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RAINFALL VARIABILITY AND DROUGHT FREQUENCIES IN EAST AFRICA

With 12 figures

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Zusammenfassung: Niederschlagsschwankungen und Häufigkeit von Dürren in Ostafrika

Niederschlagsschwankungen sind in Ostafrika von großer Bedeutung, wo die Bauern den größten Teil der Bevölkerung bilden und die landwirtschaftlichen Erträge stark von den Niederschlagsmengen abhängig sind.

Die jährlichen Gesamtregenmengen zeigen eine große Variabilität ohne klare Trends oder Zyklen. Die Niederschlagsschwankung selbst bleibt jedoch relativ gleichmäßig, wenn man 30jährige Perioden berücksichtigt.

Die absolute Niederschlagsschwankung läßt in Ostafrika eine ziemlich komplizierte räumliche Verteilung erkennen. Die relative Schwankung zeigt dagegen ein einfaches Muster, das durch die Hauptwindzirkulation über der Region erklärt werden kann.

Lokale Faktoren, von denen das Relief zu den wichtigsten gehört, verursachen außergewöhnliche Schwankungswerte an einigen Stationen in Ostafrika. Ein Modell, das Exposition und Höhe vereint – auf den Verhältnissen in einem kleinen Gebirgsteil von Zentral-Kenya beruhend – weist darauf hin, daß die relative Niederschlagsschwankung mit der Höhe abnimmt und am geringsten an südostexponierten Abhängen ist.

Dürren sind definiert als Monate, während deren die Regenmengen weniger als die Hälfte des Langzeit-Durchschnitts betrug. Die Häufigkeit ihres Vorkommens weist eine räumliche Verteilung auf, die ähnlich der relativen Schwankung ist. Aber ihre quantitative Wechselbeziehung ist nicht stark genug, um für Dürrevoraussagen auf der Basis von Schwankungsdaten von Nutzen zu sein.

Persistierende Dürren erweisen sich am ausgeprägtesten entlang der Ostküste und in der Nähe des Viktoria-Sees, beides Gebiete mit langen Regenzeiten.

There can be little doubt about the importance of rainfall variability for the population and the economy of East Africa, the region that comprises Kenya, Tanzania and Uganda. In these countries about 90 per cent of the total labour force are engaged in various forms of agriculture. Farming in the region comprises many small plots on which a great variety of subsistence crops are grown, large and small farms which produce both subsistence and cash crops, and plantations which sell most of their products on the world markets. Large areas in the drier parts of the region are used for raising cattle, sheep or goats, frequently in a nomadic manner.

The economic significance of commercial agriculture is illustrated by the fact that about 85 percent of the total exports of the three countries consist of coffee, tea, cotton, sisal, pyrethrum, meat and hides. On the other hand, low yields of subsistence crops may cause widespread famine, as most small farmers are unable to supplement their food supply from outside sources.

The main factor which controls the productivity of all forms of agriculture in the region is rainfall. Its variability from year to year causes great differences in agricultural production and is therefore of major importance to the 41 million people living in East Africa.

Rainfall variability also introduces an element of uncertainty in agricultural and economic planning, and increases the cost of construction of new water supply installations, hydro-electric power plants and flood control measures, as these have to be prepared to cope with extreme rainfall or drought conditions.

The effects of rainfall variability were illustrated recently by a series of unusually wet years in the early 1960's and by a sequence of rather dry years in the 1970's. The threat of desertification in some drier parts of East Africa, the growing danger of soil erosion where the original vegetation cover has been damaged or destroyed by man and recent floods in large parts of Kenya (April/May 1977) all show the practical importance of rainfall and its variability in the region.

For all these reasons there exists a great need to obtain more information about rainfall variability and its spatial distribution in East Africa. Yet this aspect of climate has not been studied very much. One short article deals only with anomalies of the relative variability around the annual mean (GRIFFITHS, 1959). Another paper is limited to cycles or trends in annual rainfall in some parts of East Africa (LUMB, 1965). This paper is the first comprehensive study of the subject.

The variability of annual rainfall totals is illustrated by the records of three stations in different parts of East Africa (Fig. 1). There are no clear trends or cycles in these data (RODHE and VIRJI, 1976).

