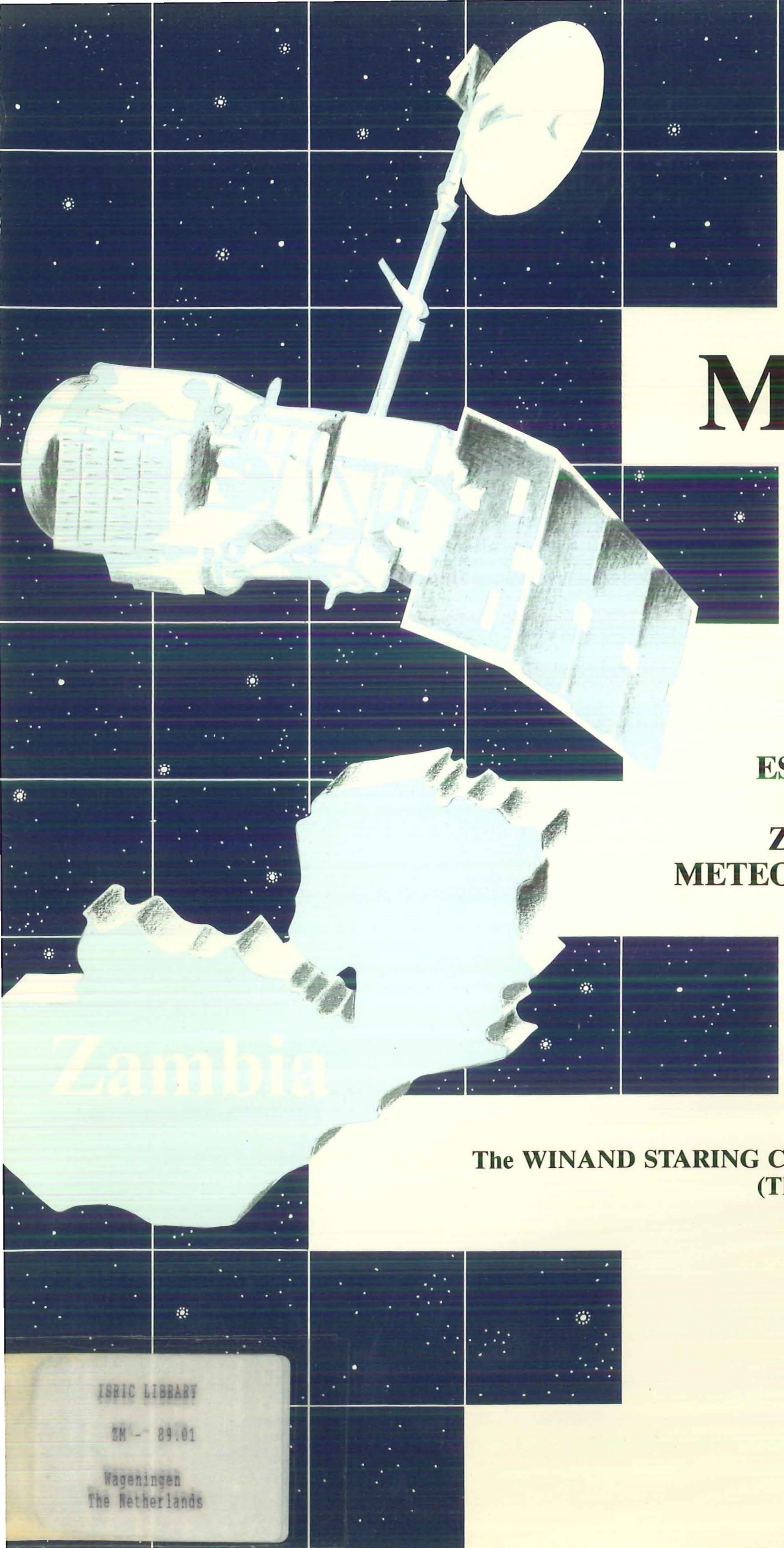

MARS

Monitoring Agro-ecological Resources with Remote sensing & Simulation

ESTIMATION OF RAINFALL IN ZAMBIA USING METEOSAT-TIR DATA

REPORT 12

The WINAND STARING CENTRE, Wageningen (The Netherlands), 1989

Estimation of rainfall in Zambia using METEOSAT-TIR data

This research has been financed by the Netherlands Remote Sensing Board (BCRS), Delft, The Netherlands.

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J. Huygen

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ABSTRACT

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In this report the results are presented of investigations on the development and validation of algorithms to map rainfall with METEOSAT data in Zambia.
The results shown indicate that it is not possible to apply simple linear relationships to relate the duration of cold cloud top, as obtained with METEOSAT, to dekadic rainfall. The coefficients of these relationships are time-dependent, so similar validation and calibration studies are to be continued for the approach to achieve full operational status.

Keywords: METEOSAT, thermal infrared, rainfall mapping, cold cloud duration, ARTEMIS, Zambia.

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Project 370.50 [REP/12]

CONTENTS

PREFACE

Rainfed, traditional agriculture in marginal and fragile ecosystems is highly sensitive to meteorological vagaries. Timely information on weather conditions and vegetation growth throughout the growing season is a useful contribution to achieve food security.

The objective of the MARS project is to establish a link between the data provided by meteorological satellites and the operational requirements of crop yield forecasting at national level. In many countries like Zambia rainfall observations are sparse. So satellite data, like the measurements of thermal infrared radiation collected by means of the METEOSAT satellite, can contribute to improve rainfall monitoring nationwide.

In this report the results are presented of investigations on the development and validation of algorithms to map rainfall with METEOSAT data in Zambia. The results shown indicate that it is not possible to apply simple linear relationships to relate the duration of cold cloud top, as obtained with METEOSAT, to dekadic rainfall. The coefficients of these relationships are time-dependent, so similar validation and calibration studies are to be continued for the approach to achieve full operational status.

The study presented in this report forms part of MARS, a demonstration research project on the combined use of simulation models, earth observation satellite and meteorological satellite data on behalf of a National Early Warning System in Zambia. MARS is executed by the Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands.

Sincere thanks are due to Drs. J. Berkhout and Dr. M. Menenti, the initiators of the rather complex MARS project.

In prepairing this report heavy use is made of MARS PPDS Annex 4: Jacobs, C.M.J., 1987. Preliminary report on the applicability of the METEOSAT-system in rainfall mapping over Zambia.

Kriging and cokriging routines were kindly made available by: Dr. A. Stein of the Department of Soil Science and Geology, Agricultural University, Wageningen.

SUMMARY

The Department of Meteorology at the University of Reading (UK) has developed a method for the estimation of dekadic (dekad = 10-day period) rainfall from METEOSAT-TIR (Thermal InfraRed) data through the determination of Cold Cloud Duration (CCD).

To assess the operational aspects of applying the CCD-technique on behalf of Early Warning on Agricultural Resources in Zambia, two months of METEOSAT-TIR data (January, February 1987) have been processed to obtain dekadic CCD-values. The CCD-values have been determined for different threshold temperatures, i.e. -40, -50 and -60°C, using 24 and 48 METEOSAT-TIR images (slots) per day. The dekadic CCD values have been calibrated with measured dekadic rainfall for the 33 stations that comprise the synoptic meteorological network of Zambia by linear regression.

Rainfall can also be estimated by:
(i) kriging the ground based rainfall observations;
(ii) cokriging the METEOSAT-TIR data and rainfall observations.
To assess the performance of the three rainfall estimation methods, for each of them the relation between the measured rainfall and the estimated rainfall for 24 meteostations and for one dekad has been established.

The conclusions of this investigation can be summarized as follows:

- Because of the need to recalibrate in the course of time, the ARTEMIS system should not deliver estimated rainfall maps based on fixed algorithms, but rather raw CCD-maps, possibly for different temperature thresholds, but certainly for a threshold of -40°C.
- To interpolate raingauge measurements with the help of METEOSAT-TIR imagery, two very usable methods i.e. linear regression and (co)kriging are available.

For situations where the raingauge network is sparse, like in Zambia, the linear regression method is preferred. Contrarywise, when a more dense meteostation network exists, a fair chance should be given to cokriging. If, for some reason METEOSAT images are not available: kriging is a worthy alternative under such conditions.

1 INTRODUCTION

The objective of the Zambian Crop Forecasting and Early Warning Unit is to provide timely and accurate information on expected crop production and food supply. Crop production can be estimated by multiplying the estimation of the hectarage of crops grown with the estimation of the actual crop yield per ha, especially with reference to the crop yield reduction due to unfavourable weather (rainfall) conditions. Meteorological observations in Zambia are carried out at only 33 main meteorological stations, reporting daily. To monitor the rainfall conditions with sufficient detail, the density of the meteostation network must be considered too low.

The same situation happens in several other African countries and a solution seems to be the use of data provided by the European METEOrological SATellite METEOSAT. Therefore FAO has installed the so called ARTEMIS system at their headquarters in Rome, an integrated system that is capable of real-time acquisition of METEOSAT data and processing the imagery from METEOSAT and NOAA satellites.

With respect to rainfall monitoring the ARTEMIS system produces the following main data products:
- a CCD-map, based on one threshold temperature;
- the estimated rainfall map (per dekad and month) for those areas where the relation between CCD and rainfall is known;
- the number of estimated rainfall days map (per dekad and month).

The spatial resolution of the maps is 7.6 km.
The rainfall estimation method applied by ARTEMIS has been developed by the Department of Meteorology at the University of Reading (UK) and is based on relating cloud top temperature below a certain threshold value to actual rainfall (Milford and Dugdale, 1987).

In this report several aspects of the application of this method in Zambia will be explained.
The report starts with a description of the synoptic climatology of Zambia (chapter 2) followed by a chapter covering the climatological aspects of rainfall including characteristics of rainfall events and rainfall variability (chapter 3). Chapter 4 is the main chapter and treats the estimation of rainfall using METEOSAT-TIR data. The full procedure to calibrate a CCD map with the help of raingauge measurements is described in the APPENDIX. In addition the FORTRAN source code of a program called RDCCDMAP, that first performs the calibration and thereafter can be used to estimate rainfall on any user specified location is given.

In his report Jacobs (1987) suggests that the Reading method cannot be applied directly in Zambia without considerable problems and that a satellite based rainfall estimation procedure in Zambia should contain:
- a cloud classification to identify rainbearing clouds;
- a delineation of the rainfall area within the rainbearing clouds;
- a classification of airmasses and/or a measurement of the moisture content of the air;
- the establishment of threshold values depending on the characteristics of the air;
- the incorporation of cloud dynamics.

However such a system is hard to implement on an operational basis because it is much too labour-intensive. Of course there is always a trade off between the desirable and the feasible. Several of the above mentioned aspects of an ideal system are touched in the report of Smit and Simons (1988). They have interpreted METEOSAT images visually to study cloud dynamics and they have analysed synoptical meteorological data provided by the European Centre for Medium-range Weather Forecasts (ECMWF) in Reading in order to investigate the possibility of distinguishing the different airmasses that converge over Zambia and to assess the rain bearing potential. At the end of chapter 4 an interesting method is presented to interpolate the existing raingauge network without or with additional support from METEOSAT data. The method stems from the field of mining geostatistics and is called (co)kriging.

In summary: scope of this study is to assess the usability of ARTEMIS products for rainfall monitoring in Zambia and if these products are found to be suboptimal, give guidelines for the design of improved future ARTEMIS products.

2 GENERAL FEATURES OF THE CLIMATE

2.1 Geography

The climate of Zambia can be explained on the basis of the movement of air masses, but since air masses are modified by the underlying earth's surface and since many aspects of local climate are influenced by local topography, no explanation would be complete without consideration being given to the physical setting of Zambia within Africa (Hutchinson, 1974).
Lying between 8°S and 18°S, Zambia is subjected to those regions of the General Circulation known as the South East Trades and the Intertropical Convergence Zone (ITCZ). These idealistic zones are modified by the distribution of land and sea, although in the main these modifications are within the zones rather than displacements of them. Invasions of cold polar air are almost unknown, while temperate latitude systems rarely incurse into Zambia, although their presence further south does influence the weather. Other important features of Zambia's geography are the relative altitude of its surface (fig. 1), its continental position within the subcontinent, and on a wider scale, the lack of high mountain ranges anywhere in southern Africa.

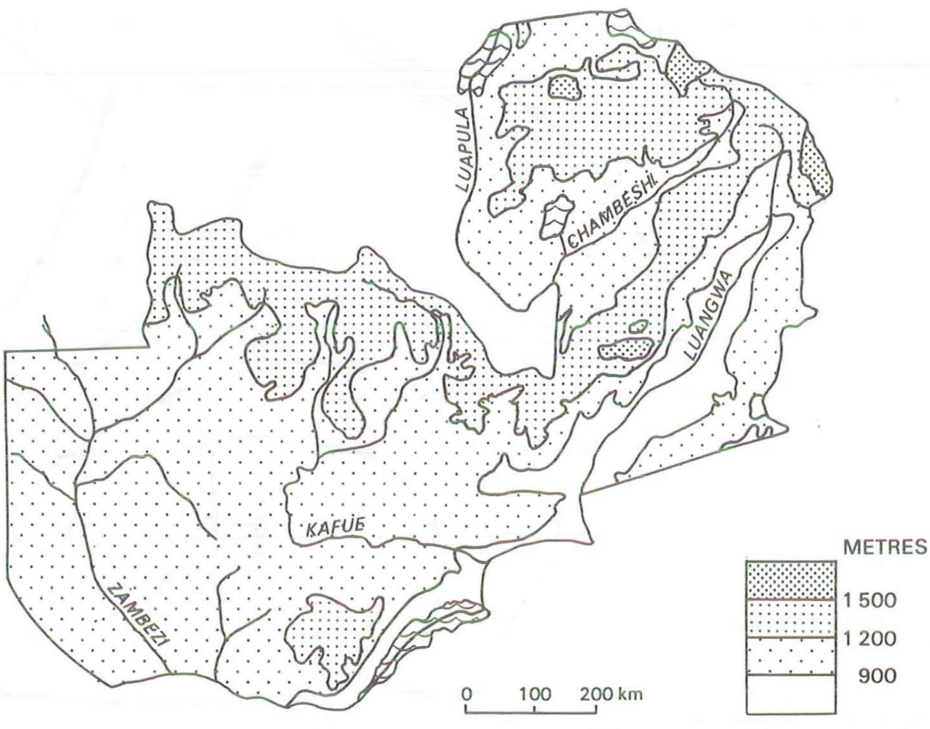

Fig. 1 Generalized relief of Zambia (Nieuwolt, 1972).

2.2 The synoptic situation

Throughout the year Zambia lies on the equatorward side of the subtropical semipermanent high pressure belt, which has three main consequences:

1) the high pressure belt acts as a buffer against travelling cyclones and anticyclones of the midlatitudes;
2) steadiness of plateau-level pressure distribution patterns, despite considerable changes in upper airstream patterns;
3) accessibility to tropical cyclones of the south-west Indian Ocean.

2.2.1 From May to September

The synoptic situation is dominated by a large and intense, semi-permanent high pressure cell (fig. 2). The centre of this cell is situated at 25°S, on the eastern part of the subcontinent and on the southern end of the Mozambique channel.
This anticyclone maintains a flow of relatively cold air from latitude 40°S, which becomes dry and stable through warming by subsidence. Under these circumstances temperatures in Zambia are relatively low, with occasionally groundfrost at night in the south-east. The air is dry and the sky usually is clear.

