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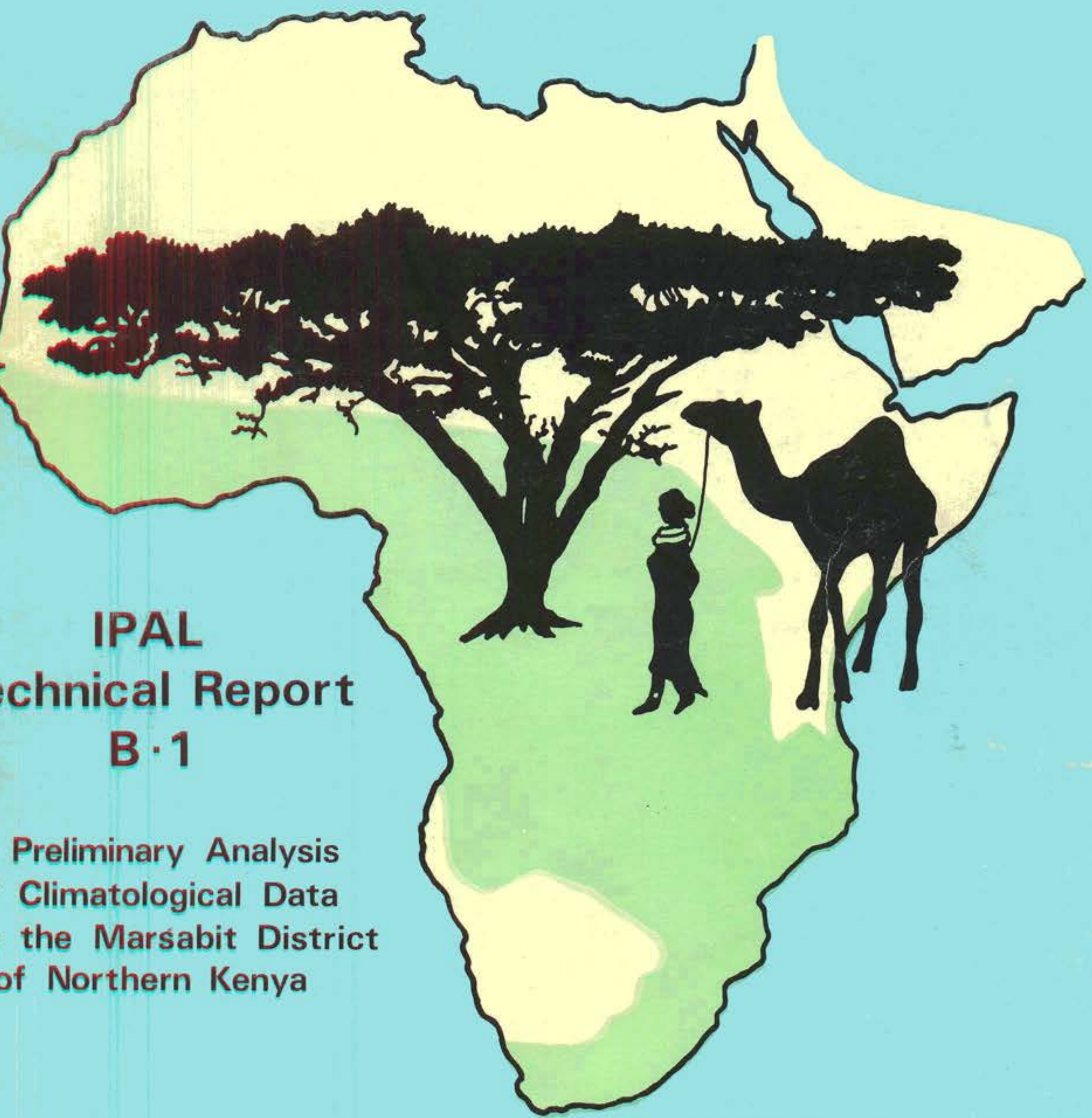

IPAL
Technical Report
B·1

A Preliminary Analysis of Climatological Data from the Marsabit District of Northern Kenya

MAN AND THE BIOSPHERE PROGRAMME

Project 3: Impact of Human Activities and Land Use Practices on Grazing Lands

IPAL Technical Paper Number B - 1

A PRELIMINARY ANALYSIS OF CLIMATOLOGICAL DATA FROM THE MARSABIT DISTRICT OF NORTHERN KENYA

by

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UNEP - MAB Integrated Project in Arid Lands

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Summary Introduction to IPAL and the Technical Report Series

The Integrated Project in Arid Lands (IPAL) was established jointly by UNEP and UNESCO in 1976 with the aim of finding direct solutions to the most urgent environmental problems associated with desert encroachment and ecological degradation of arid lands. It forms part of the operations under MAB Project 3, the Secretariat of which is jointly held by UNESCO and FAO, and also those of UNEP's Desertification Unit, established in response to the plan of Action adopted by the United Nations Conference on Desertification. It is an example of the type of pilot activity that UNEP and UNESCO, together with other organisations and a number of governments, are trying to promote to provide the scientific basis for the rehabilitation and rational development of arid and semi-arid zone ecosystems, through integrated programmes of research (including survey, observation and experimentation), training and demonstration.

During the early operational work of IPAL, a co-ordination unit was established in Nairobi and the initial field-work started in the arid zone of northern Kenya, where a field station has been constructed on the lower slopes of Mount Kulal and a working area demarkated between Lake Turkana and Marsabit Mountain. Work was started on several aspects of the ecology and experimental management, centred upon the interaction of pastoralists and their livestock with the soils and vegetation of the environment.

During the next two or three years (1979 - 1982), the investigations in progress will be extended and intensified. Initially, new activities within the IPAL project will be started in Tunisia, to be followed by other areas in the arid zones of Africa and the Near and Middle East.

This report is one of a series published by IPAL describing technical findings of the project and, where appropriate, giving management recommendations relating to the central problems of ecological and sociological degradation in the arid zone. The reports are divided into the following categories distinguished by the base colours of their covers:

A. general, introductory and historical: white.

B. climate and hydrology: blue.

C. geology, geomorphology and soils: brown.

D. vegetation: green.

E. livestock and other animal life: red.

F. social and anthropological: yellow.

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A PRELIMINARY ANALYSIS OF CLIMATOLOGICAL DATA FROM THE MARSABIT DISTRICT OF NORTHERN KENYA

1. Introduction

The Integrated Project in Arid Lands (IPAL) was initiated in 1976 in the Marsabit District of Northern Kenya to study the arid grazing lands ecosystems. One of the major inputs to the ecosystem is the climate. Rainfall, in particular, controls the moisture status of the soils, the abundance and distribution of vegetation and the availability of groundwater. Thus, the distribution and number of livestock and the size of the human populations which can subsist on the livestock are ultimately dependent upon rainfall and the balance between input and losses in the soil-plant-atmosphere system.

Recently the increase in desert areas throughout the world has received international attention (UNEP 1977). There is evidence that long-term climatic change, accentuated by man's activities in arid and semi-arid lands i.e. agriculture, irrigation, grazing and fire, has produced almost irreversible changes on the margins of the world's deserts. In addition, short term climatic fluctuations occur which are characterised by years of ample rainfall followed by quasi-cyclic droughts. The wetter years encourage the intensification of agricultural and pastoral activity within areas of marginal potential with disastrous consequences on their delicate ecosystems during the drought years (Sherbrooke and Paylore, 1973).

Early in the current decade (1970-1979), a serious drought in Sahelian Africa caused a high mortality of livestock and people throughout the area (Wade 1974, Glantz 1976, Dalby et al. 1977). Parts of northern Kenya were also affected and evidence of the severity of the drought on the IPAL study area is presented below.

There is a need, therefore, both to quantify the climatic parameters dominant in the study area and to place them in perspective in terms of the short-term climatic fluctuations. In this way, the background climatic information will be of most use to the ecologists. This report is a preliminary assessment of the first two years of data collection.

2. Climatological Studies

IPAL has established three climatological stations within the area shown in Figure 1. At Gatab, the field station headquarters, one Epsylon Automatic Weather Station was installed in June 1976. This station was replaced in November 1977 by a meteorological enclosure containing a Stevenson Screen, a recording anemometer, a Lintronic solarimeter and standard and recording raingauges. Temperature measurements are taken twice a day at 0900 and 1500 E.A.S.T.

The Epsylon Weather Station was moved to North Horr in order to sample the drier end of the climatic spectrum. In the meantime, a Didcot Automatic Weather Station had been installed in June 1977 within the grazing paddocks at Balesa Kulal.

The data from the three stations have been subjected to preliminary analysis and the results are presented in this report. It is intended as a guide to the climatology of this part of Marsabit District and also an indication of where further data collection is needed to complete the picture. Detailed printouts of the data from the automatic weather stations are available from IPAL and the Institute of Hydrology, Wallingford, U.K., where the weather station tapes are translated.

Both types of station record meteorological variables at five minute intervals on magnetic tape. The variables are listed in Table 1. The Epsylon machine uses 6mm computer tape and can run for up to three months, if a suitable power supply is available. Normally, on dry cells, the station is operational for one month periods. The Didcot machine uses commercial C-60 tape cassettes which limit the operating time to twenty-one days. Using rechargeable lead-acid batteries, the tape is changed every fourteen days as standard practice. The shorter period is to be preferred, if this is logistically possible, to minimize loss of data in the event of faults developing during a recording period.

Rainfall over the study area is particularly difficult to measure because of the sparse human population and the rugged terrain. Apart from the daily-read gauges at the meteorological stations and at missions and Police Posts, IPAL has to rely on monthly-read storage gauges of special design which can be read by the project staff who travel in the study area.

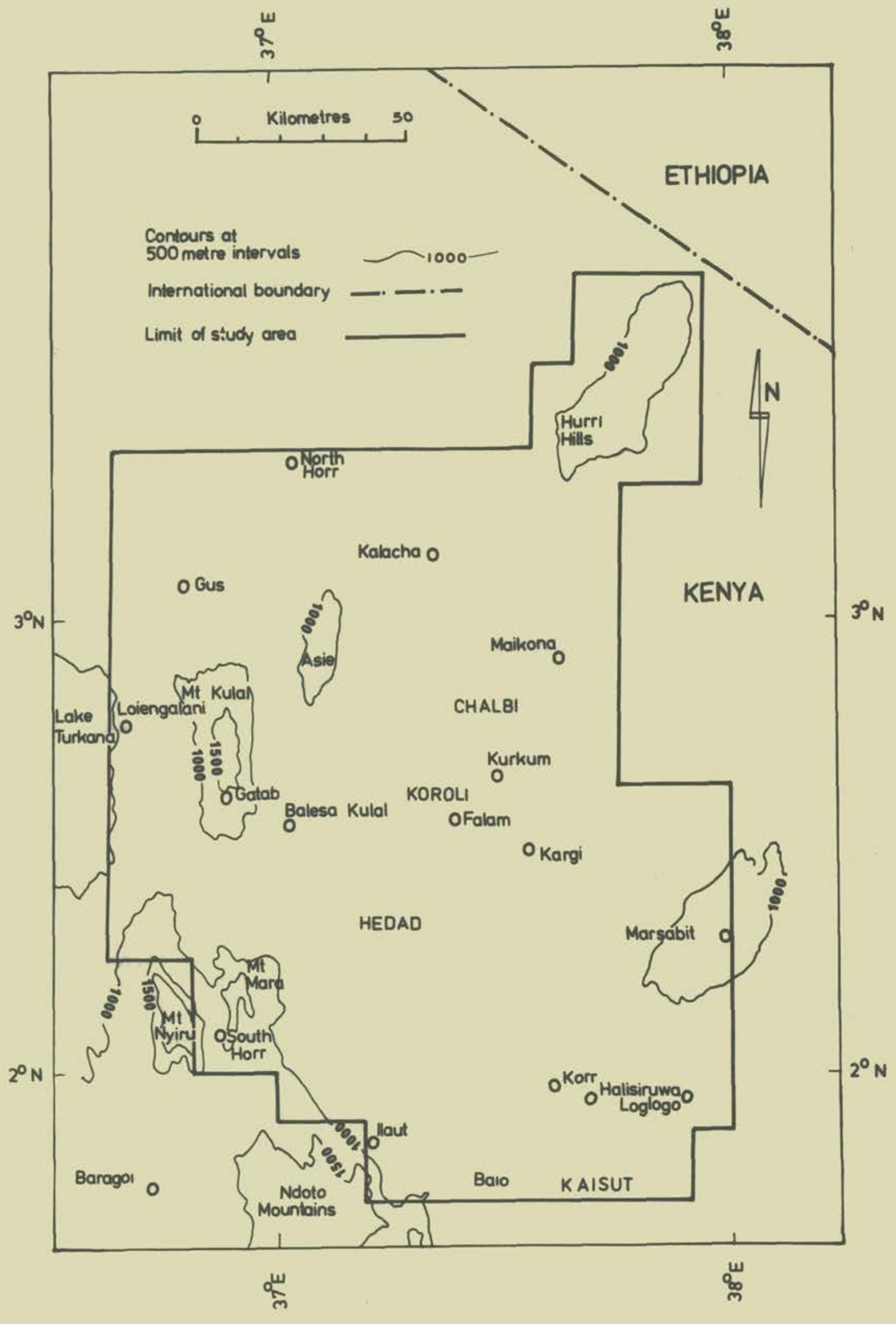


FIGURE I THE IPAL STUDY AREA

TABLE 1

Meteorological variables recorded by Automatic Weather Stations

	Epsylon	Didcot	Sensors
Solar radiation	1	1	Kipp & Zonen
Net radiation		1	Type DRN 101
Run-of-wind	1	1	Cup Anemometer
Air Temperature	1	1	Dry Bulb in Screen
Depression of Wet Bulb	1	1	Wet & Dry Bulbs in Screen
Wind Directions	1	1	Didcot
Rainfall	1	1	Tipping Bucket

There is a serious risk of vandalism with unattended raingauges in remote areas which precludes the installation of sophisticated recording gauges away from the settlements. For this reason, the results from this comparatively dense network of gauges have an intrinsic value in that they are virtually unique in the semi-arid area of northern Kenya.

3. General Climatology of Marsabit District

The climate of Eastern Africa is usually described in terms of the simple atmospheric circulation model showing a broad equatorial trough (or troughs) into which the trade wind systems converge from both hemispheres. The trough is frequently termed the intertropical convergence zone (ITCZ) and its movement north and south, following the sun, gives rise to the characteristic patterns of seasonal rainfall.

This simple model, however, is considerably modified on the margins of continents, where the distribution of land and sea creates complex pressure patterns, and in particular where topographic barriers, such as the East African Highlands, block surface flow. The main convergence zone can be displaced and distorted, giving rise to areas of enhanced convergence and divergence (Findlater 1971). One such area is southwest Marsabit District, which is arid although it lies only 2 to 4° north of the Equator.

The IPAL study area is within this area of enhanced divergence and, furthermore, lies in a corridor between the Ethiopian and Kenya Highlands. These highlands rise to more than 3,000m while the Chalbi Desert, Koroli Desert and Hedad are less than 700m in altitude. The easterly circulation of the Indian Ocean Monsoons abuts against these topographic barriers on the west, and overspilling of air currents through this corridor gives rise to strong easterly winds throughout the year. The Chalbi Desert, in fact, has a longitudinal dune orientated SE/NW and 4km in length, showing the constancy of wind through the northern part of the corridor. ERTS satellite photographs also reveal large areas of blown sand, including barchans, overlying the volcanics to the west of North Horr. This has clearly originated from the sediments of the Balesa and Balal river systems which are deposited in Chalbi basin.

