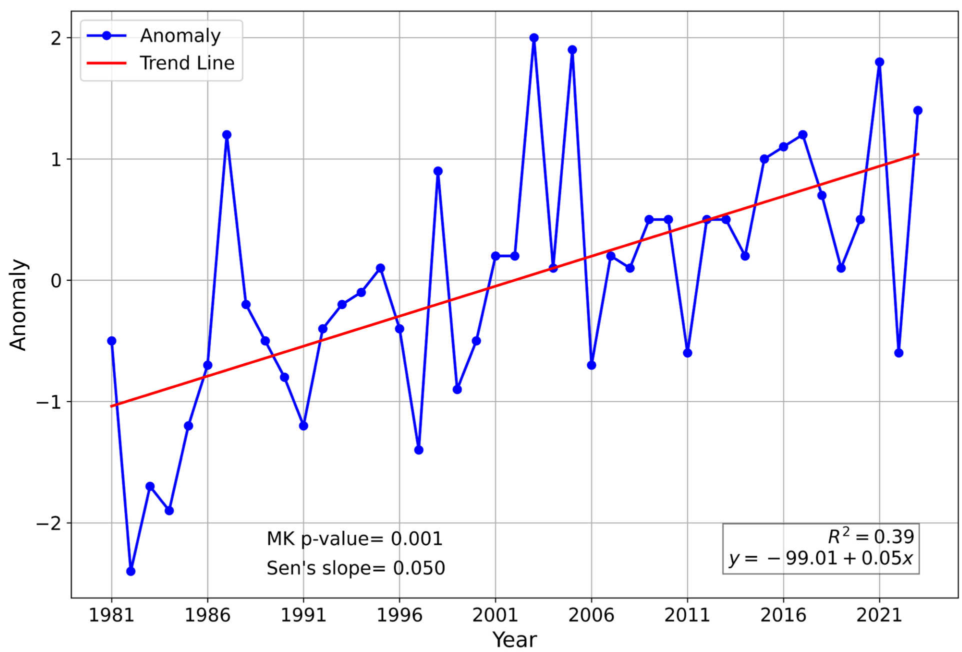


(d)

Figure 3. Temporal analysis of temperature trends and anomalies in Hanang District, Manyara Region, Tanzania (1981-2023): (a) Annual Temperature Trend (1981-2023); (b) Annual Temperature Trend Anomaly (1981-2023); (c) March to May Temperature Trend Anomaly (1981-2023); (d) October to December Temperature Trend Anomaly (1981-2023).

3.3.2. March to May (MAM) Period

The trend line plot for the MAM period (Figure 3(c)) exhibits a positive slope of 0.0276, indicating a slight upward trend in temperatures during this season. The R-squared value of 0.1199 suggests that approximately 11.99% of the variability in

MAM temperatures can be explained by the linear trend observed. Temperature anomalies during the MAM period range from a minimum of −2.2˚C to a maximum of 2.4˚C, indicating significant variability in temperature deviations from the long-term average.

3.3.3. October to December (OND) Period

The OND trend line plot (**Figure 3(d)**) also shows a positive slope, with a steeper rate of increase compared to the MAM period, reflected in a slope value of 0.0499. The R-squared value of 0.3924 indicates that approximately 39.24% of the variability in OND temperatures can be attributed to the observed trend. Temperature anomalies during the OND period vary from a minimum of −2.4˚C to a maximum of 2.0˚C, indicating notable deviations from the long-term average, with temperatures tending to be warmer overall. These findings suggest distinct seasonal temperature trends, with both the MAM and OND periods exhibiting positive anomalies and upward temperature trends. While the explanatory power of the trend lines is relatively modest, the consistent positive slopes and variability in temperature anomalies underscore the importance of considering seasonal variations in temperature when assessing long-term climate trends. Scholars have suggested that, given the complexity of temperature anomalies, further research may focus on understanding the underlying drivers of these seasonal temperature patterns and their implications for regional climate dynamics and ecosystem functioning [47].

