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1. INTRODUCTION

It is well known that among the chemical constituents circulating into the atmosphere are sizable quantities of chlorides and sulphates. Both of them are of interest in cloud and precipitation physics, since they form soluble particles which are extremely efficient as cloud or precipitation nuclei. The investigations by Turner (1955) and Spencer & Woodcock (1963) demonstrated that the raindrop salinity is the function of its radius, which is different for the raindrops falling from warm or super-cooled clouds. Measurements by Khemani & Ramana Murty (1968) have indicated that there can be what is called a 'right type of chemical climate' for a region, which when present, may help reduce the possibility of clouds remaining colloidally stable in the area. Ramachandra Murty & Ramana Murty (1969), on the basis of chemical composition of rain water found that the maritime clouds are modified to continental type with distance from the coast.

During the last 20-25 years the investigations of the chemical constituents of atmospheric precipitation have been widely developed. The increasing man-made emissions of various substances into the atmosphere and the possibility of their long term influences on rainfall (Ogden 1969, Khemani & Ramana Murty 1973), have made these investigations particularly important. Although considerable data on the chemical composition of precipitation fall-out in Europe, Australia, U.S.A., U.S.S.R. and

India are available, very few studies have been reported from Kenya or indeed from Africa. Following the preliminary investigation undertaken by Rodhe (1973) for a couple of stations in Kenya, the study was later extended (Mukolwe & Rodhe 1974) to 10-12 stations spread over East Africa (Kenya, Tanzania and Uganda). This study is largely restricted to investigate the effects of air-pollution on environment, with little or no effort being made to investigate the influence of chemical constituents on cloud microstructure or rainfall. In the present paper an attempt has been made to fill this gap by collecting and analyzing rain water samples from different parts of the country in order to study the above aspect.

2. EXPERIMENTAL

2.1. Position of Sampling Stations

Rain water samples were collected from four locations as shown in Fig. 1. The relevant geographic details of these locations are given in Table I.

Mombasa lies on the Kenyan coast of East Africa. From the coast in the east to west direction the terrain gradually rises to about 1 km in a distance of about 200 km and then it ends in a plateau called the Kenyan Highlands, with height ranging from 1 km to 3 km. Cutting across the Highlands is the Rift Valley running North-South. Nairobi and Kericho are situated on either side of the Rift Valley, roughly on the south-east and north-west slopes of the main plateau area, respectively. From Kericho the land rapidly slopes away to Kisumu, situated on Kavironda Bay - an arm of Lake Victoria.

The sampling stations are so chosen that they lie on a line running close to the usual direction of low level wind flow prevailing during the period of sampling.

2.2. Collection and analysis of rain samples

The rain samples were collected in polythene containers using polythene funnels of 25 cm diameter. They were placed on a raised platform about 1 meter high from the ground level. The duration of collection of samples varied from 10 minutes to one hour, depending on the intensity of rain. A number of samples were collected during the month of March and April 1977 but only those eight sets which were collected simultaneously at each of the four locations were considered for analysis for the purpose of this study.

Using standard techniques, the samples were analyzed for determination of concentrations in parts per million (ppm) for chloride, sulphate, sodium, potassium and calcium.

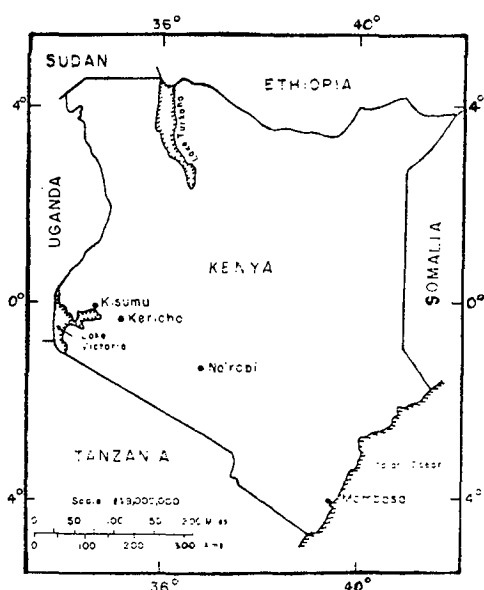


Fig. 1 Map of Kenya showing rain water sampling stations.