In this paper the calendar year is used as the unit of time. This is mainly done because most published records are based on this period *(East African Meteorological Department,* 1965, 1966). The use of the calendar year has the disadvantage that in the southern parts of East Africa, where the rainy season lasts from about November to April, the annual total combines the second half of one rainy season with the first part of the next one. However, in most other parts of the region the calendar year gives more satisfactory results, as it combines the long rains of March to May with the short rains during October and November of the

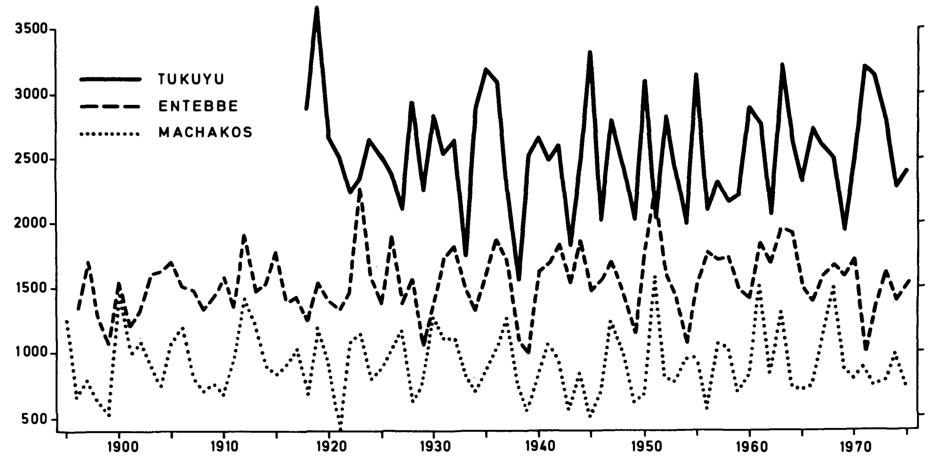

Fig. 1: Annual rainfall totals at three stations in East Africa

same year into one total figure. And there are so many differences in the seasonal rainfall distribution within East Africa that it would be impossible to collect comparable figures for single rainfall seasons (NIEUWOLT, 1974).

It is true that a different 12-months period, from July to June, shows a number of cyclic variations of rainfall totals in some parts of East Africa (LUMB, 1965). However, it is doubtful whether these cycles are persistent and widespread enough to be considered as representative of the whole region (RODHE and VIRJI, 1976).

The strong variability from year to year makes it necessary to use long periods of observation to obtain meaningful rainfall indices. A period of about 30 years must be considered the absolute minimum for this

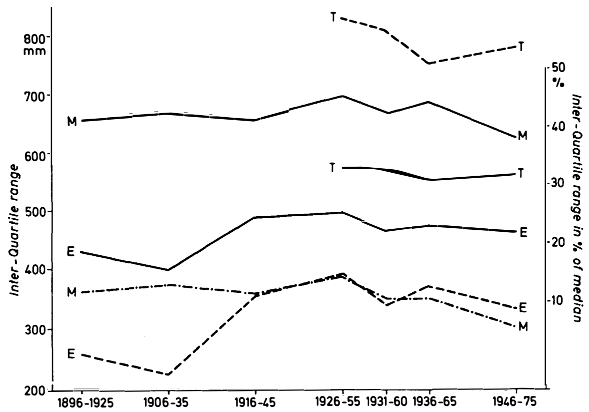

Fig. 2: Rainfall variability indicators over periods of 30 years at the same stations as in Fig. 1
broken lines: Inter Quartile Range (mm)
full lines: Inter Quartile Range in % of median rainfall
M: Machakos, Kenya T: Tukuyu, Tanzania E: Entebbe, Uganda

purpose. Yet rainfall data based on such long records are still of limited use in predicting rainfall totals, as was clearly demonstrated during the persistent wet years in the early 1960's and again during the sequence of dry years from 1972–1976.

One type of rainfall figures which remains relatively stable over time are those for the variability itself (Fig. 2). These indices do change when different periods of 30 years are used, bot not a great deal, and they may therefore be of use in the prediction of probable rainfall totals and in agricultural planning.

Absolute Rainfall Variability

In this paper the Inter Quartile Range is employed to measure the absolute variability of annual rainfall. This indicator was preferred over the more commonly used Standard Deviation, because it is much easier to compute, an advantage which reduces the danger of calculating errors. But there are also a large number of stations in East Africa where the Standard Deviation is not a truly representative indicator of variability, because the frequency distribution of the annual rainfall totals is skew, usually positively. This skewness is caused by a few extraordinary high values. It can be measured by comparing the mean to the median rainfall over the same period. At most stations in East Africa these two indices differ only a few per cent, but in some drier parts the mean may exceed the median by as much as 19 per cent (Wajir – 19%, Athi River – 17%; Kijabi Mission – 13%; Machakos – 12%). At these stations the use of the Standard Deviation and the annual mean would indicate a rainfall variability which is much too low.