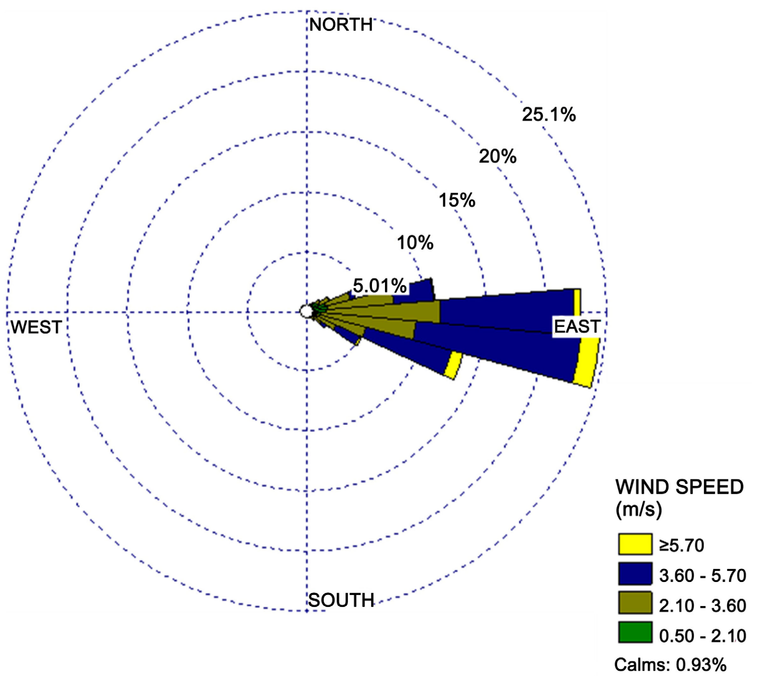
3.4. Wind Analysis

Table 2 and **Figure 4** indicates the wind rose statistics for annual, March to May (MAM) and October to December (OND) for climatology period of 1991-2020. The observed directions were SSE (South South East), EEN (East East North), SE (South East) and E (East) wind direction. Based on the wind rose statistics provided for the annual, March to May (MAM), and October to December (OND) periods from 1991 to 2020, we can observe that the predominant wind direction (SSE - EEN) accounts for the majority of occurrences, with varying wind speed ranges. Wind speeds between 2.1 m/s and 5.7 m/s constitute the largest percentage of occurrences (36.8% to 39.2%). For MAM wind distribution, the predominant wind direction is SE - E. The wind speeds between 2.1 m/s and 3.6 m/s have the highest percentage of occurrences (40.1%). For OND, the predominant wind direction is SSE - EEN, consistent with the other periods. Wind speeds between 3.6 m/s and 5.7 m/s have the highest percentage of occurrences (44.7%). Wind patterns can have significant impacts on local weather patterns, including rainfall distribution, wind speed and direction, and temperature variations. The prevailing wind directions across all periods are generally consistent, suggesting a certain regularity in wind patterns. The moderate wind speeds in the range of 2.1 m/s to 5.7 m/s are quite common, especially during the months of November and December. Wind blowing from the SSE - EEN direction, which is predominant, could potentially influence soil erosion particularly if coupled with heavy rainfall.

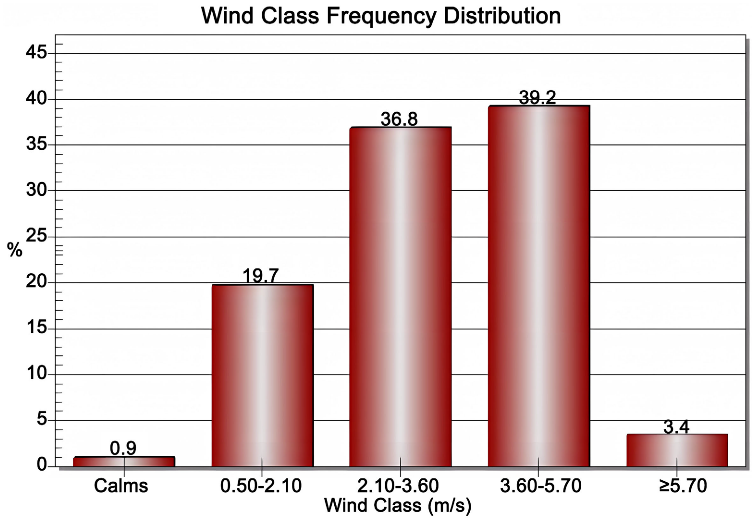
Numerous researchers have emphasized the influence of high wind speed on evaporation processes which destabilizes the boundary layer and causes deep convection, and hereafter, intensifies rainfall [48]. These rainfall patterns, especially the intense rainfall in November, could have significant implications for the occurrence of the landslides and floods in the study area.

Table 2. Wind distribution in the study area.