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Table I: Geographic details of rain water sampling stations

Station	Latitude	Longitude	Elevation (meters)	Approx. distance from the coast (km)	Mean annual precipitation (mm)
Mombasa	04°03'S	39°39'E	09	0.1	1211
Nairobi	01°18'S	36°45'E	1798	420	1079
Kericho	00°22'S	35°21'E	2134	620	2081
Kisumu	00°06'S	34°45'E	1157	685	1306

2.3 Brief outline of meteorological conditions

The climate of Kenya is controlled by the northwards and southwards movement of the sun. The sun is approximately overhead in Kenya at the end of March and again at the end of September. The movement of Inter-Tropical Convergence Zone (ITCZ) follows the sun with a slight lag of about four weeks. One can not correctly speak of summer or winter; however, at most of the places there are quite well-marked wet and dry seasons associated with the migration of ITCZ. In most of the regions of the country, there is a bi-modal rainfall regime - from mid-March to May-end (called the 'long rains') and from mid-October to mid-December (called the 'short rains'). About 75 percent of the total annual rainfall is received during the two rainy seasons. Rainfall is generally of convective type and falls mainly in the form of showers or thunderstorms.

The wet seasons are also associated with the main air currents affecting Kenya. Throughout the year the winds are predominantly easterly, generally with a low level southerly component from March to October and northerly component for rest of the year.

The low level flow over the eastern shores of Lake Victoria is at all the times of the year easterly in the morning and westerly in the afternoon. The afternoon lake breeze is therefore forced to ascend the very steep slope towards Kericho, where it converges with overlying easterlies and can produce hailstorms in the Kericho area at any time of the year.

3. RESULTS

3.1 Ionic concentrations

The mean values of concentrations (ppm) of different chemical constituents along with minimum/maximum values in rain water for the four locations are given in Table II and the variations of these constituents in different samples are plotted in Fig. 2. The behavior of different constituents is briefly outlined below:

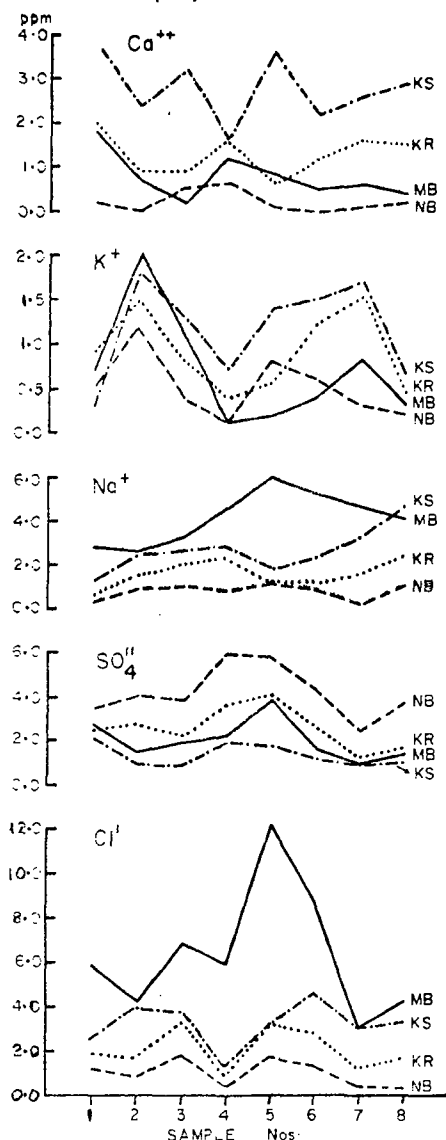
Chloride and Sodium ions

Both the constituents showed almost identical trend of variation from the coast to locations inland. Both decreased appreciably at Nairobi in

Table II: Mean values of ionic concentrations (ppm) in rain water samples
Minimum/Maximum values are given in parentheses.

Location	Cl ⁻	SO ₄ ²⁻	Na ⁺	K ⁺	Ca ⁺⁺
Mombasa	6.3 (3.0/12.0)	1.9 (0.8/3.8)	3.7 (1.6/5.9)	0.7 (0.1/2.0)	0.8 (0.2/1.8)
Nairobi	1.0 (0.3/1.7)	4.1 (2.3/5.8)	0.7 (0.1/1.0)	0.5 (0.1/1.2)	0.2 (0.0/0.7)
Kericho	2.1 (0.9/3.4)	2.5 (1.1/4.0)	1.5 (0.5/2.3)	0.9 (0.4/1.5)	1.3 (0.7/2.0)
Kisumu	3.2 (1.2/4.6)	1.2 (0.8/2.1)	2.6 (1.2/4.5)	1.1 (0.3/1.7)	2.8 (1.6/3.8)

Fig. 2 Variation in ionic concentrations of Mombasa (MB), Nairobi (NB), Kericho (KR) and Kisumu (KS).



comparison to Mombasa value but increased at Kericho and further increased at Kisumu but never reached the coastal value.

Sulphate ions - In almost all the samples this constituent increased markedly at Nairobi but decreased progressively at the other two inland locations, attaining values less than the coastal figures at Kisumu.

Potassium ions - This constituent did not exhibit significant variation from the coast to the plateau but the general trend (SO₄^{''} exceptional) of decrease at Nairobi and progressive increase at the lake area is well maintained.