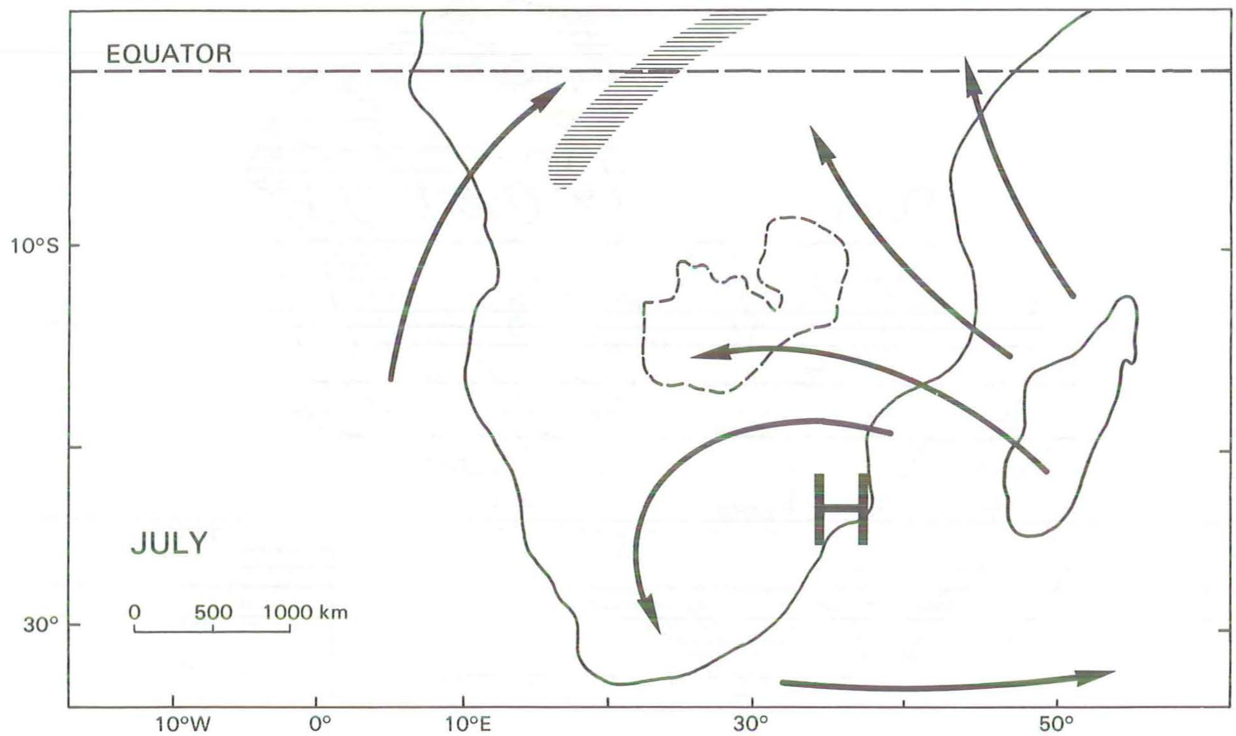

Fig. 2 The synoptic situation over southern Africa during July (Nieuwolt, 1972).

Resulting average winds most of the time are from the E-ESE and are strong compared to winds in the other seasons. The ITCZ is, of course, at this time following the sun well to the north of Zambia.

2.2.2 In October and November

In October the high pressure system weakens and, with the relative changes in land and sea temperature, tends to slip eastwards. Resulting average winds are from the E-NE and these advect moist airmasses from the Indian Ocean that partly reach Zambia (fig. 3).
The changes in relative land and sea temperatures to the west of the subcontinent have a more pronounced effect, which is the development of the Angola low, characterized by the recurvature of the south easterly trades off the west coast of Angola, and pushing from the north-west towards Zambia. The result is a very moist airmass entering Zambia from the north-west. This airmass is called the Zaire Air and its leading edge is called the Zaire Air Boundary (ZAB). Meanwhile the ITCZ is moving southwards and enters Zambia at the beginning of December from the north. The ZAB prevents the ITCZ from keeping a rather straight east-west line: moving southwards the ITCZ does not replace the ZAB, it rather curves around the ZAB, combining with it.

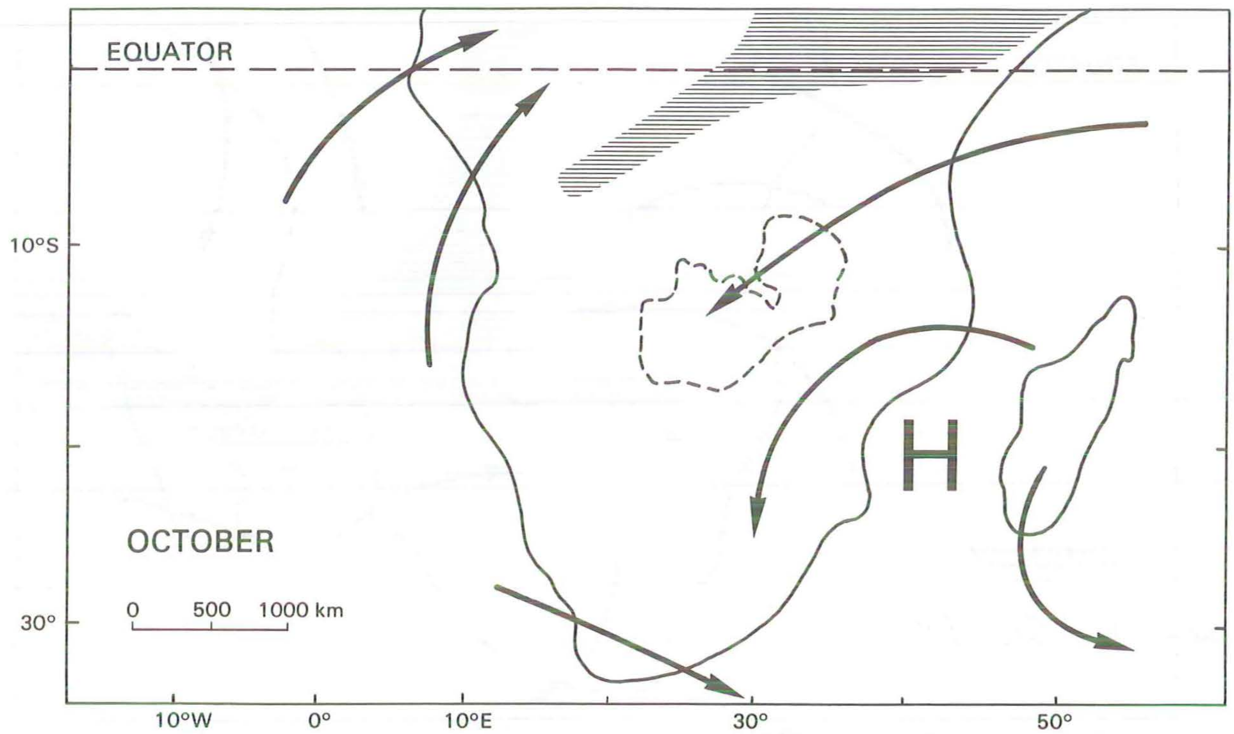

Fig. 3 The synoptic situation over southern Africa during October (Nieuwolt, 1972).

The ZAB and the ITCZ control the weather in Zambia during the rainy season. October usually is the warmest month with average maximum temperatures of 28-35°C. The combination of high surface temperatures and moist, conditionally unstable air leads to the development of convective thunderstorms, which announce the rainy season.

2.2.3 During the rainy season, December-March

By January pressure over the southern part of the subcontinent is at its annual minimum. The ITCZ is at its most southern position, which is about 17°S, and the Zaire Air covers a maximum area of Zambia. Thus three airmasses converge over the region (fig. 4):

1) tropical maritime air from the northern hemisphere, the north-east monsoon north of the ITCZ, of which the moisture content depends on its recent track over sea;
2) tropical maritime air from the southern hemisphere, the south-east trades south of the ITCZ, usually dry and stable;
3) the Zaire Air from the west and the north, usually very moist and conditionally unstable.

The position of the ITCZ and the ZAB oscillates in accordance with the passage of pressure systems at the midlatitudes further to the south. The convergence and subsequent rising of airmasses leads to the formation of clouds and can yield prolonged and heavy rainfall.

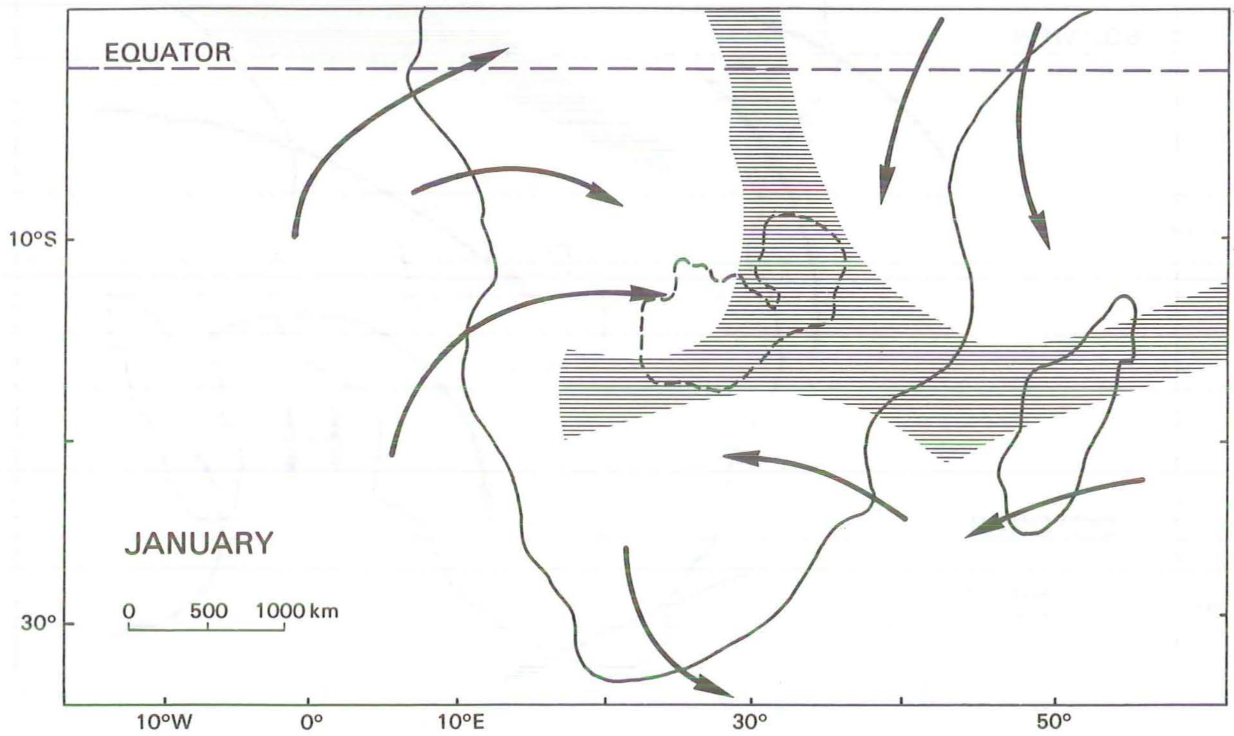

Fig. 4 The synoptic situation over southern Africa during January (Nieuwolt, 1972).

2.2.4 In April

The synoptic situation in April (fig. 5) is very much like the situation in October, but winds are more easterly and airmasses over Zambia are generally more stable.

The high pressure cell to the south-east of the continent starts to rebuild and moves back towards the continent. In accordance with oscillations in the rebuilding of this high pressure system, depending on passages of midlatitudinal pressure systems, the ITCZ and the ZAB start to retreat from Zambia more or less slowly. The ZAB leaves the area first, at the beginning of April. The ITCZ, broken and diffuse, exists in the very north until the end of April.

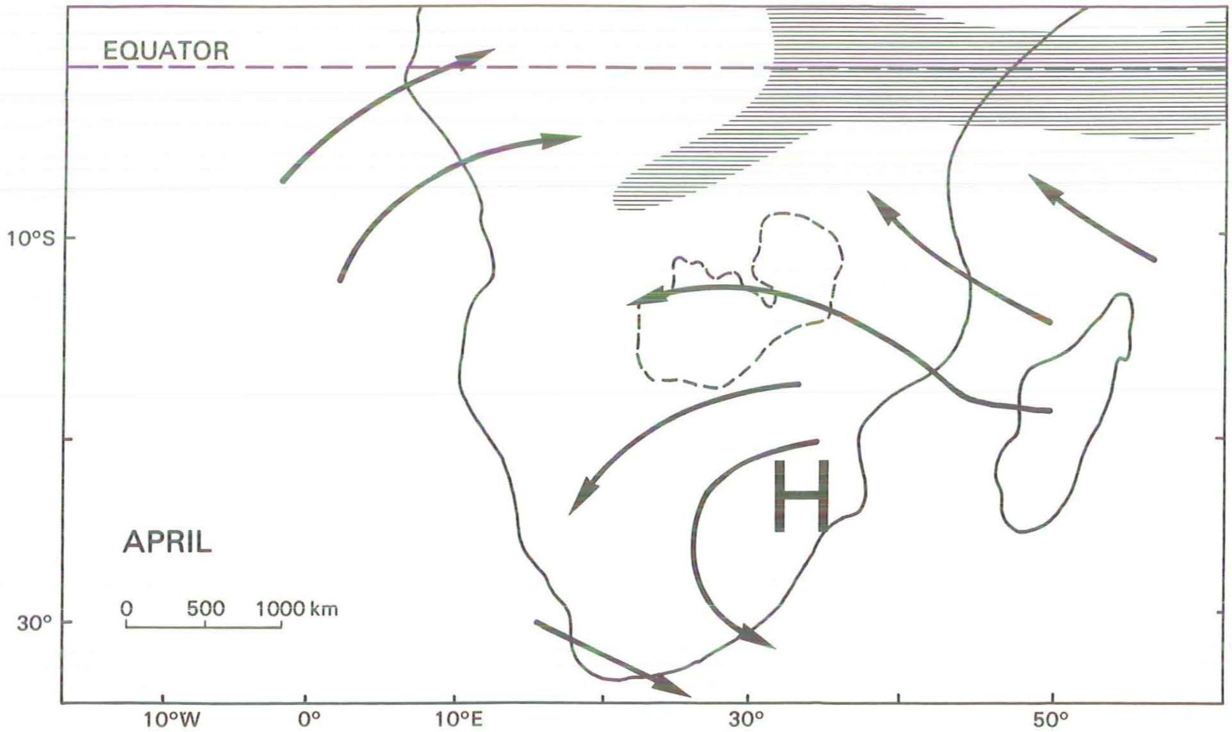

Fig. 5 The synoptic situation over southern Africa during April (Nieuwolt, 1972).

3 RAINFALL IN ZAMBIA

Although it may rain at any time of the year at any place, the majority of the rainfall (about 90%) is associated with the movement of Zaire Air and the Intertropical Convergence Zone. Because these air masses remain for longer, and their boundaries pass over more frequently, rainfall is considerably greater in the north and north-west of Zambia than in the south.
The map of annual rainfall (fig. 6) thus illustrates an approximate north-west to south-east decreasing rainfall gradient, within which, there are however, several marked anomalies.

Positive anomalies may be detected on a line between Kawambwa and Kasama and to the south of the Line of Rail between Mazabuka and Livingstone, both areas being of rather higher altitude than their surrounds. A further positive anomaly occurs around Lake Bangweulu, which has been attributed to additional atmospheric moisture being picked up from the Lake and Swamp.
A further positive anomaly occurs on the north bank of Lake Kariba. The lake causes an increase in rainfall because of a change in temperature distributions and not because moisture is added to the atmosphere. One important negative anomaly occurs in the Luangwa Valley which is an extremely well marked physical feature inducing significant atmospheric subsidence and consequent drying of the air at lower levels.

