Rainfall distribution on the slopes of Mt Kilimanjaro

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Abstract Observations from new precipitation gauges on the southern slopes of Mt Kilimanjaro are used together with observations from the regular network to establish an elevation function for the precipitation on the southern hillside of Mt Kilimanjaro. A third-order polynomial function is found to best describe the distribution of precipitation with elevation for the lower half of the hillside. On the upper half of the hillside, an exponential function is found to best describe the precipitation distribution with elevation. The availability and quality of the precipitation records is often a limiting factor for analyses and may influence the results. A reference precipitation series for the area is established through thorough screening and quality checks of the available data. The elevation function is compared with an isohyetal map for the area. The findings indicate that the maximum precipitation on the southern hillside of Mt Kilimanjaro takes place at about 2200 m a.s.l. which is 400–500 m higher than assumed previously.

Key words precipitation analysis; homogeneity; precipitation measurement; elevation distribution; gradient; Mt Kilimanjaro, Tanzania

INTRODUCTION

Water is a limiting factor for development on the dry plains below the heavily populated slopes of Mt Kilimanjaro. The major part of the available water falls as rain on the steep slopes of Mt Kilimanjaro. The subsequent surface flow is utilized until it vanishes on the plains due to evaporation and to the withdrawal of water from the streams on the upper slopes. Knowledge and understanding of this essential water
resource, its origin, amount and distribution can facilitate a management scheme that is beneficial for the majority of the inhabitants of the area.

A study of catchments on the southern slopes of Mt Kilimanjaro will require knowledge about the precipitation distribution in time and space between the lowland plains at 700 m a.s.l. and the peak at about 6000 m a.s.l. The majority of today’s meteorological observations take place below 1500 m a.s.l. Extrapolation of the results from hydrological analyses of the data from the lowland plains to the upper slopes of Mt Kilimanjaro can lead to erroneous conclusions.

Mt Kilimanjaro is located in the northern part of the 42 200 km² Pangani River basin in northeast Tanzania towards the Kenyan border (see Fig. 1). The wet and fertile southern slope of Mt Kilimanjaro is intensively utilized for agricultural activities by the dense and increasing population. Scarce and erratic rainfall results in low population and little agricultural activity on the other slopes. The plains south of Mt Kilimanjaro are close to the East African region, which has a pronounced bimodal rainfall pattern (Griffiths, 1972), the short rains lasting from late October until December and the long rains from March until May. Very little rain occurs in the

![Map showing the location of the research area and the stations used in the statistical analysis only. Major sites are also shown. (See also Tables 1 and 2 for further details.)](image)
period between June and September. Probably the earliest isohyetal map describing the precipitation distribution on the southern hillside of Mt Kilimanjaro and on the lowland plains was established by Klute (1920), based on his own observations. Teale & Gillman (1935) give a description of the climate and discuss the water problems in the region. They point out that the rapid decrease of precipitation towards the upper reaches, which had been investigated by Klute (1920), is supported by indirect observations of morphological and vegetation features observed in the higher parts of Mt Kilimanjaro. Analysis by Tanzanian Authorities (1977) indicates that the highest precipitation in the area can be found on the slopes of Mt Kilimanjaro, with annual values above 2000 mm in smaller parts of the area. Although no stations are present on the upper part of the hillside, detailed precipitation distribution maps are presented in e.g. Tanzanian Authorities (1977) and Perzyna (1994). Tanzanian Authorities (1977) developed an isohyetal map for rainfall distribution based on 18 precipitation stations on the lower slopes of Mt Kilimanjaro below 1600 m a.s.l. No analysis of any trends, nor documentation of the continuity of each individual station is provided.

DATA AVAILABILITY

Precipitation data for 21 stations were available from various sources for use in the analysis. Digitized readings were obtained from the University of Dar es Salaam (Tanzania) and manual readings were obtained from the local Maji Office (Water Authorities office) in Moshi, Tanzania. The data vary widely in extent and quality.

Nine of the 21 stations have been operational for more than 50 years. Four of the nine stations have between 7 and 28% missing values and/or stopped operating 6–10 years ago. Therefore, they were discarded from further analysis. The remaining five stations have an observation period of 62–79 years and less than 3% missing values and were used for the further analysis.

The other twelve of the 21 stations have been operational for about 20–46 years. Six of these stations have more than 12% missing values and they were also discarded from further analysis. One station missing 11% of the values was partly used for the analysis. One station had not been operational for 14 years and was discarded from further analysis. The remaining four stations have less than 10% missing values. Additionally, two newer stations from the regular observation network were used for verification purposes.