The climate of the area can best be described in terms of the low level airflow over the Western Indian Ocean. Findlater (1971) has outlined the salient features of the general circulation and presented monthly charts of airflow at the 1km and 3km levels. These are an excellent guide to the mean flow pattern, and, in particular, the 3km streamlines give a clear indication of low level divergence and convergence. This in turn illustrates the stability pattern over northern Kenya and explains why the rains occur often with very little shift in wind direction and speed, in contrast to other regions in Kenya.

From December to March, the north-east Monsoon is well established with a core of high wind speeds (c. $8m\ s^{-1}$) reaching Lake Turkana from Arabia. This hot, dry airmass flows into East Africa and one branch turns westwards to flow through the Lake Turkana corridor. Flow is divergent over most of eastern and northern Kenya giving rise to a stable situation and no rainfall. In exceptional years like 1961/2 and 1977/8, the whole system may be displaced northwards so that the northern equatorial trough extends into Kenya and rain may occur at any time between October and April. Conversely, during the dry years of the early seventies, there was little penetration of the northern equatorial trough into northern and eastern Kenya and severe drought conditions were widespread.

By April, the northern equatorial trough is on the Equator, the north-easterly flow has weakened and a low pressure system in the region of Lake Victoria gives rise to a convergent easterly flow off the Indian Ocean. The wide-spread rain will extend into northern Kenya in good years provided that the south-easterly flow has displaced the residual Arabian airstream.

May to September are months characterized by the establishment of the south-west monsoon in the Indian Ocean. The south-east trade wind belt reaches eastern Africa in the form of a southerly flow which is blocked by the highlands and curves into the south-westerly flow across the Indian Ocean. This strong clockwise flow dispaces the equatorial troughs to the east at the lowest levels. Over northern Kenya the flow is divergent and, except on mountains which may give rise to orographic rainfall, the general pattern is of little or no rainfall in spite of the northerly position of the equatorial troughs.

During October and November the equatorial troughs are moving southwards and the north-east Monsoon is establishing itself once again. There is a convergence over northern Kenya as the south-easterly flow is blocked by the advance of the north-east Monsoon. This gives rise to rainfall until the north-east flow begins to dominate and the equatorial troughs move well to the south.

Clearly such generalizations can be misleading with regard to individual seasons in particular years. They establish the general pattern, however, and the subsequent discussions of recorded meteorological variables can be related to the mean or average conditions which may be expected and explanations for some of the anomalies can be tentatively given in terms of the low level airflow pattern.

4. Rainfall

4.1 Historic Records

4.1.1 Annual Rainfall Pattern

The most complete rainfall records (56 years) from the area come from Moyale, about 180km to the north-east of Marsabit. From 1915 to 1951, there appears to have been a seven-year interval between peaks of rainfall. This changed to a 4, 6 or 10-year interval from 1951 to the present.

At Marsabit. records are less complete. They follow the Moyale pattern of a seven-year interval until 1930. Rainfall at subsequent seven-year intervals between 1930 and 1951, although not the highest recorded, was well above average with a mean for the three peaks of 993mm compared with 826mm for the whole 51 year period. The pattern was disrupted after this, there being a decade before the next high peak in 1961 followed by peaks in 1963 and 1966. A pronounced drought, which was only broken in 1977, then occurred in the next decade.

4.1.2 Rainfall in the study area since 1961

There are only three stations within the study area with a decade or more of rainfall records. Two of these, Marsabit and Gatab, are located on mountains and the third, North Horr, is adjacent to the Chalbi desert.

Annual totals for these three stations are shown in Figure 2. Moyale lies outside the study area but its data are relevant to the regional pattern.

High rainfall levels were recorded in 1961 and, with the exception of Moyale, they were the highest recorded. There followed a dry year at all stations (1962) and then another moderately wet year (1963). Both 1964 and 1965 had below average rainfall at the three gauges which were then operating. By 1967, however, higher rainfall was again being recorded, except at N. Horr, and this persisted until 1968. There then followed eight to ten years of below average or drought conditions at all stations with exceptionally dry years in 1973 and 1976.

From the similiarities in the rainfall patterns recorded from the four different gauges it is apparent that the whole study area lies within a larger rainfall zone which extends over the greater part of northern Kenya including Moyale.

The eight year drought from 1969 to 1976 inclusive appears to have been severe at Gatab and N. Horr on the basis of plant production and livestock mortality but the long term records for Moyale and Marsabit suggest that it was little worse than historic droughts in the early 1920's and 1930's.

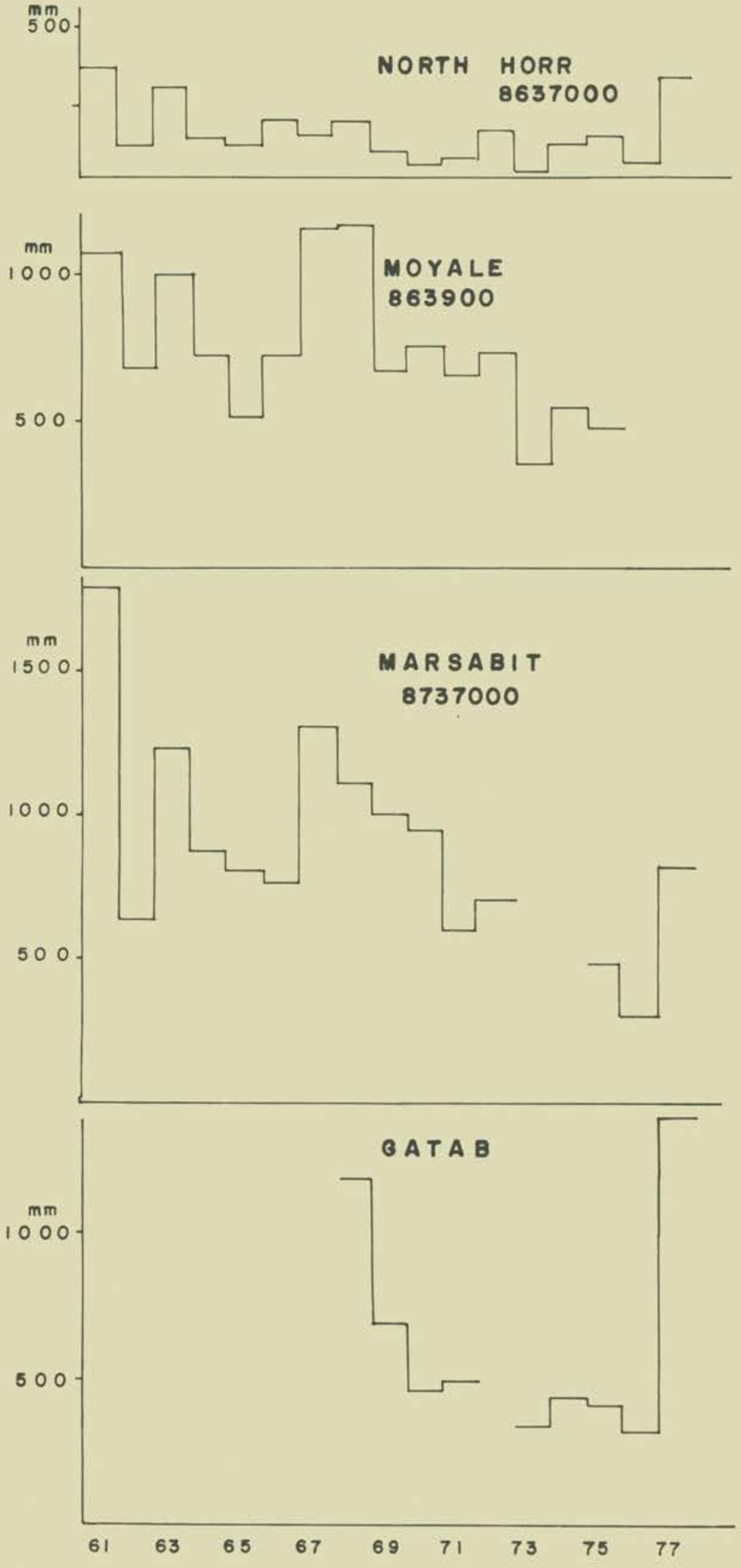


FIGURE: 2 ANNUAL RAINFALL TOTALS

4.1.3 Monthly Rainfall

Mean monthly rainfall histograms have been drawn for three stations in the study area together with median values in Figure 3. Gatab (1867m) and Marsabit (1360m) are mountain stations while North Horr (500m) is a lowland station. All three histograms show a bimodal seasonal rainfall pattern with peaks in April and November.

4.1.4 Deviation of 1970's drought from mean

Sufficient data exist from Marsabit and N. Horr from 1970 to the present to assess the percentage deviations of annual rainfall from the long term mean. These are shown as histograms in Figure 4. In the case of Marsabit, data were available for only six of the eight years. Of these six, four showed less rainfall than the mean and two more than the mean. The latter occurred at either end of the period of lower rainfall. The greatest deviation was minus 60.7% or 39.3% of the mean in 1976. At North Horr larger deviations were recorded. Six of the years had less rainfall than the mean and, of these, four had less than 50% of the mean. An extreme deficit occurred in 1973, only 5% of the mean being recorded. This was balanced four years later when the drought broke and there was 220% more than the mean. These large fluctuations in rainfall demonstrate the low reliability of rainfall in arid areas and illustrate the severe nature of the drought (particularly at N. Horr) during the period 1970 to 1976.

4.2 Spatial Variation in Rainfall

4.2.1 Isohyetal Maps

During 1976 and 1977 IPAL established a series of monthly-read storage rain gauges in the study area. Criteria for design of such gauges were that they should withstand both extreme environmental conditions and the attentions of nomadic people and that they should approximate as nearly as possible to the standard Kenya Meteorological Department gauge. A 1.3m length of 12.5cm (5") diameter steam pipe with a welded base plate is cemented into the ground and a thin layer of vehicle sump oil is added to minimise evaporation.

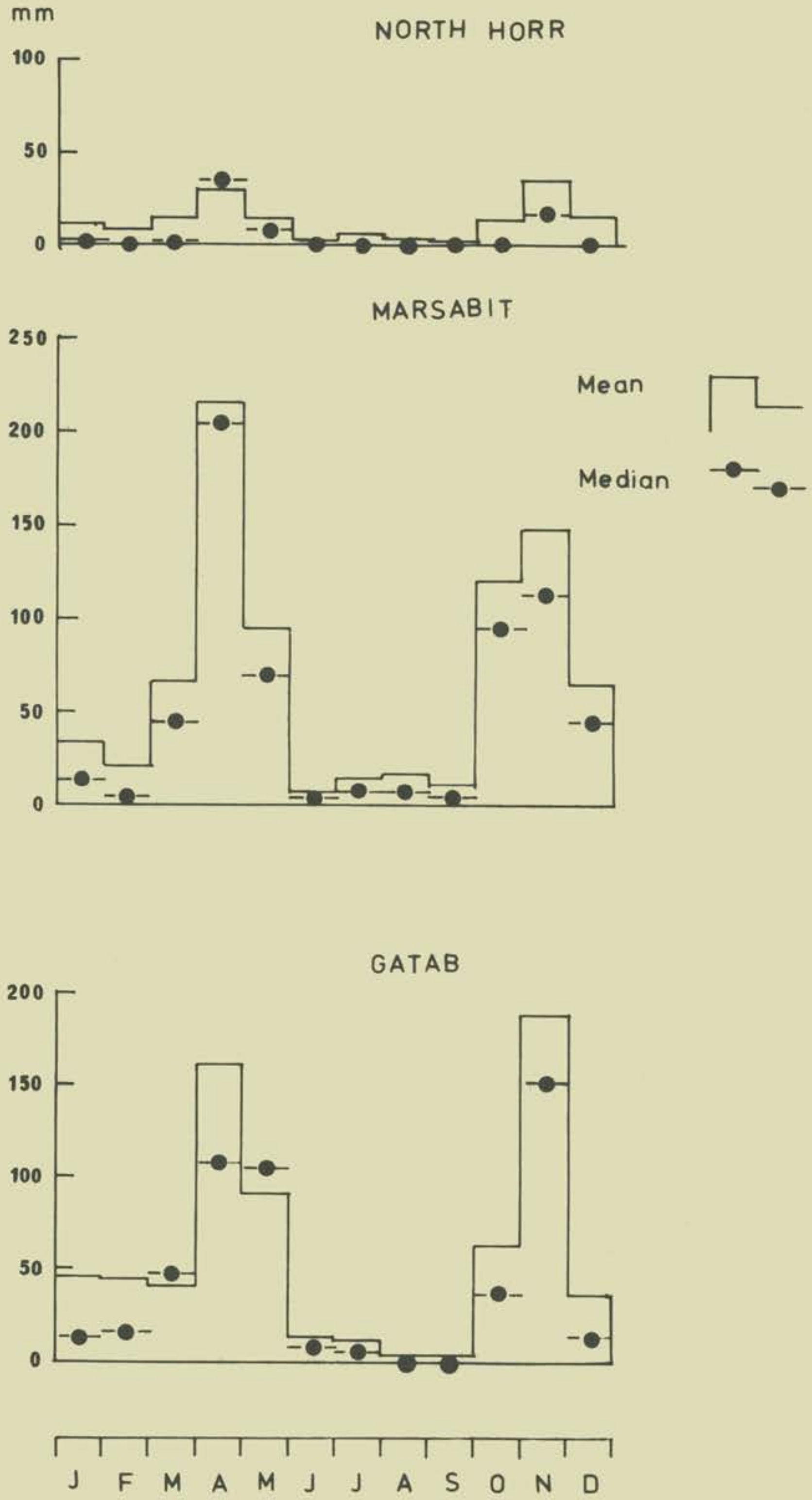


Figure 3 Mean monthly rainfall

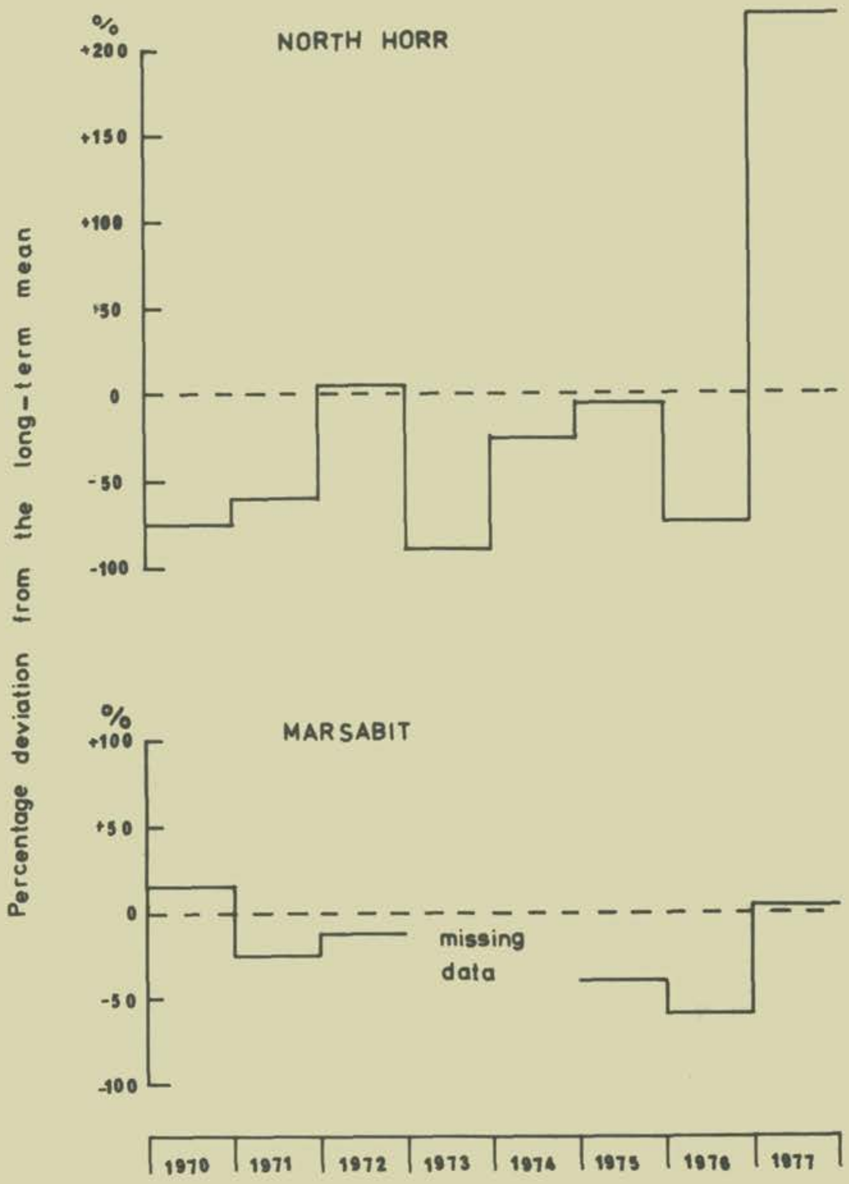


Figure 4 Deviation of annual rainfall from the mean

Readings are taken with a dipstick and are cumulative. Thus a monthly total is obtained by subtraction of the previous month's reading. An added refinement is a perforated container which fits inside the cylindrical gauge and can be removed, bearing with it any rocks which may have been thrown in by passing people. At present, twenty four such gauges have been established in the study area. These augment ten daily-read standard K.M.D. gauges and two gauges at the automatic weather stations. Thus, there are thirty six gauges in the study area of which four are duplicates. The distribution of these gauges is shown in Figure 5.