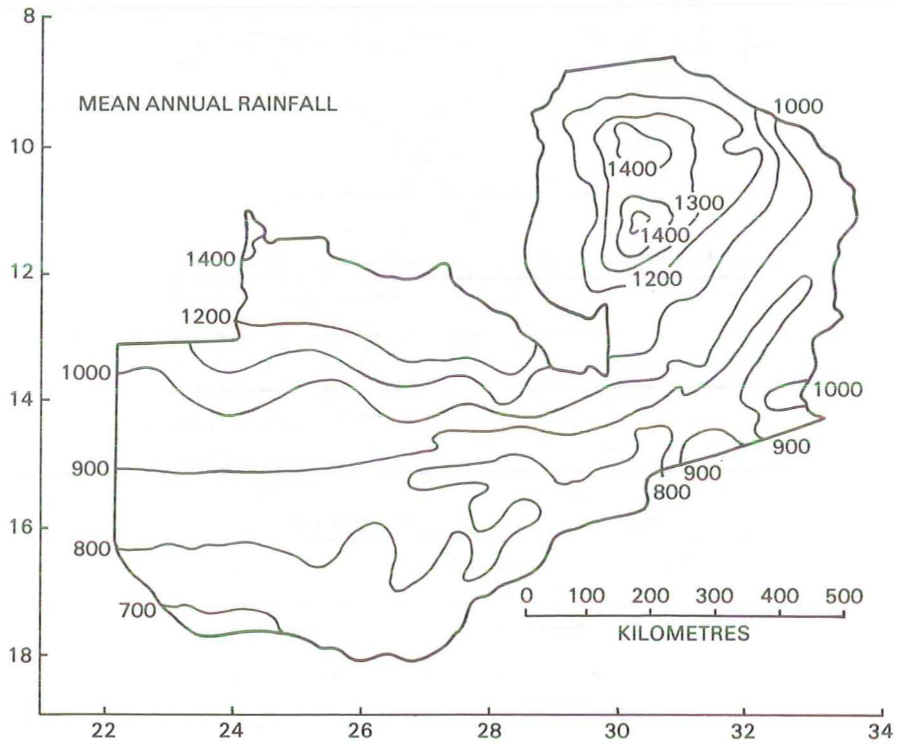

Fig. 6 Mean annual rainfall amounts in mm (Hutchinson, 1974).

3.1 Onset and retreat of the rains

The average dates of the onset of the rains is indicative of the advance of the ZAB. Appearing first to the north of Mwinilunga, on 10 October on average, the rains advance steadily south-eastwards, reaching the Copperbelt by the end of October, Lusaka by 15 November and covering the entire country by 25 November. Anomalies to this pattern and to that for the retreat can be attributed to variations in surface relief, for example in those areas already picked out before. The retreat of the rains shows a starting date of March 15th, north of Lake Kariba with a northerly movement, finally leaving Zambia by the end of April. These dates do not enclose all the rains in Zambia, as before and after isolated showers may occur, for example, due to extended cold fronts or troughs.

It would be wrong to assume that, once the season has started, rain is continuous. In some regions dry days occur on over half the days, even in the wettest months.

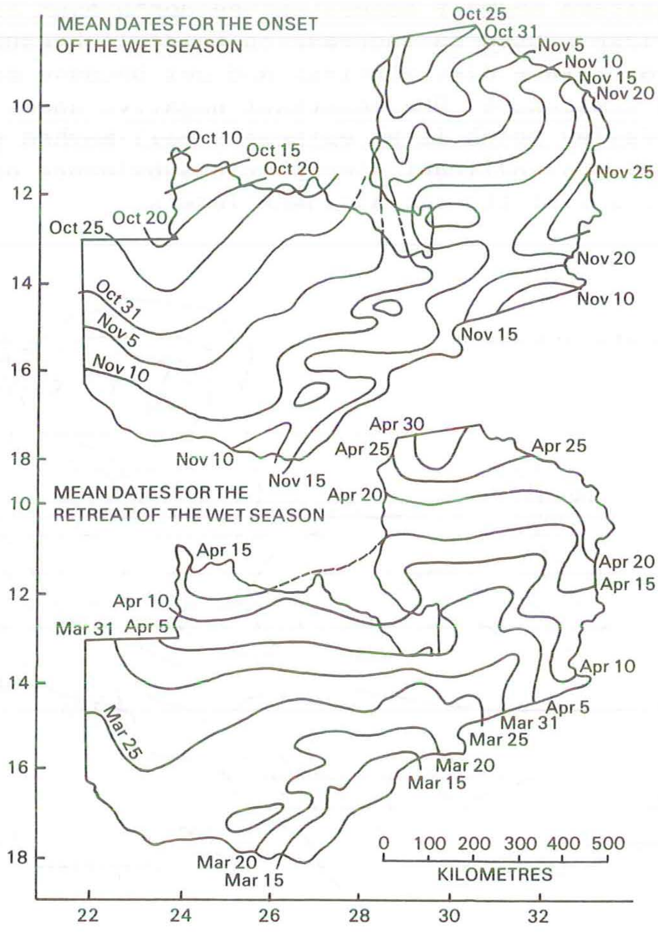

Fig. 7 Mean dates for the onset and retreat of the wet season (Hutchinson, 1974).

Because of the two passages of the ITCZ in the northern part of Zambia (one at the onset and one at the retreat of the ITCZ) the northern stations show usually two monthly rainfall maxima: generally one in December and one in March. At the time the ITCZ reaches its southernmost position (January-February) the northern stations show a slight decrease in rainfall. Southern stations show only one rainfall maximum, generally in January on the approach of the ITCZ. When the ITCZ starts to retreat to the north, rainfall steadily decreases.

3.2 Characteristics of showers

Many of the showers are accompanied by lightning and thunder. Thunderstorms are virtually limited to the rainy season, with a maximum frequency in the months December and January. The number of thunderstorm days decreases from the north (180 days a year) to the south (80 days a year).

Diurnal variation

The conventional explanation of rainfall in the tropics attributes the majority of rain to random convectional activity during the afternoon. The charts indeed show that at both Lusaka and Livingstone there is a peak between about 1200 and 1800 hours throughout the wet season, but they also show activity throughout the day and night, and a secondary peak in the early morning between 0300 and 0800 hours. The true explanation must be therefore rather more complicated than the random convectional idea, although afternoon convection is admitted to be part of the explanation. Most rainfall in Zambia occurs as a result of organised, not random, convection, due to the covergence zones i.e. the ZAB and the ITCZ. Assuming the convergence zones pass over any point in Zambia at any time of the day, there must be some physical mechanism causing intensification of activity in the early morning or afternoon.

These intensifications may be attributed to variations in the slope of the ZAB (Frost, 1971). The hypothesis is that, during the day, the Zaire Air is cool, moist and cloudy and the north-easterlies, being drier and warmer are forced to rise over the Zaire Air, producing instability and Cumulonimbus. But during the night radiative cooling of the lower layers of the north-easterlies reduces the temperature at the lower levels, hence, the north-easterlies in turn undercut the Zaire Air, at least to a depth of a few thousand feet. The result is a slight increase in rainfall activity at night. This activity is, of course, superimposed on widespread convergence and uplift along the boundary zones and it should only be considered as a reinforcement of the already existing convergence.

Size

The distribution of the cloud spectrum in the tropics with respect to size tends to be log-normal. Small clouds are far more numerous than extensive clouds (Houze and Hobbs, 1982). Thus, given the local character of the showers in Zambia, sizes of convective systems may vary from a few kilometers to a few tens of kilometers. The height reached by Cumulonimbus clouds from which lightning and thunder develop, is generally about 13-15 km and in some rare cases 16-18 km.

Lifetime

Eighty percent of the thunderstorms have lifetimes of less than 2 hours, 65% of less than 1.5 hours, 50% less than 1 hour and 33% less than 0.5 hour. Especially in February and March their lifetimes are short (Acharya and Bhaskara Rao, 1981). However steady rain may continue for some time after an initial thunderstorm as the thunder clouds degenerate into stratified layers. Light continuous rain or drizzle is also experienced under so called 'GUTI' conditions when strong, moist but stable south-easterly winds prevail over the subcontinent, giving rise to Stratus and Stratocumulus clouds.

Rainfall intensities

The amount of rainfall from a shower depends on the season and on the moisture content of the air. In more humid air precipitation from Cumulus or Cumulonimbus clouds starts at a much earlier stage of development than in drier air and rainstorms are more numerous, but less violent (Torrance, 1972). From analyses of rainfall intensities in the Kafue Basin it was deduced that intensities increased with increasing annual rainfall amounts up to about 915 mm. However, in the graphs presented by Hutchinson (1974, fig. 8) the effect of annual rainfall is hardly recognizable, especially for the longer return periods. For durations of about 60 minutes the effect is almost absent. This confirms the findings of Das (1974) that the rainfall intensities are not depending on annual rainfall amounts.

Although the graphs in fig. 8 must be used with care, it becomes clear that the rainfall intensity increases with a decreasing duration.

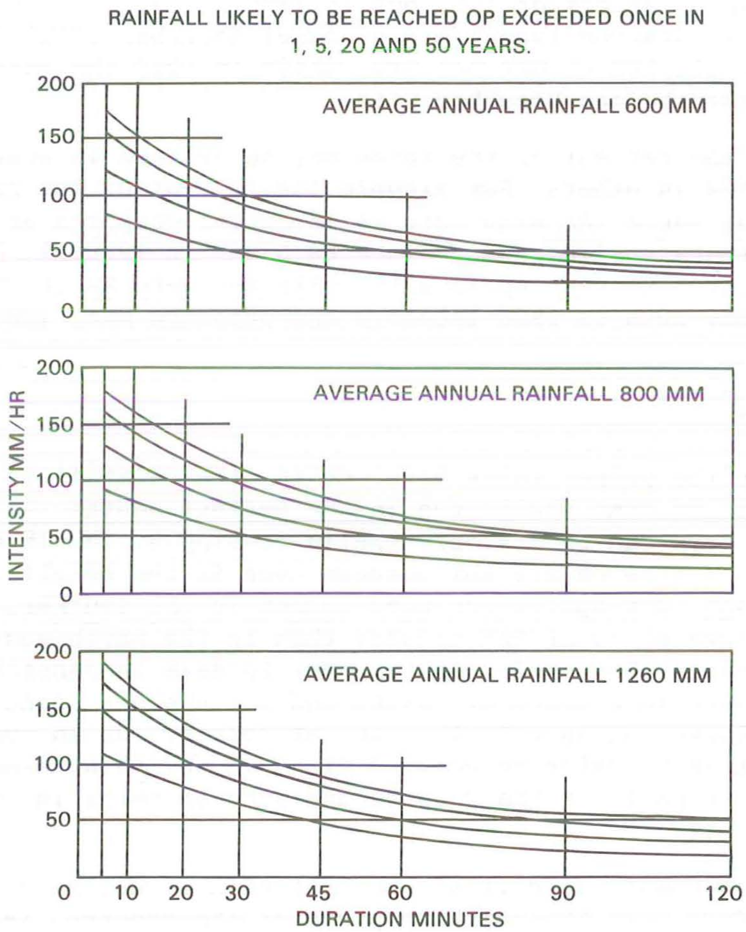

Fig. 8 Rainfall intensity duration curves (Hutchinson, 1974).

3.3 Rainfall variability

Rainfall amounts show a large spatial and temporal variation. This is rather obvious because most of the rainfall originates from convective cells. Moreover, the location and the intensity of the ITCZ and the ZAB, which highly determine Zambian rainfall, show a large variability. Although mean values of rainfall are indicative of the general rainfall regime, variations from the mean have just as important an effect on man's response to climate.

Onset and cessation of the rainy season

The onset of the rains may be delayed in some years and occur early in some others. For instance, at Mwinilunga (with October 10th as the mean date for the onset) the rains of the season 1931-1932 set in on September 1st, but in 1935 as late as November 20th. At Livingstone (mean date of onset November 15th) in 1919 the season started on October 9th, while in 1940 the rainy season did not start before December 24th.

Similarly the retreat of the rains may be delayed in some years and advanced in others. For example the retreat of the rains at Livingstone where the mean date is 16 March, occurred as early as 25 February in 1933 and as late as 5 May in 1932. At Mbala (mean date for retreat April 27th) extremes were March 30th in 1948 and May 20th in 1926 (Acharya and Bhaskara Rao, 1981).

Dry spells

Even after the proper rains have set in, the rainfall is not continuous. In some areas even in the wettest months, half the number of days can be dry. Dry spells lasting 5, 10, 15 or even 20 days at a stretch are not unknown even in the height of the rainy season. Dry spells are more common in the southern and south-western parts of the country than in the north-western and northern parts. Dry spells lasting for 10 days in January can be expected once in 2 years at Lusaka and Livingstone, once in 5 years at Mansa and once in 12 years at Solwezi. On an average one can expect such spells to occur 3 times in any rainy season in the southern parts of the country and once or twice in the northern half.

The average number of days of precipitation of 0.4 mm or more is 20 to 24 days over the northern parts of the country, 18 to 20 in the eastern parts and 12 to 14 in the extreme southern parts in each of the months of December, January and February (Acharya and Bhaskara Rao, 1981).

Hutchinson (1974) presents a simple model for the calculation of the probability of a dry spell of X days of less than 0.25 mm of rainfall a day. Under the assumption that the memory is only one day, the probability of a dry day occurring depends on whether the previous day was dry (q0) or wet (q1). Thus the probability of a run of at least X days is: q1*q0**(X-1) and a run of exactly X days: q1*q0*(1-q0)**(X-1). The probabilities q0 and q1 should be derived from climatological tables. This model should fit Zambian data reasonable well.

Seasonal rainfall variability

A gamma-distribution fits rainfall data in Zambia for most time intervals (Hutchinson, 1974 and Anonymus, 1970). For seasonal rainfall the gamma-distribution approaches a normal distribution and hence the seasonal variability (fig. 9) is well described by the standard deviation or by the coefficient of variation (cv, standard deviation divided by the mean). In Zambia cv values vary from about 15% in the north to about 25% in the south. The Department of Meteorology of Zambia (Anonymus, 1971A) calls the cv a good measure for reliability of rainfall. The probability (P) of a year with less or more than a certain amount relative to the mean (k/m) can easily be calculated using the cv. In table 1 these probabilities are given for some values of k/m and cv.