The Inter Quartile Range was computed at 194 East African stations over the period 1931–1960, for which published records are available *(East African Meteorological Department,* 1965, 1966). The distribution of these stations over the region is rather uneven (Fig. 3). A comparison with an annual mean rainfall map reveals that the wetter parts of East Africa are well represented, while the drier areas are poorly covered (*East African Meteorological Department,* 1971). There is, therefore, a bias in the sample of stations towards the wetter ones. On the other hand, the wetter parts of the region are those where agriculture is most intensive and productive and where, consequently, the rural population density is highest (NIEUWOLT, 1977). The distribution of the stations follows, in a very general way, the population distribution and general agricultural development of East Africa.

It was found that a number of stations showed rather exceptional values of the Inter Quartile Range, when compared with neighbouring stations. These inconsistencies are, of course, the result of local factors, and they are often caused by the strongly localized character of convectional rainfall, which constitutes a large proportion of the total precipitation in most of East Africa. These exceptional values were disregarded when they occurred at only one station in an area, and therefore a fair amount of generalization was used when draughting the map (Fig. 4). Nevertheless the distribution of the Inter Quartile Range in East Africa shows a complicated pattern. Low values below 200 mm occur in the northeast, west and central parts of the region. High values, over 300 mm, prevail in the eastern coastal areas, the southern parts, the Lake Victoria region and some of the Central Highlands of Kenya.

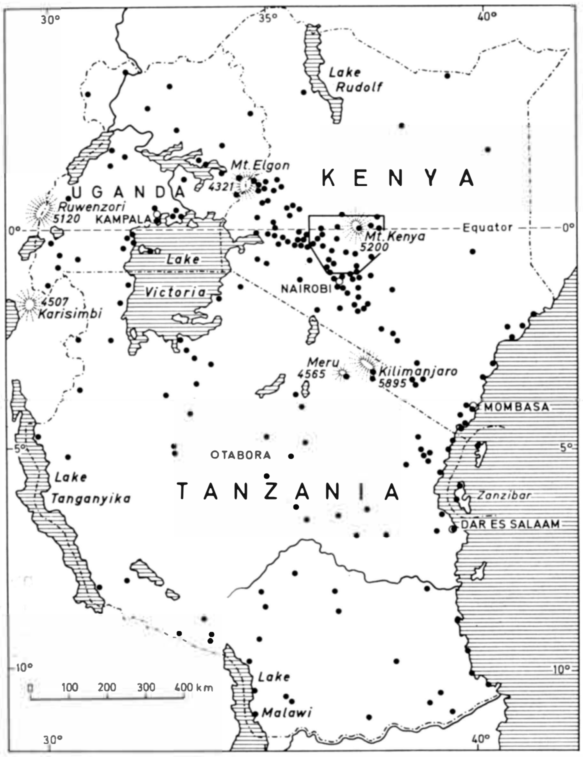

Fig. 3: Location of stations used in the computation of rainfall variability indicators

Relative Rainfall Variability

The absolute rainfall variability may produce misleading impressions regarding its general significance. An absolute variability of 200 mm is a very serious matter at a station where the annual mean rainfall is in the order of 400 mm, but it is of little consequence where the annual total is about 2000 mm. It is therefore often more relevant to compare the absolute variability to the average rainfall by indicating the relative rainfall variability.

The relative variability of annual rainfall can be expressed as the Quartile Deviation (which is half the Inter Quartile Range) in percents of the median annual total (Fig. 5). In the construction of this map again some exceptional values had to be disregarded, but the number of these cases was smaller than for the absolute variability map.

The relative rainfall variability shows a rather clear distribution over East Africa. High values prevail in the northeastern and central areas, while low values occur mainly in the western parts. These variations can be explained by the main wind and pressure systems over the region, in relation to some major surface features.