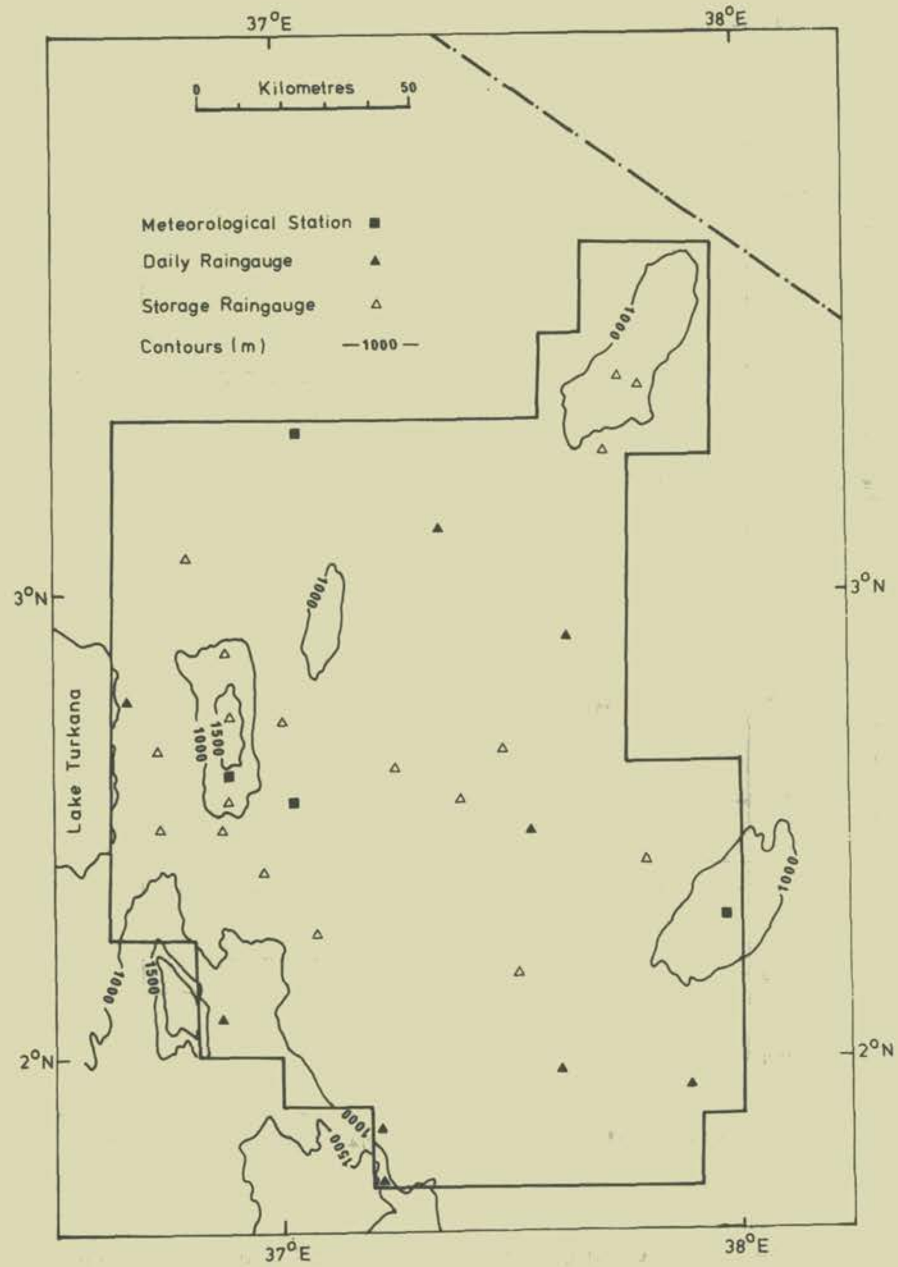


Figure 5 Distribution of raingauges

It has been possible to construct rainfall isohyets for the three rainy periods March to May and October to November 1977 and February to April 1978 (Fig. 6.7 and 8). The first rains came a month early in 1978 and also ended early, hence the different period taken. It is apparent that there is a marked association of rainfall with altitude with the highest recorded amounts coming from Mt. Kulal, the Ndoto Mountains, Marsabit and the Hurri Hills.

4.2.2 Rain Shadows and Cloudstreams

Mt. Kulal, the Hurri Hills and Marsabit Mountain lie in the path of the prevailing easterly winds. A narrowing of the isohyets to the west of the mountains, particularly Mt. Kulal, suggests a rain shadow effect (Figures 6, 7, 8). Easterly winds experience massive uplift as they ascend the eastern flanks of the mountains. The air temperature falls and, beyond the dewpoint, cloud forms and rain may occur.

This moisture depletion of the air lowers the dewpoint so that, when the air descends the western slopes, the base of the cloud is higher and the air warms adiabatically through a greater altitude range than during ascent. This mechanism leads to warmer and drier conditions than average on the lee-side of the mountains. The distribution of taller, more dense forest on the east side of Mt. Kulal corroborates this feature. In addition, satellite images show a similar asymmetry in the distribution of forest on Marsabit Mountain and again, similar features have been noted on the Hurri Hills (Herlocker, 1979).

Cloudstreams have been observed frequently in the general area. In particular, a stream develops almost daily to the south of the study area and stretches from the Ndoto mountains to Baragoi and westwards. This cloudstream often develops into rain which is probably the cause of the strip of *Acacia tortilis* woodland around Baragoi within the *Duosperma eremophilum* dominated El Barta plains.

A similar although weaker cloud stream has been observed running northwestwards from Marsabit Mountain. The effect of this cloudstream during February to April 1978 is clearly seen in Figure 8. Furthermore, there is evidence (November 1977) that the vegetation on a line from Marsabit to Kulal and Asie is more dense and sometimes of a different composition from that to the north fringing the Chalbi desert and to the south around the Kaisut desert, Korr and Hafarei.

4.2.3 Rainfall and Altitude

The storage gauges have been deliberately concentrated on the slopes of Mt. Kulal to determine the effect of altitude on rainfall.