Table 1 Probabilities of the occurrence of a year with less than (<) or more than (>) a fraction k/m of the average rainfall amount.

k/m	P-values at cv =		
< or >	0.15	0.20	0.25
1.0	0.50	0.50	0.50
0.95 or 1.05	0.37	0.41	0.42
0.90 or 1.10	0.25	0.31	0.34
0.85 or 1.15	0.16	0.23	0.27
0.80 or 1.20	0.09	0.16	0.21
0.70 or 1.30	0.03	0.07	0.12
0.60 or 1.40	0.004	0.02	0.05
0.50 or 1.50	0.0005	0.006	0.02

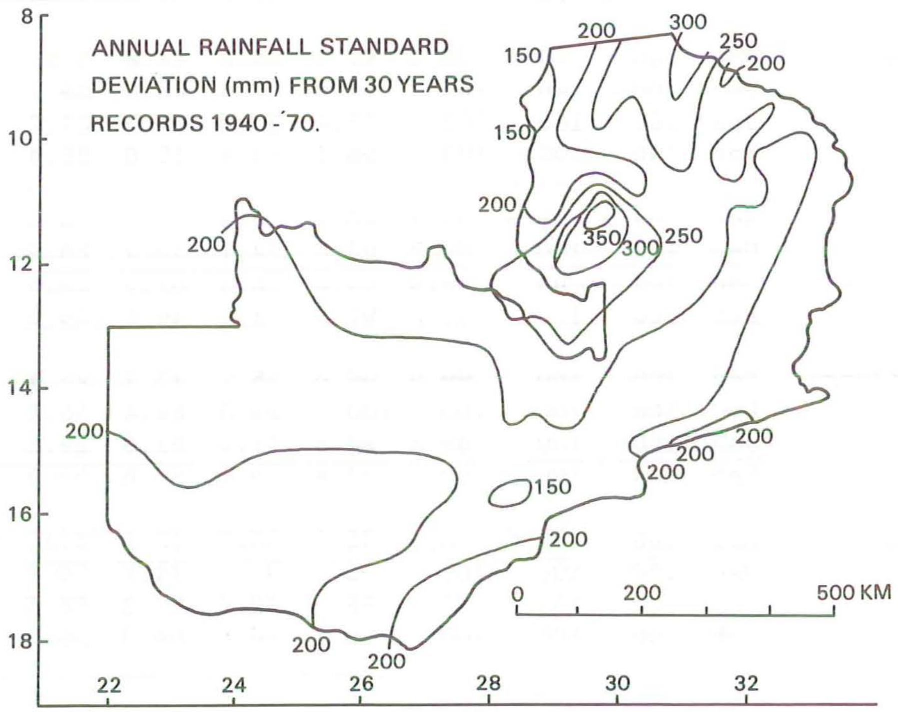

Fig. 9 Annual rainfall standard deviation (Hutchinson, 1974).

Monthly rainfall variability

Monthly totals follow a gamma-distribution. Table 2 is derived from such a gamma-distribution for various stations and gives the probability that a given amount of rainfall is exceeded. The mean is usually just under 50% of the exceedence probability value.

Table 2 Probability of the given amount of rainfall being exceeded for the stated month in any year (Hutchinson, 1974).

Rainfall in mm		12.5	25	50	100	150	200	250	400
		Probability (%)							
Chipata	Nov	96.8	89.2	69.2	34.2	14.8	6.0	2.3	0.2
	Dec	100	100	99.5	92.0	72.4	48.3	28.1	4.7
	Jan	100	100	99.9	96.3	82.6	60.7	38.6	7.7
	Feb	100	100	99.6	93.3	76.8	55.0	35.0	7.8
Livingstone	Nov	98.6	92.8	71.4	29.2	9.1	2.4	0.5	0
	Dec	99.7	98.5	92.5	71.6	49.4	30.3	18.5	4.3
	Jan	100	99.6	96.5	79.9	56.6	35.8	20.8	4.2
	Feb	99.3	97.0	89.0	67.0	45.9	29.8	18.5	5.1
Lusaka	Nov	99.2	94.6	74.8	31.2	9.6	0.8	0	0
	Dec	100	100	99.2	87.7	62.3	36.0	17.8	1.9
	Jan	100	100	100	97.2	82.2	55.9	30.7	3.4
	Feb	99.9	99.4	96.0	79.4	57.2	37.3	22.6	5.3
Mansa	Nov	100	99.6	95.2	67.7	35.2	14.8	5.3	0.3
	Dec	100	100	100	97.9	86.4	63.9	39.3	5.8
	Jan	100	100	100	98.4	86.7	61.5	34.7	3.6
	Feb	100	100	100	98.4	84.6	55.0	26.4	1.5
Mongu	Nov	99.9	98.3	85.7	40.9	12.8	3.1	0.6	0
	Dec	100	100	99.7	93.5	74.1	48.4	26.9	3.7
	Jan	100	100	99.8	94.2	76.2	51.4	29.6	4.5
	Feb	100	100	99.5	91.9	71.6	46.6	26.2	3.9
Mwinilunga	Nov	100	100	99.9	95.0	75.7	47.7	24.4	2.3
	Dec	100	100	100	100	99.5	89.4	55.9	1.8
	Jan	100	100	99.8	94.8	77.1	51.8	29.3	4.1
	Feb	100	100	100	97.8	83.7	56.6	30.2	2.8
Ndola	Nov	100	99.6	95.1	66.3	33.1	13.1	4.4	0.1
	Dec	100	100	100	99.2	92.5	74.7	50.7	9.8
	Jan	100	100	100	98.9	92.6	78.2	58.6	18.1
	Feb	100	100	100	98.1	86.8	64.0	39.1	5.9

Nieuwolt (1972) used the quartile deviation (the difference between upper quartile and lower quartile) as a percentage of the monthly mean as a variability index. The results are depicted in fig. 10. The monthly rainfall variability is relatively high for dry months and dry regions. The differences for October and April are striking: in fact one is able to follow the onset and retreat of the rainy season by regarding monthly variability indices.

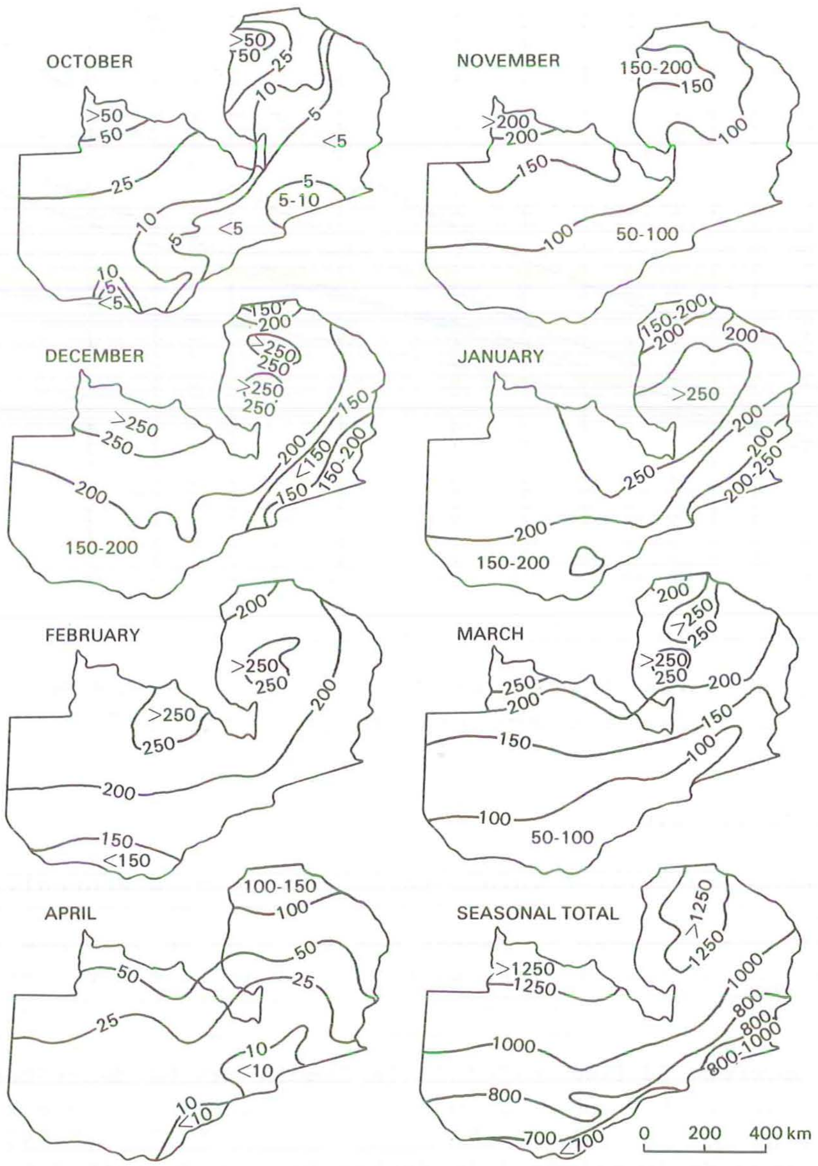

Fig. 10 Monthly and seasonal distribution of variability index, based on quartile deviation (Nieuwolt, 1972).

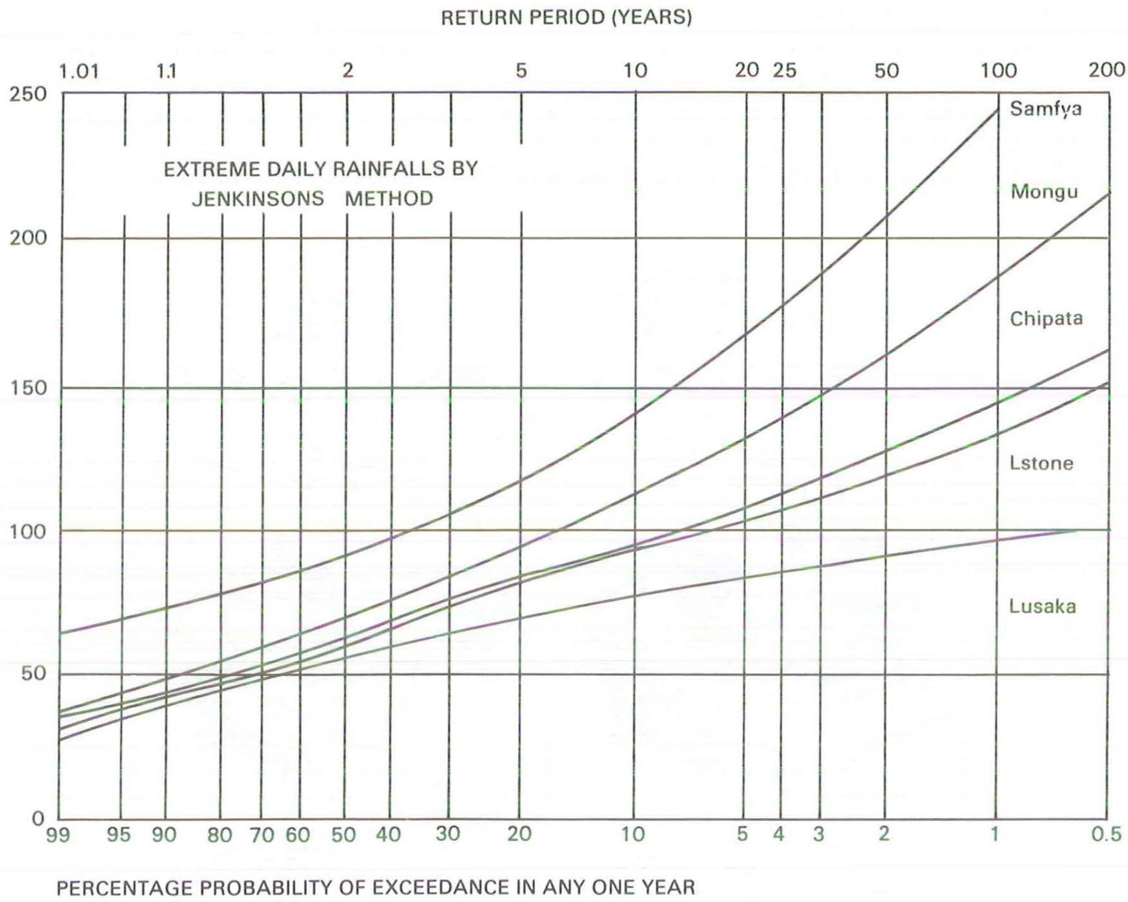

Fig. 11 Extreme daily rainfall as determined by Jenkinson's method (Hutchinson, 1974).

Maximum daily rainfall

With respect to daily rainfall variability one is generally most interested in maximum daily rainfall amounts. The highest daily rainfall ever recorded in Zambia was 307.6 mm in 24 hours at Sesheke, one of the stations with the lowest annual rainfall (720 mm on average). Torrance (1972) presented a simple rule of thumb to estimate maximum daily rainfall amounts. For example, the 30-year maximum 24-hour rainfall in Zambia can be described as (65 mm + 5% of the annual mean) and the 100-year maximum 24-hour rainfall as (75 mm + 6% of the annual mean). Bailey (1969) found that maximum daily rainfall in Zambia is well described by the method of Jenkinson. A diagram based on this method is presented in fig. 11. From this diagram the return period of a given daily rainfall amount can be derived. E.g. at Mongu a daily rainfall amount of 100 mm might be exceeded once in 7 years.

4 ESTIMATION OF POINT RAINFALL USING METEOSAT-TIR IMAGERY AND RAINGAUGE MEASUREMENTS

In order to estimate rainfall amounts in the Sahel with the help of METEOSAT imagery, the Department of Meteorology at the University of Reading (UK) has developed the so called Cold Cloud Duration (CCD) technique (Milford and Dugdale, 1987). Recently (1986) the research activities were extended to Sudan and southern Africa to investigate the applicability of the method developed for the Sahel in these areas.

4.1 Cold cloud duration technique

The basis of the CCD-technique of rainfall estimation is that in the Sahel most of the rain comes from thunderstorms which extend high in the atmosphere as Cumulus and Cumulonimbus cells. These clouds can be recognized on METEOSAT-TIR images by their cold tops. The longer an area is affected by cold clouds, the more rain it will receive. In other words, the longer the cold cloud duration over an area, the higher the amount of rain. To average out the variation in intensity of the individual showers, the CCD is determined over minimal a 10-day period, which is likely to include several rainfall events. Daily estimates would require modulation factors which reflect the physical and dynamical structure of the atmosphere at that time on that place.

The CCD is determined on a pixel by pixel basis. Pixels showing radiation temperatures below a threshold temperature (Tt) are given a score corresponding to the time interval between two consecutive METEOSAT images. The scores are added and the CCD for the area is mapped. The choice of Tt is essential for the method. The temperature threshold must be high enough so that most precipitating clouds are included but low enough to exclude warmer clouds which are not associated with heavy rainfall. In the Sahelian experiment it was found that Tt might depend on latitude (distance from the ITCZ) and on the time of the season. The relation between CCD and amount of rain is based on calibration with raingauge measurements. The most commonly used statistical method to establish this relation is linear regression but also more complex relations like a cross-variogram are feasible as will be shown in the section covering (co)kriging.

The Reading method is developed and tested primarily for the West-African squall systems. About 80% of the rainfall in West-Africa comes from these systems. Squall lines are organized thunderstorm systems, approximately oriented in north-south direction. They move westward at a speed of about 15 m/sec.

Along the leading edge new active Cumulonimbus cells are generated. The systems can reach a horizontal extension of several hundred kilometres and have lifetimes of 15-85 hours with an average of 35 hours. Rainfall from squall lines is highly variable. It starts with heavy rain from the active Cumulonimbus cells at the leading edge. The first 30 minutes yield some 60% of the total rainfall amount per event and is very variable with respect to place. The period of heavy rain is followed by a longer period of moderate or slight rain, which is much less variable and tends to last longer in the south than in the north of the line.

The climatic situation in Zambia differs widely from the situation in the Sahel. The rain bearing systems are smaller in horizontal extension (by a factor 10 or more) and have shorter lifetimes. Moreover they show hardly any organization in relatively well defined structures like the squall lines in the Sahel. Another complicating factor is that three airmasses with different influences on rainfall characteristics converge over Zambia. However, most rainfall in both Zambia and the Sahel results from convective Cumulonimbus cells, which can be identified on METEOSAT thermal infrared images by their cold tops.

The main objective of this study is to assess the operational aspects of applying the CCD-technique in Zambia. Therefore it is necessary to establish relationships between CCD and rainfall.

4.1.1 Establishing relationships between CCD and rainfall

METEOSAT data

METEOSAT thermal infrared data (TIR, wavelength 10.5-12.5 μ) covering southern Africa were obtained from the University of Reading, Department of Meteorology, for the period 1 January to 1 March 1987. Data were delivered on 6250 bpi (bits per inch) magnetic tapes, that contained 48 METEOSAT images (slots) per day. In fig. 12 the position of Zambia within these METEOSAT images is shown.