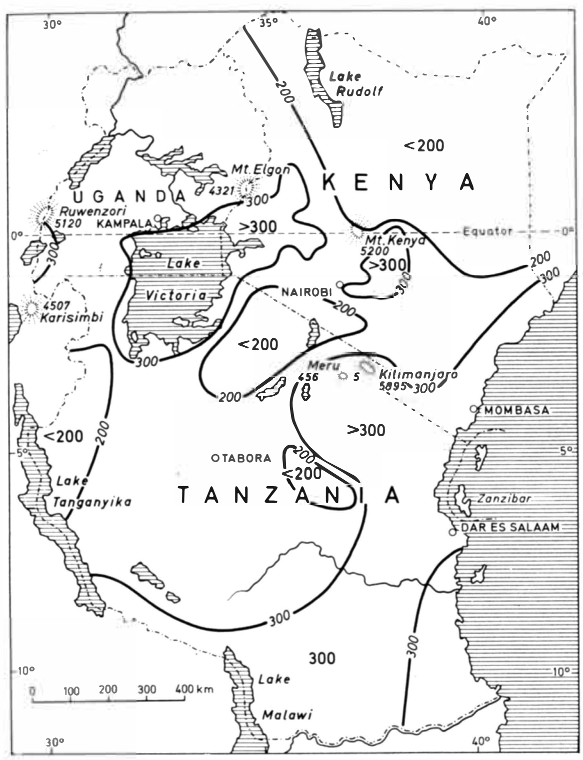

Fig. 4: East Africa: absolute variability of annual rainfall (Inter-Quartile range (mm))

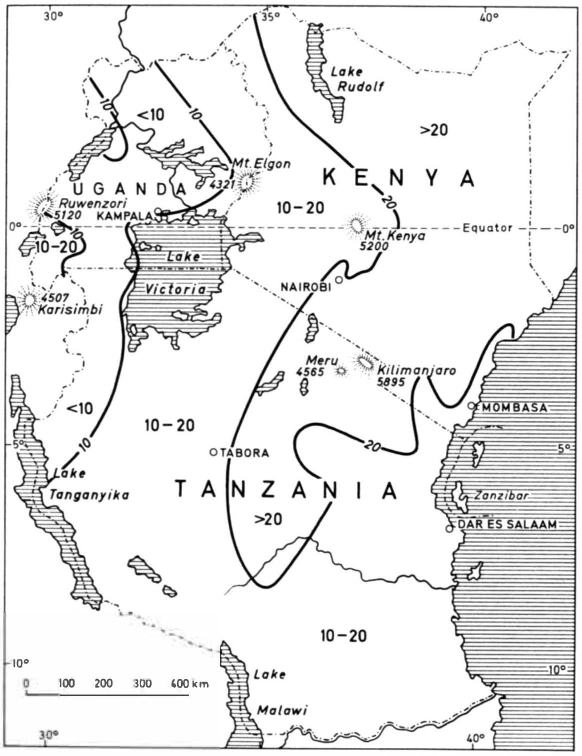

Fig. 5: East Africa: relative variability of annual rainfall (Quartile Deviation in % of median)

The prevailing wind direction in East Africa during most of the year is easterly, varying between northeast and southeast in the two main monsoon seasons. These easterly winds come directly from the relatively warm Indian Ocean, bringing large amounts of water vapour in their lowest layers. These produce dependable rainfall conditions over most of the coastal areas. Only in the northern parts of the coast, where both monsoon winds arrive after longer journeys over land, the rainfall is less reliable, as shown by the higher relative variability. The same condition applies to central Tanzania and northeastern Kenya, where the monsoons bring little rainfall and a high relative variability prevails. Exceptions are the mountainous regions, where orographic lifting and convectional rainfall over slopes produce more reliable precipitation.

In the western parts of East Africa, a fair proportion of rain is caused by intrusions of air streams from the west. These bring air masses which are moisture laden as they have moved over the dense vegetation of the Congo Basin. These westerly air masses frequently converge with easterly air streams in the Rift Valley Convergence Zone, which is centred around Lake Victoria, where a quasi-permanent low pressure area prevails (Flohn, 1965). The reliable rainfall caused by these air movements in the western parts of the region decreases towards the east, though there is some reactivation of the rain-producing processes over the Kenyan highlands, which explains the eastward bulge of the 20% isolines to the east of Lake Victoria (Fig. 5).

Apart from these large-scale influences, the mountains in East Africa, which normally receive more rainfall than the surrounding lowlands, seem not to be favoured with a lower relative rainfall variability, and the same applies to the areas around Lake Victoria.

Correlations with Median Rainfall

A comparison of the two variability maps with a map of mean or median annual rainfall shows a general similarity in the distribution patterns over East Africa. Where the average rainfall is high, as in the western parts of the region and the highlands, the absolute variability is also high, while the relative variability is generally quite low. In the drier parts of East Africa, for instance northeastern Kenya and Central Tanzania, the absolute variability is low and the relative one is high. There exists, therefore, a general correlation between average rainfall and the two variability indicators.

The regression equations for these correlations are:

Absolute Variability:

$$\text{I.Q.R.} = 125 + 0.18 \times \text{Median} \quad \text{(mm)}$$

Relative Variability:

$$\frac{\text{I.Q.R.}}{\text{Median}} = 22.45 + \frac{8740}{\text{Median}} \quad (\%)$$

For both equations $n = 194$ and the correlation coefficients are $+0.57$ and $+0.45$ respectively, which indicate a statistical significance at better than the 99.9% level.

