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LIMITED AREA MODELLING
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"Limited-Area Model Developments in Kenya"

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ABSTRACT

A three-dimensional limited area model is used to study the mesoscale and convective-scale systems over Kenya. The model has 36 grid-points in the east-west direction, 25 grid-points in the north-south direction and 13-sigma levels in the vertical. The model uses a nested grid system in a two-way interactive manner with the fine-mesh resolution being 40 km and the coarse-mesh resolution being 120 km. The fine-mesh domain is centred on Kenya while the coarse-mesh domain covers most of East, Central and Southern Africa.

The model is used to simulate both mesoscale and convective scale weather patterns in Kenya during the dry period of January 1976 and wet season of April 1976. Particular attention is given to both mesoscale and convective systems, the interactions between them and how they possibly influence the larger scale weather systems over Kenya.

The mesoscale systems of interest are the lake/sea breezes, mountain flows and synoptically induced mesoscale systems. The convective-scale systems of great concern are the thunderstorms/hailstorms and lightning hazards, while the larger-scale phenomenon is the Intertropical Convergence Zone (ITCZ) and the large-scale flow.

The results indicate that high ground plays a significant role in the development of these hazardous weather activities by gathering the moisture necessary for condensation and subsequent precipitation. The results further show that the release of latent heat by condensational warming plays a significant role in the development and maintenance of the thunderstorms/hailstorms and lightning activities over the Kenya highlands. It is suggested that this phenomenon be parametrized accurately into the numerical simulations to help understand the physics and dynamics of the hazardous weather over Kenya especially above the highlands.

The results of this study will have a significant impact on the energy and water budgets and will also be useful for the improvements of weather forecasting and cloud modification programme over Kenya.

1. INTRODUCTION

Small scale atmospheric features such as land and sea breezes, mountain and valley winds are referred to as mesoscale systems while phenomena such as thunderstorms/hailstorms, lightning and squall lines are known as convective-scale systems. These systems have horizontal scales of a few kilometers to a few hundred kilometers. The vertical scales normally extend from tens of meters to the entire depth of the troposphere. Their time scales are in the order of a few minutes to one day.

Over the Kenya highlands there is a high frequency of thunderstorms/hailstorms and lightning throughout the year. The interest of this study is centred on the accurate simulations of these small-scale flows, their development and the interactions between them and the larger-scale environment.

The region under study is surrounded by Lake Victoria on the western side and the Indian Ocean on the eastern side. In between the two water masses there are chains of highlands making the meteorology of the country rather complicated (Fig. 1). This configuration is favourable for the development of lake/sea breezes because of the striking difference in the response of land and water to solar radiation and radiative cooling. Water has a very large thermal capacity compared to land and consequently it responds much more slowly to solar insolation than land.

It is hypothesized that the high frequency of hailstorms over the highlands is a consequence of the convergence of the moist lake breeze from Lake Victoria, upslope flows, the large scale easterlies and the prevalent convective instability of the tropical atmosphere. The thunderstorms/hailstorms of western Kenya cause severe damage to crops (especially tea), and lightning hazard is now a national problem.

Many lives are lost due to lightning and about 12,000kgs of tea are destroyed every year by hailstorms(Alusa, 1978). Attempts to minimize hailstorm destruction of the tea crop in the Kericho-Nandi area of the Kenya highlands by seeding the clouds proved unsuccessful. Research to study the dynamics and Physics of the mesoscale and convective scale phenomena over Kenya, especially over the highlands has led to analytical, observational and numerical studies of these phenomena over the region.

The nocturnal phase of the lake circulation has been shown to account for most of the mean annual rainfall over the lake, while over the highlands most of the activity takes place during day time due to the convergence between the lake breeze, upslope flows and the large-scale easterlies (Flohn, 1970; Fraedrich, 1972; Sansom and Gichuiya, 1971). Chaggar (1977) showed that there was no correlation between the thunderstorm pattern and the climatological features. He, however, noted that the association of thunderstorms with high ground and convergence zones was well illustrated.

In a two-dimensional numerical model, Okeyo (1982) showed that strong convergence occurred over the Kenya highlands at 1300 h local time in direct agreement with the observations and observational studies of the thunderstorm/hailstorm occurence over the highlands. In another study, Okeyo (1987) the author found that Lake Victoria was a major source of moisture and energy neccessary for the development and maintenance of these convective-scale hazards over the highlands.