The 10 stations used in the analysis are located between 690 and 1433 m a.s.l. and are valuable for analysis of the hydrology between these elevations. However, use of these stations will not be appropriate for the upper slopes towards the peak, which are some of the wettest areas of the Pangani River basin.

Due to this lack of a regular observation network above 1433 m a.s.l. and the importance of this area in terms of the availability of water resources, measurements up to 4000 m a.s.l. were organized for a limited period. In addition, a number of synoptic observations obtained from the Kilimanjaro National Parks (KINAPA) authorities were used for verification of the findings. All stations used in the analysis are shown in Fig. 1. Details for the 10 stations used for the statistical analysis, the nine new stations, the three KINAPA stations and the two stations used in the verification are given in Tables 1 and 2.
### Table 1
Details of the stations from the regular observation network used for the analysis. See Fig. 1 for location of stations.

<table>
<thead>
<tr>
<th>Station no.</th>
<th>South (decimal degree)</th>
<th>East (decimal degree)</th>
<th>Altitude (m a.s.l.)</th>
<th>Start year</th>
<th>End year</th>
<th>Obs. period (years)</th>
<th>Available observations (years)</th>
<th>Missing data (%)</th>
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<td><strong>Long series:</strong></td>
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<td></td>
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<td>1999</td>
<td>20</td>
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<tr>
<td><strong>Additional series for verification:</strong></td>
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<td>1999</td>
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<td>13</td>
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### Table 2
Details of the nine newly established stations (G1–G9) and the three stations from Kilimanjaro National Parks authorities (KINAPA). See Fig. 1 for location of stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>South (decimal degree)</th>
<th>East (decimal degree)</th>
<th>Altitude (m a.s.l.)</th>
<th>Start month/year</th>
<th>End month/year</th>
</tr>
</thead>
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<td>09/2001</td>
</tr>
<tr>
<td>G2</td>
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<td>37.43</td>
<td>3512</td>
<td>10/1999</td>
<td>09/2001</td>
</tr>
<tr>
<td>G3</td>
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<td>37.43</td>
<td>2993</td>
<td>10/1999</td>
<td>09/2001</td>
</tr>
<tr>
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<td>37.38</td>
<td>2626</td>
<td>10/1999</td>
<td>09/2001</td>
</tr>
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<td>2367</td>
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</tr>
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<td>1863</td>
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<td>1710</td>
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<td>09/2001</td>
</tr>
<tr>
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<td>10/1999</td>
<td>09/2001</td>
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<td><strong>Stations from KINAPA:</strong></td>
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<td>01/2000</td>
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<td>01/2000</td>
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<td>2438</td>
<td>01/1999</td>
<td>01/2000</td>
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## HOMOGENEITY OF PRECIPTIATION SERIES

### Methods for homogeneity testing

Alexanderson’s test (e.g. Olaussen & Roald, 1996) assumes a constant proportionality between the controlled station and the reference station. The two time series to be compared; $P_A$ and $P_B$, form a new series of the ratio between these two, which is normalized as:
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\[ p_i = \frac{P_{Ai}}{P_{Bi}} \quad \text{and} \quad Z_i = \frac{P_i - \bar{P}}{\text{std}_p} \]  

(1)

where \( p_i \) is the ratio between \( P_A \) and \( P_B \), \( P_{Ai} \) and \( P_{Bi} \) are the observed precipitations at station A or B in year \( i \), \( Z_i \) is the normalized value of the ratio for year \( i \), \( \bar{P} \) is the average ratio and \( \text{std}_p \) is the standard deviation for the ratio \( p_i \). The value of \( Z_i \) is tested against the following two hypotheses:

- \( H_0 \): null hypothesis—the time series is homogeneous; and
- \( H_1 \): alternative hypothesis—the series is inhomogeneous; break in year \( m \).

A test parameter for each of the \( n \) years in the observation series is:

\[ T(m) = m \times z_1^2 + (n - m) \times z_2^2 \]  

(2)

where \( T(m) \) is the test parameter for the year \( m \), \( z_1^2 \) is the mean value from year 1 to year \( m \) and \( z_2^2 \) is the mean value from year \( m + 1 \) to year \( n \). The highest value for the test parameter is:

\[ T_x = \max(T(m)) \quad \quad m = [1, 2, ... n] \]  

(3)

The probability that \( T_x \) will achieve a certain value, provided that the null hypothesis is correct, depends only on the length of the time series (Førland et al., 1991). If a time series is found to be inhomogeneous, the probability is highest for a break in the year when \( T \) equals \( T_x \).