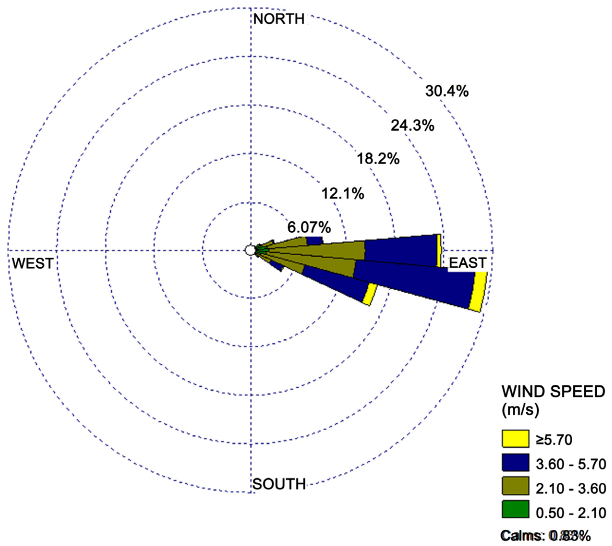
Item	Wind speed range (m/s)	Percentage	Wind direction
Annual	Calm	0.9	SSE - EEN
	>5.7	3.4	SSE - EEN
	3.6 - 5.7	39.2	SSE - EEN
	2.1 - 3.6	36.8	SSE - EEN
	0.5 - 2.1	19.7	SSE - EEN
MAM	Calm	0.8	SE - E
	>5.7	3.3	SE - E
	3.6 - 5.7	36.3	SE - E
	2.1 - 3.6	40.1	SE - E
	0.5 - 2.1	10.5	SE - E
OND	Calm	1.0	SSE - EEN
	>5.7	3.8	SSE - EEN
	3.6 - 5.7	44.7	SSE - EEN
	2.1 - 3.6	30.5	SSE - EEN
	0.5 - 2.1	20.0	SSE - EEN



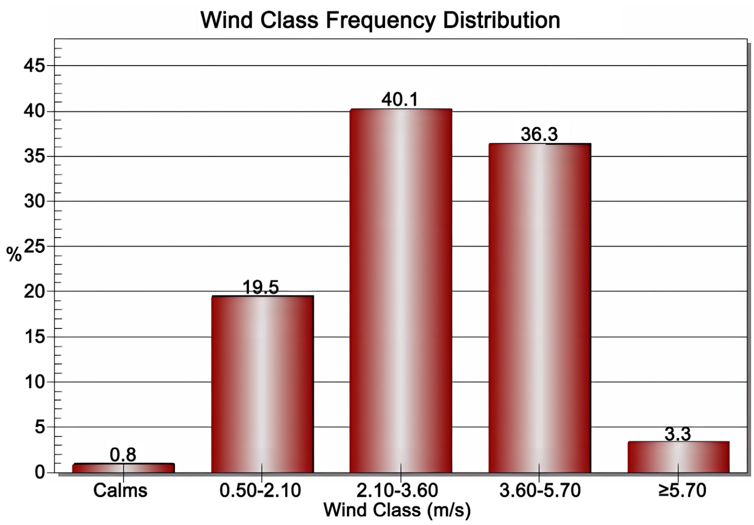
(a)


Wind Class Frequency Distribution
45
40
35
30
25
%
20
15
10
5
0
0.9
19.7
36.8
39.2
3.4
Calms
0.50-2.10
2.10-3.60
3.60-5.70
≥5.70
Wind Class (m/s)