Departures from these regression equations at individual stations indicate whether the rainfall variability is above or below 'normal', when compared to East Africa as a whole. The distribution patterns of these residuals from the two equations were remarkably similar, so that only one is shown here (Fig. 6). Positive residuals prevail in the east, while negative residuals occur mainly in the western parts of the region, with the exception of small areas around Lake Victoria, near Lake Nyasa and over the Central Kenyan highlands. The dividing line between the two major zones coincides with the one produced in an earlier study of isonomals of the relative variability (Griffiths, 1959).

The conclusions mentioned before are confirmed: both the mountains and the area around Lake Victoria stand out as having a higher rainfall variability than could be expected on the basis of their median annual rainfall.

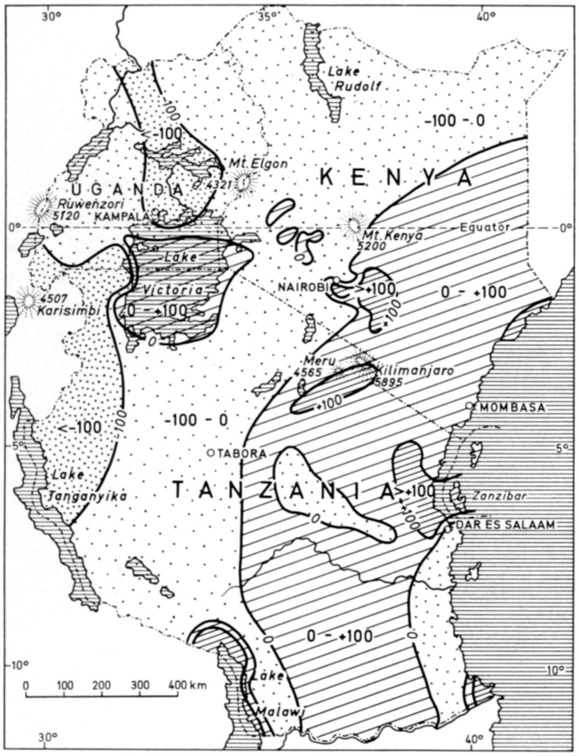

Fig. 6: East Africa: residuals from the equation I.Q.R. = 125 + 0.18 × Median (in mm)

Local Variations

As indicated, local factors cause exceptional variability figures at some stations in East Africa. Of these local factors, landforms are the most important ones. They can cause orographic rainfall and rainshadow effects which strongly affect the rainfall variability. As far as these influences are concerned, relief features have two main components: exposure and elevation.

For a more detailed study of these local effects, an area in the Mount Kenya and Aberdare Range region of Central Kenya was chosen, because here reliable and comparable rainfall data were available at 34 stations. The location of these stations in relation to the main landforms is shown in Fig. 7. The location of the study area is indicated on Fig. 3.

Median annual rainfall and variability maps for this area failed to show a clear pattern of distribution. This is probably caused by small-scale differences in exposure, which cannot be shown on maps of this size. To test this conjecture, a model was constructed of a hypothetical mountain with purely circular contour lines, on which each station was located according to its elevation and the main direction of exposure, as determined on topographic maps of the scale of 1:250,000. Then the various rainfall indicators for each station were plotted on the map. Both the median

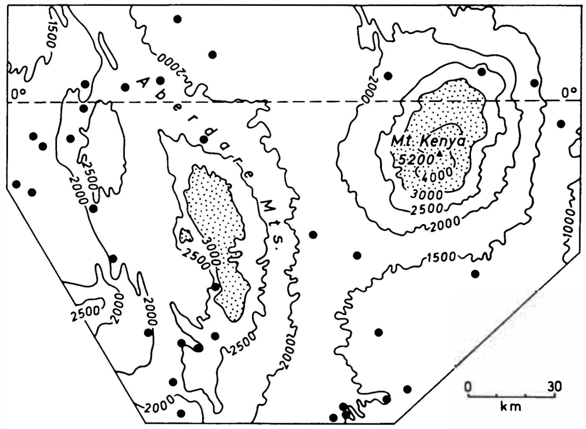

Fig. 7: Location of 34 rainfall stations in Central Kenya, used to study local differences in rainfall variability. Contour lines in metres, areas over 3000 metres shaded.

rainfall and the absolute variability showed little more than a general increase with elevation, and no effect of the direction of exposure. The data for relative variability, however, showed a clear difference with exposure: on the southeastern slope of the model values were clearly lower than at comparable levels on the other slopes (Fig. 8). The small number of stations with northwestern exposure prevented the drawing of conclusions regarding this direction. On all slopes the relative rainfall variability decreased with elevation, as was expected.