Rainfall data

Rainfall data for the first two months of 1987 were obtained from the Meteorological Department of Zambia. The synoptic meteorological network of Zambia comprises 33 stations. See table 3 for more detailed information about this network. For January 1987 records from the stations 571 (Serenje), 580 (Msekera) and 543 (Kabompo) were missing while for February 1987 no records were available from the stations 403 (Kawambwa), 571 (Serenje), 665 (Lusaka) and 743 (Livingstone).

In the report of Jacobs (1987) a procedure is presented to obtain a crude impression of the quality of the data. Three pairs of stations were selected where the stations of a pair are located very close together. The difference between those stations was found to be acceptable.

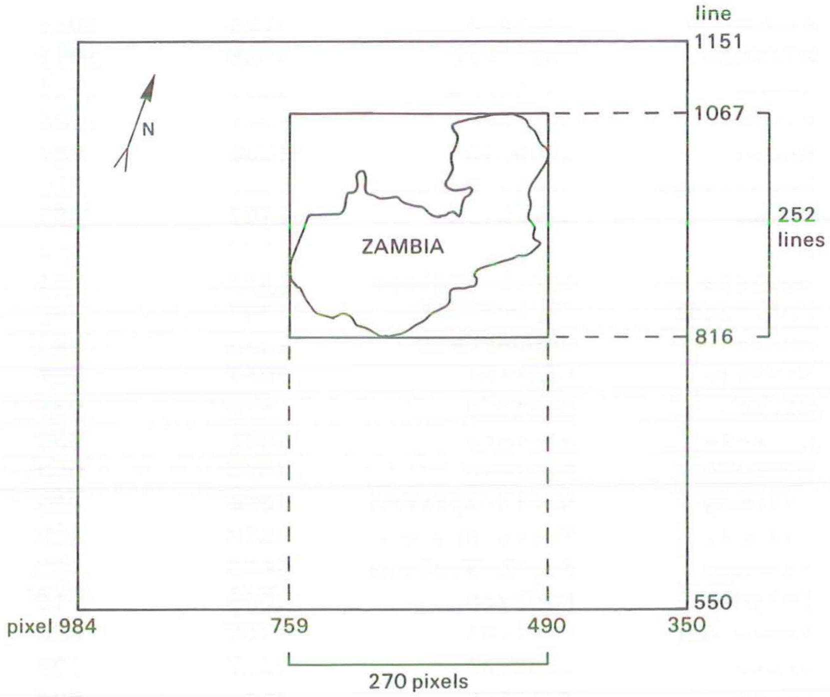

Fig. 12 The position of Zambia within METEOSAT images as used in this study. Numbers refer to line and pixelcoordinates in the METEOSAT reference frame (Smit and Simons, 1988).

Table 3 The meteorological stations in the Zambian climatological network; line and pixel coordinates of meteostations in the METEOSAT reference frame are also shown.

Meteostation		Province	Elevation(m)	line	pixel
413	Mbala	Northern	1673	1040	543
403	Kawambwa	Luapula	1324	1017	589
476	Misamfu	Northern	1536	1011	548
481	Isoka	Northern	1360	1011	522
475	Kasama	Northern	1384	1008	550
461	Mansa	Luapula	1258	987	597
441	Mwinilunga	North-Western	1363	970	688
477	Mpika	Northern	1402	969	549
583	Lundazi	Eastern	1143	962	517
551	Solwezi	North-Western	1386	961	639
563	Kafironda	Copperbelt	1243	952	615
561	Ndola	Copperbelt	1270	943	606
571	Serenje	Central	1384	938	576
585	Mfuwe	Eastern	570	938	544
581	Chipata	Eastern	1032	932	533
580	Msekera	Eastern	1025	930	534
541	Kasempa	North-Western	1234	929	663
531	Zambezi	North-Western	1078	928	720
543	Kabompo	North-Western	1075	927	697
673	Petauke	Eastern	1036	915	560
662	Kabwe Agr.	Central	1165	910	613
663	Kabwe	Central	1207	909	614
641	Kaoma	Western	1213	899	688
655	Mumbwa	Central	1218	894	641
665	Lusaka Int.	Lusaka	1154	889	617
633	Mongu	Western	1053	888	724
667	Mount Makulu	Lusaka	1213	884	622
659	Kafue Polder	Southern	978	879	629
751	Magoye	Southern	1018	873	636
731	Senanga	Western	1027	869	724
753	Choma	Southern	1278	854	649
741	Sesheke	Western	951	838	707
743	Livingstone	Southern	986	831	678

Method

In the first instance only hourly METEOSAT images have been used, analogous to the proposed ARTEMIS procedure. From every hourly TIR METEOSAT image 33 pixels, corresponding to the location of the 33 meteostations, were extracted. For those pixels the raw METEOSAT counts were converted to temperature (°K).

As a first step in this process, raw counts are converted to radiance:

$$Radiance = F * MIEC * (C-Co)$$

Radiance	.... W/M**2*STERADIAN
F	FAG factor (Fine Adjustment of Gain)
MIEC	Calibration factor W/M**2*STERADIAN
C	Raw counts
Co	Count offset

The values for F and MIEC for every METEOSAT slot are published by ESOC (Darmstadt, West-Germany).

For the first two months of 1987 the MIEC calibration coefficient was as follows:

date	MIEC
1.1.87 to 9.1.87, slot 19	0.0467
slot 20, 9.1.87 to 13.2.87, slot 21	0.0470
slot 22, 13.2.87 to 28.2.87	0.0482

and for the FAG factor the following values were stated:

date	FAG
1.1.87 to 14.1.87	1.114
15.1.87 to 29.1.87	1.142
18.1.87 slot 36	1.148
19.1.87 slot 17	0.958
30.1.87 to 13.2.87	0.970
14.2.87 to 28.2.87	0.987

As a next step, the temperature (°K) can be read from the so called radiance-temperature table.
The temperatures are then compared to three threshold temperatures, -40, -50 and -60°C respectively. Temperatures below a threshold temperature are adding to a score that is kept for each pixel and each threshold temperature. The score reached after a dekad multiplied with the time interval between the slots is the dekadic cold cloud duration.

4.1.2 Established relationships between CCD and rainfall

One of the METEOSAT tapes could not be read properly, therefore the linear regressions of measured rainfall on cold cloud duration have been calculated for the three threshold temperatures and for all but the last dekad. Their equations together with the correlation coefficient (r) and the coefficient of variation (cv) are given in table 4. The optimum threshold temperature should ideally have an associated regression equation

with a zero intercept. A positive intercept will exclude rainfall events, while a negative intercept includes non-precipitating clouds in the estimation. If r and cv for different threshold temperatures are more or less even, the best fit regression line is the one whose intercept is nearest to zero.
A quick glance at table 4 learns that -60°C is less promising as a threshold temperature.

Table 4 Linear regressions of cold cloud duration and rainfall for threshold temperatures -40, -50 and -60°C over five dekads (January, February 1987) using 24 slots per day.

	- 40°C	- 50°C	- 60°C
1/10 Jan. M=37	P = 2.1 CCD - 4.5 r = 0.58 cv= 84	P = 2.6 CCD + 9.0 r = 0.43 cv= 93	P = 3.1 CCD + 24.5 r = 0.27 cv= 99
11/20 Jan. M=83	P = 1.1 CCD +28.8 r = 0.24 cv= 51	P = 1.1 CCD +47.8 r = 0.19 cv= 51	P = 0.9 CCD + 68.3 r = 0.11 cv= 52
21/31 Jan. M=79	P = 1.9 CCD +11.6 r = 0.53 cv= 59	P = 2.6 CCD +26.9 r = 0.47 cv= 61	P = 4.3 CCD + 40.7 r = 0.48 cv= 61
1/10 Feb. M=67	P = 2.3 CCD -14.9 r = 0.61 cv= 52	P = 2.9 CCD + 6.0 r = 0.48 cv= 58	P = 4.4 CCD + 20.0 r = 0.39 cv= 61
11/20 Feb. M=58	P = 2.3 CCD - 5.6 r = 0.82 cv= 52	P = 4.0 CCD - 8.5 r = 0.81 cv= 52	P = 7.0 CCD + 6.7 r = 0.75 cv= 60

P Precipitation (mm/dekad)
CCD Cold Cloud Duration (hours/dekad)
r correlation coefficient
cv coefficient of variation (standard deviation as % of mean measured rain)
M Mean measured rain for the dekad concerned

It appeared (more details will come up in the discussion) that for a few meteostations there is quite a big discrepancy between measured and estimated rainfall. This does not necessarily mean that the observations of those stations are erroneous but for some reason they do not fit in the linear model as good as we would like. Therefore the regression calculations have been repeated with a certain elimination criterion (twice the standard deviation) over and over again while discarding the worst fitting station until the criterion was no longer satisfied. Table 5 shows the modified regression equations together with a list of the eliminated stations, for threshold temperatures of -40°C and -50°C.

Table 5 Linear regressions of cold cloud duration and rainfall for threshold temperatures -40°C and -50°C over five dekads (January, February 1987/24 slots per day) after application of the worst point elimination procedure.

elimination criterion: 2 * stand. dev.

	- 40°C	- 50°C	eliminated
1/10	P = 1.4 CCD - 9.5	P = 2.1 CCD - 5.4	441 403 476 413
Jan.	r = 0.91	r = 0.84	662 561 551 475
M=37	cv= 20	cv= 26	673 563(2)
11/20	P = 1.8 CCD -18.9	P = 2.0 CCD + 1.8	665 743 481 667
Jan.	r = 0.83	r = 0.75	633 731 585(1)
M=83	cv= 15	cv= 18	477
21/31	P = 2.5 CCD -15.1	P = 3.9 CCD - 3.9	662 563 663
Jan.	r = 0.90	r = 0.77	655(1) 585 581
M=79	cv= 25	cv= 38	481(1)
1/10	P = 2.0 CCD - 8.9	P = 2.9 CCD + 1.2	551
Feb.	r = 0.61	r = 0.56	
M=67	cv= 46	cv= 48	
11/20	P = 2.0 CCD - 7.9	P = 3.8 CCD - 6.0	475 477 531 563
Feb.	r = 0.94	r = 0.94	543(2) 585(2)
M=58	cv= 24	cv= 24	731(2) 580(2)

P Precipitation (mm/dekad)
CCD Cold Cloud Duration (hours/dekad)
r correlation coefficient
cv coefficient of variation (standard deviation as % of mean measured rain)
M Mean measured rain for the dekad concerned
(1) only eliminated for threshold temperature -40°C
(2) only eliminated for threshold temperature -50°C

4.1.3 Discussion

Table 4 shows that the best fit regression lines are associated with a threshold temperature of -40°C. None of the lines comes close to the ideal of a zero intercept and the slope of the lines varies considerably, which means there is as yet no reason to assume a constant relation between CCD and rainfall. The best results are obtained for the second dekad of February and very poor results emerge for the second dekad of January. Overall the results don't look very encouraging but the impression is that in most cases for the majority of the stations there is a rather good resemblance between measured and estimated rainfall.

See for instance the columns with measured and estimated rainfall for the second dekad of February, depicted in table 6; only for a few stations the estimated amount of rain is utterly different from the measured one.

The reasons for such a deviating behaviour can be manyfold:

1 Raingauges do not always measure the actual rainfall amount reaching the ground properly (differences of up to 30% have been reported).
2 Rainfall has a spatial variability. A raingauge measurement is a point observation that cannot always be held representative for an area of 25 sq.km, the size of a METEOSAT pixel. Especially when rainfall originates from convective systems, as is the case in Zambia, observed rainfall amounts may vary considerably even within a distance of a few hundred meters. A good indication of this scale problem can be obtained from table 6, where under the heading RAINint the rainfall for each station is estimated by weighted distance interpolation of the rainfall observed at five neighbouring stations. It appears that sometimes there is a better correspondence between CCD and the estimation by interpolation than between CCD and the actual measured rainfall, which means that for such a station the actual measured rainfall is perhaps not representative for the neighbourhood.
3 Deviating behaviour may be more structural as opposed to the first two cases where the deviations are just accidental. Structural deviations may be caused by topographical or climatological peculiarities. To identify deviating behaviour positively as structural, the analysis should be extended to the whole rainy season and even to other years, but already some conclusions can be drawn from the present work as will be shown later on.
4 In section 4.1 it was pointed out that the variation in intensity of the individual showers had to be averaged out before something useful could be expected from the CCD-method. A period of 10 days was indicated as a minimum in this respect. It is very well possible that for a certain dekad this averaging process does not go far enough and that exceptional events with a complete different relation between CCD and rainfall dominate the overall relation for the whole dekad.

Realizing that, in the worst case, these four effects act in one direction, it is not surprising that a few points (meteostations) deviate substantially from the regression lines. Because it is a regression line, the general trend that is set by the majority of the points is this way obscured. To estimate rainfall for any location, the general trend is of course the desired one and it can be obtained by discarding or eliminating the worst fitting stations. For this purpose an iterative procedure has been applied: the point with the largest deviation is examined and eliminated if it is outside two times the standard deviation from the regression line. Next the regression line is recalculated and so on.

Table 5 shows the optimalized regression equations for threshold temperatures of -40°C and -50°C, together with a list of eliminated stations (sometimes a station is eliminated for one threshold value only). The best fit regression lines are associated with a threshold temperature of -40°C. All of them have a negative intercept which means that some non-precipitating clouds contribute to the final equations. The optimal threshold temperature (zero intercept) is somewhere between -40°C and -50°C for the second dekad of January and the first dekad of February while it is even lower than -50°C for the other three dekads. But, taken into account the course of the values for r and cv, a threshold value of -40°C seems a good choice for the Zambian climatic conditions. Because of the varying slope of the regression lines there is still no reason to assume a constant relation between CCD and rainfall.

It has been stated in chapter 3 that anomalies in the general rainfall pattern can be attributed to orographic effects and that positive anomalies (more rainfall than expected from the general trend) occur at the higher altitudes between Kawambwa and Kasama in the north and to the south of the railway between Mazabuka and Livingstone. Further positive anomalies are related to the vicinity of a lake or a swamp. A negative anomaly can be found in the Luangwa Valley. Meteostations in these areas are: Kawambwa (403), Misamfu (476) and Kasama (475) in the north and Mfuwe (585) in the Luangwa Valley. Of course, stations with higher or lower rainfall amounts than the general trend do not show up automatically as deviating in a regression analysis. As long as the relative high and low rainfall amounts are accompanied by high respectively low CCD-values a high correlation will be observed, only if this relation is basically different deviating stations can be identified as such. In the list with eliminated stations none of these stations shows up strikingly much, nor does any other station. First indications therefore are that structural topographical or climatological effects are not so pronounced and that they just participate in lowering the signal to noise ratio of the information on METEOSAT-TIR images as do the other accidental factors pointed out above and which makes the application of the CCD-technique so questionable.

Table 6 Linear regression of cold cloud duration and rainfall (threshold temperature of -40°C) for the second dekad of February 1987, without (A) and with (B) application of the worst point elimination procedure. The numbers under the heading RAINreg are produced using the regression equations, while the estimations under the heading RAINint are calculated by weighted distance interpolation of the measured rainfall from the five nearest by meteostations.