The parametrization of convective-scale processes is therefore a significant aspect of any numerical model especially when these processes are organized in mesoscale systems smaller than a few hundred kilometers. Such convective-scale systems are dominating features in the tropics especially in our area of study.

In this study we parameterize these systems to investigate their interaction with the larger mesoscale environment and their influence on forecasting for Kenya. Such studies have been extensively done in the United States by Anthes and Warner (1978), Kuo and Anthes (1984a, b, c) and in Australia by Gauntlett et al (1984). In general observations related to parametrization schemes have two aims:

i) to verify the parametrization scheme, and

ii) to increase our understanding of the physical processes which should be parametrized, thereby improving our forecasting procedure. That means there is an interaction between the observations and the development of the parametrization schemes.

Cumulus convection plays an important role in at least three different parametrization problems:

i) interactions of cloud ensembles and the larger-scale fields,

ii) it provides vertical transports of heat, moisture and momentum, and

iii) it modifies the short-wave and long-wave radiation, thereby changing the atmospheric state.

The significance of convection models is therefore threefold. The first is to improve the understanding of convective processes including dynamical mechanisms and microphysical interactions and to provide an experimental apparatus on which the sensitivity of the convection to various parameters can be tested. The second is to use the model field as a dynamically and thermodynamically consistent data set on which suitable budget analysis can be performed and interpreted parametrically.

The third is the essentially practical use as a forecasting tool. It is the latter which is most pertinent in the present context and has barely been exploited at all, either by modellers or by people with experience in observational data analysis in the tropics.

The problem of establishing the physical nature of the interaction of organised cumulus convection with the larger-scale environment is fundamental to tropical meteorology. A clear knowledge of this interaction is in all ways essential to an understanding of the dynamics of tropical phenomena in general and equatorial systems in particular. In recent years, many diagnostic and some prognostic studies have been made that have led to an improvement of cumulus parameterization theory. Simple conceptual models have proven to be useful in diagnosing the interaction of precipitating and non-precipitating cumulus ensembles with the large-scale motions (e.g. Yanai et al, 1973; Ogura and Cho, 1973, Betts, 1975; Nitta, 1975, 1977, 1978, and Johnson, 1976, 1977). These and other studies have helped to establish a general concensus on how cumulus convection modifies and maintains the larger-scale thermodynamic fields.

2. THE NUMERICAL MODEL

The numerical model used in this study is similar to that of Anthes et al (1987). The model incorporates parametrization of cumulus convection, full physics and dynamics of both the mesoscale and convective scale systems over Kenya. A passive moisture scheme in which the moisture variable does not interact with other dynamic and thermodynamic variables is also used to distinguish the impact of cumulus convection on weather patterns over Kenya. Both versions of the model use nested grid system.

a) The passive moisture scheme

In this scheme, the model equations in flux form are formulated for an equatorial atmosphere. The equations are given in a coordinate system using a mercator map projection. For an equatorial atmosphere, the map scale factor m is given by

$$m = \frac{\cos\theta_0}{\cos\theta} = 1$$

where θ_0 is the latitude at which the projection is true (usually $\theta_0 = 0$, the equator) and θ is the latitude of model domain.

The u-component

$$\frac{\partial up^*}{\partial t} = -\left(\frac{\partial uup^*}{\partial x} + \frac{\partial uvp^*}{\partial y}\right) - \frac{\partial u\dot{\sigma}p^*}{\partial\sigma} - p^*\left[\frac{RT}{(p^*+P_t/\sigma)}\frac{\partial p^*}{\partial x} + \frac{\partial\varphi}{\partial x}\right] + p^*fv + FU \qquad (1)$$

The v-component

$$\frac{\partial vp^*}{\partial p} = -\left(\frac{\partial uvp^*}{\partial x} + \frac{\partial vvp^*}{\partial y}\right) - \frac{\partial v\dot{\sigma}p^*}{\partial\sigma} - p^*\left[\frac{RT}{(p^*+p_t/\sigma)}\frac{\partial p^*}{\partial y} + \frac{\partial\varphi}{\partial y}\right] - p^*fu + FV \qquad (2)$$

The continuity equation

$$\frac{\partial p^*}{\partial t} = -\left(\frac{\partial p^*u}{\partial x} + \frac{\partial p^*v}{\partial y}\right) - \frac{\partial p^*\dot{\sigma}}{\partial\sigma} \qquad (3)$$