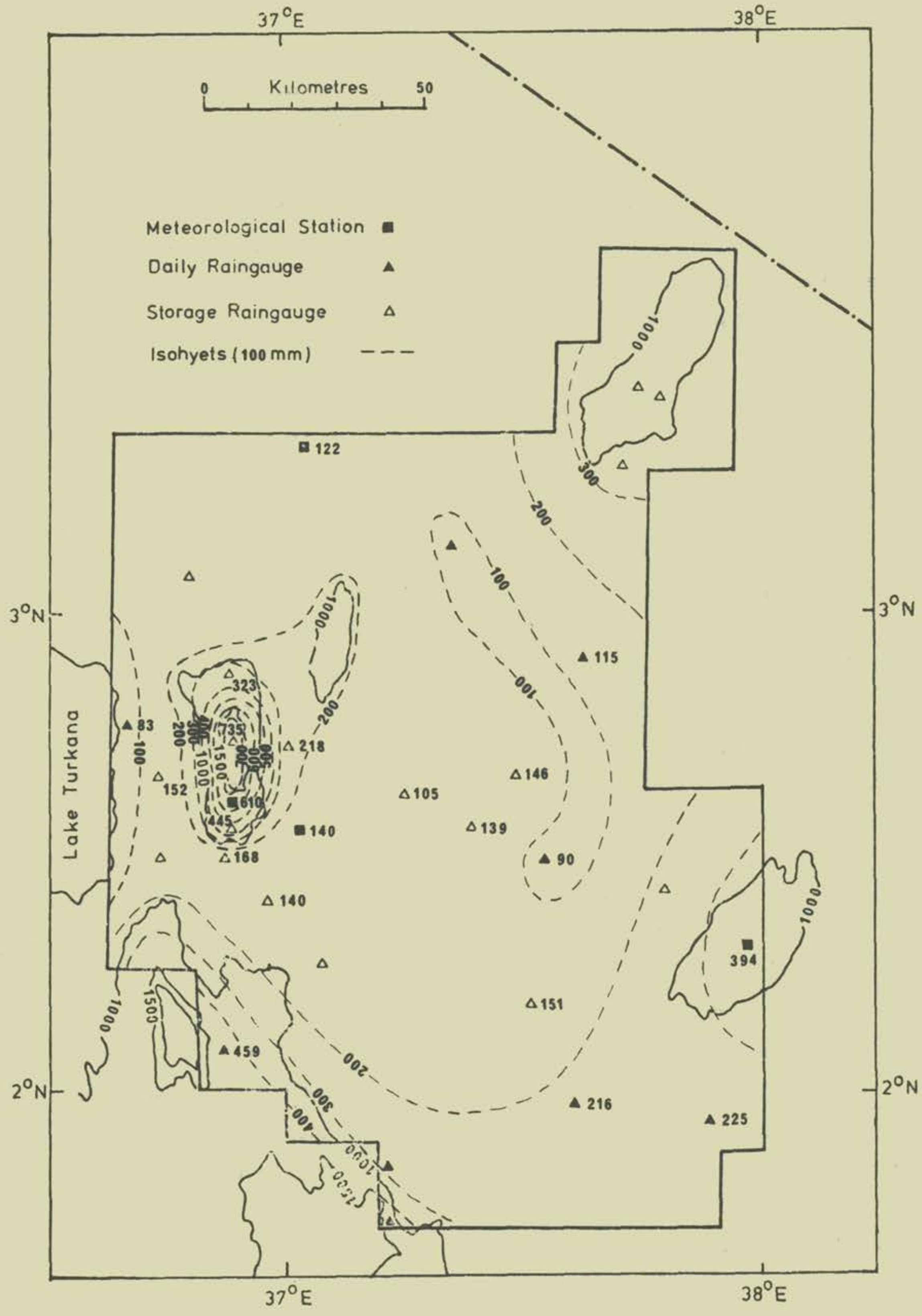


Figure 6 Isohyets for March - May 1977

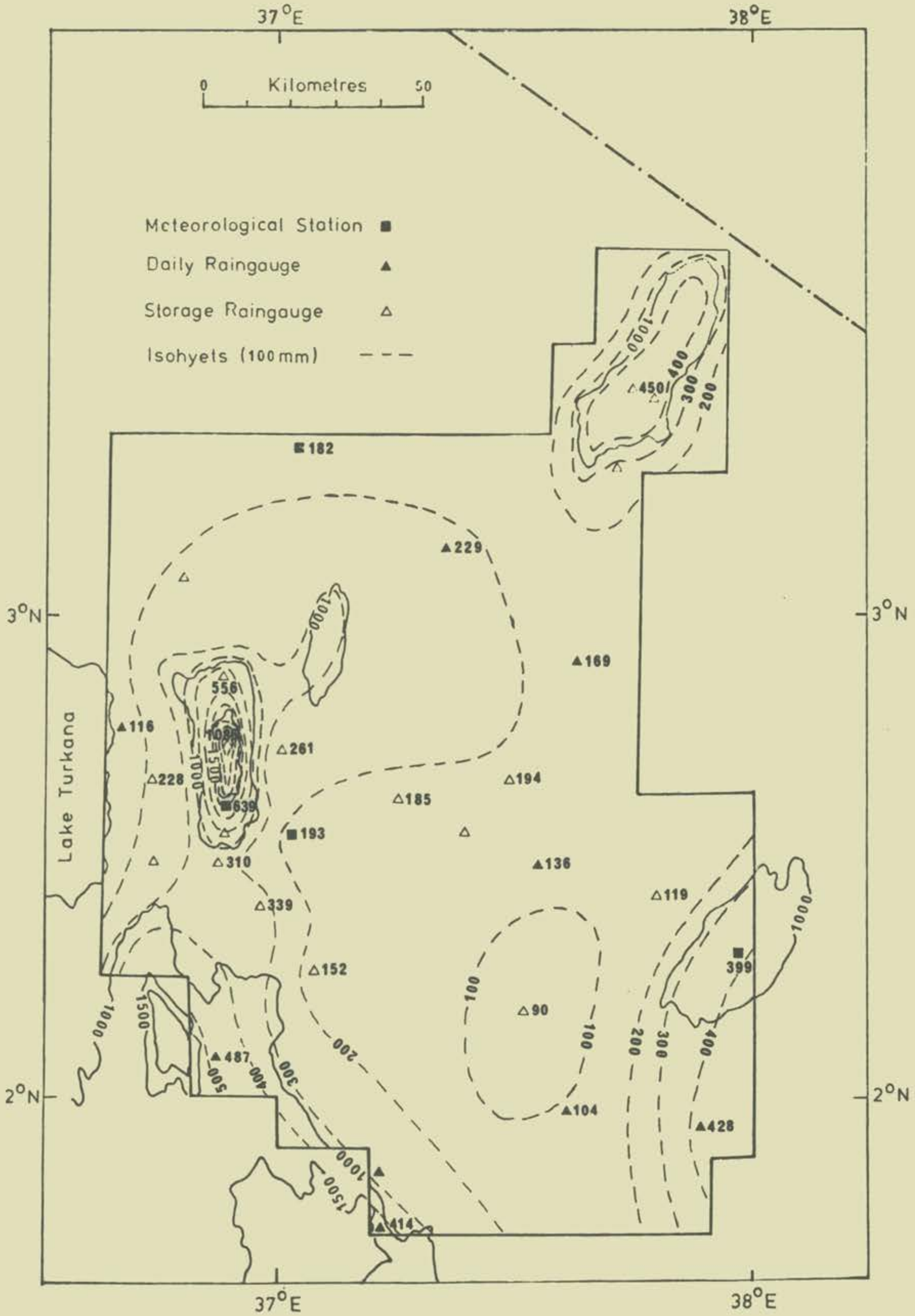


Figure 7 Isohyets for October – December 1977

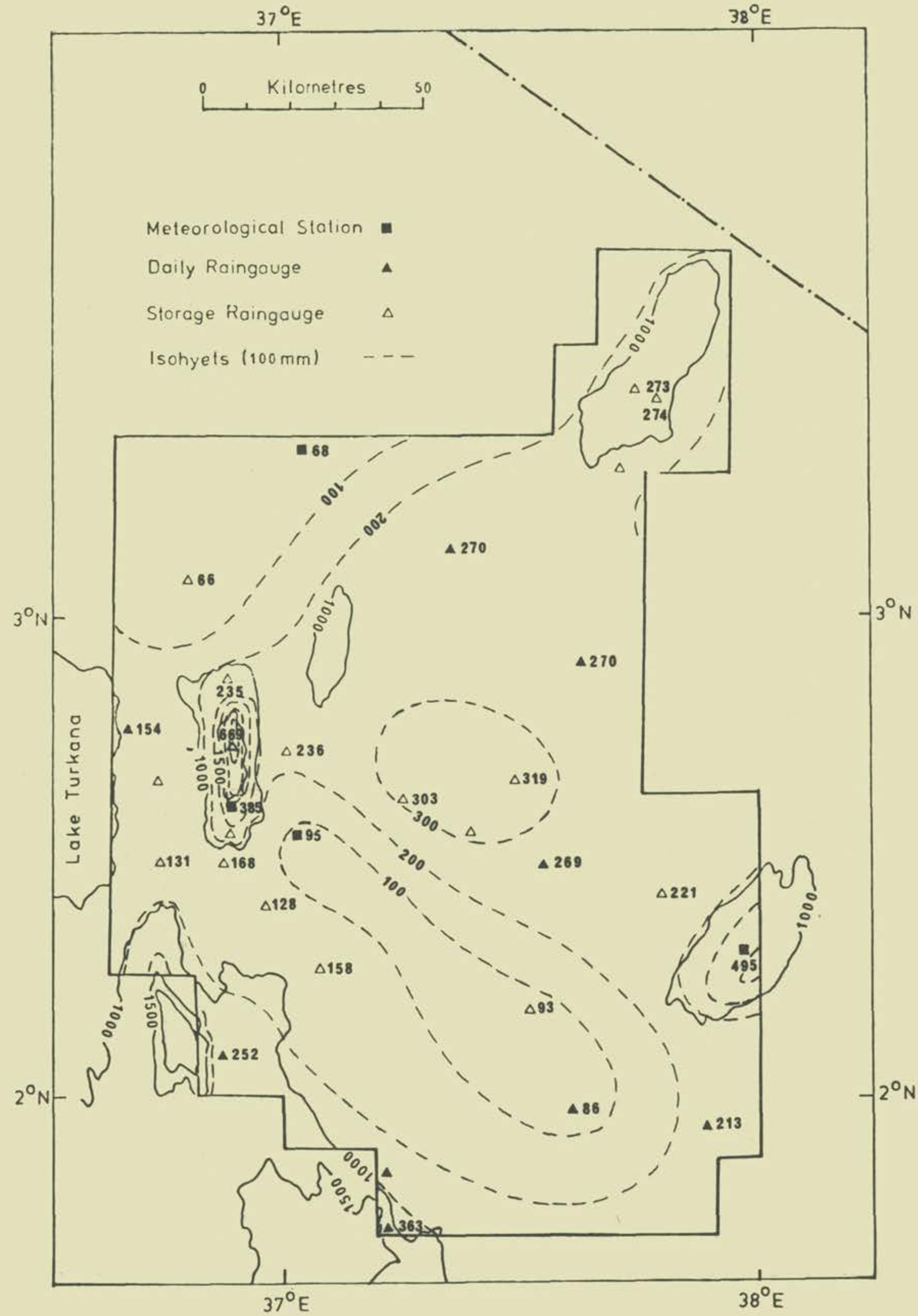


Figure 8 Isohyets for February- April 1978

The complete rainfall records for 1977 are plotted against the altitude of each gauge in Figure 9. There is a good relationship between altitude and rainfall which may be expressed as:

Rain = 0.84 Alt - 178.3

where Rain is the rainfall from 12 stations in mm and Alt is the altitude in metres. The correlation coefficient is 0.93. If one station, Arabel on the north side of Mt. Kulal, is omitted from the data set, the regression becomes:

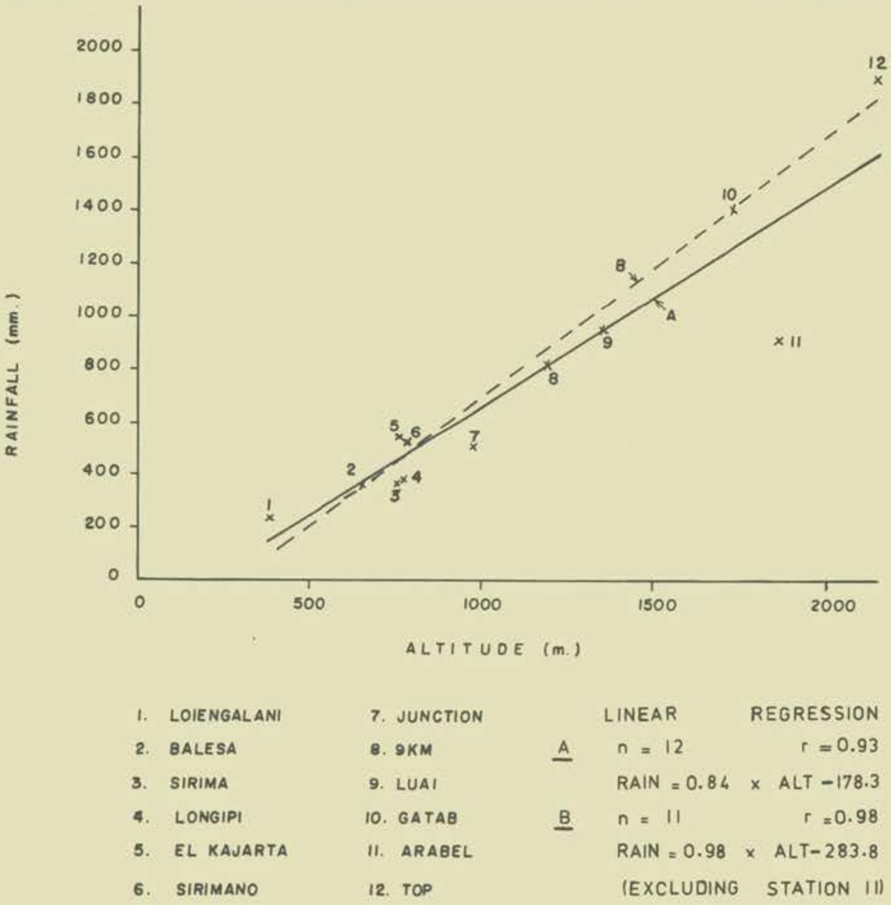
Rain = 0.98 Alt - 283.8 with a correlation of 0.98.

It should be noted that the slope of this line is likely to change from one season to the next and from year to year.

Using this relationship, it will be possible to draw isohyets based on altitude around the Kulal Massif (with due allowance being made for the difference between windward and leeward sites) and to calculate the rainfall input to the water balance.

FIGURE 9

RELATIONSHIP BETWEEN RAINFALL AND ALTITUDE ON MT. KULAL



4.3 Rainfall Intensity

A Dines Tropical Pattern, Tilting Syphon, Recording Raingauge has been operating at the IPAL station, Gatab, Mt. Kulal since the beginning of November 1977. The duration and amount of each fall of rain has been recorded during the seven months of observations and a histogram of rainfall intensity drawn (Figure 10). This shows that almost half the storms had intensities of 5mm or less per hour. At such intensities the risk of soil erosion is minimal. Six percent of the storms, however, had intensities above 25mm per hour, an intensity which could lead to considerable runoff if large amounts fell. The mean amounts of rain at each intensity have been analysed to determine whether erosion was likely. They are shown above the histogram for each intensity. From these figures it is apparent that the mean amount of rain falling at the lowest intensity was only 2mm and it is unlikely there would have been erosion. In contrast, at the five highest intensities, mean amounts varied from 14.5mm to 30mm and these falls, fifteen in all, were likely to be accompanied by considerable runoff and erosion on the steeper slopes around Gatab.

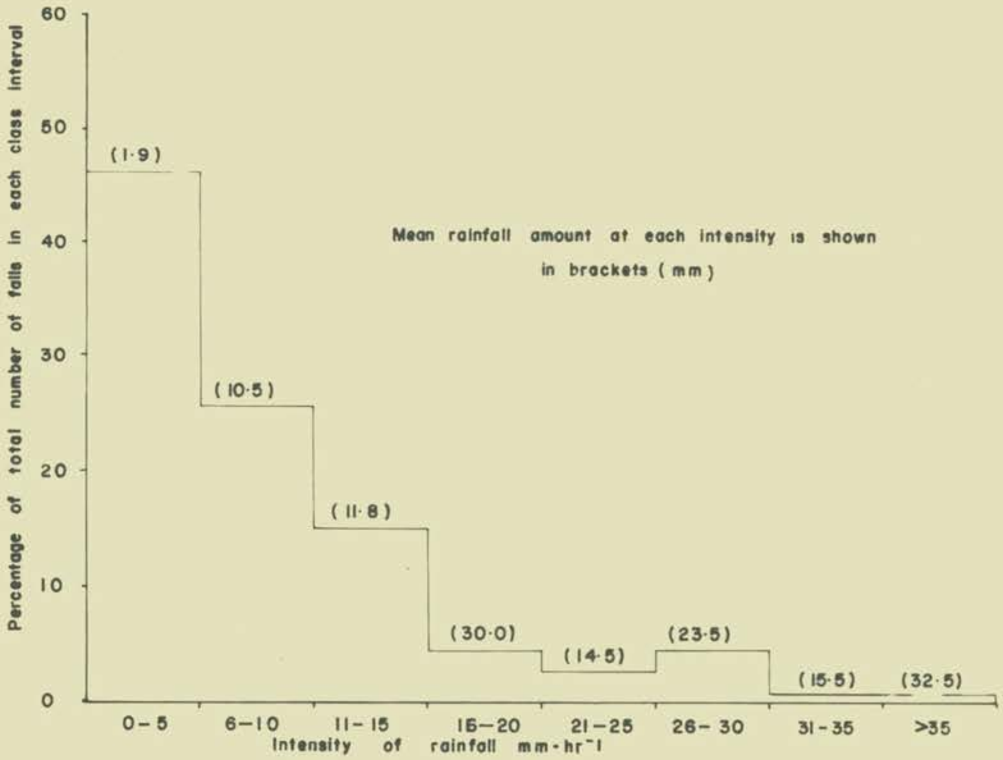


FIGURE 10 INTENSITY AND AMOUNT OF RAINFALL AT GATAB

4.4 Diurnal Variation in Rainfall

The diurnal variation in rainfall (Figure 11) was also determined from the recording raingauge charts. Rain was most frequent around noon and during early afternoon when thermal convection is strongest and when breezes from Lake Turkana oppose the overall easterly air flow. The rainfall intensities were relatively low at this time of the day, however, indicating only mild instability leading to frequent light showers.

Rain was less frequent but more intense at night, particularly during the evening and early morning. Local winds around Lake Turkana reinforce the easterly flow at night so that there is massive orographic uplift over Mt. Kulal. This coincides with high night-time values of relative humidity and leads to heavy rain on some occasions.

4.5 Occult Precipitation

It has been shown in South and South-West Africa (Marloth, 1904, 1907, Nagel, 1962) that mist may contribute from 40% to 94% of the total precipitation on high ground such as Table Mountain and elsewhere. At Gatab on Mt. Kulal, mist or low cloud occurred from 25% to 75% of the time according to the month of the year. Generally the wetter months, April and November, had the most mist while February and September had the least.

It has been observed that trees in the area, particularly *Juniperus procera*, provide surfaces upon which the moisture in the cloud may condense and then fall to the ground. Associated with this is a distinct patch of understorey which is larger on the leeward side than on the windward side of the tree. The understorey is often dominated by *Myrsine indica* and appears to be dependent on the occult precipitation for its survival.

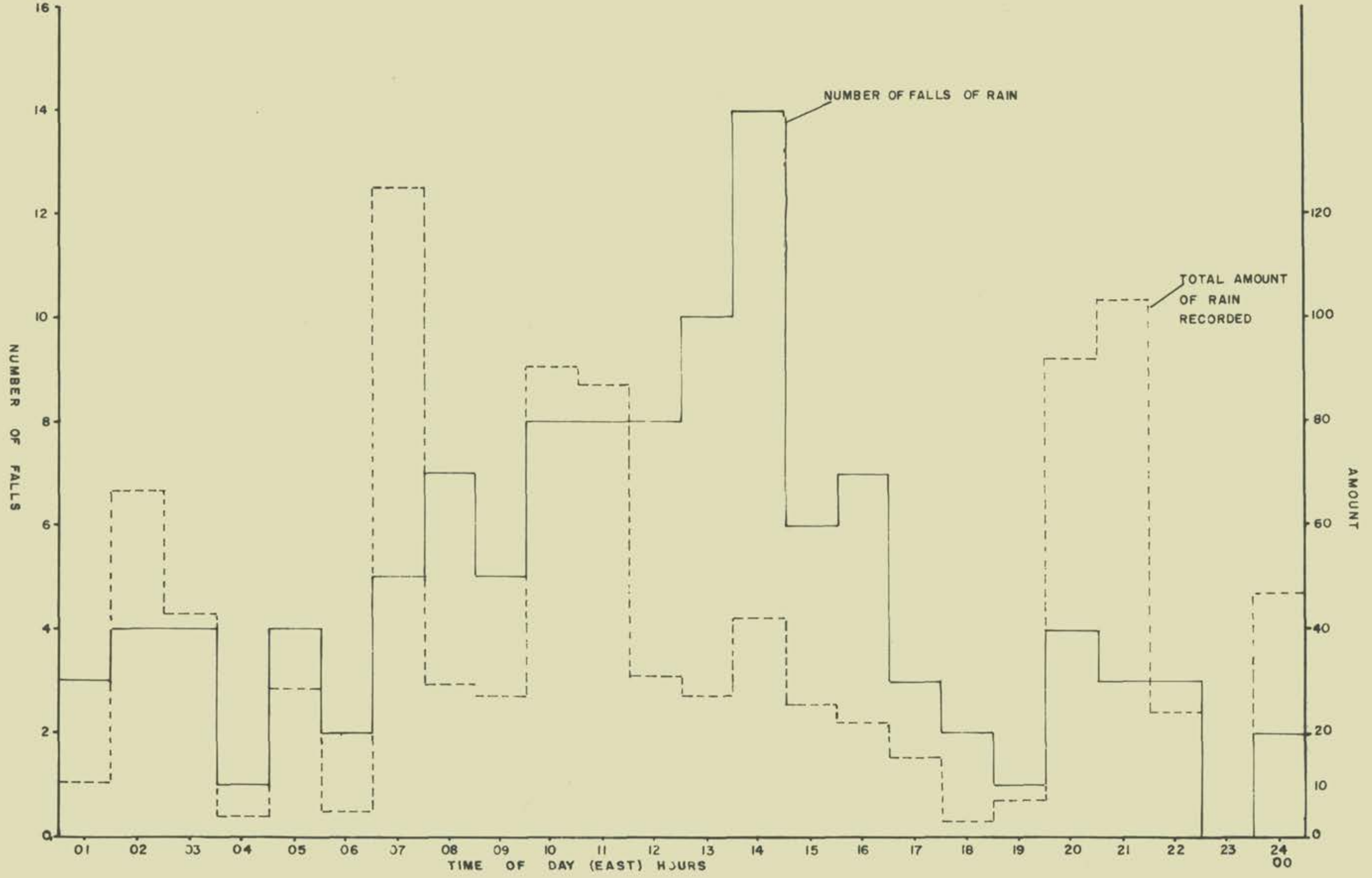


FIGURE II DIURNAL VARIATION IN FREQUENCY AND AMOUNT OF RAINFALL.