Garbrecht & Fernandez (1964) describe an improved approach for visualization of trends in climatic records based on rescaled adjusted partial sums. A time series of precipitation observations is represented by \( Y = \{Y_t; t = 1, ..., n\} \) for which the expected value \( \mu \) and variance \( \sigma^2 \) are usually unknown. The value \( Y_t \) is assumed normally distributed. The rescaled adjusted partial sum is defined as:

\[ X_k = \sum_{i=1}^{k} \frac{Y_i - \bar{Y}}{\sigma_y} \quad k = 1, ..., n \]  

(4)

where \( \bar{Y} \) is the sample mean, \( \sigma_y^2 \) is the variance, \( n \) is the number of values in the series and \( k \) is the counter (see Buishand, 1982 for details). A test for a change in level based on the adjusted partial sums is:

\[ Q = \max_{0 \leq k < n} |X_k| \]  

(5)

A high value of \( Q \) might be an indication for a change in level. Critical values for the test statistic are given in Buishand (1982). Buishand (1982, 1984) describes the use of Bayesian procedures for detection of change in the mean. With \( \sigma^2 \) unknown for the distribution, it is replaced with the sample variance in the test statistic, which gives:

\[ U = \frac{1}{n(n+1)} \sum_{k=1}^{n} X_k^2 \]  

(6)

Critical values for the test statistic may be found in e.g. Buishand (1982).

For emphasizing shifts near the end points of a series of observed values, Worsley’s likelihood test based on weighted rescaled adjusted partial sums may be
used (Buishand, 1982; Worsley, 1979). The weighted rescaled adjusted sum is given by:

$$Z_k = \frac{X_k}{\sqrt{k(n-k)}} \quad k = 1, \ldots, n-1$$

(7)

In equation (7), the largest weight is given to the values at each end of the series and smaller weight is given to the values in the middle of the series. The test value $W$ is given by:

$$W = \sqrt{\frac{(n-2)V}{n-1-V^2}}$$

where $V = \max_{1 \leq k \leq n-1} |Z_k|$

(8)

Critical test values for $W$ may be found in Worsley (1979).

The double mass analysis (e.g. ASCE, 1996) is based on regional correlation over long time periods, no inconsistency of the compared stations and the use of annual precipitation values in the analysis. The accumulated sums are plotted against each other, or against a composite of regional series. A break in the curve can indicate nonhomogeneity. If a break occurs around the same time in the compared time series, it can be difficult to trace.

**Results from trend and homogeneity testing**

The tests with rescaled adjusted partial sums, Bayesian procedures and Worsley’s likelihood test were performed on individual series with a significance level of 0.95. The double mass analysis and Alexanderson’s test were performed on a combination of series. Table 3 shows the results from the analysis.

The results for the long series, shown in the upper half of Table 3, indicate that the series from station 9337006 on the southeastern side of Mt Kilimanjaro and station 9337028 on the plains below Moshi are nonhomogeneous. For the three series found to be homogeneous, double mass analysis was performed for a common, continuous

<table>
<thead>
<tr>
<th>Station number</th>
<th>$Q/\sqrt{n}$</th>
<th>$U$</th>
<th>$W$</th>
<th>$T_{\text{max}}$</th>
<th>Conclusion based on test value</th>
<th>$Q/\sqrt{n}$</th>
<th>$U$</th>
<th>$W$</th>
<th>$T_{\text{max}}$</th>
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</table>

* $Q/\sqrt{n}$: adjusted partial sums; $U$: Bayesian procedures; $W$: Worsley’s likelihood test; $T_{\text{max}}$: Alexanderson’s test.

† ok: series is homogeneous; Nonhom: series is nonhomogeneous—according to test value.
observation period of 62 years from 1938 to 1999. Figure 2 shows the double mass curves for each of the three series against a weighted combination of the other two. The series from stations 9337004 and 9337021 show moderate changes in gradient, while that from station 9337031 shows some changes, which can be traced to the 1970s. Inspection of the time series shows that the lowest, and the fourth and fifth lowest annual precipitation values for the observation period can be found in this decade, which can explain the changes. The three series are weighted according to the average annual precipitation value and used for forming a reference series. Double mass curves with the reference series and the other long series, from stations 9337006 and 9337028, show several changes in gradient, and support the conclusion about nonhomogeneity.