The thermodynamic equation

$$\frac{\partial p^*T}{\partial t} = -\left(\frac{\partial up^*T}{\partial x} + \frac{\partial vp^*T}{\partial y}\right) - \frac{\partial p^*T\dot{\sigma}}{\partial \sigma} + \frac{RT\omega}{Cp(p^*+p_t/\sigma} + \frac{p^*Q}{Cp} + FT \qquad (4)$$

The moisture equation

$$\frac{\partial p^*q}{\partial t} = -\left(\frac{\partial up^*q}{\partial x} + \frac{\partial vp^*q}{\partial y}\right) - \frac{\partial p^*q\dot{\sigma}}{\partial \sigma} + p^*F_Hq + p^*F_vq \qquad (5)$$

The vertical velocity, ω

$$\omega = p^*\dot{\sigma} + \frac{\sigma dp^*}{dt} \qquad (6)$$

where

$$\frac{dp^*}{dt} = \frac{\partial p^*}{\partial t} + u\frac{\partial p^*}{\partial x} + v\frac{\partial p^*}{\partial y} \qquad (7)$$

b) The cumulus parametrization scheme

The cumulus parametrization scheme used in this study is the modified Kuo (1974) scheme similar to that used by Anthes et al (1987). The vertical heating profile is prescribed following Yanai et al (1973). The total amount of convective rainfall is determined by moisture convergence within a grid column following Kuo (1965, 1974). In this scheme the equations of heat and moisture are given as

$$\frac{\partial p^*T}{\partial t} = -\nabla.p^*\vec{V}T - \frac{\partial p^*\dot{\sigma}T}{\partial \sigma} + \frac{RT_v\omega}{C_{pm}(\sigma+p_t/p^*)} + \frac{L}{C_{pm}}N_h(\sigma)(1-b)gM_t \qquad (8)$$

$$\frac{\partial p^*q}{\partial t} = bgM_tN_m(\sigma) + V_{qf}(\sigma) + FQ \qquad (9)$$

Where N_h and N_m are respectively non-dimensional convective heating profiles and V_{qf} is the vertical flux divergence of moisture by cumulus convection.

The integrated moisture convergence is defined by

$$M_t = -g^{-1}\int_0^1 \nabla . p^*\vec{V}_q d\sigma \qquad (10)$$

A portion (1-b) of M_t is assumed to condense and fall as rain, and the other portion (b) of M_t is used to moisten the grid column. Hence,

$$\int_0^1 p^*C^*d\sigma = (1 - b)gM_t \qquad (11)$$

N_m is defined as

$$N_m(\sigma) = \frac{q_s(\sigma)}{\int_o^1 q_s(\sigma)d\sigma} \qquad (12)$$

where q_s is the saturation mixing ratio. Both $N_h(\sigma)$ and $V_{qf}(\sigma)$ are prescribed functions of σ, with the constraints

$$\int_0^1 N_h(\sigma)d\sigma = 1 \qquad (13)$$

and

$$\int_0^1 V_{qf}(\sigma)d\sigma = 0 \qquad (14)$$

In this scheme cumulus convection is activated when $gMt > gMc$, where Mc is a critical value of moisture convergence (usually taken as $3.0\text{x}10^{-5}\text{kgm}^{-2}\text{s}^{-1}$). $N_h(\sigma)$ often takes the shape of the Q1 profile determined by observed large-scale budgets, such as those of Yanai et al (1973) and Kuo and Anthes (1984a). V_{qf} is estimated assuming a vertical profile of cloud vertical motion ($\dot{\sigma}_c$) and q' (which is the deviation between q_c, cloud mixing ratio and the environment mixing ratio q).

c) Numerical techniques

Various types of numerical techniques are applied to control any spurious waves that would influence our simulations. The techniques applied here include finite differencing, both spectral and temporal, horizontal diffusion and temporal filtering.

i) The finite difference scheme

The finite difference scheme used in this study is similar to Anthes and Warner (1978). Using Hovermale's (1968) notation, the finite-difference operators are given as:

$$\alpha_x = (\alpha_{i,j+½} - \alpha_{i,j-½}) \,/\, \Delta x$$

$$\alpha_y = (\alpha_{i+½,j} - \alpha_{i-½,j}) \,/\, \Delta y \qquad (15)$$

$$\overline{\alpha}^{x} = (\alpha_{i,j+½} + \alpha_{i,j-½}) \,/\, 2$$

$$\overline{\alpha}^{y} = (\alpha_{i+½,j} + \alpha_{i-½,j}) \,/\, 2$$

where α is any variable, j is east-west index and i is north-south index. The vertical differences and averages are defined as:

$$\overline{\alpha}^{\sigma} = (\alpha_{K+½} - \alpha_{K-½}) \,/\, 2 \qquad (16)$$

$$\delta\alpha = (\alpha_{k+½} - \alpha_{k-½})$$

The finite difference analogs for the velocity components, heat and moisture are given by Anthes and Warner (1978) and Anthes et al (1987).