		A				B			
		RAINreg = 2.3 CCD - 5.6				RAINreg = 2.0 CCD - 7.9			
		r = 0.82				r = 0.94			
		cv = 52				cv = 24			
STAT#	RAINint	CODE	CCD	RAIN	RAINreg	CODE	CCD	RAIN	RAINreg
413	132.3	0	73	113.9	159.2	0	73	113.9	135.0
476	168.4	0	57	108.0	123.1	0	57	108.0	103.6
481	128.4	0	61	134.6	132.1	0	61	134.6	111.5
475	109.9	0	50	190.3	107.3	1	50	190.3	89.9
461	108.3	0	41	57.6	87.0	0	41	57.6	72.3
441	86.7	0	59	111.8	127.6	0	59	111.8	107.6
477	69.3	0	30	130.5	62.1	2	30	130.5	50.8
583	68.3	0	40	76.8	84.7	0	40	76.8	70.4
551	73.5	0	35	68.6	73.4	0	35	68.6	60.6
563	42.7	0	30	110.6	62.1	4	30	110.6	50.8
561	63.5	0	27	50.7	55.4	0	27	50.7	44.9
585	50.3	0	23	12.1	46.3	0	23	12.1	37.1
581	25.3	0	26	56.8	53.1	0	26	56.8	43.0
541	52.4	0	25	19.4	50.8	0	25	19.4	41.0
531	62.4	0	36	124.0	75.7	3	36	124.0	62.5
543	78.5	0	30	78.9	62.1	0	30	78.9	50.8
673	27.6	0	12	11.0	21.5	0	12	11.0	15.6
662	2.5	0	4	0.0	3.4	0	4	0.0	-0.1
663	2.4	0	3	0.0	1.2	0	3	0.0	-2.1
641	54.7	0	25	52.5	50.8	0	25	52.5	41.0
655	5.8	0	9	0.6	14.7	0	9	0.6	9.7
633	54.0	0	27	33.1	55.4	0	27	33.1	44.9
667	4.0	0	7	10.5	10.2	0	7	10.5	5.8
659	7.0	0	5	5.3	5.7	0	5	5.3	1.9
751	4.7	0	5	9.6	5.7	0	5	9.6	1.9
731	51.5	0	26	21.5	53.1	0	26	21.5	43.0
753	12.4	0	9	2.6	14.7	0	9	2.6	9.7
741	24.1	0	11	26.4	19.2	0	11	26.4	13.6

RAINreg Amount of rain estimated using the regression lines (mm)
RAINint Rainfall obtained by interpolating 5 neighbouring meteostations (mm)
r correlation coefficient
cv coefficient of variation
STAT# Meteostation number
CODE Number of elimination round (CODE > 0 only)
CCD Cold Cloud Duration (hours/dekad)
RAIN Measured amount of rain (mm)

4.2 Attempts to improve the linear regression method

Note: The work presented in section 4.2 was carried out before the January tapes were processed, so only the first two dekads of February have been involved. The results obtained for this short period however are so unequivocally clear that there is not much sense in considering the dekads of January afterwards.

The foregoing regression analysis was based on hourly METEOSAT images. This has been done because all present ARTEMIS products are based on 24 METEOSAT images per day. It is imperative to assess first what can be done with these data before one is able to develop design criteria for improved ARTEMIS products.

The rainbearing systems (mainly thunderstorms) in Zambia have relative short lifetimes, sometimes less than one hour. It might therefore be useful to do a similar regression analysis using half hourly METEOSAT images and assess how much precision is lost by using only hourly images.

Through the lifetime of a storm the cloud top temperature drops rapidly during the development stage, reaches a minimum and then increases slowly over a longer period of up to several hours. The storms which dominate in West Africa produce much of their rainfall before and at the time that the clouds reach their lowest temperature. In order to gain an insight into this influence of cloud dynamics on the CCD-technique of rainfall estimation, another procedure to calculate the CCD-values has been followed. From the period during which the top of a cloud is colder than a threshold temperature, only that part is considered when the temperature is actually decreasing: the development phase of a shower. The Cirrus remnant of a cloud, which is still cold, but does not produce much rain (at least under the Sahelian conditions) is in this way left out of consideration.

Using 48 METEOSAT images per day

In table 7B the results of the regressions based on 48 slots/day are represented. When compared with the results depicted in table 4 (copied in table 7A), the conclusion may be drawn that the precision of the rainfall estimation procedure is not seriously affected by using hourly images, as does the ARTEMIS system, instead of half hourly images, the highest frequency at which the METEOSAT satellite can deliver images.

Table 7 Linear regressions of cold cloud duration and rainfall for threshold temperatures -40, -50 and -60°C over two dekads (February 1987) using 24 slots per day (7A) and 48 slots per day (7B).

7A: 24 slots/day

	< 1/10 February >		< 11/20 February >	
	P	= 2.3 CCD - 14.9	P	= 2.3 CCD - 5.6
-40	r	= 0.61	r	= 0.82
	cv	= 52	cv	= 52
	P	= 2.9 CCD + 6.0	P	= 4.0 CCD - 8.5
-50	r	= 0.48	r	= 0.81
	cv	= 58	cv	= 52
	P	= 4.4 CCD + 20.0	P	= 7.0 CCD + 6.7
-60	r	= 0.39	r	= 0.75
	cv	= 61	cv	= 60

7B: 48 slots/day

	< 1/10 February >		< 11/20 February >	
	P	= 2.3 CCD - 16.0	P	= 2.3 CCD - 8.0
-40	r	= 0.61	r	= 0.82
	cv	= 52	cv	= 52
	P	= 3.0 CCD + 1.5	P	= 4.2 CCD - 8.8
-50	r	= 0.53	r	= 0.82
	cv	= 57	cv	= 52
	P	= 4.8 CCD + 15.5	P	= 7.0 CCD + 7.0
-60	r	= 0.42	r	= 0.76
	cv	= 60	sd	= 60

-40 threshold temperature of -40°C
-50 threshold temperature of -50°C
-60 threshold temperature of -60°C
P Precipitation (mm/dekad)
CCD Cold Cloud Duration (hours/dekad)
r correlation coefficient
cv coefficient of variation

Using only the development stage of a thunderstorm

The results of the calculations with the modified CCD-values are depicted in table 8 both for 24 and 48 slots/day and they are not really encouraging especially not for the first dekad: the correlation coefficients become lower and the standard deviations become higher. It is obvious that using only the development phase of the period during which a cloud is colder than a certain threshold does not improve the CCD-method of rainfall estimation in Zambia.

Table 8 Linear regressions of cold cloud duration and rainfall for threshold temperatures -40, -50 and -60°C over two dekads (February 1987) using 24 slots per day (8A) and 48 slots per day (8B).
The CCD values are calculated considering the development time of a thunderstorm only.

8A: 24 slots/day, development phase only

	< 1/10 February >		< 11/20 February >	
	P	= 3.5 CCD + 3.5	P	= 4.5 CCD - 6.4
-40	r	= 0.51	r	= 0.81
	cv	= 58	cv	= 53
	P	= 4.2 CCD + 19.5	P	= 8.2 CCD - 16.7
-50	r	= 0.39	r	= 0.82
	cv	= 61	cv	= 45
	P	= 4.6 CCD + 37.3	P	= 12.0 CCD - 1.1
-60	r	= 0.26	r	= 0.81
	cv	= 63	cv	= 53

8B: 48 slots/day, development phase only

	< 1/10 February >		< 11/20 February >	
	P	= 4.8 CCD + 2.5	P	= 4.8 CCD - 3.8
-40	r	= 0.47	r	= 0.80
	cv	= 59	cv	= 54
	P	= 5.8 CCD + 8.0	P	= 8.5 CCD - 10.0
-50	r	= 0.46	r	= 0.84
	cv	= 59	cv	= 49
	P	= 8.6 CCD + 18.3	P	= 12.6 CCD + 7.3
-60	r	= 0.39	r	= 0.78
	cv	= 61	cv	= 59

-40	threshold temperature of -40°C
-50	threshold temperature of -50°C
-60	threshold temperature of -60°C
P	Precipitation (mm/dekad)
CCD	Cold Cloud Duration (hours/dekad)
r	correlation coefficient
cv	coefficient of variation

4.3 Comparison of simple linear regression with two alternative rainfall estimation techniques i.e. kriging and cokriging

In the preceding part of this chapter, a method to estimate point rainfall in Zambia from raingauge measurements and METEOSAT data has been evaluated. The method, developed by researchers at the University of Reading (UK), is based on an assumed linear relation between cumulative cold cloud duration as observed by METEOSAT and actual rainfall. The linear relation has to be requantified for each considered period (i.e. a ten day period or longer) by comparing the measured rainfall data from a number of meteostations and the CCD-values of the corresponding METEOSAT pixels. The resulting regression equation is next used to estimate the rainfall on any place by translating the CCD-value of the METEOSAT pixel on that same location into an amount of rainfall.

The method developed so far does not consider spatial correlation of rainfall: each estimation is calculated independently of the estimation for any other place. It was felt therefore, that no optimal use was made of the available two independent information sources: the measurements from the raingauge network and the METEOSAT images. In the following section the results of the extended analysis using spatial prediction techniques that are well known from the geosciences i.e. kriging and cokriging will be compared with simple linear regression.

For this comparative study the following data covering the period 11-20 February 1987 (= second dekad of February) have been used:

1 Rainfall data for 28 of the 33 stations that comprise the meteorological network of Zambia were obtained from the Meteorological Department of Zambia (table 3).
2 METEOSAT-TIR data for the relevant period covering southern Africa were obtained from the University of Reading (UK), department of Meteorology.
  From the METEOSAT data a CCD-map of Zambia has been produced using 24 images per day and a threshold temperature of -40°C. Such a map consists of roughly 60 000 pixels, which is too much to handle in the cokriging calculations. Therefore a drastic data reduction has been carried out and the resulting CCD-map with a raster distance of 15 pixels has been depicted in table 9 together with the METEOSAT line and pixel numbers.

4.3.1 Linear regression

The linear regression of measured rainfall on cold cloud duration was calculated in section 4.1.2. The resulting regression equation together with the standard deviation as a percentage of the mean measured rainfall (the so called coefficient of variation) and the correlation coefficient are given once again in table 10A.

Table 9 CCD-map of Zambia (threshold temperature of -40°C.) for the second dekad of February 1987.
CCD is expressed in hours/dekad and has been calculated using 24 METEOSAT images per day.
Only one out of fifteen lines and one out of fifteen columns have been depicted.

Line	Pixel																	
	745	730	715	700	685	670	655	640	625	610	595	580	565	550	535	520	505	490
1055	38	58	73	71	75	82	69	51	46	51	61	76	82	64	71	73	92	85
1040	43	43	46	63	77	69	60	50	66	66	52	55	62	81	69	70	76	66
1025	40	35	46	63	66	67	56	61	51	58	68	66	66	69	67	64	72	66
1010	45	38	43	61	65	65	76	58	46	51	56	61	67	59	50	65	70	93
995	44	45	53	59	75	76	81	57	43	39	46	46	47	43	47	50	66	86
980	56	54	59	72	73	70	60	46	29	32	39	51	37	48	46	38	65	70
965	42	47	44	60	64	58	49	38	34	26	38	49	41	30	38	40	54	55
950	44	53	42	53	57	36	44	28	24	25	31	28	27	15	29	24	49	55
935	42	46	36	44	39	40	32	28	29	23	18	14	22	21	26	34	37	32
920	42	37	37	32	33	29	27	23	12	11	8	11	16	15	20	25	30	23
905	27	30	25	28	30	20	21	9	4	2	8	9	7	10	9	16	18	17
890	33	27	33	29	17	25	11	7	3	8	4	0	3	2	4	3	2	20
875	34	31	22	24	19	10	0	8	7	5	0	3	4	6	6	0	7	5
860	23	16	24	18	27	11	6	8	16	14	5	4	6	8	5	1	3	5
845	18	23	11	14	19	13	11	16	13	19	14	8	8	3	4	0	0	2
830	16	19	15	12	17	11	5	8	8	5	8	6	2	0	0	0	0	0

The regression equation depicted in table 10B stems from table 5 and is obtained after application of the worst point elimination procedure. Four stations have been eliminated and 24 stations contribute to the optimized equation.

Kriging and cokriging are linear methods as well. It proved to be necessary to discard the same 4 stations in order to be able to calculate a usable semi-variogram, a basic tool for (co)kriging. The kriging and cokriging calculations will therefore be performed using only the data from the remaining 24 meteostations.

4.3.2 Kriging

Kriging is a means of spatial prediction and can be used for interpolating the rainfall data from the meteostations. It is a form of weighted local averaging where the weights do not come from any convenient deterministic spatial function but from a geostatistical spatial analysis based on the sample semi-variogram, a device which reflects the nature of spatial dependence for the feature under consideration.

Table 10 Linear regression of cold cloud duration and rainfall (threshold temperature of -40°C) for the second dekad of February 1987, without (A) and with (B) application of the worst point elimination procedure. The numbers under the heading RAINreg are produced using the regression equations, while the estimations under the heading RAINint are calculated by weighted distance interpolation of the measured rainfall from the five nearest by meteostations.

		<—— A ——>				<—— B ——>			
		RAINreg = 2.3 CCD - 5.6 r = 0.82 cv = 52				RAINreg = 2.0 CCD - 7.9 r = 0.94 cv = 24			
STAT#	RAINint	CODE	CCD	RAIN	RAINreg	CODE	CCD	RAIN	RAINreg
413	132.3	0	73	113.9	159.2	0	73	113.9	135.0
476	168.4	0	57	108.0	123.1	0	57	108.0	103.6
481	128.4	0	61	134.6	132.1	0	61	134.6	111.5
475	109.9	0	50	190.3	107.3	1	50	190.3	89.9
461	108.3	0	41	57.6	87.0	0	41	57.6	72.3
441	86.7	0	59	111.8	127.6	0	59	111.8	107.6
477	69.3	0	30	130.5	62.1	2	30	130.5	50.8
583	68.3	0	40	76.8	84.7	0	40	76.8	70.4
551	73.5	0	35	68.6	73.4	0	35	68.6	60.6
563	42.7	0	30	110.6	62.1	4	30	110.6	50.8
561	63.5	0	27	50.7	55.4	0	27	50.7	44.9
585	50.3	0	23	12.1	46.3	0	23	12.1	37.1
581	25.3	0	26	56.8	53.1	0	26	56.8	43.0
541	52.4	0	25	19.4	50.8	0	25	19.4	41.0
531	62.4	0	36	124.0	75.7	3	36	124.0	62.5
543	78.5	0	30	78.9	62.1	0	30	78.9	50.8
673	27.6	0	12	11.0	21.5	0	12	11.0	15.6
662	2.5	0	4	0.0	3.4	0	4	0.0	-0.1
663	2.4	0	3	0.0	1.2	0	3	0.0	-2.1
641	54.7	0	25	52.5	50.8	0	25	52.5	41.0
655	5.8	0	9	0.6	14.7	0	9	0.6	9.7
633	54.0	0	27	33.1	55.4	0	27	33.1	44.9
667	4.0	0	7	10.5	10.2	0	7	10.5	5.8
659	7.0	0	5	5.3	5.7	0	5	5.3	1.9
751	4.7	0	5	9.6	5.7	0	5	9.6	1.9
731	51.5	0	26	21.5	53.1	0	26	21.5	43.0
753	12.4	0	9	2.6	14.7	0	9	2.6	9.7
741	24.1	0	11	26.4	19.2	0	11	26.4	13.6

RAINreg Amount of rain estimated using the regression lines (mm)
RAINint Rainfall obtained by interpolating 5 neighbouring meteostations (mm)
r correlation coefficient
cv coefficient of variation
STAT# Meteostation number
CODE Number of elimination round (CODE > 0 only)
CCD Cold Cloud Duration (hours/dekad)
RAIN Measured amount of rain (mm)

Kriging is an optimal interpolation method in the sense that it provides estimates of values at unobserved places without bias and with minimum and known variance. Kriging depends on first constructing an accurate semi-variogram, by determining (estimating) some of its points with the help of the data points. Semi-variances, obtained from the linear model fitted to the computed points, are then used to determine the weights applied to surrounding data points and the value at an unobserved point is then predicted by a linear combination of the values at those points. A semi-variogram was computed for the measured rainfall data from the 24 remaining meteostations and a linear model has been fitted to the estimated values of semi-variance.