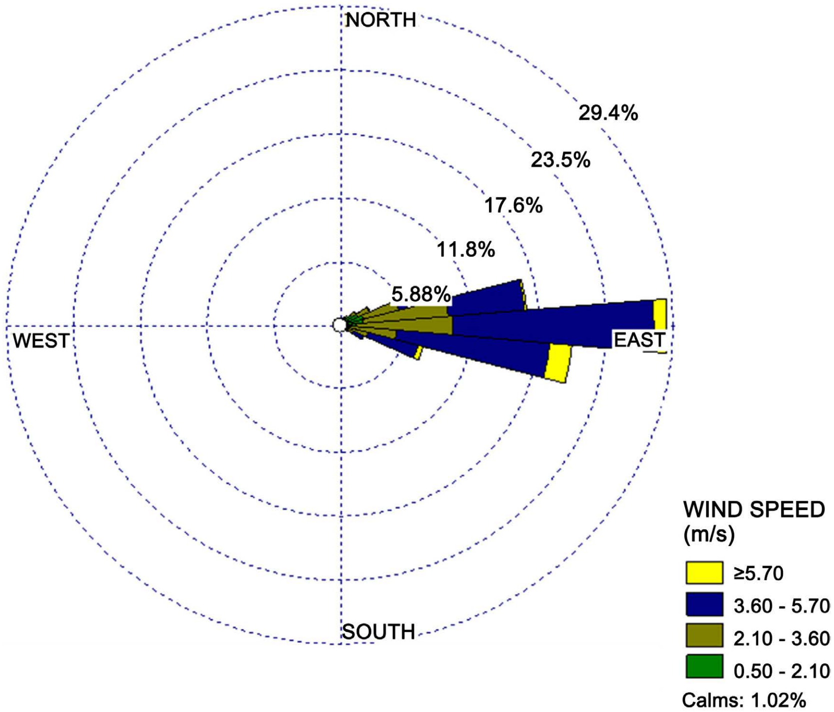
(b)


NORTH
SOUTH
WEST
EAST
30.4%
24.3%
18.2%
12.1%
6.07%
WIND SPEED
(m/s)
≥5.70
3.60 - 5.70
2.10 - 3.60
0.50 - 2.10
Calms: 0.83%

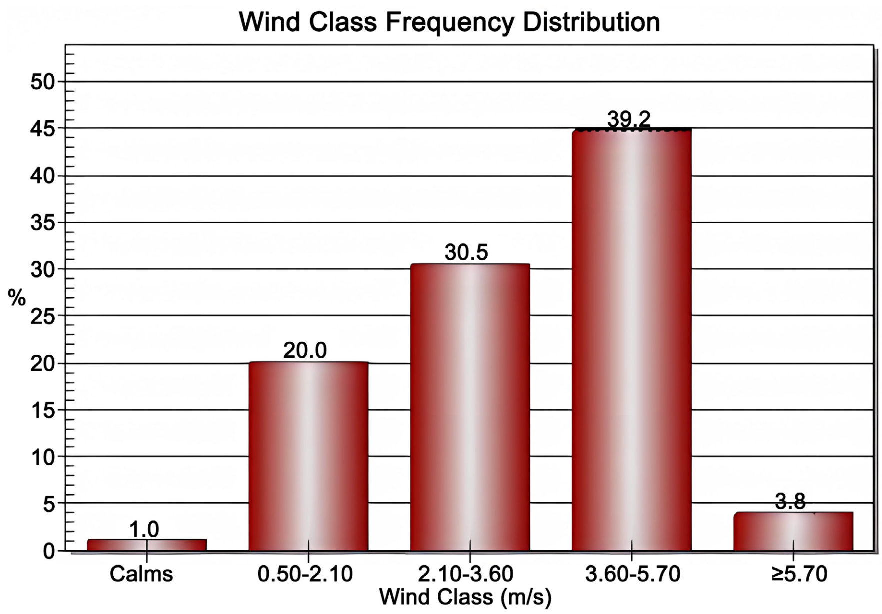
(c)


Wind Class Frequency Distribution
45
40
35
30
25
%
20
15
10
5
0
0.8
19.5
40.1
36.3
3.3
Calms
0.50-2.10
2.10-3.60
3.60-5.70
≥5.70
Wind Class (m/s)

(d)



(e)



(f)

Figure 4. Wind rose to show wind direction in Hanang District, Manyara Region, Tanzania (1990-2020). (a) Annual Windrose; (b) Annual wind frequency distribution; (c) MAM Windrose; (d) MAM wind frequency distribution; (e) OND Windrose; (f) OND wind frequency distribution.

4. Conclusion and Recommendation

The comprehensive analysis of rainfall, wind and temperature trends in the Hanang District, Manyara Region, Tanzania, spanning the period from 1981 to