For station 9337028, the changes can be traced to the mid-1960s. This coincides with the establishment of the Nyumba ya Mungu Reservoir. The precipitation station is located about 9 km north of the reservoir (Fig. 1), which has a surface area of about 160 km². The establishment of the reservoir may have resulted in changes in the local climate. The average annual precipitation for the period 1938–1966 is 401 mm, while for the period 1967–2000 it is 557 mm—a 39% increase. On the arid plains, the increased water surface nearby has increased the total evaporation in the area, which may have resulted in increased precipitation.

The results from the analysis of the shorter series are shown in lower half of Table 2. Double mass curves for some of the stations are shown in Fig. 3. The curve for station 9337078 has several changes in gradient. The analysis indicates non-homogeneity for this station, which has observations from 1954 to date, but about 10% of the data are missing. The double mass curves indicate a break around 1983. The
average annual precipitation from 1954 to 1983 is 1122 mm and for the period 1984–1999, it is 1588 mm. This is an increase of 42%, though it should be noted that the missing observations might influence the result.

**PRECIPITATION GRADIENT**

A linear gradient for correcting precipitation data due to change in elevation is commonly used in hydrological analysis and modelling. For most areas, the linear gradient with a constant increase in precipitation with altitude will provide satisfactory results, while in certain areas it may give considerable errors. Due to the sparse or absent observation network for the upper slopes of Mt Kilimanjaro, a temporary observation network was installed in September 1999 with nine raingauges in a transect on the southern slope of Mt Kilimanjaro. This covers the elevation zones from the lowermost border of the forest reserve and into the moorland and alpine desert at 4000 m a.s.l. Further details about locations of the stations can be seen in Table 2 and Fig. 1. The raingauges were located in clearings in the forest about 1 m above the ground, and the surrounding vegetation was kept down. The gauges provided cumulative measurements of precipitation with a 5” gauge and monthly readings. The results from the two years of measurements are given in Fig. 4. The measurements indicate that the maximum precipitation on the southern hillside of Mt Kilimanjaro can be found at 2200–2300 m a.s.l. From the area below the forest reserve, three stations from the regular observation network were selected to obtain a south–north transect for the precipitation distribution as a function of elevation. Stations 9337004 and 9337021
were used for establishing the reference series, while station 9337028 was discarded for this purpose due to nonhomogeneity. Before and after the break point in the mid-1960s, station 9337028 shows a homogeneous pattern and was therefore selected for use in the study concerning the gradient, as there are no other stations on the lowland plains.

The observed precipitation data from the nine new stations and from the three stations in the regular observation network were used for fitting a function describing the distribution of precipitation as a function of elevation in the south–north direction. Two types of equation were used: a third-order polynomial for the distribution below 2700 m a.s.l. and an exponential equation for that above 2700 m a.s.l. The least squares method was used for fitting the functions and the result is shown in Fig. 5. The solid circles show the observed precipitation at different elevations. The three curves are the precipitation from the three stations in the regular observation network, corrected for difference in elevation to represent the precipitation at the other 11 observation points. The equation for correcting the precipitation due to change in elevation is based on a ratio between the precipitations at different elevations. A relative precipitation for a given elevation \( X \) above sea level can be expressed as:

\[
R = -2.93 \cdot 10^{-10} X^3 + 7.71 \cdot 10^{-7} X^2 + 6.15 \cdot 10^{-4} X - 0.445 \quad \text{for} \quad 680 < X < 2700
\]

\[
R = 5.87 \times e^{-0.35 \times 10^4 X} \quad \text{for} \quad 2700 < X < 5895
\]  

(9)

If a precipitation station at elevation, \( X_1 \) has an observed precipitation, \( P_1 \), the elevation function can be used for finding the precipitation, \( P_2 \) at elevation \( X_2 \), according to the expression:

\[
P_2 = P_1 \frac{R_2}{R_1}
\]

(10)

where \( R_1 \) and \( R_2 \) are the relative precipitations at elevations \( X_1 \) and \( X_2 \), respectively.
Fig. 5 Function for correcting precipitation due to change in elevation in a south–north transect on the southern slopes of Mt Kilimanjaro. The three curves are calculated by use of the new function and observations at stations 9337004, 9337021 and 9337028.

Fig. 6 Verification of the function for correcting precipitation due to change in elevation with another independent dataset. See text for details.

Equation (10) was used on precipitation data from each of the three stations from the regular observation network to correct for the differences in elevation from each of the other 11 stations forming the three curves in Fig. 5. The average deviation from the observed precipitation represented by the solid circles is about 3%.

For validation of the function for correcting precipitation due to change in elevation (equations (9) and (10)), an independent set of data was used. These data were
obtained from KINAPA and from the regular observation network, both partly from different observation periods. Observations from seven different stations are shown in Fig. 6: four observations below 1590 m a.s.l. from the regular observation network and three points located at 2500, 3500 and 4500 m a.s.l. from the KINAPA observation network.