The linear model that describes the shape of the sample semi-variogram has the equation:

Gamma= 18.4*distance + 0.0

where Gamma: semi-variance;
distance expressed in METEOSAT pixels

After application of the kriging equations, the kriged rainfall estimates were obtained and they are depicted in table 11 together with the measured rainfall data.

Table 11 Measured and kriged estimates of rainfall for 24 meteostations in the Zambian meteorological network for the second dekad of February 1987.

STAT#	Rmeas	Rkriged	STAT#	Rmeas	Rkriged
413	113.90	108.12	673	11.00	7.14
476	108.00	110.52	662	0.00	1.97
481	134.60	103.38	663	0.00	0.48
461	57.60	83.47	641	52.50	43.77
441	111.80	71.76	655	0.60	5.52
583	76.80	81.72	633	33.10	37.32
551	68.60	75.04	667	10.50	3.81
561	50.70	36.16	659	5.30	9.56
585	12.10	44.58	751	9.60	4.03
581	56.80	21.42	731	21.50	29.93
541	19.40	51.35	753	2.60	15.57
543	78.90	72.99	741	26.40	11.38

STAT# Meteostation number
Rmeas Measured amount of rain (mm)
Rkriged Rainfall estimates produced by kriging (mm)

4.3.3 Cokriging.

Sometimes, a variable may not have been sampled sufficiently to provide estimates of acceptable precision. The precision of this estimation may then be improved by considering the spatial correlation between this variable (called the predictand) and another better sampled variable (or covariable). A very densely sampled variable in our situation is CCD, even the reduced CCD-map still delivers 288 well spaced CCD values, which is a high number in comparison with only 24 meteostations.
In order to apply cokriging another semi-variogram (the one for the covariable) and a cross-variogram, which describes the spatial correlation between the predictand and the covariable are needed. The semi-variogram of the covariable has been computed by using the CCD values in column 2 of table 10B, where code > 0. The values in the reduced CCD-map could have been used as well. The linear equation for the second semi-variogram is:

$$\text{Gamma} = 3.923 * \text{distance} + 0.0$$

For the computation of the cross-variogram paired values of predictand and covariable must be used (columns 3 and 2 of table 10B, code > 0).
The linear equation for the cross-variogram is:

$$\text{Gamma} = 15.672 * \text{distance} + 0.0$$

where Gamma: cross-variance;
distance expressed in METEOSAT pixels.

With the help of the cross-variogram and both semi-variograms the cokriging equations can be solved. The cokriged rainfall estimates for the meteostations are given in table 12, together with the measured rainfall data.

Table 12 Measured and cokriged estimates of rainfall for 24 meteostations in the Zambian meteorological network for the second dekad of February 1987.

STAT#	Rmeas	Rcokrig	STAT#	Rmeas	Rcokrig
413	113.90	108.01	673	11.00	4.22
476	108.00	110.66	662	0.00	1.98
481	134.60	104.46	663	0.00	0.38
461	57.60	79.64	641	52.50	41.85
441	111.80	70.73	655	0.60	5.58
583	76.80	81.81	633	33.10	36.09
551	68.60	73.62	667	10.50	3.82
561	50.70	34.49	659	5.30	9.47
585	12.10	40.75	751	9.60	3.85
581	56.80	21.66	731	21.50	29.58
541	19.40	52.02	753	2.60	7.94
543	78.90	73.40	741	26.40	11.83

STAT# Meteostation number
Rmeas Measured amount of rain (mm)
Rcokrig Rainfall estimates produced by cokriging (mm)

4.3.4 Results and discussion

To assess the performance of the three rainfall estimation methods, for each of them the relation between the measured rainfall and the estimated rainfall for the 24 meteostations has been established. Preferably this relation should have a slope of 1 and an intercept of 0. In table 13 the calculated relations are shown. As one can see, they are all deviating a bit from the ideal shape: all three methods overestimate the lower rainfall quantities somewhat, while the higher quantities are underestimated.

There is not much difference between the methods. The best results are obtained with simple linear regression. Kriging and cokriging give practically the same results and are lagging somewhat behind. It is amazing that kriging, that only uses the raingauge measurements, performs so well. It is reassuring to have such a powerful method for situations when METEOSAT images are not available. Cokriging is a more elegant method than simple regression and it possibly can do better than it has shown here. The 24 meteostations must be considered an absolute minimum to construct a usable semi-variogram and cross-variogram.

Table 13 Relation between measured and estimated rainfall quantities for three alternative methods: linear regression, kriging and cokriging.

Linear regression ———> RAINest = 4.18 + 0.91 * RAINmeas

Standard deviation : 28% of mean measured rainfall
Correlation coefficient: 0.95

Kriging ———> RAINest = 7.76 + 0.80 * RAINmeas

Standard deviation : 36% of mean measured rainfall
Correlation coefficient: 0.90

Cokriging ———> RAINest = 6.27 + 0.81 * RAINmeas

Standard deviation : 35% of mean measured rainfall
Correlation coefficient: 0.91

RAINest Estimated rainfall (mm)
RAINmeas Measured rainfall (mm)

4.4 Conclusions

The analysis has shown that the CCD-technique of rainfall estimation has potential, in spite of the fact that the climatic situation in Zambia is quite different from the situation in the Sahel.

- Although the standard deviations of the regression equations are rather high, the linear regression method should enable us to distinguish areas with ample rain from areas that suffer more or less from drought, which is after all one of the main tasks of an Early Warning System.

- The analysis suggests that it will not be possible to work with a fixed algorithm to estimate rainfall. The constants in the linear regression equation vary from dekad to dekad as does even the optimum temperature threshold level. It is probably inevitable to always use the METEOSAT images in combination with good quality raingauge measurements and recalibrate every dekad or whatever timebase is used, at least for a few years.
The regression lines are rather close to the optimum algorithm found by Milford and Dugdale, 1987 for the climatic conditions of the Sudan: Rain = 2.7 * CCD, with a threshold level of -50°C.

- The attempts to improve the CCD-method did not lead to much. Using only 24 slots/day in stead of the maximum 48 does not detract from the precision.

- Because of the need to recalibrate in the course of time, the ARTEMIS system should not deliver rainfall estimation maps based on fixed algorithms, but rather raw CCD-maps, possibly for different temperature thresholds, but certainly for a threshold of -40°C.

- To interpolate raingauge measurements with the help of METEOSAT-TIR imagery, two very usable methods i.e. linear regression and (co)kriging are available.
For situations where the raingauge network is not dense, like in Zambia, the linear regression method is preferred. Contrariwise, when a more dense meteostation network exists, a fair chance should be given to cokriging.
If, for some reason METEOSAT images are not available, not all is lost: kriging is a worthy alternative under such conditions.

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GLOSSARY OF ACRONYMS

ARTEMIS	:	Africa Real-Time Environmental Monitoring using Imaging Satellites (satellite data processing system at FAO HQ.)
CCD	:	Cold Cloud Duration
cv	:	coefficient of variation (standard deviation divided by the mean)
ECMWF	:	European Centre for Medium-range Weather Forecasts
FAO	:	Food and Agricultural Organization of the United Nations
ITCZ	:	InterTropical Convergence Zone
MARS	:	Monitoring Agro-ecological Resources using Remote Sensing and Simulation
METEOSAT	:	METEOrological SATellite
NOAA	:	National Oceanic and Atmospheric Administration
TIR	:	Thermal InfraRed
ZAB	:	Zaire Air Boundary

APPENDIX

****
** HOW TO READ A CCD-MAP **
****

estimation of rainfall with the help of a calibrated CCD-map

USER MANUAL Ver ZA/1.0

CONTENTS Page

This manual is accompanied by a floppy disk containing the following files:

RDCCDMAP.FOR	ZA87FEB2.H24	ZA87FEB.RAI
RDCCDMAP.EXE	FEB2H24.LFT	RAIN.FRM

1 INTRODUCTION

Recently, the Rome based ARTEMIS system has become operational. ARTEMIS is an integrated system, that is capable of real-time acquisition of METEOSAT data and processing the imagery from METEOSAT and NOAA satellites.
With respect to rainfall monitoring ARTEMIS produces a very interesting product called a CCD-map, where CCD stands for Cold Cloud Duration. The underlying rainfall estimation method itself has been developed by the Department of Meteorology at the University of Reading (UK) and is based on relating cloud top temperature below a certain threshold value to rainfall.
The validity of the method is restricted to areas where most of the rain comes from thunderstorm systems that extend high in the atmosphere and therefore can be recognized on METEOSAT-TIR (Thermal InfraRed) images by their cold tops. The longer an area is affected by cold clouds, the more rain it will receive. In other words: the longer the cold cloud duration over an area, the higher the amount of rain. To average out the variation in intensity of the individual showers, the CCD is determined over minimal a 10-day period (a dekad) which is likely to include several rainfall events. The CCD is determined on a pixel by pixel basis. Pixels showing radiation temperatures below a certain threshold temperature are given a score corresponding to the time interval between two consecutive METEOSAT images. The scores are added and the CCD for the area is mapped. The choice of the threshold temperature is essential. It must be high enough so that most precipitating clouds are included but low enough to exclude warmer clouds which are not associated with heavy rainfall. The relation between CCD and amount of rainfall is based on calibration with raingauge measurements. The most commonly used statistical method to establish this relation is linear regression.

In this manual the full procedure to calibrate a CCD-map with the help of raingauge measurements is explained. In addition the FORTRAN source code of a program called RDCCDMAP, that first performs the calibration and thereafter can be used to estimate rainfall on any user specified location is given in Annex 1.
The CCD-map supplied with the program covers an area between latitudes 8° and 18° south and longitudes 22° and 33.5° east i.e. Zambia. With reference to the METEOSAT coordinate system, this means the area between linenrs. 816 - 1067 (252 lines) and pixelnrs. 490 - 759 (270 pixels).

ARTEMIS : Africa Real-Time Environmental Monitoring using Imaging Satellites
MARS : Monitoring Agro-ecological Resources by means of remote sensing and Simulation
METEOSAT : METEOrological SATellite
NOAA : National Oceanic and Atmospheric Administration

2 HOW TO USE THE PROGRAM RDCCDMAP

To run the program, type : RDCCDMAP

Next the program asks the user to give the name of a CCD-map, which must be a full filename (including extension) of maximum 12 characters.
The filename must have a special format, because part of this name is used by the program to find the table with measured rainfall data.

The sample CCD-map is called ZA87FEB2.H24 and this name contains the following information:

ZA = ZAmbia
87 = the year 1987
FEB = the month FEBruary

2 = second dekad (11-20 February)
1,3 or 4 would have meant:..first/third dekad or the whole month
H = High temperature threshold of -40°C
M or L would have meant:.....Medium (-50°C) or Low (-60°C) thresholds

24 = the map is based on hourly METEOSAT images
48 would have meant:....based on half-hourly METEOSAT images

The filename is shifted to the right as far as possible in the 12 position name-field and the first 7 characters (ZA87FEB) are concatenated with '.RAI' to ZA87FEB.RAI, the name that is indeed associated with the file containing rainfall data from the Zambian synoptic climatological network for February 1987.

The table with rainfall data is depicted in annex 2. Such a table can be prepared with the help of a wordprocessor, starting with the prefab empty table (filename: RAIN.FRM) given in annex 3.

The results of the regression analysis are written to a separate output file (annex 4) named FEB2H24.LFT, a name composed of parts of the name of the CCD-map and extension '.LFT'.

After completion of the regression analysis the program can be used interactively to estimate the rainfall on any location by specifying its position in degrees and decimal fraction of degrees (not minutes!).
Lattitudes south of the equator and longitudes on the western hemisphere should be preceded by a minus sign.

3 DESCRIPTION OF THE PROGRAM RDCCDMAP

As it is the program only works for the area specified in the program heading. In order to use it for other countries, some minor modifications to the source code are required.

- A - The name of the CCD-map is read from keyboard and is adjusted to the right in the 12 position name-field. The shifting procedure is essential because the name contains encoded information: the 8th position for instance delivers the dekad number which will be used to read the correct column from the array with rainfall data.

- B - CCD-values, formatted as 3-character integers, are read from the file CCDNAME, specified in section A and stored in the array CCDMAP(252,270).

- C - In this section rainfall data from the meteostations are read. The name of the file with rainfall data is derived from CCDNAME.
For each meteostation, the stationnumber, the location in real world coordinates (degrees and fraction of degrees) and 4 columns of rainfall data (3 dekads & monthly total) are read. The real world coordinates are converted to line- and pixel coordinates in the METEOSAT reference frame with the help of subroutine WTOM and the number of stations is counted.

- D - The CCD-values for the pixels corresponding with the location of the meteostations are extracted from the CCD-map and stored in the linear array CCD.

- E - The linear relation between CCD-values in the array CCD and the corresponding column with rainfall data in the array RAIN is established using a two-stage procedure.
The first stage is a straight forward regression analysis and the results are written to the output file FEB2H24.LFT.
During the second stage, the worst fitting point is detected and if it deviates more than WPCONST (=2.0) times the standard deviation, it is eliminated and the regression equation is determined again. Another worst fitting point is found .... and so on untill the elimination criterion is no longer satisfied. The CODE column in the second half of the output file shows which stations are eliminated and in what order.

- F - The optimized regression equation finally can be used to estimate rainfall for any location. The user specified real world coordinates are first converted to METEOSAT line- and pixel number, the corresponding CCD-value is obtained from the CCD-map and the estimation for the amount of precipitation is calculated.