2023, reveals significant insights into the region's climatic dynamics. The examination of annual rainfall data indicates an upward trend in precipitation levels, accompanied by notable variability in rainfall patterns, including seasonal anomalies and deviations from historical averages. Concurrently, the analysis of temperature trends highlights a consistent warming trend, with both annual mean temperatures and seasonal anomalies exhibiting positive slopes over the observed period. Notably, the occurrence of extreme events, such as the landslide and floods event in December 2023 and the highest historical temperature recorded in the same year, underscores the significance of recent climate variability and its potential impacts on local ecosystems and communities. These findings underscore the importance of continued monitoring and assessment of climate trends, as well as the implementation of proactive measures to mitigate the impacts of climate variability and change. The occurrence of a landslide and flood event on December 3rd, 2023, underscores the need for proactive measures to mitigate landslide hazards in the region. The combination of elevated rainfall, anomalies in rainfall patterns, and potentially unfavourable terrain characteristics may have contributed to increased landslide risk during this period. Future research should focus on integrating rainfall and temperature data with comprehensive landslide susceptibility assessments, considering factors such as terrain stability, land cover, and land use practices. Implementing early warning systems, land use planning strategies, and infrastructure improvements can help mitigate the impacts of landslide events and enhance community resilience to natural hazards in the Hanang District and similar regions.

Authors' Contributions

This work was carried out in collaboration among all authors. Author SS involved in designing the study, wrote the research protocol and involved in manuscript writing and proofreading. Authors AAM and JSC involved in designing the study, data collection, performed the statistical analysis and wrote the first draft of the manuscript. Author JN involved in statistical analysis and manuscript writing. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Chaudhary, M.T. and Piracha, A. (2021) Natural Disasters—Origins, Impacts, Management. *Encyclopedia*, **1**, 1101-1131. https://doi.org/10.3390/encyclopedia1040084

[2] Thomas, A. and López, R. (2015) Climate-Related Disasters and Human Security. *Climate Policy*, **15**, 662-677.

[3] Wei, W., Wang, H. and Zhang, L. (2012) Assessing the Impacts of Climate Change on Water Resources in the Arid Region of Northwest China. *Environmental Science and Technology*, **46**, 7112-7118.

[4] Centre for Research on the Epidemiology of Disasters (CRED) (2022) Disasters in

Numbers 2021. https://www.cred.be/sites/default/files/CredCrunch66.pdf

[5] Kamai, T., Weisbrod, N. and Dragila, M.I. (2009) Impact of Ambient Temperature on Evaporation from Surface-Exposed Fractures. *Water Resources Research*, **45**, W02417. https://doi.org/10.1029/2008wr007354

[6] Kulina, M. (2008) Correlation between Air Temperature, Rainfall and Weekly Fruit Growth Rate in Some Apple Varieties. *Acta Agriculturae Serbica*, **26**, 39-48.

[7] Nkuna, Z. and Odiyo, J.O. (2016) Rainfall Variability and Its Implications for Water Resources in Southern Africa. *Physics and Chemistry of the Earth Parts A/B/C*, **92**, 27-33.

[8] Chobo, J.S. and Huo, L. (2024) The Relationship between Extreme Precipitation Events in East Africa during the Short Rainy Season and Indian Ocean Sea Surface Temperature. *Journal of Geoscience and Environment Protection*, **12**, 1-16. https://doi.org/10.4236/gep.2024.129001

[9] Henke, D., Smyth, P., Haffke, C. and Magnusdottir, G. (2012) Automated Analysis of the Temporal Behavior of the Double Intertropical Convergence Zone over the East Pacific. *Remote Sensing of the Environment*, **123**, 418-433.

[10] Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., Kramers, J., *et al.* (2004) Holocene Records of Rainfall Variation and Associated ITCZ Migration from Stalagmites from Northern and Southern Oman. In: Diaz, H.F. and Bradley, R.S., Eds., *The Hadley Circulation*: *Present*, *Past and Future*, Springer Netherlands, 259-287. https://doi.org/10.1007/978-1-4020-2944-8_10

[11] Lietzke, C.E., Deser, C. and Vonder Haar, T.H. (2001) Evolutionary Structure of the Eastern Pacific Double ITCZ Based on Satellite Moisture Profile Retrievals. *Journal of Climate*, **14**, 743-751. https://doi.org/10.1175/1520-0442(2001)014<0743:esotep>2.0.co;2

[12] Mamalakis, A., Randerson, J.T., Yu, J., Pritchard, M.S., Magnusdottir, G., Smyth, P., *et al.* (2021) Zonally Contrasting Shifts of the Tropical Rain Belt in Response to Climate Change. *Nature Climate Change*, **11**, 143-151. https://doi.org/10.1038/s41558-020-00963-x

[13] Schneider, U., Becker, A., Finger, P. and Meyer-Christoffer, A. (2014) The New/Global Gridded Data Set of Monthly Precipitation and Temperature for the Period 1951-2010. *Global Change Research Data Publishing*, **56**, 1455-1465.