Calcium ions - This element also maintained the general trend but the variations are quite significant. The Nairobi value is one-fourth of the coastal value on the mean but increased to six times at Kericho and doubled itself at Kisumu.

3.2. Ionic ratios

The values of ionic ratios were also computed and are summarized in Table III. The sample-to-sample ionic ratios are plotted in Fig. 3.

Fig. 3 Variation in ionic ratios at Mombasa (MB), Nairobi (NB), Kericho (KR) and Kisumu (KS).

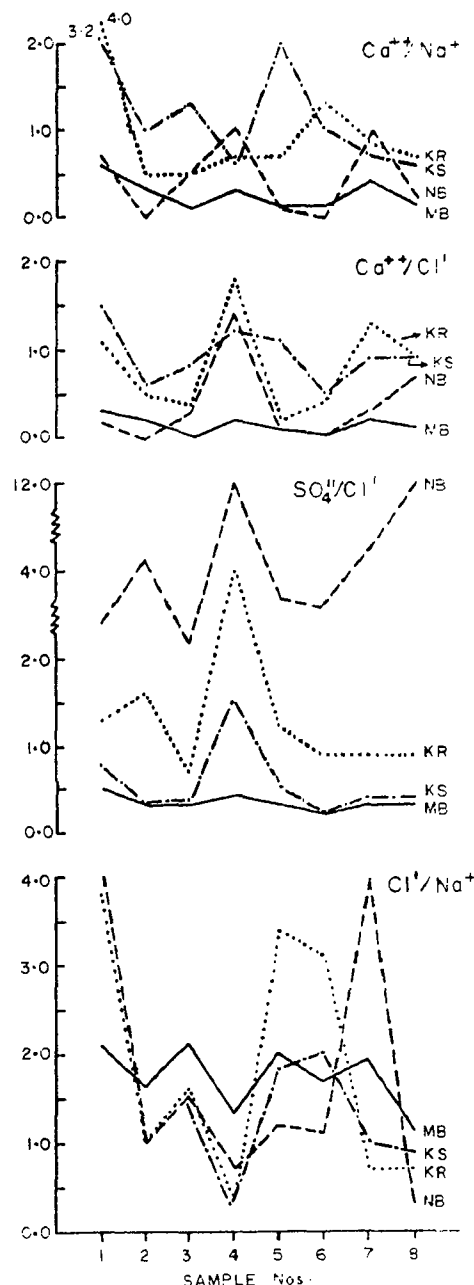


Table III: The ionic ratios in rain samples

Location	$\frac{Cl^-}{Na^+}$	$\frac{SO_4^{''}}{Cl^-}$	$\frac{Ca^{++}}{Cl^-}$	$\frac{Ca^{++}}{Na^+}$
Mombasa	1.7	0.3	0.1	0.2
Nairobi	1.4	4.1	0.2	0.3
Kericho	1.4	1.2	0.6	0.9
Kisumu	1.2	0.4	0.9	1.1

The following observations are made:

Ratio of chloride to sodium - The mean ratio of these ions at the coast compare favorably with the sea water value of 1.8. It ranged from 1.1 to 2.1 with a mean value of 1.7. Although the average value decreased with distance from the coast, large variations between samples were observed at the inland stations (Fig. 3).

Ratio of sulphate to chloride - The value varied from 0.2 to 0.5 at the coast as against the sea water value of 0.14. The ratio sharply increased at Nairobi but dipped to roughly coastal value, at Kisumu.

Ratio of calcium to chloride - The mean value of this ratio on the coast is 0.1 as against 0.02 of sea water. It showed a systematic increase with increasing distance from the coast. (See Table III).

Ratio of calcium to sodium - In this case also the mean ratio indicated a systematic increase with increasing distance from the coast. The mean ionic ratio in this case is 0.2 as against the sea water value of 0.04.

4. DISCUSSIONS

The sampling site at the coast is situated on Diani Beach, about 25 km south of Mombasa town. All the industries lie downwind of this site. As the low level wind flow is predominantly south-easterly (i.e. of maritime origin), it is most unlikely that the rain water samples collected at this site would have been influenced by the air masses of land origin. It is therefore no coincidence that the results have pointed out the mean ratio of chloride to sodium (1.7) as very close to the sea water value (1.8). Also the mean ratio values for sulphate to chloride, calcium to chloride and calcium to sodium, do not exhibit pronounced departures from their respective sea water values. The sample-to-sample variations in the ionic ratios are not large, either. It is therefore safe to assume that the chemical constituents detected in the samples collected at Mombasa, are by and large of marine origin.