In order to obtain a preliminary assessment of the importance of occult precipitation at Gatab a storage gauge was placed under a *Juniperus procera* and the monthly totals compared with a similar gauge set up about 200m away but in the open. Results show only four months when rainfall totals from the occult gauge exceeded those from the gauge in the open. Considerable rainfall occurred on all but two of the remaining months and it is likely that stem flow and the evaporation of intercepted moisture account for the underestimation of rainfall in the occult gauge. The results are summarized in Table II and show that in the four months when the rainfall in the occult gauge exceeded that in the gauge exposed in the open, the occult precipitation amounted to 40mm. Clearly, the final interpretation of these data must be based on simultaneous measurement of stemflow, interception and throughfall, but the indications are that occult or mist precipitation may be a significant addition to the soil moisture store.

TABLE II

A comparison of the catch in a raingauge situated under a *Juniperus procera* and that of a similar gauge in the open.

	Standard gauge (mm)	Occult gauge (mm)	Difference in catch (mm)
Aug 1977	14	12	- 2
Sept	0	2	+ 2
Oct	80	106	+ 26
Nov	497	438	- 59
Dec	62	56	- 6
Jan 1978	128	103	- 25
Feb	110	103	- 7
Mar	229	213	- 16
Apr	53	57	+ 4
May	2	10	+ 8
Jan	0	0	0
Jul	0	0	0

Minimum excess "occult" over "standard" = 40mm

5. Radiation

Incoming Solar Radiation is measured at Gatab, North Horr and Balesa Kulal. At Gatab, a Kipp and Zonen Solarimeter Type CM5 was used during the period June 1976 to November 1977 while the Epsylon Automatic Weather Station was in the meteorological enclosure. A Lintronic solarimeter (Monteith-type thermopile) was exposed at the same time and is now the only radiation instrument in operation. From November 3rd 1977, the Epsylon station has been operating at North Horr. The Didcot Weather Station at Balesa Kulal has a Kipp & Zonen Solarimeter and a Net Radiometer Type DRN 101 which measures the balance of incoming and outgoing radiation between the range of 0.3μ to 80μ.

Both automatic weather stations take the mean of 12 five-minute sample values as hourly radiation. The Lintronic solarimeter system uses a digital volt-time integrator which is read once a day to give the daily total. In both cases, the meteorological day (0900 to 0900 E.A.S.T.) is used.

Up to the present time, no calibration checks have been carried out on the three solarimeters and the manufacturer's quoted sensitivities have been used to convert recorded data to incoming solar radiation (MJ m^{-2}).

5.1 General Radiation Environment

As its location would suggest, the study area experiences high solar radiation levels for much of the year. On Mt. Kulal, however, orographic cloud regularly forms at about 2000m and this results in lower insolation totals then the rest of the area. This can be seen in Figure 12 where frequency histograms of daily insolation for the two stations Gatab and Balesa Kulal have been prepared from days between June and November 1977 when both automatic weather stations were operating. Balesa Kulal has a higher percentage of high radiation days. Also shown in the figure is the frequency histogram for a whole year at Gatab (July 1977 to June 1978). It can be seen that the period chosen for the interstation comparison had a much higher frequency of days when between 20 and 25 MJ m^{-2} was received and a lower frequency of days recording more than 25 MJ m^{-2}.

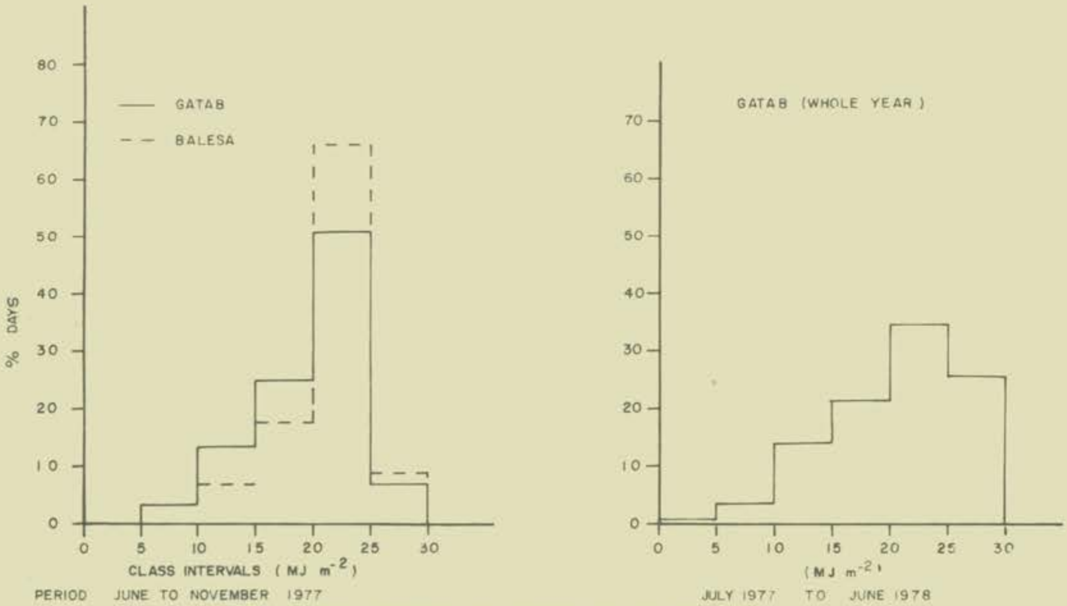


FIGURE 12 SOLAR RADIATION AT GATAB AND BALESA KULAL

It is not typical, therefore, of the general picture although it serves to illustrate how orographic cloud can decrease insolation at Gatab during certain times of the year.

Figure 13 shows the mean daily insolation (Rc) for individual months in 1976 and 1977 at Gatab and the same data expressed as a fraction of the radiation received at the top of the atmosphere (RA). On a daily basis, only about 60% of the latter penetrates the atmosphere. If one considers the hourly data, the peak radiation received at Gatab was 1087 Wm^{-2} (93.5 langleys) on the 9th October, 1976. This corresponds to an average level of 1.56 cal. cm^{-2}min.$^{-1}$ or 80% of the solar constant.

Comparing the march of seasonal insolation with other stations in Kenya (Figure 14). Gatab does not appear to exhibit the same seasonal trends shown by the long-term averages of stations further south. The data sample is very small, however, and it is apparent that solar radiation decreases sharply in the rainy months. Thus January, 1977, which was a moderately rainy month (71mm), shows a striking decrease in radiation compared to the generally high levels one might expect. On the other hand, the June-July-August minimum experienced on the Central Highlands of Kenya is only reflected in a single sharp decrease in radiation during July at Gatab.

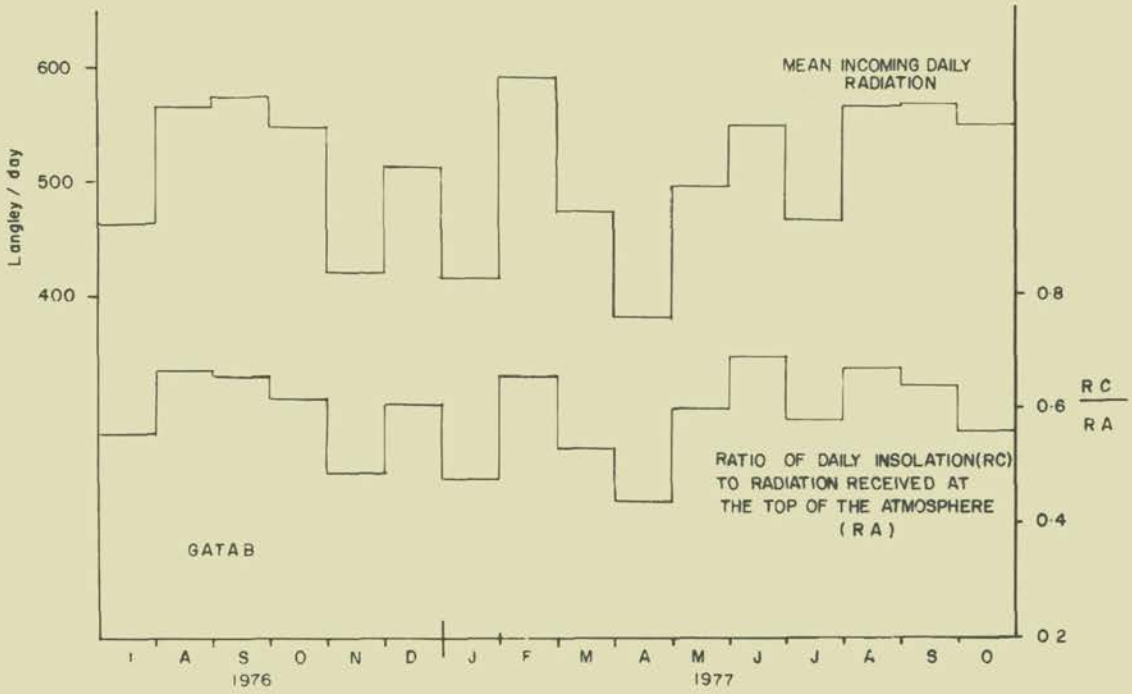


FIGURE 13 SOLAR RADIATION AT GATAB AND RC/RA RATIOS

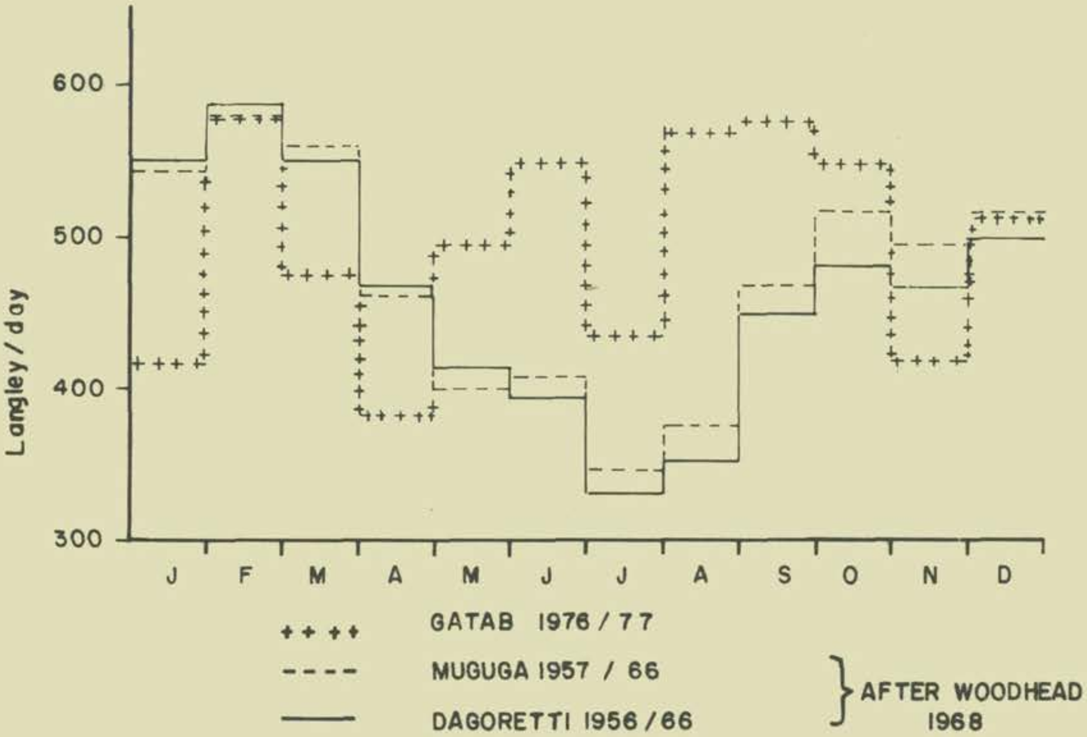


FIGURE 14 SOLAR RADIATION CONTRASTS BETWEEN NORTH AND CENTRAL KENYA

5.2 Relationship between Net and Solar Radiation

Net radiation values obtained at the Balesa Kulal site are not representative of the well-vegetated parts of the study area because the sensor is mounted 1m above the ground and receives radiation only from the low vegetation in the vicinity of the site.

In addition, a certain amount of disturbance was inevitable during the installation of the weather station and vegetation around the mast did not recover until the rains some five months later. The records represent sparsely vegetated sandy soils typical of the Basement Complex area to the east of the Balesa River.

In Figure 15 totals of daytime net radiation of the period June 1977 to February 1978 are plotted against incoming short wave solar radiation. During the first four months of operation, the soil surface was dry and there was little recovery of plant life. This is indicated by a very close relationship between net and solar radiation and the regression line shown on the diagram applies to these dry season data. Once rain began to fall, however, net radiation values rose relative to incoming solar radiation, effectively increasing the scatter of points to the right of the regression line over a wide range of solar values. The extreme points to the right of the regression line would indicate that net values approach 70% of the incoming solar values at certain times. It is apparent from the rainfall records, however, that the high values of daytime net do not always correspond to periods when the soil surface was wet. Two factors can be said to be important. One is the general increase in plant cover following the rains in October 1977 and the second is the flood event in early November which caused a thin layer of silt of different albedo to be deposited over the meteorological site.

It is too early to comment on the radiation balance in detail but the present indications are that approximately one half to two-thirds of incoming solar radiation is available as heat energy for evaporation on the Hedad. This ignores the advective heat energy which is undoubtably a large factor in the study area. More plant cover increases the energy available for evaporation. Similarly, one would expect net radiation to be higher on the darker volcanic soils of the Kulal Massif and the Marsabit and Hurri Hills.