[14] Kebacho, L.L. (2022) Interannual Variations of the Monthly Rainfall Anomalies over Tanzania from March to May and Their Associated Atmospheric Circulations Anomalies. *Natural Hazards*, **112**, 163-186. https://doi.org/10.1007/s11069-021-05176-9

[15] Lashkari, H. and Jafari, M. (2021) Annual Displacement and Appropriate Index to Determine ITCZ Position in East Africa and the Indian Ocean Regions. *Meteorology and Atmospheric Physics*, **133**, 1111-1126. https://doi.org/10.1007/s00703-021-00797-y

[16] Indeje, M., Semazzi, F.H.M. and Ogallo, L.J. (2000) ENSO Signals in East African Rainfall Seasons. *International Journal of Climatology*, **20**, 19-46. https://doi.org/10.1002/(sici)1097-0088(200001)20:1<19::aid-joc449>3.0.co;2-0

[17] Kew, S.F., Philip, S.Y., Hauser, M., Hobbins, M., Wanders, N., van Oldenborgh, G.J., *et al.* (2021) Impact of Precipitation and Increasing Temperatures on Drought Trends in Eastern Africa. *Earth System Dynamics*, **12**, 17-35. https://doi.org/10.5194/esd-12-17-2021

[18] Kharb, A., Bhandari, S., Moitinho de Almeida, M., Castro Delgado, R., Arcos González, P. and Tubeuf, S. (2022) Valuing Human Impact of Natural Disasters: A Review

of Methods. *International Journal of Environmental Research and Public Health*, **19**, Article 11486. https://doi.org/10.3390/ijerph191811486

[19] Venton, C.C. and Hansford, G. (2006) Reducing Risk of Disaster in Our Communities. Tearfund. https://learn.tearfund.org/en/resources/series/roots-guides/reducing-risk-of-disaster-in-our-communities--a-roots-guide

[20] Peduzzi, P., Dao, H., Herold, C. and Mouton, F. (2009) Assessing Global Exposure and Vulnerability towards Natural Hazards: The Disaster Risk Index. *Natural Hazards and Earth System Sciences*, **9**, 1149-1159. https://doi.org/10.5194/nhess-9-1149-2009

[21] Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., *et al.* (2012) Changes in Climate Extremes and Their Impacts on the Natural Physical Environment. In: Field, C.B., Barros, V., Stocker, T.F. and Dahe, Q., Eds., *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, Cambridge University Press, 109-230. https://doi.org/10.1017/cbo9781139177245.006

[22] Srinivas, R. (2022) Understanding Disaster Management: A Socio-Environmental Approach. *Disaster Studies Quarterly*, **8**, 150-174.

[23] Bankoff, G., Frerks, G. and Hilhorst, D. (2003) Mapping Vulnerability: Disasters, Development and People. Routledge.

[24] Juntunen, L. (2005) Addressing Social Vulnerability to Hazards. *Disaster Safety Review*, **4**, 3-10.

[25] Flanagan, B.E., Hallisey, E.J., Adams, E. and Lavery, A. (2018) Measuring Community Vulnerability to Natural and Anthropogenic Hazards: The Centers for Disease Control and Prevention's Social Vulnerability Index. *Journal of Environmental Health*, **80**, 34-36.

[26] Global Center on Adaptation (GCA) (2022) Climate Risks in Africa. State and Trends in Adaptation Report. https://gca.org/wp-content/uploads/2023/01/GCA_State-and-Trends-in-Adaptation-2022_Climate-Risks-in-Africa.pdf

[27] Murtugudde, R., Seager, R. and Thunell, R. (2004) Climatic Variability in the Indian Ocean Region. *Bulletin of the American Meteorological Society*, **85**, 1413-1425.

[28] Kijazi, A.L. and Reason, C.J.C. (2007) Interannual Variability of Rainfall Characteristics over Tanzania and Their Connections to El Niño Southern Oscillation. *International Journal of Climatology*, **27**, 683-692.

[29] Mutai, C.C., Ward, M.N. and Colman, A.W. (1997) Towards the Prediction of the East African Short Rains Based on Sea-Surface Temperature-Atmosphere Coupling. *International Journal of Climatology*, **17**, 1177-1192.