ANNEX 1 FORTRAN source code of the program RDCCDMAP

```
C Filename: RDCCDMAP.FOR ########################################

      PROGRAM RDCCDMAP

C     Program to estimate rainfall for any location within the
C     METEOSAT-subarea: lines 816..1067, pixels 490..759 i.e.
C     Zambia.

C     Input files: - dekadic or monthly CCD-map covering Zambia
C                  - rainfall data from  meteostations (max.=100)
C###############################################################

      INTEGER ISTATNR(100),ILIN(100),IPIX(100),CODE(100)
      INTEGER CCDMAP(252,270)

      REAL RAIN(100,4),CCD(100)

      CHARACTER CCDNAME*12,F11NAME*11,ANSWER

      PARAMETER (WPCONST=2.0)
C -A- ##########################################################

      WRITE (*,'('' Specify full name of CCD-map: '',$)')
      READ  (*,'(A12)') CCDNAME

C --- Shift CCDNAME to the right as far as possible
      INB = 0
 2    IF (CCDNAME(12-INB:12-INB).EQ.' ') THEN
        INB=INB+1
        GOTO 2
      ENDIF
      DO 4 I=12-INB,1,-1
 4    CCDNAME(I+INB:I+INB)=CCDNAME(I:I)
      DO 6 I=1,INB
 6    CCDNAME(I:I)=' '

C --- Derive dekad number from CCDNAME
      IDEK = ICHAR(CCDNAME(8:8))-48

C -B- Read matrix CCDMAP(252,270) from file CCDNAME

      OPEN (10,FILE=CCDNAME,STATUS='OLD',RECL=810)
      DO 8 ILINE=1,252
 8    READ (10,'(270I3)') (CCDMAP(ILINE,IPIXEL),IPIXEL=1,270)
      CLOSE (10)
```

```
C -C- READ rainfall data for the specified period from a . C RAI file.
C     Read station#, latitude, longitude, 4 columns of rainfall data,
C     Count number of meteostations -> NSTAT,
C     Convert real world coordinates of the stations to METEOSAT coord.

      F11NAME = CCDNAME(1:7)//'.RAI'
      OPEN (10,FILE=F11NAME,STATUS='OLD')
      READ (10,'( //////)')
      NSTAT=0
      DO 10 I=1,100
        READ (10,'(BN,I10,6(E10.0))',END=12) ISTATNR(I),ALAT,ALON,
     $                                       (RAIN(I,J),J=1,4)
        NSTAT=NSTAT+1
        CALL WTOM(ALAT,ALON,ILIN(I),IPIX(I))
 10   CONTINUE
 12   CLOSE (10)

C -D- Find CCD for each station and put it in array CCD(  )

      DO 14 I=1,NSTAT
        CCD(I)=CCDMAP((ILIN(I)-815),(IPIX(I)-489))
 14   IF (CCDNAME(11:12).EQ.'48') CCD(I)=CCD(I)/2

C -E- LINEAR REGRESSION of CCD and MEASURED RAINFALL

      DO 16 I=1,NSTAT
        CODE(I)=0
        IF (RAIN(I,IDEK).LT.0) CODE(I)=-1
16    CONTINUE

      F11NAME=CCDNAME(5:8)//CCDNAME(10:12)//'.LFT'
      OPEN (20,FILE=F11NAME,STATUS='NEW')

      DO 1000 NRUN=1,2
        ITER=1
        IFIN=0

C ---   calculation of REGRESSION COEFFICIENTS A and B

100     SUMX   =0.
        SUMY   =0.
        SUMXY  =0.
        SUMXSQR=0.
        IACTIVE=NSTAT
        DO 120 I=1,NSTAT
          IF (CODE(I).EQ.0) THEN
            SUMX   =SUMX+CCD(I)
            SUMY   =SUMY+RAIN(I,IDEK)
            SUMXY  =SUMXY+CCD(I)*RAIN(I,IDEK)
            SUMXSQR=SUMXSQR+CCD(I)**2
```

```
        ELSE
          IACTIVE=IACTIVE-1
        ENDIF
120   CONTINUE
      XBAR=SUMX/IACTIVE
      YBAR=SUMY/IACTIVE
      B=(SUMXY-SUMX*SUMY/IACTIVE)/(SUMXSQR-SUMX**2/IACTIVE)
      A=YBAR-B*XBAR

C --- Calculation of STANDARD DEVIATION

      SUMLS=0.
      DO 140 I=1,NSTAT
        IF (CODE(I).EQ.0) THEN
          YMINYEST=RAIN(I,IDEK)-(A+B*CCD(I))
          SUMLS=SUMLS+YMINYEST**2
        ENDIF
140   CONTINUE
      STANDEV=SQRT(SUMLS/(IACTIVE-1))

      IF ((IFIN.EQ.1).OR.(NRUN.EQ.1)) GOTO 200

C --- Worst point elimination

      YMYMAX=0.
      IBIG=0
      DO 150 I=1,NSTAT
        IF (CODE(I).EQ.0) THEN
          YMINYEST=RAIN(I,IDEK)-(A+B*CCD(I))
          IF (ABS(YMINYEST).GT.ABS(YMYMAX)) THEN
            IBIG=I
            YMYMAX=YMINYEST
          ENDIF
        ENDIF
150   CONTINUE
      WPCRIT=WPCONST*STANDEV
      IF (ABS(YMYMAX).LT.WPCRIT) THEN
        IFIN=1
      ELSE
        CODE(IBIG)=ITER
        ITER=ITER+1
      ENDIF
      GOTO 100

C --- Calculation of CORRELATION COEFFICIENT

200   SSR=0.
      SST=0.
      DO 210 I=1,NSTAT
        IF (CODE(I).EQ.0) THEN
          SSR=SSR+(A+B*CCD(I)-YBAR)**2
          SST=SST+(    RAIN(I,IDEK)-YBAR)**2
        ENDIF
```

```
210     CONTINUE
        R=SQRT(SSR/SST)

C ---   Write results to output file

        WRITE (20,310) A,B
310     FORMAT(//,' RAINest = ',F6.2,' + ',F6.2,' CCD')
        WRITE (20,320) STANDEV,R
320     FORMAT(' ST.DEV. =',F6.1,/,' R       =',F4.2,/)
        WRITE (20,'('' CODE...CCD....RAIN..RAINest'')')
        DO 330 I=1,NSTAT
          IF (CODE(I).EQ.-1) GOTO 330
          WRITE (20,325) CODE(I),CCD(I),RAIN(I,IDEK),(A+B*CCD(I))

325       FORMAT (I3,3(F8.1))
330     CONTINUE

1000  CONTINUE
      CLOSE(20)


C -F- ESTIMATION of RAINFALL for any LOCATION within the MAP AREA

      WRITE (*,'('' Do you want to estimate rainfall for a location ''
     $        ,''(Y/N) ? '',$)')
      READ  (*,'(A1)') ANSWER
      IF (ANSWER.EQ.'N'.OR.ANSWER.EQ.'n') GOTO 600

500   WRITE (*,'(//'' Latitude Longitude'',/,''*****.** *****.**'')')
      READ  (*,'(F8.2,1X,F8.2)') ALAT,ALON
      CALL WTOM (ALAT,ALON,ILINE,IPIXEL)
      IF (((ILINE.LT.816).OR.(ILINE.GT.1067)).OR.
     $    ((IPIXEL .LT.490).OR.(IPIXEL .GT.759 ))) THEN
        WRITE (*,'(''  Try again -- location outside map area !!!'')')
        GOTO 500
      ENDIF
      CCDVAL = CCDMAP(ILINE-815,IPIXEL-489)
      IF (CCDNAME(11:12).EQ.'48') CCDVAL=CCDVAL/2
      RAINEST = A+B*CCDVAL
      WRITE (*,'(//,'' Rainfall in mm.: '',F5.1)') RAINEST
      WRITE (*,'(//,'' Again (Y/N) ? '',$)')
      READ  (*,'(A1)') ANSWER
      IF (ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y') GOTO 500

600   STOP 'Have a good day'
      END
```

```
C*********************************************************************
      SUBROUTINE WTOM(ALAT,ALON,ILINE,IPIXEL)

C**Routine to convert real world coordinates into Meteosat coordinates**

C     INPUT PARAMETERS:
C     ALAT Latitude of point  (Degrees : negative on Southern H.)
C     ALON Longitude of point (Degrees : negative on Western  H.)
C
C     OUTPUT PARAMETERS:
C     ILINE  Meteosat Linenumber
C     IPIXEL   Meteosat Pixelnumber
C
C*********************************************************************

C --- H      : Altitude of reference satellite
      H      = 42164.0 - 6378.155
C --- RE     : Equatorial radius
      RE     = 6378.155
C --- A      : Coefficient of earth oblateness
      A      = 1./297.
C --- RP     : Polar Radius
      RP     = RE/(1.0+A)
      PI     = 3.141592653
      CDR    = PI/180.
      CRD    = 180.0/PI
C --- LPSI2  :  1 If spin axis points normally,
C ---          -1 if axis points in reverse direction
      LPSI2  = 1
C --- DELTAX : Radiometer Scanning step E-W (Degrees)
      DELTAX = 18.0/2500.
C --- DELTAY : Radiometer Scanning step S-N (Degrees)
      DELTAY = 18.0/2500.
C --- RFLON  : Longitude of reference satellite
      RFLON  = 0.0

      XFI = ALAT*CDR
      XLA = ALON*CDR
      ROM = (RE*RP)/SQRT(RP**2*COS(XFI)**2+RE**2*SIN(XFI)**2)
      Y   = SQRT(H**2+ROM**2-2*H*ROM*COS(XFI)*COS(XLA))
      R1  = Y**2+ROM**2
      R2  = H**2
      RS = RE +H
      REPH = RE
      RPPH = RP
      COSLO = COS(RFLON*CDR)
      SINLO = SIN(RFLON*CDR)
      TETA  = ATAN((RPPH/REPH)*TAN(XFI))
      XT = REPH * COS(TETA)* COS(XLA)
      YT = REPH * COS(TETA)* SIN(XLA)
      ZT = RPPH * SIN(TETA)
```

```
      PX = ATAN((COSLO * (YT-RS*SINLO)-(XT-RS*COSLO)*SINLO)/
     $(SINLO*(YT-RS*SINLO)+(XT-RS*COSLO)*COSLO))

      PY = ATAN(ZT * ((TAN(PX)*SINLO-COSLO)/(XT-RS*COSLO))*COS(PX))

      PX = PX*CRD
      PY = PY*CRD
      XR = PX/(DELTAX*LPSI2)
      YR = PY/(DELTAY*LPSI2)
      IF(XR.GE.0.0) XR = INT(PX/(DELTAX*LPSI2))+ 0.5
      IF(XR.LT.0.0) XR = INT(PX/(DELTAX*LPSI2))- 0.5
      IF(YR.GE.0.0) YR = INT(PY/(DELTAY*LPSI2))+ 0.5
      IF(XR.LT.0.0) YR = INT(PY/(DELTAY*LPSI2))- 0.5
      IPIXEL = XR+1250.5
      ILINE  = YR+1250.5

      RETURN
      END
```

ANNEX 2 Hardcopy of the input file ZA87FEB.RAI

Filename: ZA87FEB.RAI

-- Measured rainfall in mm./dekad, month (-1. : missing value) ---

-- Year: 1987 Month: February Country: Zambia --

<=Stat.#=>	<=Latit.=>	<=Longi.=>	<==Dek1==>	<==Dek2==>	<=Dek3=>	<=Month=>
413	-8.85	31.33	103.90	113.90	58.60	276.40
403	-9.80	29.08	-1.	-1.	-1.	-1.
476	-10.10	31.25	100.30	108.00	101.20	309.50
481	-10.12	32.63	112.90	134.60	42.90	290.40
475	-10.22	31.13	100.10	190.30	58.60	349.00
461	-11.10	28.85	122.60	57.60	15.20	195.40
469	-11.35	29.53	-1.	-1.	-1.	-1.
441	-11.75	24.43	55.30	111.80	86.60	252.70
477	-11.90	31.43	7.20	130.50	27.30	165.00
583	-12.28	33.20	70.80	76.80	65.60	213.20
551	-12.17	26.87	179.70	68.60	97.70	346.00
563	-12.60	28.12	44.40	110.60	53.40	208.40
561	-13.00	28.65	66.10	50.70	84.20	201.00
571	-13.23	30.22	-1.	-1.	-1.	-1.
585	-13.27	31.93	8.20	12.10	41.50	61.80
581	-13.55	32.58	28.40	56.80	110.00	195.20
580	-13.65	32.57	51.10	19.40	115.70	186.20
531	-13.53	23.12	131.60	124.00	17.60	273.20
543	-13.60	24.20	131.80	78.90	15.50	226.20
673	-14.25	31.28	37.60	11.00	65.10	113.70
662	-14.40	28.50	10.50	0.00	23.70	34.20
663	-14.45	28.47	75.60	0.00	13.20	88.80
641	-14.80	24.80	82.80	52.50	40.50	175.80
655	-15.07	27.18	88.80	0.60	52.80	142.20
665	-15.32	28.45	-1.	-1.	-1.	-1.
633	-15.25	23.15	69.80	33.10	63.10	166.00
667	-15.55	28.25	18.90	10.50	46.10	75.50
659	-15.77	27.92	14.90	5.30	15.00	35.20
751	-16.00	27.60	44.70	9.60	49.20	103.50
731	-16.10	23.27	23.00	21.50	16.80	61.30
753	-16.83	27.07	26.90	2.60	4.70	34.20
741	-17.47	24.30	72.10	26.40	2.90	101.40
743	-17.82	25.82	-1.	-1.	-1.	-1.

ANNEX 3 Hardcopy of the empty input table RAIN.FRM

Filename:

-- Measured rainfall in mm./dekad, month (-1. : missing value) --

-- Year: Month: Country: Zambia --

<=Stat.#=>	<=Latit.=>	<=Longi.=>	<==Dek1==>	<==Dek2==>	<=Dek3=>	<=Month=>
413	-8.85	31.33				
403	-9.80	29.08				
476	-10.10	31.25				
481	-10.12	32.63				
475	-10.22	31.13				
461	-11.10	28.85				
469	-11.35	29.53				
441	-11.75	24.43				
477	-11.90	31.43				
583	-12.28	33.20				
551	-12.17	26.87				
563	-12.60	28.12				
561	-13.00	28.65				
571	-13.23	30.22				
585	-13.27	31.93				
581	-13.55	32.58				
580	-13.65	32.57				
531	-13.53	23.12				
543	-13.60	24.20				
673	-14.25	31.28				
662	-14.40	28.50				
663	-14.45	28.47				
641	-14.80	24.80				
655	-15.07	27.18				
665	-15.32	28.45				
633	-15.25	23.15				
667	-15.55	28.25				
659	-15.77	27.92				
751	-16.00	27.60				
731	-16.10	23.27				
753	-16.83	27.07				
741	-17.47	24.30				
743	-17.82	25.82				

ANNEX 4 Hardcopy of the output file FEB2H24.LFT

<straightforward regression>

RAINest = -5.59 + 2.26 CCD
ST.DEV. = 30.0
R = .82

CODE	CCD	RAIN	RAINest
0	73.0	113.9	159.2
0	57.0	108.0	123.1
0	61.0	134.6	132.1
0	50.0	190.3	107.3
0	41.0	57.6	87.0
0	59.0	111.8	127.6
0	30.0	130.5	62.1
0	40.0	76.8	84.7
0	35.0	68.6	73.4
0	30.0	110.6	62.1
0	27.0	50.7	55.4
0	23.0	12.1	46.3
0	26.0	56.8	53.1
0	25.0	19.4	50.8
0	36.0	124.0	75.7
0	30.0	78.9	62.1
0	12.0	11.0	21.5
0	4.0	.0	3.4
0	3.0	.0	1.2
0	25.0	52.5	50.8
0	9.0	.6	14.7
0	27.0	33.1	55.4
0	7.0	10.5	10.2
0	5.0	5.3	5.7
0	5.0	9.6	5.7
0	26.0	21.5	53.1
0	9.0	2.6	14.7
0	11.0	26.4	19.2

<worst point elimination method>

RAINest = -7.94 + 1.96 CCD
ST.DEV. = 14.1
R = .94

CODE	CCD	RAIN	RAINest
0	73.0	113.9	135.0
0	57.0	108.0	103.6
0	61.0	134.6	111.5
1	50.0	190.3	89.9
0	41.0	57.6	72.3
0	59.0	111.8	107.6
2	30.0	130.5	50.8
0	40.0	76.8	70.4
0	35.0	68.6	60.6
4	30.0	110.6	50.8
0	27.0	50.7	44.9
0	23.0	12.1	37.1
0	26.0	56.8	43.0
0	25.0	19.4	41.0
3	36.0	124.0	62.5
0	30.0	78.9	50.8
0	12.0	11.0	15.6
0	4.0	.0	-.1
0	3.0	.0	-2.1
0	25.0	52.5	41.0
0	9.0	.6	9.7
0	27.0	33.1	44.9
0	7.0	10.5	5.8
0	5.0	5.3	1.9
0	5.0	9.6	1.9
0	26.0	21.5	43.0
0	9.0	2.6	9.7
0	11.0	26.4	13.6