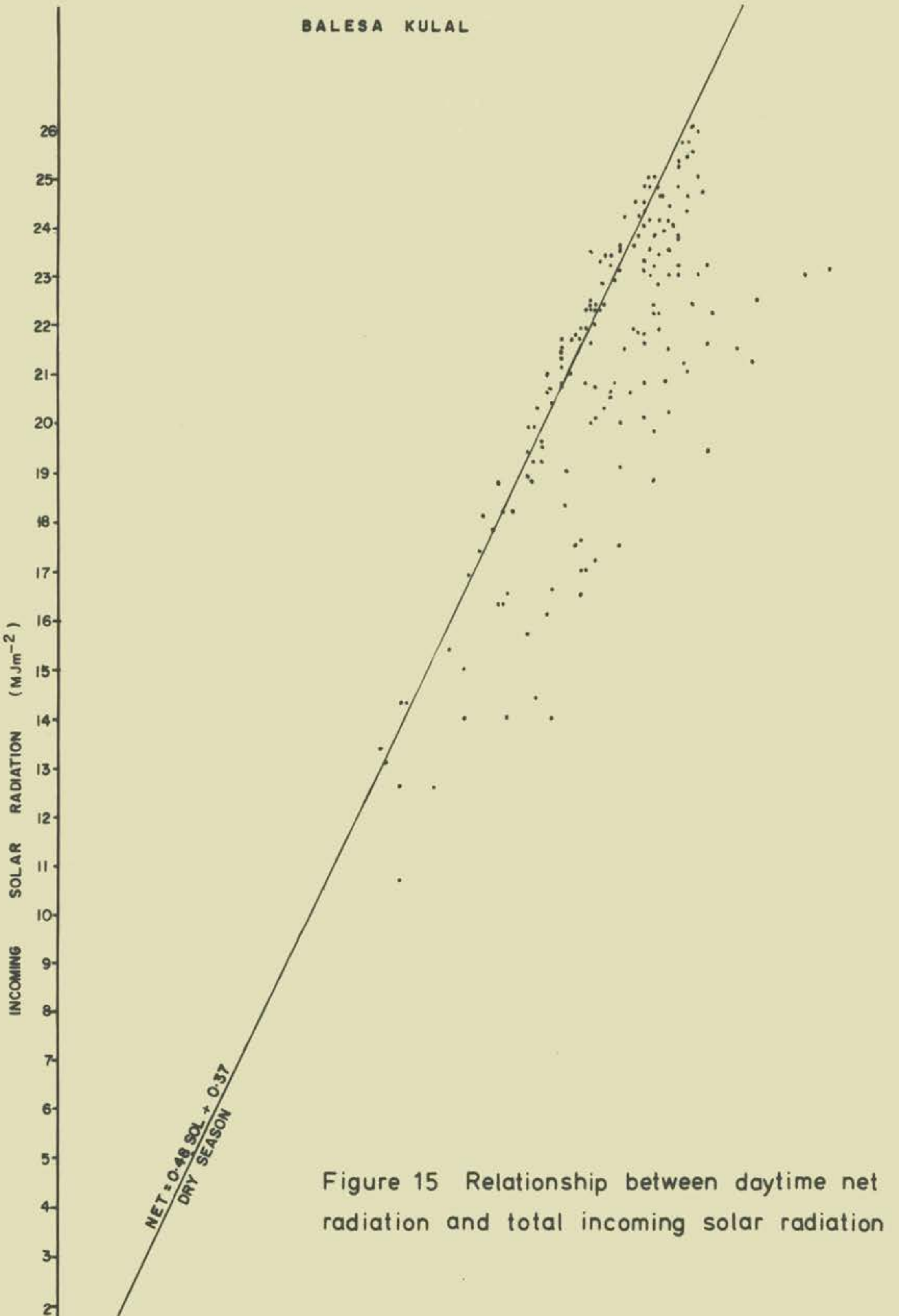


Figure 15 Relationship between daytime net radiation and total incoming solar radiation

5.3 Night-time Net Radiation

Night-time net radiation is a valuable indicator of the radiative cooling effect which is characteristic of true deserts. It was thought that because northern Kenya experiences desert conditions as a result of low level divergence, the strong advection accompanying this feature would mask any radiative cooling. Certainly, the temperature records at Gatab do not indicate any pronounced night-time cooling at that altitude.

If net radiation is plotted against time as in Figure 16 for typical clear sky conditions at Balesa Kulal, however, it can be seen that back radiation reaches a peak just after sunset and decreases steadily as the surface cools. If these night-time values are plotted against screen temperature (Figure 17), assuming that the latter bears a reasonably constant relationship to surface temperature, the radiative cooling effect is clearly demonstrated. Also shown in the diagram are mean wind directions for hours in question. As the surface cools a reversal of wind direction occurs around midnight.

At the same time the wind drops to less than 0.5m s^{-1} indicating that a gentle Katabatic flow established itself in the direction of the Chalbi Desert.

The fact that such a reversal occurs at Balesa Kulal when mean wind speeds of 7.3m s^{-1} (mean direction 88°) for 27/28 September and 7.1m s^{-1} (mean direction 84°) for 28/29 September were recorded at Gatab, some 1600m higher, shows that the effect is powerful enough to counteract the general easterly flow. Since the south-westerly flow is not directly off the slopes of Mt. Kulal, it is clearly not a katabatic effect resulting solely from rapid radiative cooling of the volcanic rocks. On the other hand, if it is associated with the radiation balance of the Chalbi Desert, a similar effect might be expected to occur at North Horr.

At North Horr, there are occasions when a reversal of flow occurs but, over most of the period during which the automatic weather station has been operating, the Chalbi Desert has been flooded and its radiation balance would have been completely different to more normal, drier conditions when it would have a high albedo, especially where salt crystallisation has occurred on the surface.

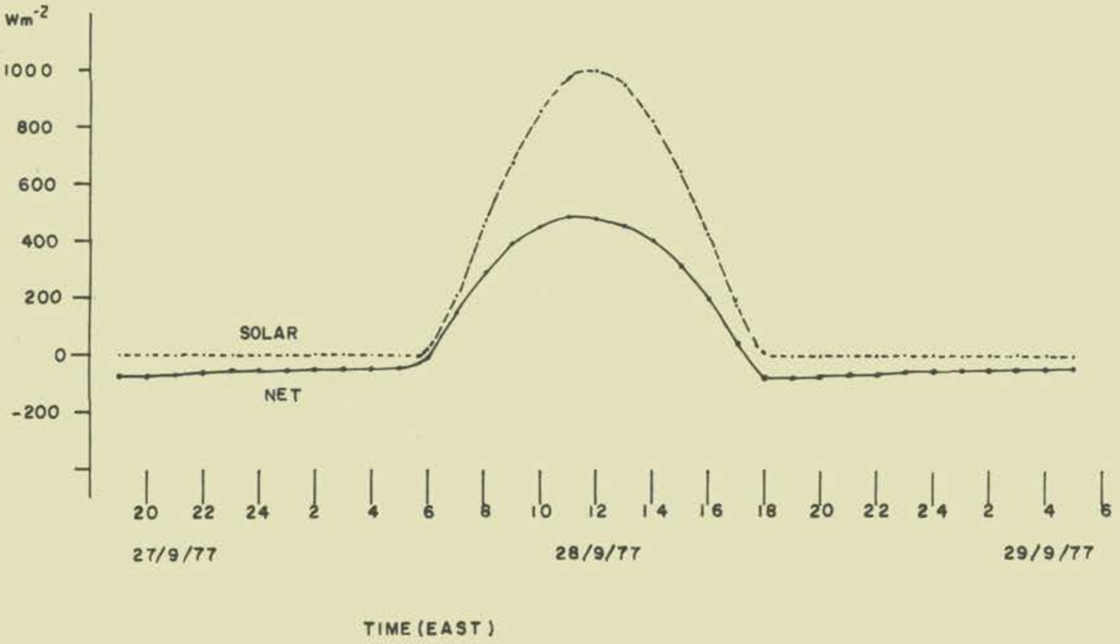


FIGURE 16 CLEAR SKY RADIATION AT BALESA KULAL

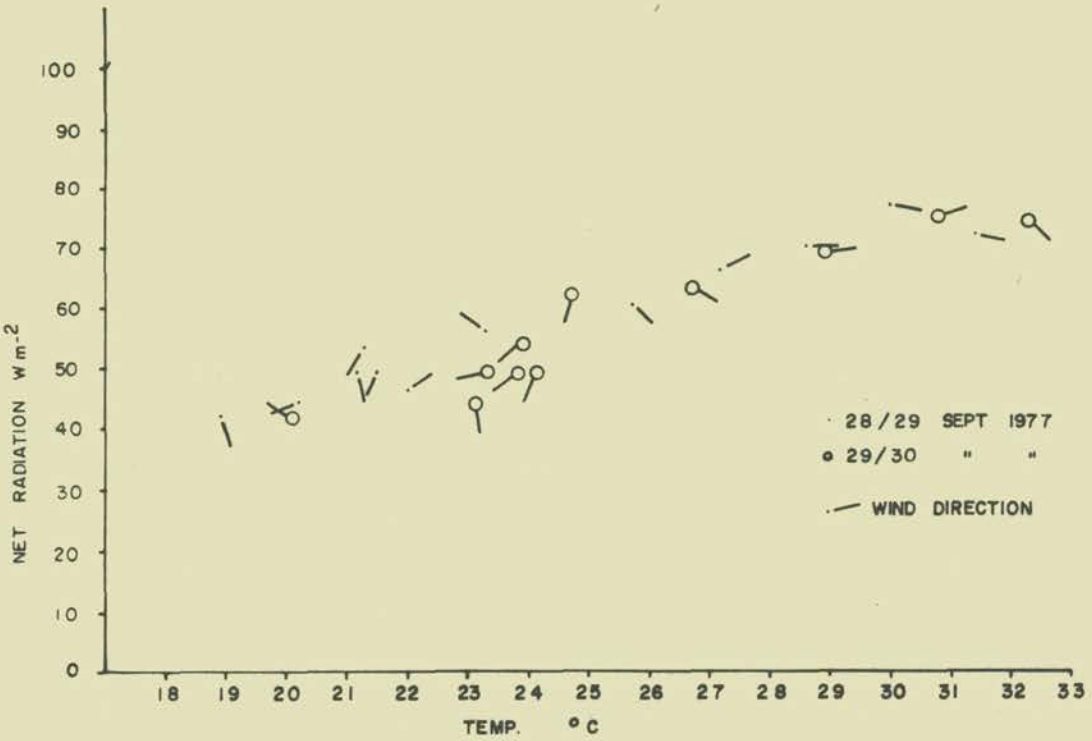


FIGURE 17 NIGHT TIME RADIATION COOLING AT BALESA KULAL

While flooded, the albedo would be at a minimum and, although very shallow, the water would alter the heat and radiation balances significantly.

Until more temperature and wind data are recorded at North Horr, it is not possible to account fully for the katabatic flow at Balesa Kulal. Apart from the meteorological significance of the effect, it can clearly create conditions conducive to dew formation on the east side of the mountain. This could be an important factor in the survival of cetain plant species. In contrast, the west side of the mountain experiences a combination of adiabatic heating of downslope winds (föhn effect) and a reversal of the lake breeze during the night. This accounts for the hot, dry and strong easterly winds which are well-known in the vicinity of Loiyangalani during the night-time.

6. Potential Evaporation

In semi-arid areas where rainfall only exceeds potential evaporation in a few months of the year, actual evaporation is very difficult to estimate. For shallow-rooting vegetation which dies off at the end of the rains, actual evaporation during the dry months is zero. For deeper-rooting bushes and trees with no access to phreatic water, as a first approximation, actual evaporation equals dry season rainfall, if any. In the riverine zone or where trees can tap a shallow water table, transpiration can continue throughout the dry season. With large amounts of advective heat energy available from upwind drier areas, it is to be anticipated that actual evaporation might exceed potential evaporation due to the so-called "oasis" effect. It is likely, however, that physiological controls on the stomatal opening limit the transpiration losses during periods of maximum evaporative stress and actual water losses may be only a few percent above calculated potential evaporation.

Although detailed water budgets cannot be drawn up in the absence of actual evaporation estimates, a good idea of the average seasonal pattern of water use can be obtained from the index of potential evaporation.

In East Africa, this index is normally the Penman estimate of open-water evaporation (EO). Woodhead (1968) has prepared maps of EO for annual and monthly periods. The nearest station to the study area is Marsabit (873700)and the mean monthly values of EO, together with 90% confidence limits, are reproduced in Figure 18. Also shown is the long term rainfall averages (1935-72) for the same station. Since the frequency distribution of monthly rainfall in these regions is markedly skew and bounded at zero, the fitting of leptokurtic theoretical distribution curves is not always satisfactory. In view of the relatively small sample number, approximate confidence limits have been obtained by ranking the monthly rainfall totals and taking the third highest and third lowest as an indication of scatter equivalent to the confidence limits on evaporation.

It can be seen that potential evaporation is a much more conservative quantity than rainfall and with the addition of the approximate confidence limits on rainfall there are slight changes in the seasonal pattern of likely water surplus. Taking the mean rainfall totals alone, rainfall exceeds potential evaporation in only two months, namely April and November. Taking the approximate upper 90% rainfall totals, however, there are five months when rainfall could exceed potential evaporation,March, April, May, October and November.

In Figure 19, monthly rainfall totals for 1977 at Gatab are shown together with potential evaporation estimates. In this particular year, three months experienced rainfall in excess of potential evaporation, April, May and November.

In terms of potential recharges to groundwater stores, 1977 was clearly a good year provided that a significant proportion of the rainfall surplus infiltrated. At Balesa Kulal, insufficient data are available at present to comment on the water balance. In general, however, since potential evaporation decreases and rainfall increases with altitude in this region, the chances of rainfall exceeding evaporation are considerably less on the lower lying parts of the study area. In this context, the most obvious effect of any overgrazing will be to reduce infiltration by compressing the surface layers and removing organic residues. Once infiltration is reduced, rainfall excess becomes a destructive agent in accelerating sheet and gully erosion. In a delicately poised water balance situation, as in the study area, it is very easy to destroy the chances of soil moisture and groundwater recharge in this way.

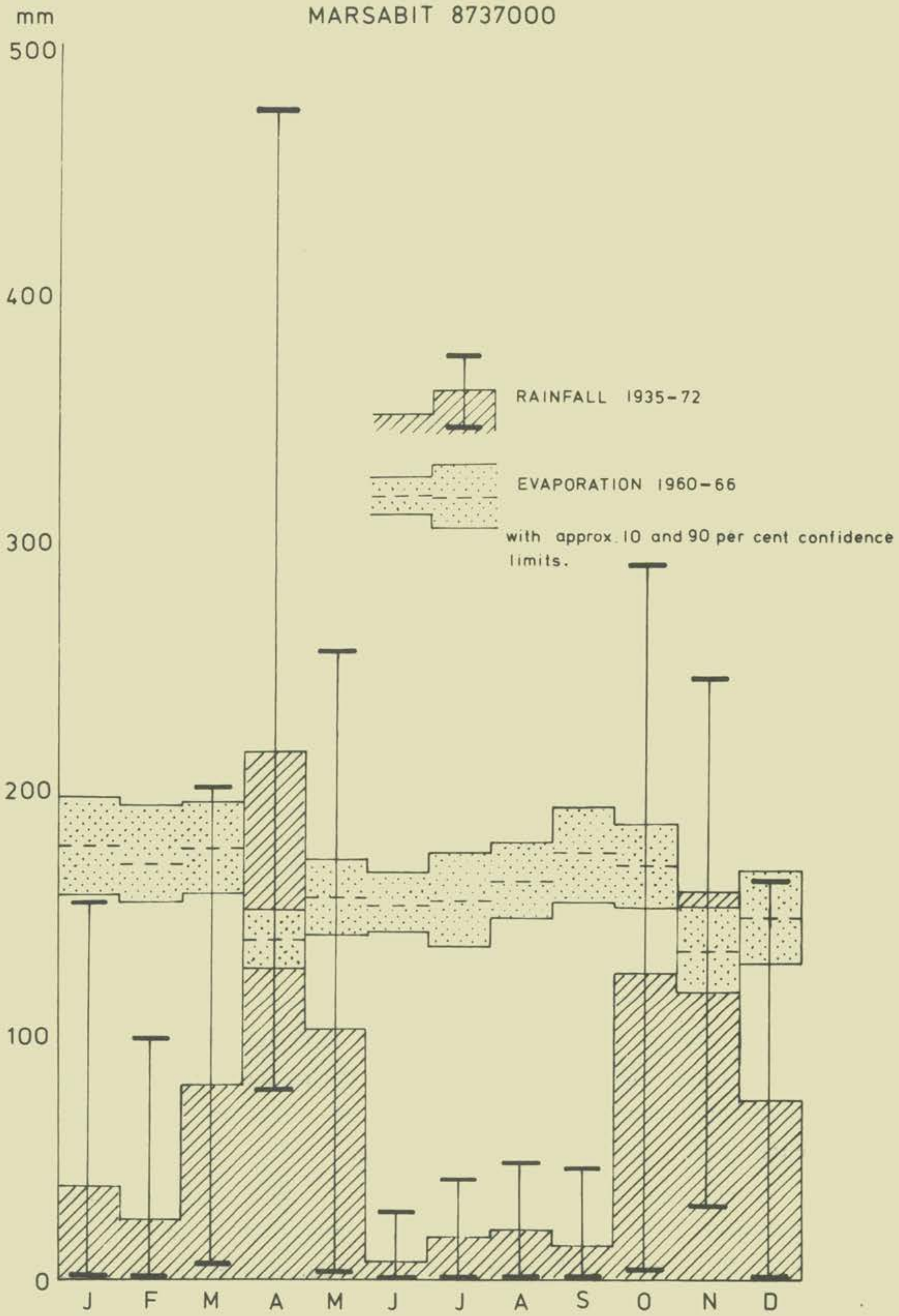


FIGURE 18 POTENTIAL EVAPORATION AND RAINFALL AT MARSABIT.