[30] Semazzi, F.H.M., Ogallo, L.J. and Indeje, M. (1993) A GCM Study of the Teleconnections between the Regional Climate of East Africa and Global Sea Surface Temperature Anomalies. *Journal of Climate*, **6**, 1274-1289.

[31] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., *et al.* (2015) The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes. *Scientific Data*, **2**, Article ID: 150066. https://doi.org/10.1038/sdata.2015.66

[32] McMahon, T.A. and Peel, M.C. (2001) Two Centuries of Australian Rainfall and Runoff Data. *Australian Journal of Water Resources*, **5**, 5-15.

[33] Ehsan, S. and Sadiq, R. (2015) Seasonal Rainfall Anomalies and Their Impact on

Water Availability in Arid Regions. *Journal of Hydrology*, **528**, 100-110.

[34] McKee, T.B., Doesken, N.J. and Kleist, J. (1993) The Relationship of Drought Frequency and Duration to Time Scales. *Proceedings of the* 8*th Conference on Applied Climatology*, Anaheim, 17-22 January 1993, 179-183.

[35] Sen, P.K. (1968) Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, **63**, 1379-1389. https://doi.org/10.1080/01621459.1968.10480934

[36] Kendall, M.G. (1975) Rank Correlation Methods. Charles Griffin.

[37] Mann, H.B. (1945) Nonparametric Tests against Trend. *Econometrica*, **13**, 245-259. https://doi.org/10.2307/1907187

[38] Kutner, M.H., Nachtsheim, C.J., Neter, J. and Li, W. (2004) Applied Linear Statistical Models. 5th Edition, McGraw-Hill Irwin.

[39] Saito, K. and Aoki, K. (2016) Climate Change Impacts on Extreme Precipitation and Its Relation to Atmospheric Circulation. *Journal of Climate Research*, **45**, 1023-1035.

[40] Kilembe, C., Thomas, T.S., Waithaka, M., Kyotalimye, M. and Tumbo, S. (2012) East Africa Agriculture and Climate Change: A Comprehensive Analysis—Tanzania. IFPRI. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/127936

[41] Lobell, D.B. and Burke, M.B. (2010) On the Use of Statistical Models to Predict Crop Yield Responses to Climate Change. *Agricultural and Forest Meteorology*, **150**, 1443-1452. https://doi.org/10.1016/j.agrformet.2010.07.008

[42] Malekela, A.A., Sieber, S., Mapunda, J. and Chobo, J.S. (2024) Contemporary Agricultural Land Management Practices under Climate Change and Population Increase Scenarios: Insights from Tanzania's Southern Highlands. *Journal of Geography*, *Environment and Earth Science International*, **28**, 41-52. https://doi.org/10.9734/jgeesi/2024/v28i4763

[43] Mkonda, M.Y. (2022) Awareness and Adaptations to Climate Change among the Rural Farmers in Different Agro-Ecological Zones of Tanzania. *Management of Environmental Quality*: *An International Journal*, **33**, 1502-1527. https://doi.org/10.1108/meq-10-2021-0241

[44] Cánovas, J.B., Stoffel, M., Corona, C., Schraml, K., Gobiet, A., Tani, S., Sinabell, F., Fuchs, S. and Kaitna, R. (2016) Debris-Flow Risk Analysis in a Managed Torrent Based on a Stochastic Life-Cycle Performance. *Science of the Total Environment*, **557-558**, 142-153.

[45] Dowling, C.A. and Santi, P.M. (2013) Debris Flows and Their Toll on Human Life: A Global Analysis of Debris-Flow Fatalities from 1950 to 2011. *Natural Hazards*, **71**, 203-227. https://doi.org/10.1007/s11069-013-0907-4

[46] Fuchs, S., Keiler, M., Sokratov, S. and Shnyparkov, A. (2012) Spatiotemporal Dynamics: The Need for an Innovative Approach in Mountain Hazard Risk Management. *Natural Hazards*, **68**, 1217-1241. https://doi.org/10.1007/s11069-012-0508-7

[47] Gamoyo, M., Reason, C. and Obura, D. (2014) Rainfall Variability over the East African Coast. *Theoretical and Applied Climatology*, **120**, 311-322. https://doi.org/10.1007/s00704-014-1171-6

[48] Johansson, B. and Chen, D. (2003) The Influence of Wind and Topography on Precipitation Distribution in Sweden: Statistical Analysis and Modelling. *International Journal of Climatology*, **23**, 1523-1535. https://doi.org/10.1002/joc.951