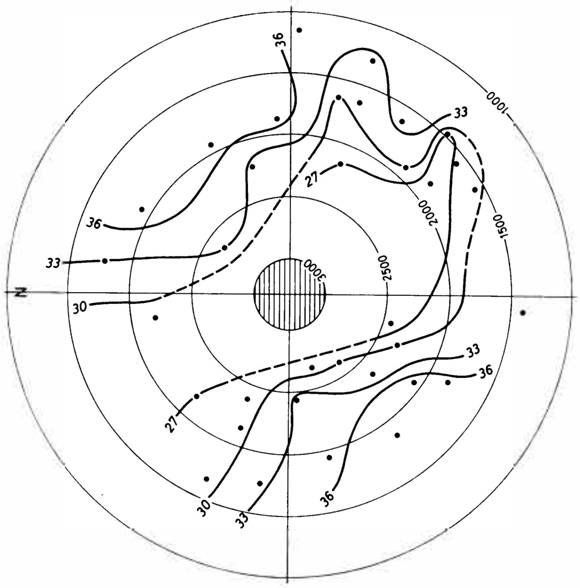

Fig. 8: Relative variability (I.Q.R. in % of Median) of annual rainfall at the 34 stations as shown on the relief model.
Contour lines in metres.

The results of this study were confirmed by data from the Mt. Elgon and Kilimanjaro-Mt. Meru areas, but the number of stations in these two regions is too small to draw definite conclusions.

Drought Frequencies

One consequence of rainfall variability, which is of special interest to agriculture, is the occurence of periods with much less than the normal rainfall. These periods, or droughts, may be of different duration and intensity. They cannot be identified from annual rainfall totals, because an annual figure may conceal a relatively long drought, if it was preceded or followed by some wet periods during the same year. Therefore monthly rainfall figures must be used to indicate droughts.

There exists no generally accepted quantitative definition of a drought, but it should be based on the ratio between actual rainfall and the amount that may normally be expected. For example, a month with a total rainfall of 50 mm will cause no limitations in agricultural production at a station where the normal average rainfall for that month is also about 50 mm, since all agricultural activities are geared to this amount. Yet this same total of 50 mm will cause severe restrictions at a station where normally about 250 mm of rainfall is received during the same month.

In this paper a drought is defined as a month during which rainfall was less than 50 percent of the long-term mean (based on the period 1931–1960). An exception is made for months during which rainfall was 100 mm or more. Even if this amount is less than half the mean, it will almost never create restrictions in any form of agricultural production, and therefore months with rainfall above this limit were not considered droughts.

The frequency of drought months was computed for the period 1931–1960 at 167 stations in East Africa where rainfall records were fairly complete. However, in this computation all months with a mean rainfall below 50 mm were excluded. It is assumed that agriculture during these normally dry months is based on soil moisture or irrigation, or will be in a stage where the water requirements of the crops are minimal, as for instance during the ripening stage of grain crops. Also, for purposes of water supply, the rainfall during these months is of little significance. Therefore, even if no rainfall at all is received during these months, the consequences will generally not be serious, and these months cannot be considered as droughts.

The limit of monthly rainfall of 50 mm has been used before to define the agricultural growing season in East Africa (Griffiths, 1969, 1972). The number of months above this limit varies strongly over East Africa and gives a general indication of the agricultural possibilities as far as they are controlled by the length of the period of sufficient rainfall (Fig. 9).