On the positive side, however, there are at least two months of the year at Gatab, on average when water can be stored either naturally or artificially for stock survival in the dry months.

In view of the limited data run available at the three stations, it is useful to compare the evaporation estimates with those given in the maps of Woodhead (op.cit.). Figure 20 shows the available monthly totals calculated from weather station data together with the long term estimates from Marsabit and Lodwar. For the most part, there is good agreement with Marsabit but Lodwar yields much higher totals. This may be a result of the much higher mean wind speeds recorded at Lodwar and it will be interesting to see how dry season values for North Horr compare with those for Lodwar when more data become available.

7. Temperature

7.1 Seasonal and Diurnal Variations

The seasonal variation of temperature in the study area is related to the characteristics of advecting air masses. These in turn vary according to the seasonal march of the north and south equatorial troughs over the Indian Ocean. Nevertheless, the annual range of mean monthly temperature is small, reaching 4.0°C at Balesa Kulal and only 2.6°C at Gatab (Figure 21).
January and February are relatively warm months when dry stable air flows across northern Kenya from the north-east. Clear skies allow high levels of insolation and mean daily maximum temperatures of 35.0°C are recorded at Balesa Kulal (600m) while those at Gatab are 23.5°C (Figure 22). Very low minima are recorded at Balesa Kulal at this time. Due to calm clear nights and the pooling of chilled air in the low-lying areas, temperatures as low as 15.4°C have been recorded, while the concurrent minimum temperature at Gatab was 16.2°C.

In late March and April the north-easterly airflow breaks down and is replaced by unstable convergent air masses from an easterly direction. Heavy rain may occur over high ground during April and daily maximum temperatures fall to 21.4°C at Gatab and 33.1°C at Balesa Kulal. Minima remain much the same at Gatab (16.2°C) but at Balesa Kulal, the greater humidity and reduced back-radiation prevents them falling below 21.6°C.

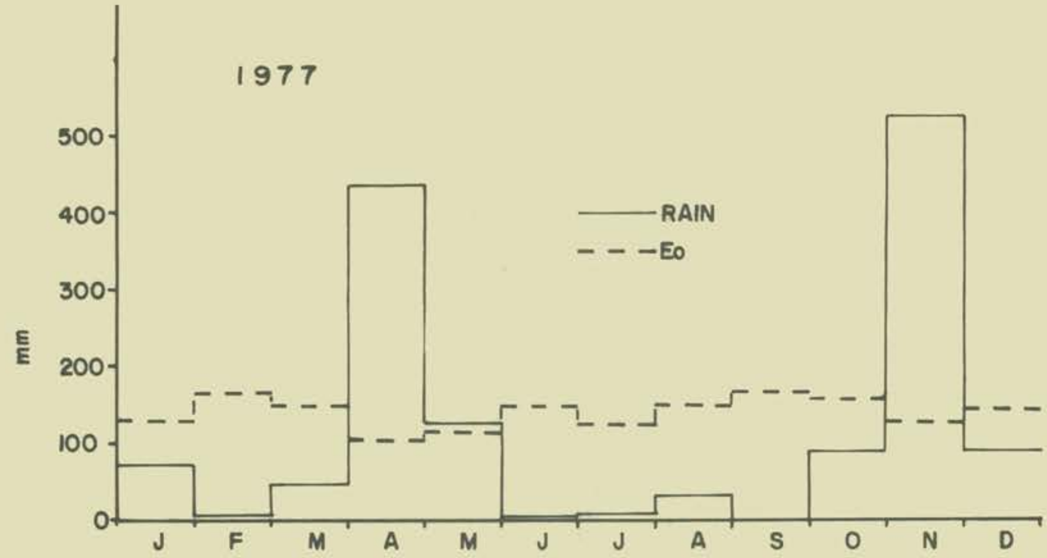


FIGURE 19 WATER SURPLUS AT GATAB

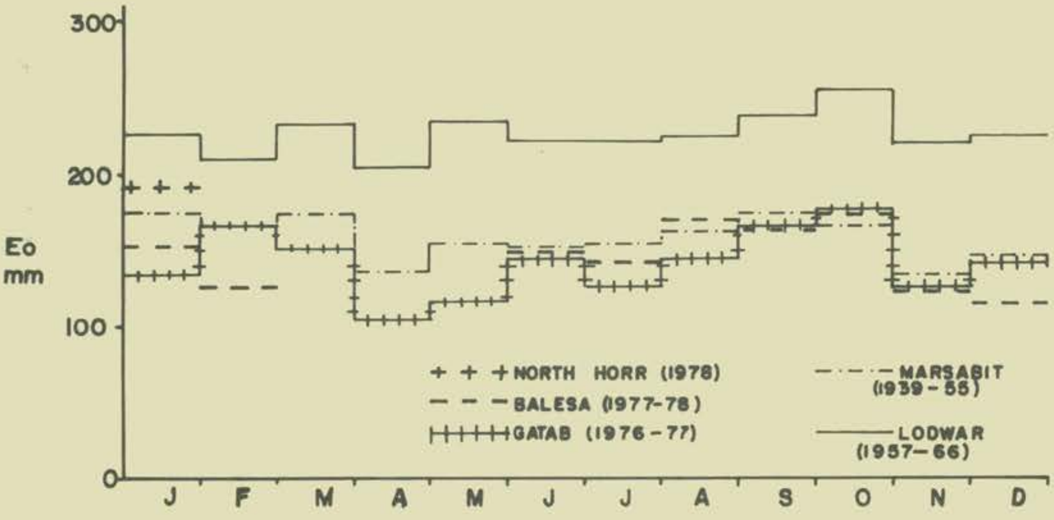


FIGURE 20 POTENTIAL EVAPORATION IN NORTHERN KENYA

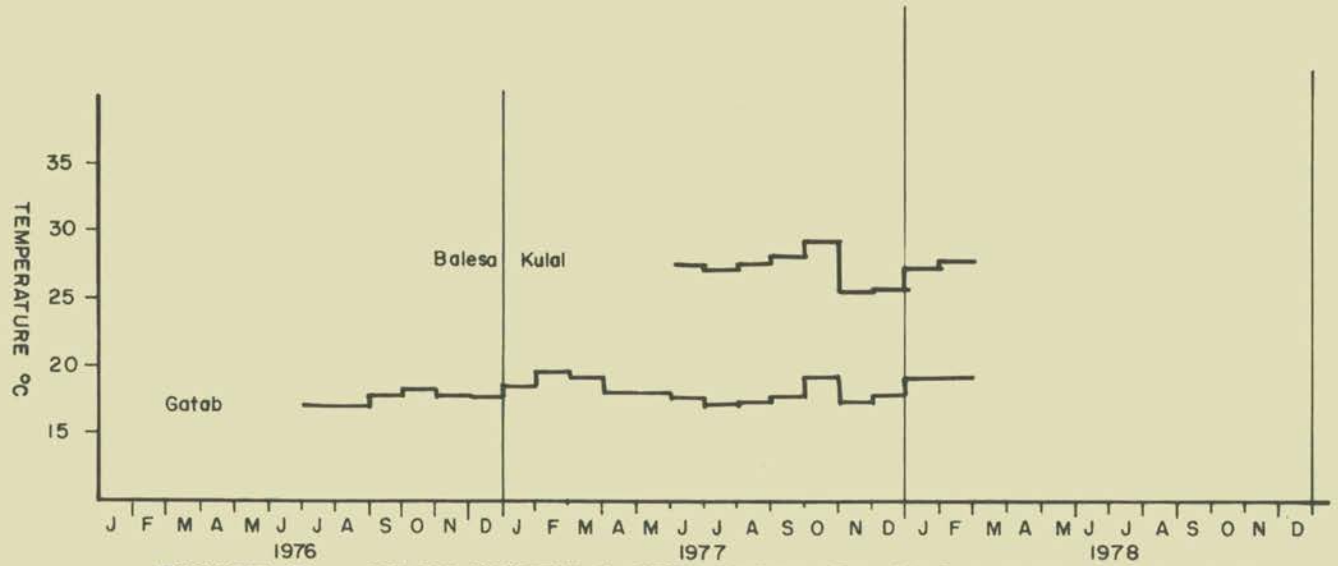


FIGURE 21 MEAN MONTHLY TEMPERATURES AT BALESA KULAL AND GATAB

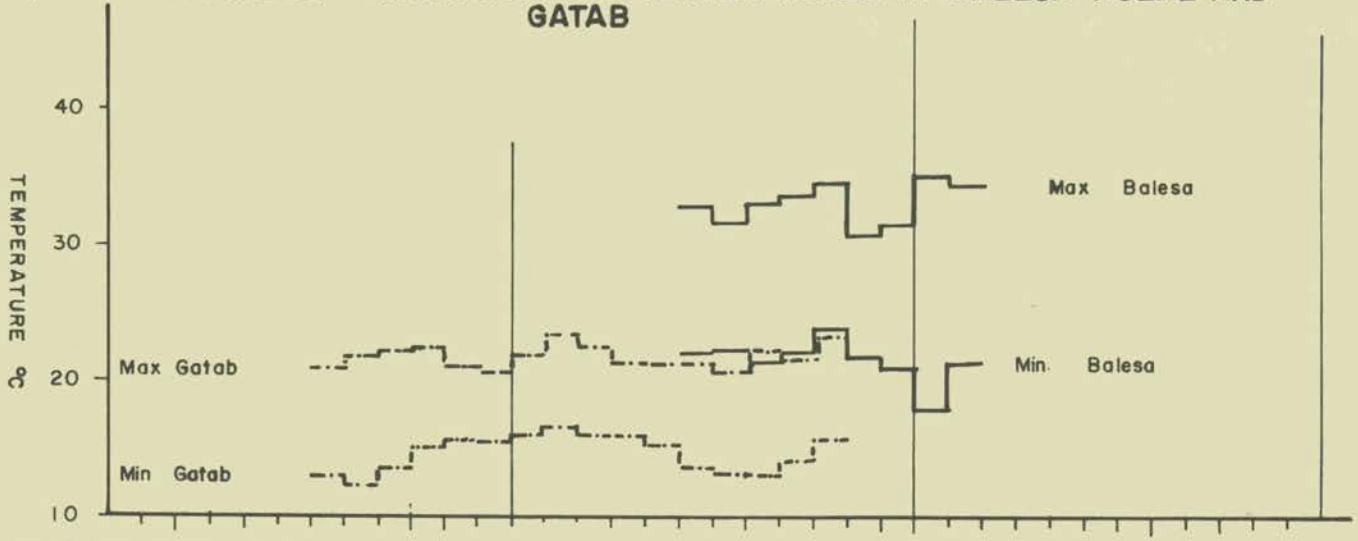


FIGURE 22 MEAN MONTHLY MAXIMUM AND MINIMUM TEMPERATURES AT BALESA KULAL AND GATAB

More stable air intrudes over northern Kenya during late May as the southern equatorial trough passes into the northern hemisphere. Although this period is marked by strong south-easterly trade winds at the Kenya Coast, the overspill through the gap between the Kenya and Ethiopian highlands appears to reach a minimum in the vicinity of Mt. Kulal and a dry season of great stability may persist until October. Although frequent clear skies permit considerable sunshine this is a time of reduced radiation intensity over areas close to the equator because the earth's orbital radius is at its greatest. Accordingly, daily temperature maxima at both Balesa Kulal and Gatab are relatively low. July is the coolest month of the year at Gatab and maxima of 20.8°C are typical. The clear, dry nights allow temperatures to fall to 13.0°C. July is also a cool month at Balesa Kulal where maxima and minima of 31.7°C and 22.2°C are recorded. It may not be the coolest month at this station, however,especially during years when the November rains are plentiful e.g. 1977.

As the sun's power increases during August and September, temperatures rise correspondingly. In October, there may be strong intrusions of warm air from the south-east as the southern equatorial trough passes back into the southern hemisphere. During October 1977, daily maximum temperatures of 34.6°C were recorded at Balesa Kulal and 23.4°C at Gatab. The ground chill effect at Balesa Kulal was not as effective as in February due to stronger night time winds. Thus minimum temperatures fell only to 24.0°C at Balesa Kulal and to 15.6°C at Gatab.

November is a month during which there is a renewed convergence of maritime air masses over Kenya. High humidity leads to heavy rain on high ground and reduces radiation levels so that temperatures drop at both Gatab and Balesa Kulal.

Maximum temperatures of 30.6°C and 19.8°C occur at Balesa Kulal and Gatab respectively. Minima remain relatively high so that the diurnal range of temperature is least at this time of the year.

Both equatorial troughs proceed southwards during December and stable air from the north-east once again intrudes over northern Kenya. Radiation levels rise, humidity falls and temperatures rise, therefore, to reach maximum values again in February.

8. Wind Speed and Direction

8.1 Seasonal Variations

The IPAL study area is located in a relatively low-lying topographical funnel between the Ethiopian and Kenyan highlands. The varying airstreams from Arabia and the Indian Ocean are therefore constrained to flow from an easterly direction with variations in speed which can be related to the seasonal march of the equatorial troughs.

Gatab, at 1700m but situated in this generally low-lying area, is a station from which some of the characteristics of these large scale patterns can be discerned. Wind speeds are high due partly to local vertical acceleration in the vicinity of Mt. Kulal but mainly to the funnelling between the adjacent highlands. Thus, in the period July 1976 to February 1978 the mean monthly wind speed (Figure 23) was in excess of 4m s^{-1} for all but two months (July of 1976 and 1977). At other high altitude stations in Kenya, e.g. Muguga (2100m), where there is extensive high ground, mean monthly wind speeds rarely reach 4m s^{-1} in any month.