An inspection in June 1999 of the KINAPA gauge at Kibosho, located at 2500 m a.s.l. inside the forest on the southern slopes of Mt Kilimanjaro, revealed that this station was partly covered by vegetation. This will give lower observed precipitation compared to gauges not covered by vegetation, due to interception loss. This station has a coincident observation period from October 1999 to January 2000 with station G5 located at 2480 m a.s.l. The nearest area around station G5 was cleared for vegetation and the station data should therefore not be influenced by vegetation covering the gauge. A correction factor for station Kibosho was calculated based on the coincident observations and applied for the whole observation period. The corrected value is indicated as the circle in Fig. 6. The two other stations from the KINAPA observation network, Mweka and Kibo, are located above the forest belt around Mt Kilimanjaro, and only have minor influence from the surrounding low vegetation.

The new elevation function was applied for correcting three of the precipitation values from the regular observation network and from the curves in Fig. 6. The calculated curves fit relatively well to the seven observed values, particularly on the upper slopes of Mt Kilimanjaro. The small discrepancy may be explained by varying influence from the vegetation around the gauges in the forest belt.

The deviation from the curves for station 9337147 (1050 m a.s.l.) is difficult to explain. No systematic deviation can be found. In the trend analysis, this station was found to be homogeneous. This station had the shortest observation period of the stations used for the analysis. The short observation period may make tests on non-homogeneity less significant. When comparing the observations from station 9337147 (1050 m a.s.l.) and station 9337148 (1470 m a.s.l.) for the 10-year period from 1990, the latter, at the highest elevation, had the highest annual precipitation for the major part of the period. However, for some years the opposite was the case. This is the case for the period used for verification of the function for correcting precipitation due to change in elevation shown in Fig. 6. Errors in the observations can be one explanation of the deviation from the curve, but it is difficult to say that a certain explanation is more reliable than another.

DISCUSSION AND CONCLUDING REMARKS

The precipitation analysis for the southern slopes of Mt Kilimanjaro has exposed many of the problems connected with precipitation data in developing countries. There are often discontinuities in the observations with a smaller or larger number of years missing. Lack of, or changes in, procedures, or lack of follow up, may have influenced the readings with subsequent nonhomogeneity in the observation material. The break in homogeneity may also have been caused by relocation of a station, growth or removal of vegetation, or influence from new buildings.

The screening and quality checks of the data condensed and focused the most reliable data from the area formed by three precipitation series from the 1930s to date.
These series were used for constructing a reliable reference series, which could be used for verification and filling in missing data. More data could have been used in the analyses with less rigid exclusion criteria, and filling in missing values with various techniques (e.g. ASCE, 1996). However, such completion of data can make the series more dependent on each other and possibly conceal errors in the observation material.

The nine new stations established on the southern slope of Mt Kilimanjaro gave interesting new information concerning the precipitation gradient in this area. A comparison between the isohyetal map presented in Tanzanian Authorities (1977) and the observed precipitation from the new stations indicates that the maximum precipitation for a transect on the southern slopes of Mt Kilimanjaro takes place at a higher elevation than was previously indicated. The solid circles in Fig. 7 for elevations above 1500 m a.s.l. represent the average annual precipitation for gauges G1–G9 during the observation period. The two non-solid circles in Fig. 7, for elevations below 1500 m a.s.l., are observed values from the regular observation network for the same period. The diamond symbols represent the values from the isohyetal map in Tanzanian Authorities (1977), which indicates that the elevation for maximum annual precipitation on the southern hillside is 1600–1800 m a.s.l. The new measurements indicate that the elevation for maximum precipitation on the southern slopes of Mt Kilimanjaro is 2000–2200 m a.s.l., an increase of 400 m. Therefore, more rain fell on the forest reserve, and not in the heavily utilized, populated and productive agricultural area below approximately 1500–1600 m a.s.l., as assumed previously. Although the new observations give some indications about the elevation at which maximum precipitation takes place, the magnitude of the annual precipitation from this study cannot be compared with those of Tanzanian Authorities (1977). The isohyetal map is constructed based on long-term observations. The new measurements cover a
period of only two years and may not be representative of long-term levels of annual precipitation. Yet, this study has shown that, by use of an elevation function, the existing observation network can be used for determination of the precipitation on the most intensively used and fertile southern slopes of Mt Kilimanjaro. Extended measurements would be useful in order to confirm the results further and extend their application east- and westward from the transect considered herein.

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