ii) Temporal integration scheme

In this study we use a time-integration scheme similar to that of Brown and Campana (1978). This is an explicit scheme which permits for a time step nearly equal to two times larger than that allowed by the conventional leapfrog scheme. The stability of the scheme depends on the computation of the values of p* and φ at the timestep $\tau+1$ before computing the momentum values at timestep $\tau+1$. Then a weighted average of the values of p* and φ at timesteps $\tau-1$ and $\tau+1$ are utilized in the pressure gradient force terms 1 and 2. In these equations

$$p^* = \eta\,(p^{*\tau-1} + p^{*\tau+1}) + (1 - 2\eta)\, p^{*\tau} \qquad (17)$$

with a similar expression for φ. The scheme is stable for $\eta \leq 0.25$ and permits maximum time tep for $\eta \simeq 0.25$. In this study a value of 0.2495 is used following Anthes and Warner (1978) and Anthes et al (1987).

iii) Horizontal and vertical grids

In this study a staggered grid system similar to the s1 grid described by Anthes (1972) is used. In this scheme the horizontal velocity components are defined at the full grid points while all the other variables are defined at the half grid points. The vertical grid is also staggered, with the horizontal velocity components, geopotential and temperature defined at one set of levels while the vertical velocity ($\dot{\sigma}$) is defined at adjacent levels. The horizontal and vertical grid spacings are variable. In the horizontal we use a fine mesh grid nested inside a course grid. In this formulation a constant grid resolution of 40 km is surrounded by a grid with separation of 120 km. In this case there is discontinuity between the fine and the coarse grids as opposed to the extended grid approach where changes in grid size are defined by a continuous function. This gridding system was used with considerable success by Gauntlett et al (1984) and Anthes et al (1987).

d) Boundary layer formulation

Deardorff (1972, 1978) and Blackadar (1978) discussed two approaches to representing the vertical transports in the planetary boundary layer. The first approach is the bulk-type parametrization in which the PBL is represented by a single layer and the fluxes of heat, moisture and momentum are related to the surface conditions and the temperature, humidity and momentum variables at the lowest level of the model through exchange coefficients. Although this scheme is efficient computationally and is suitable for many purposes, it may not be adequate for systems that depend critically on the vertical details of the flow and stability in the PBL. The second approach is the high resolution type. In this approach the structure of the PBL is resolved explicitly by including several computational levels within the boundary layer. Review of the high resolution PBL models was done by Blackadar (1978).

The high resolution approach is suitable for those systems whose vertical variations of the wind, temperature and moisture in the lowest layers are of major concern. Such systems include flow over complex terrain, sea and land breezes, urban heat island flows, flows under strongly baroclinic situations, and flows in which a strong vertical gradient of water vapor exists. It is therefore necessary that in this study we adopt the high resolution PBL model developed by Blackadar and described by Zhang and Anthes (1982) and Anthes et al (1987). For details of this scheme the reader is referred to the two papers.

e) Initial and boundary conditions

Initial and boundary conditions have considerable influence on the numerical model simulations of any scale especially of limited area type. These conditions must therefore be defined or prescribed correctly if the forecasts from a limited area model has to be of any significance.

i) Initial conditions

All the integrations in this study were started from an atmosphere rest at 0600 h local time. This was consistent with the objective of the study which is mainly the simulation of mesoscale and convective scale systems and the interactions between the two scales of motion and their larger-scale environment.

In Kenya and indeed in many equatorial areas near the seas or oceans and characterized by many hills and highlands, the transition between noctumal and daytime flow takes place at just about sunrise. During the period under study the sun rises at about 0600 h local time. At this time the atmosphere is assumed to be calm. This is known as the transition period i.e. the time when the flow is changing from land breeze to sea breeze and from downslope flow to upslope flow.