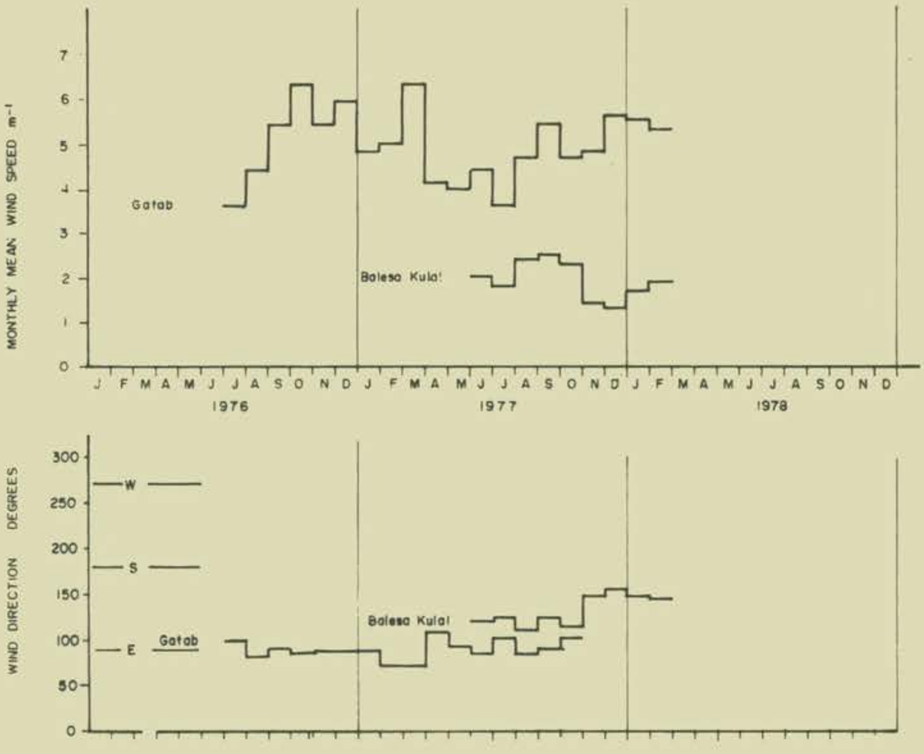


FIGURE 23 MONTHLY WIND SPEEDS AND DIRECTION AT GATAB (2200m)
AND BALESA KULAL (600m)

Although only nine months data are available from Balesa Kulal (600m) they suggest that over low-lying ground in the study area the seasonal variations are somewhat different in character to those at Gatab and may reflect important local effects.

Minimum wind speeds at Gatab occur during July (3.6m s^{-1} in both 1976 and 1977). The equatorial troughs are at the northern limits of their range and a southerly and south-easterly flow sweeps the Kenya Coast. The overspill over northern Kenya is light due possibly to the extension over Central Africa of high pressure from the south.

As the sun and the equatorial troughs move south, the south-easterly flow weakens as pressure rises to the north. More south-easterly air is deflected through the corridor and wind speeds at Gatab become progressively higher to reach maximum values of 6.3m s^{-1} in October 1976 and 5.4m s^{-1} in September 1977.

By October the equatorial troughs straddle the equator and, at high altitudes, air from the north-east flows across Ethiopia and northern Kenya. At low altitudes air from the south-east continues to escape through the corridor. Thus convergence of air masses is marked during November and rainfall may be recorded throughout the study area. The mean monthly wind speed remains relatively high during November (5.4m s^{-1} in 1976 and 4.9m s^{-1} in 1977). The north easterly flow strengthens at progressively lower altitudes and by December all of Kenya is normally influenced by dry winds originating from the Persian Gulf. At Gatab 5.9m s^{-1} was recorded in December 1976 and 5.6m s^{-1} in December 1977. Normally, the north-easterly airflow influences northern Kenya throughout January and February, although in 1977 its strength weakened somewhat. The equatorial troughs reach their southerly limit in late February or early March after which winds become progressively blocked and are forced at relatively high speed through the corridor (March 1977, 6.3m s^{-1}).

As early as late March, relatively cool moist air may intrude at low altitudes from the southern Indian Ocean while the north-easterly stream persists at high altitudes. Thus, another period of pronounced convergence and instability ensues, and, in March 1977, heavy rain was recorded in the IPAL study area. The south-easterly air encroaches quite slowly at 4m s^{-1} (April 1977) and at Gatab the mean monthly wind direction had a pronounced southerly component. By the end of May the north-easterly flow has practically ceased at all altitudes. The Kenya coast is swept tangentially by a core of high winds from the south but the overspill through the corridor is generally slight. Thus, in June 1977 only 4.4m s^{-1} was recorded at Gatab and this fell to 3.6m s^{-1} in July.

As the equatorial troughs commence their southerly swing in late July the south-east trade winds themselves become blocked. Their escape through the corridor is intensified until maximum values are again reached in September or October after which north-easterly air again intrudes and induces a period of rainy, unsettled weather.

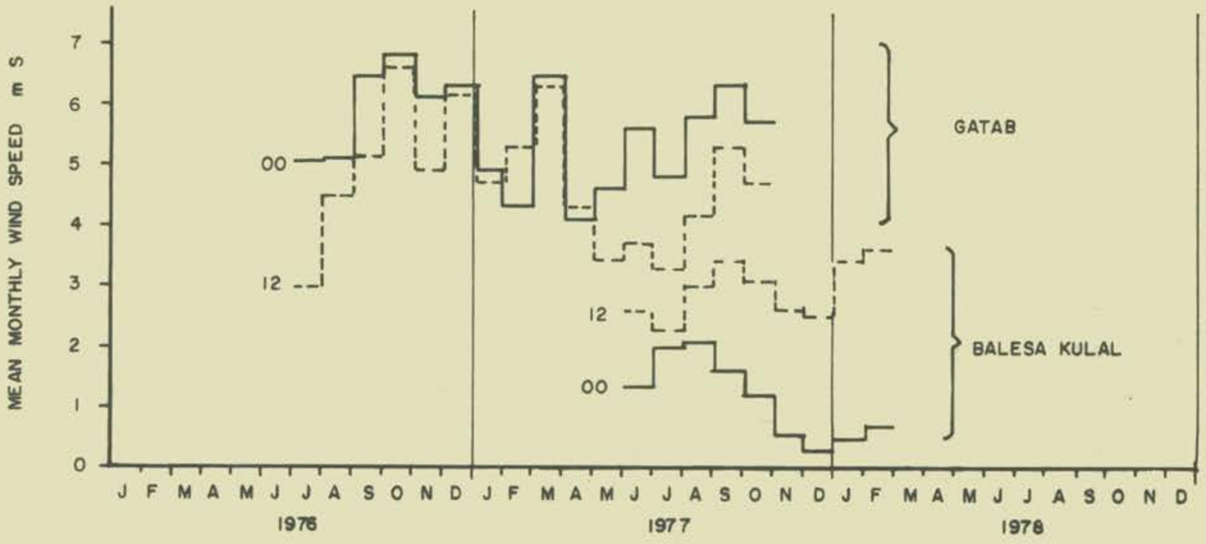
The seasonal variation of wind speed at Balesa Kulal (600m) does not exhibit the same characteristics. Mean monthly values are of course lower than those at Gatab. For no month in the period June 1977 to February 1978 were there values greater than 2.5m s^{-1}. The mean direction appears to have a more southerly component and the cyclic variation in speed seems to be directly opposed to that at Gatab. To understand these differing wind patterns it is necessary to consider the diurnal variations at each station.

8.2 Diurnal Variations of Wind Speed and Direction

Mean monthly values of wind data recorded at mid-day and mid-night are compared in Figure 24.

Balesa Kulal data show that day-time wind speeds and directions correspond to the easterly flow recorded at Gatab. At night, however, the wind speeds falls abruptly and there is a shift in direction towards the south whereas at Gatab wind speeds increase and directions remain easterly.

This feature of the Balesa Kulal regime is associated with the slow subsidence of ground-cooled air down the local topographic gradients. It is least effective in July and August and becomes most pronounced in December when warm dry air flows over northern Kenya from the Persian Gulf. In December 1977 the mean mid-night wind speed was only 0.3m s^{-1} and it comes from the south-south west. There are insufficient data to follow the annual cycle but night-time winds do appear to slowly strengthen and back towards the east during February and March.



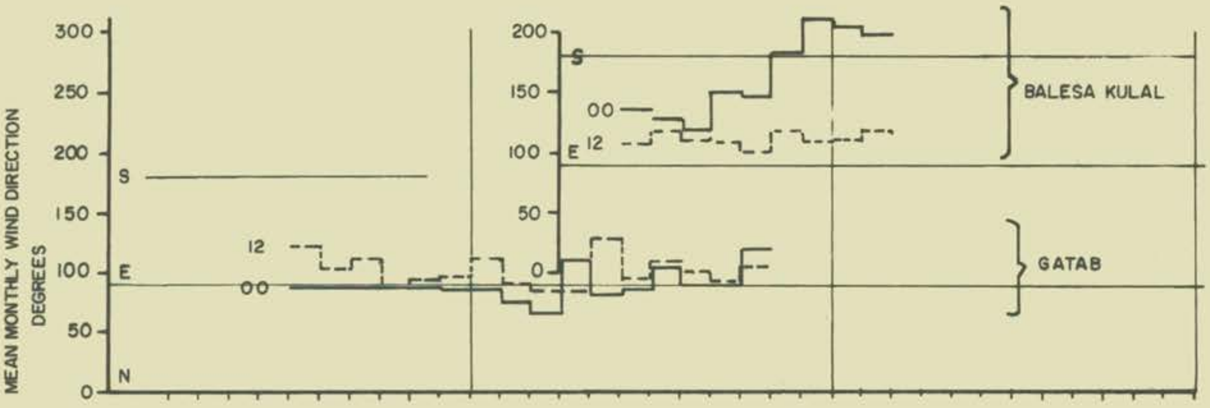


FIGURE 24 MEAN MONTHLY WIND SPEEDS AND DIRECTION AT MIDDAY AND MIDNIGHT AT GATAB (2200 m) AND BALESA KULAL (600 m)

At Gatab the diurnal variations are less marked. Night-time speeds are high due to the interaction with lake breezes on Lake Turkana which alternately reinforce and then counteract the general easterly air-flow as night becomes day. This was particularly clear during the period May to August 1977 when the easterly flow was weak. The variation in direction is for the most part insignificant except, perhaps during May to July 1977.

9. Humidity

9.1 Seasonal Variations

Only wet bulb depressions are available from the IPAL study area. Although the depression is not an independent variable it does provide a guide to the seasonal fluctuations of humidity. Records from Gatab commence in July 1976 and from Balesa Kulal in June 1977.

Mean monthly wet and dry bulb temperatures (Figure 25) reveal that the greatest depressions occur at both stations in the period June to September. Then, the intrusion of maritime air through the topographic corridor is at its weakest.

FIGURE 25 MONTHLY DRY(D) AND WET(W) BULB TEMPERATURES AT GATAB AND BALESA KULAL

The depressions retain the same magnitude during October but, since dry bulb temperatures rise appreciably, this indicates rising humidity which corresponds to the deflection of south-east monsoonal air across northern Kenya. The November "short rains" occur during convergence of the south-easterly air with air from the north-east which encroaches over Kenya due to mounting pressure over Arabia and India. Low wet bulb depressions are recorded during this season. This was particularly striking in November and December 1977 when very heavy rain was recorded at Gatab and Balesa Kulal (616.5mm at Gatab; at least 45.0mm at Balesa Kulal where records are incomplete).

As the north-east monsoon develops during the late December and January, drier and more stable air is drawn through the corridor. High temperatures and large wet bulb deficits are recorded. Even so, mean daily relative humidities of 60% were typical at Gatab during February 1977 and night-time orographic cloud was commonly observed on hills such as Mt. Kulal. Only data for February 1978 are available from Balesa Kulal. This month was unusually wet and the data suggest mean RH values of 56% whereas those at Gatab were typically 67%

Renewed convergence and instability occurs during late March, April and May. This is the season of the "long rains". Only data for the 1977 "long rains" at Gatab are available. 561.8mm were recorded during April and May. In May the mean dry bulb temperature was 18.1°C with a mean depression of only 1.1°C suggesting RH values in excess of 90%. The meteorological station was frequently enveloped in orographic cloud.

In June and July the south-east monsoon sweeps the Kenya Coast but relatively dry and calm conditions prevail in the study area once more. Dry bulbs fall to 27.0°C at Balesa Kulal and 17.0°C at Gatab. The depressions become large e.g. 7.0°C at Balesa Kulal in July 1977 suggesting mean RH values as low as 46%; and 3.1°C at Gatab with RH values of 70%.

Thus it can be seen that although the IPAL study area is situated in a semi-arid region, the humidity remains comparatively high at Gatab throughout the year.

The aridity of low-lying areas is attributable to the persistent stability of the air which only breaks down during discrete seasons of convergence. Where local relief forces an uplift of air, orographic cloud forms readily and, on most hilltops in the region, except the Hurri Hills, dense forest occurs. Even over low-lying land the daily build-up of clustered fair weather cumulus cloud at 600m to 1000m above ground level indicates that the air is sufficiently humid for condensation to result from convectional uplift.

9.2 Diurnal Variations of Humidity

Mean monthly maximum and minimum wet bulb temperatures from Gatab and Balesa Kulal (Figure 26) are striking for their low minima, particularly in the case of Gatab. In the period July 1976 to October 1977 at Gatab the minimum depression only exceeded 1°C during one month, February 1977, when a mean value of 2.0°C was recorded. This feature illustrates the relatively high humidity of the air masses which affect the Mt. Kulal massif and shows that even in the driest months, some overnight mist or dew is likely to occur. Orographic cloud is common throughout the year and, during the rainy seasons, there is likely to be nightly cloud at the meteorological site and this may persist well into the following day. Thus, in April and May 1977, mean minimum depressions of 0.0°C were observed and cloud enveloped Gatab almost every night.

Low minimum depressions were also a feature of the data from Balesa Kulal. 1.0°C was recorded in November 1977 and by February 1978 this had risen to only 2.5°C.

Dew formation was probable in November and December and may have occurred on a few nights in January and February. The low night-time temperatures and wind speeds, with direction backing to the south, that characterised this period, coupled with the low depressions, all suggest extensive ground cooling.

Higher minimum depressions were recorded in the period June to October 1977 when ground-cooling appears to have been less effective. Night-time wind speeds and temperatures were relatively high and the diurnal variation in wind direction was less pronounced.

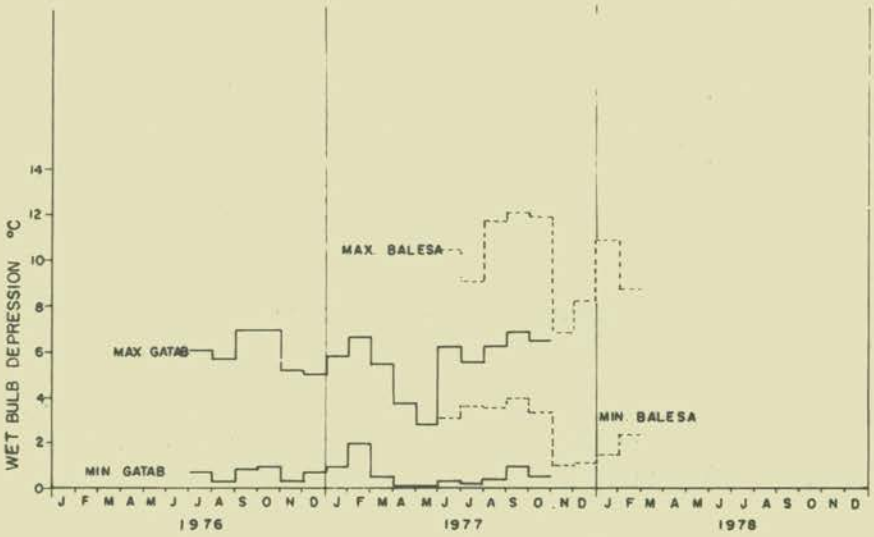


FIGURE 26 MEAN MONTHLY MAXIMUM AND MINIMUM WET BULB DEPRESSIONS AT GATAB AND BALESA KULAL

10. Conclusion

The preceding paragraphs outline the climatology of the IPAL study area in Marsabit as deduced from a preliminary analysis of the first two years of records. As more data accumulate, it will be possible to elaborate further on the trends and patterns which are discussed in this report.

The authors would like to acknowledge the considerable help in collecting rainfall data from the field assistants of IPAL, the missionaries and officers of the Kenya Police and also the generous loan of meteorological equipment from the Ministry of Water Development, Nairobi, the U.K. Institute of Hydrology, the Agricultural Research Department (formerly EAAFRO) and the Overseas Development Ministry of the British Government.

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