It is interesting to note that with the exception of sulphate, all the rest of the constituents (Cl, Na, K and Ca) showed remarkably similar patterns of variation from the coast to the locations inland. The concentrations of all these elements decreased appreciably at Nairobi as compared to the Mombasa value but increased slightly at Kericho and increased further at Kisumu. The values compare well with those from inland stations in Europe and U.S.A. (Junge, 1963).

It is well known that a major source of atmospheric sodium and chloride is the sea spray. The fallout decreases rapidly with increasing distances inland. In the present study the two elements decreased to about one-sixth of their coastal value, at Nairobi. The increase in values of concentrations of the two, further inland at Kericho and Kisumu is not surprising, since the air masses in these regions are also influenced by the westerly lake breeze in the afternoon (all the samples at these locations were collected in the afternoons). The water of Lake Victoria as well as the surfaces

along its shores may contain a large amount of chloride and sodium. The same may be true for potassium but the values for calcium at Kisumu is unexpectedly high.

The trend of variation in sulphate values is exactly opposite as compared to the rest of constituents. It sharply increased at Nairobi to twice its coastal value and then decreased progressively to reach three-fourths of its coastal value at Kisumu. The major source of atmospheric sulphur besides the sea spray are, hydrogen sulphides formed in nature by biological actions and by man-made emissions (mainly in the form of sulphur dioxide). Due to long distance from the sea, the sea spray contribution would be small (all the other constituents detected have indicated a decreasing trend from the coast to Nairobi). Since the sampling site at the coast lies upwind of industries and township of Mombasa and the Nairobi sampling site downwind of industrial complex and urban area, the major contributor for sulphate to Nairobi samples would be the man-made emissions. In England, the large values of sulphate have been attributed to heavy industries (Junge, 1963) in the region.

Glancing at the mean values of the ionic ratios, chloride to sodium, sulphate to chloride, and calcium to chloride, it is observed that the values differ significantly on approach to the highlands from the coast. As considerable fraction of atmospheric chloride is resident on sea-salt aerosols of giant size range (Junge, 1954), the relative high values of sulphate to chloride and calcium to chloride and low values of chloride to sodium in the inland region, seem to suggest considerable depletion of giant sea-salt nuclei in the air masses entering the Kenyan Highlands. As the giant sea-salt aerosols contribute to the precipitation particles, the clouds inland are markedly depleted of the droplets in this size range, thereby, rendering the clouds to become colloidally stable. Further, the appreciable increase noticed in the mean value of the sulphate component, from 1.9 at the coast to 4.1 at entry into the highlands, suggests addition of these ions into the air masses from some sources lying in the path of their journey from the coast to the highlands. As atmospheric sulphate is largely resident on aerosols in the large size range (Junge, 1954), the presence of higher contents of sulphate would mean higher concentrations of large size aerosols and clouds forming in such nucleus-rich air, will have higher droplet concentrations and, as demonstrated by Squires and Twomey (1958), such clouds are colloidally more stable and their susceptibility to shed rain is limited. Khemani and Ramana Murty (1968) by classifying the values of sulphate and chloride on the basis of light rain and heavy rain, pointed out that higher values of the ratio sulphate to chloride were associated with light rains.

Thus, it is clear from the foregoing that by the preferential depletion of giant chloride sea-salt aerosols from the coast to regions inland and by addition of relatively smaller sulphate aerosols from some sources enroute, the number of precipitable size droplets would decrease and the gross droplet population would increase, rendering the cloud colloidally more stable. Such types of clouds do not ordinarily rain, unless they build up to sufficient heights. It is believed that lee waves produced by ascending air-flow along the orographic slopes, though under certain conditions

encourage convection, generally dampen the build-up of the cloud. This aspect however, may have to be critically examined.

5. CONCLUSIONS

The present study which supports the earlier conclusions drawn by Ramachandra Murty and Ramana Murty (1969), suggests that the clouds over the Kenyan Highlands, particularly over the south eastern flanges, may have a narrow droplet size spectra and higher droplet concentration - a situation where the clouds tend to be colloiddally more stable and therefore their susceptibility to release rain is limited. It would be interesting to seed the clouds artificially over the regions upwind of Nairobi (which are also the areas of marginal rainfall), with giant sized chloride particles with a view to making up for the deficiency and thus make them unstable to shed some more liquid water in the form of rain.

Since very little data on the microphysics of clouds have been available so far, for the equatorial region of Africa and for that matter Kenya, the results of present study, to a certain extent, contribute to our knowledge about the micro-structure-stability characteristics of clouds in the region and in the process, also reveals the chemical state of the atmosphere. However, it must be noted that these findings have to be supported by more direct measurements of aerosols and of cloud droplet size spectra, by organizing further careful work to confirm and extend the above conclusions to the point of their becoming a useful tool in characterising the nature of clouds.

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