The temperature and specific humidity fields were taken from radiosonde soundings typical of January and April from Nairobi, Garisa, Entebbe and Dar-es-Salaam. These data were initialised according to Wamer et al (1978).

ii) Boundary conditions

The specification of meteorological variables at the boundaries is a fundamental problem when using limited area numerical models. In general circulation models, lateral boundary conditions are eliminated by considering the entire global domain. The treatment of boundary conditions varies tremendously from one atmospheric phenomenon to the other. Open lateral boundary conditions has been discussed previously by Moretti (1969), Shapiro (1970), Oliger and Sundstrom (1976) and Anthes and Warner (1978). Periodic boundary conditions for limited area models are discussed by Hsie (1983), while time-dependent boundary conditions are found in Perkey and Kreitzberg (1976).

In this study the lateral boundary conditions consist of large-scale time-varying tendencies linearly combined with model calculated tendencies. The large-scale tendencies for temperature and specific humidity are generated from real data analysis of these variables, while large-scale tendencies of velocity components are assumed zero. This type of boundary condition is referred to as "sponge" condition by Perkey and Kreitzberg (1976).

f) The nested grid mesh

The integration for fine-mesh and coarse-mesh proceed simultaneously using the temporal integration scheme described in section c) ii) above. Each time increment of the coarse mesh is followed by an appropriate number (coarse-mesh/fine-mesh grid ratio) of small time increments of the fine-mesh grid. During the time integration of the fine grid, boundary values are updated continuously in a two-way interactive sense using tendencies from observations linearly combined with model calculated tendencies. The boundary update process is limited to a region that includes the fine mesh boundary and the next four interior fine-mesh grid-points.

3. THE OBSERVATIONAL ANALYSIS

In this section we present the mean observed features of weather over Kenya during January and April 1976. The data used in this analysis were taken from the Kenya Meteorological Department. The year 1976 was chosen for this study for two reasons:

i) it was a relatively normal year and

ii) the data was available from most East African Stations before the break up of the East African Community in 1977.

The significance of this analysis is mainly to verify the model results given in Section 4.

a) Mean conditions in January

January is generally a dry month over most parts of Kenya except the Western, Central and Coastal areas which experience some precipitation due to mesoscale circulations of lake/sea and land breezes and mountain flows.

In Fig. 2a we show the 850 hPa mean wind field for January 1976. The major highlights include:

i) a diffluent northeasterly flow almost parallel to the Indian Ocean coast with an easterly branch towards the Kenya highlands.

ii) a vortex above the Kenya highlands near Lake Victoria. This vortex is apparently due to the convergence between the lake breeze and the easterly branch and also the upslope flows over the highlands. In most other areas, the flow is rather weakly convergent if not diffluent altogether. In northeastern Kenya for instance, although the air is convergent (Anyamba, 1983), it is dry having traversed the highlands of Ethiopia and Somalia. Hence the large scale flow over here is dry and cannot deposit any moisture to the highlands of Kenya.

The diffluent nature of the northeast monsoon stream results generally in very dry and cloudless air over most part of Kenya especially over northeastern and eastern regions. There are however some isolated weather activities over some parts of the country especially over high ground areas and along the coasts of Lake Victoria and Indian Ocean as illustrated by the mean rainfall distribution for January 1976 (Fig. 2b). It must, however, be emphasized that these isolated activities are related to the mesoscale systems which seem to dominate most of Kenya's weather activities. As Fig. 2b shows most rainfall is found along the coasts of Lake Victoria and Indian Ocean and over most high ground. These rainfall patterns can be attributed to the convective activities due to lake/sea and land breezes and mountain circulations as will be demonstrated by the numerical results in Section 4.

b) Mean conditions in April

Fig. 2c illustrates the 850 hPa mean flow for April 1976. It is evident from the figure that the flow is mainly easterly. April is climatologically a wet month during which time the Intertropical Convergence Zone (ITCZ) is traversing the region on its northward trend. The flow during this time is fickle but moist as it flows directly from the Indian Ocean. One strong feature in the figure is again the convergence between this easterly flow and the mesoscale circulations close to Lake Victoria. Most other areas, however, experience some general diffluence due to the increasing wind speeds towards the ITCZ. This fact is demonstrated clearly by the rainfall field Fig. 2d. As in January, most rainfall in April is concentrated along the coasts of Lake Victoria and Indian Ocean and also over the high grounds. This demonstrates that mesoscale systems have a strong impact on gathering moisture and heat and thus influencing convective activities over Kenya even during the wet seasons. In April, although the ITCZ is passing over Kenya the mesoscale phenomena have a strong effect on its activities and indeed over most parts of the tropics.