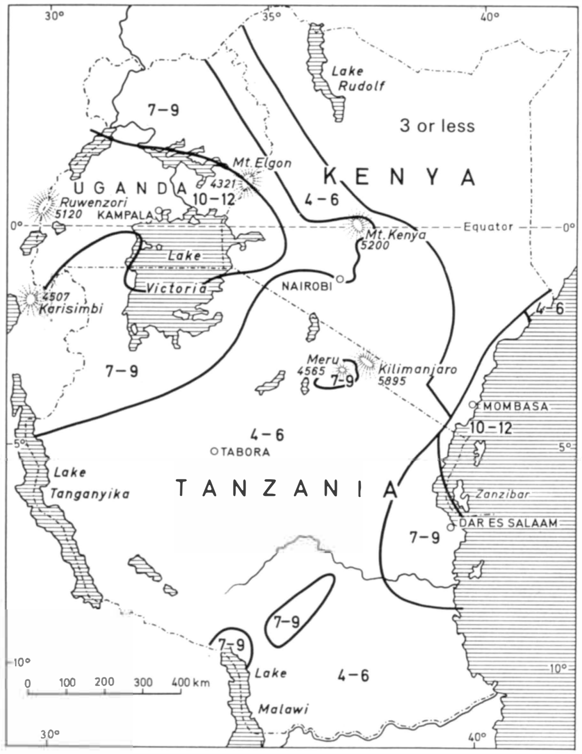

Fig. 9: East Africa: number of months with a mean rainfall over 50 mm

The mean frequency of drought months per year shows a simple pattern over the region (Fig. 10). Most of East Africa experienced between 1 and $1^1/_2$ drought months per year. Higher values occurred only along the East Coast and in an area to the north and east of Lake Victoria, while lower values are limited to southern and western Tanzania.

It is interesting that the distribution of the frequency of drought months shows little similarity to that of the variability of annual rainfall (Fig. 4, 5). This may largely be due to differences in the number of months under consideration, as only those with a mean rainfall over 50 mm were taken into account.

These effects of different lengths of the agricultural growing season were removed by expressing the frequency of drought months as a percentage of the total number of months considered (Fig. 11). The figures on this map indicate the probability that a month with a mean rainfall over 50 mm will receive less than half of its mean rainfall (or less than 100 mm). The area distribution of these percentages is rather similar to that of the relative variability of annual rainfall (Fig. 5). On both maps the highest values occur in the dry parts of East Africa, notably northeastern Kenya and Central Tanzania, while low values prevail in the southern and western parts of the region.

Because of this similarity, the correlation between these two sets of data was computed. For n = 162, the correlation coefficient r = +0.59. While this shows a statistical significance at the 99.9% level, it should be remembered that the coefficient of determination r^2 = 0.35, to that the relative variability explains only about one third of the variations in drought frequency. Obviously this relationship is therefore of only limited value in the prediction of droughts.

In these data the seasonal occurrence of droughts is, of course, not reflected. A drought month at the beginning of the growing season has usually much more serious effects than one towards the end of the growth cycle. However, growing seasons in East Africa differ so much, not only with location but also with the various crops and agricultural techniques, that it proved impossible to quantify these effects.

Drought Persistence

The effects of a drought become much more serious when it extends over more than one month, as is frequently the case in East Africa. In an effort to quantify these effects, the following arbitrary scale of persistence points was devised after consultation with agricultural officers and planters in Kenya:

duration in months	persistence points
2	1
3	3
4	6
5	10

This scale implies that a drought lasting 5 consecutive months has effects which are about ten times as serious as one which continued only during two months. It is obvious that the values on this scale cannot be realistic in estimating drought damage in all different forms of agriculture. In particular, tree crops will be able withstand long droughts much better than annual crops. Soil and drainage conditions also strongly influence the effects of droughts which persist over a number of months. The above scale must therefore be considered as a first approach to indicate the effects of drought persistence.

The total number of persistence points at each station depended on the total number of drought months recorded. As it was intended to quantify the persistence tendency only, an index was computed for each station:

Persistence Index =

$$\frac{\text{total number of persistence points}}{\text{total number of drought months}} \ (\%)$$

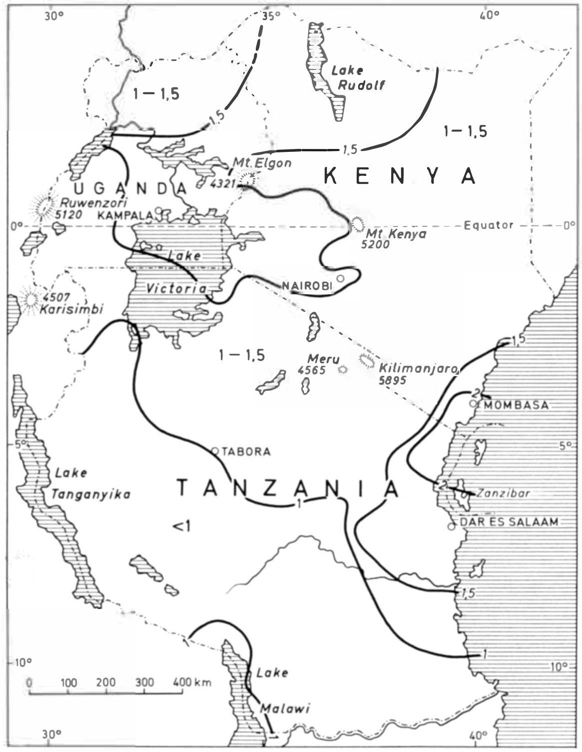

Fig. 10: East Africa: frequency of drought months per year (1931–1960)

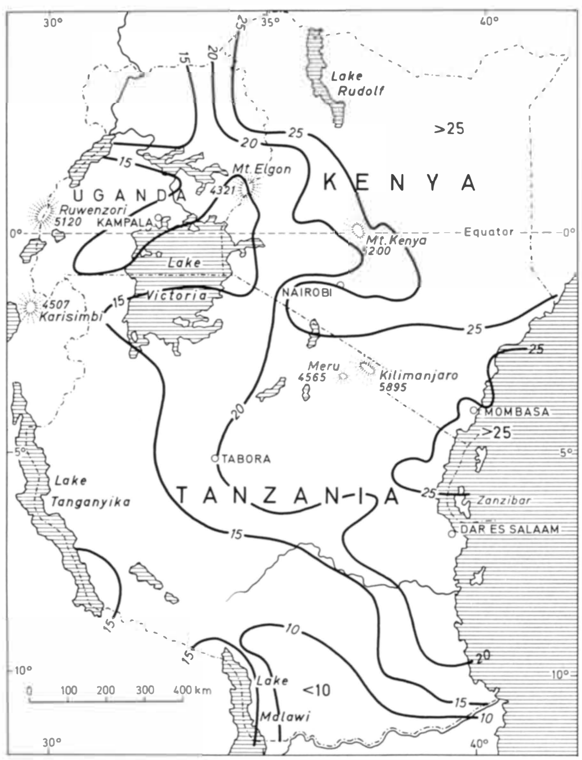

Fig. 11: East Africa: Drought frequency in % of all months with a mean rainfall over 50 mm (1931–1960)

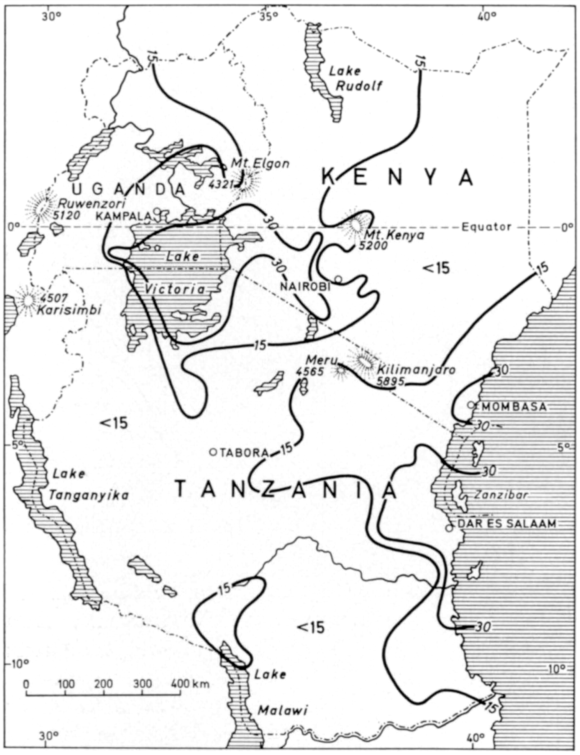

Fig. 12: East Africa: Persistence Index of droughts

$$= \frac{\text{persistence points}}{\text{total drought months}} \, (\%)$$

and the distribution of this index was mapped (Fig. 12). The distribution over East Africa shows two areas of high values: near the East Coast, and to the north and northeast of Lake Victoria. Both these areas are characterized by long rainy seasons (Fig. 9). They differ, however, in the frequency of droughts: the coastal areas have frequent droughts, but these are much rarer near Lake Victoria (Fig. 11). This means that droughts, once established over the latter region, will often persist for more than one month.

There exists also some similarity between the distribution of the persistence index and that of the Inter Quartile Range (Fig. 4). Clearly a strong absolute variability is often correlated with drought persistence.

Conclusions

Maps of the rainfall variability in East Africa indicate that the western parts are favoured with less variable rainfall than the rest of the region. Droughts are also less frequent.

Mountainous regions, which generally receive more rainfall than the surrounding lowlands, have similar variability figures, constituting positive departures from the normal correlation between median rainfall and variability. The same situation prevails in areas around Lake Victoria.

Locally, rainfall variability tends to decrease with elevation and southeastern slopes are generally favoured with lower variability than slopes facing other directions.

Drought frequencies and persistence of droughts follow similar patterns as the variability indicators, but the correlations are not strong enough to be of help in predicting drought probabilities.

Acknowledgement

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