4. COMPUTATIONAL RESULTS AND DISCUSSIONS

Four experiments were run using the scheme described above. These experiments include:

- MM1 - This was the control experiment. It included the necessary physics for the model and utilized the cumulus parametrization scheme.
- MM2 - This was the passive moisture experiment. In this experiment, the moisture variable was not allowed to interact with the other meteorological variables.
- MM3 - Same as MM1 but for flat terrain.
- MM4 - Same as MM1 but increased moisture and different temperature profiles.

a) Control experiment (MM1)

i) Wind field

Fig. 3a illustrates the vector wind field at surface from model simulations at 1800 h local time (12 h model run). The highlights from this figure include strong low-level convergence on

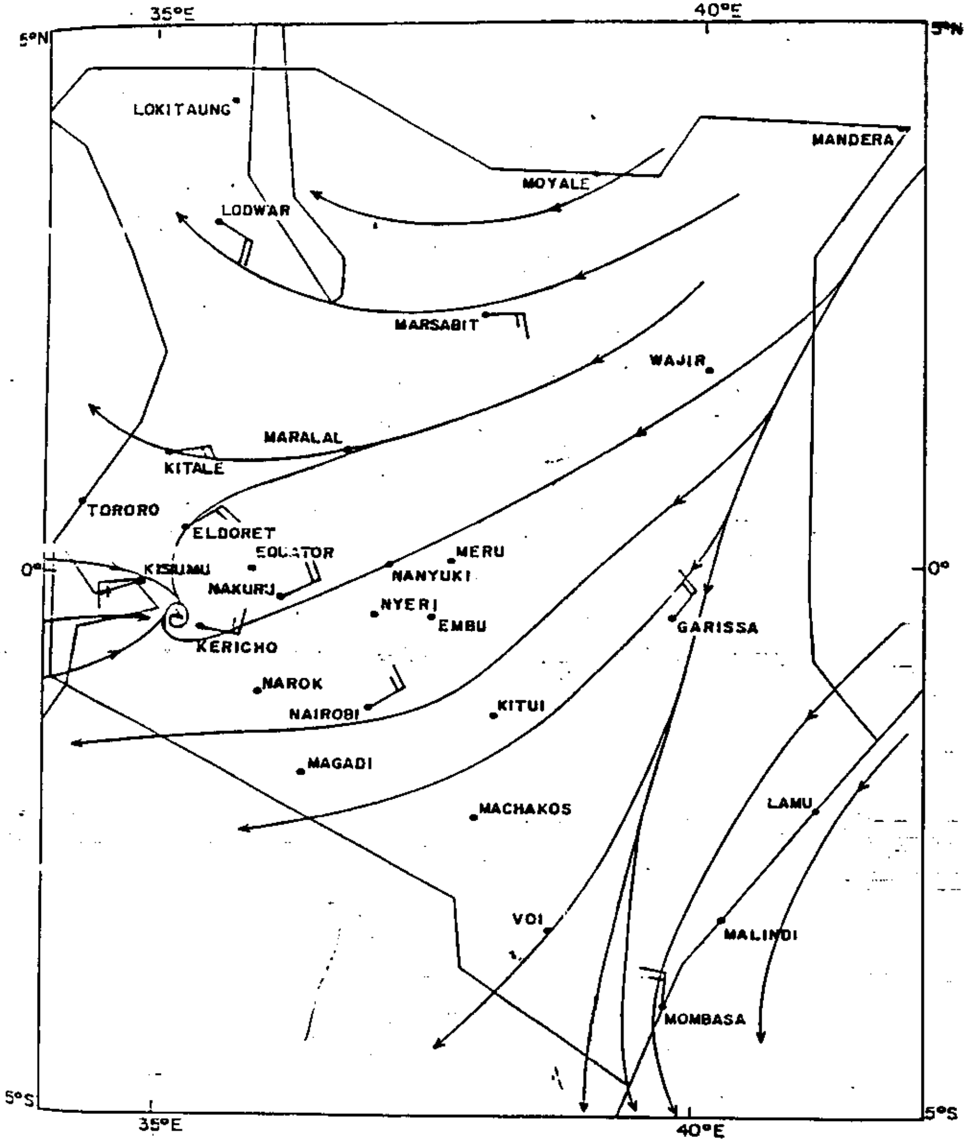

Fig. 2a: 850-mb Mean January 1976 wind Flow.
Units are in knots.

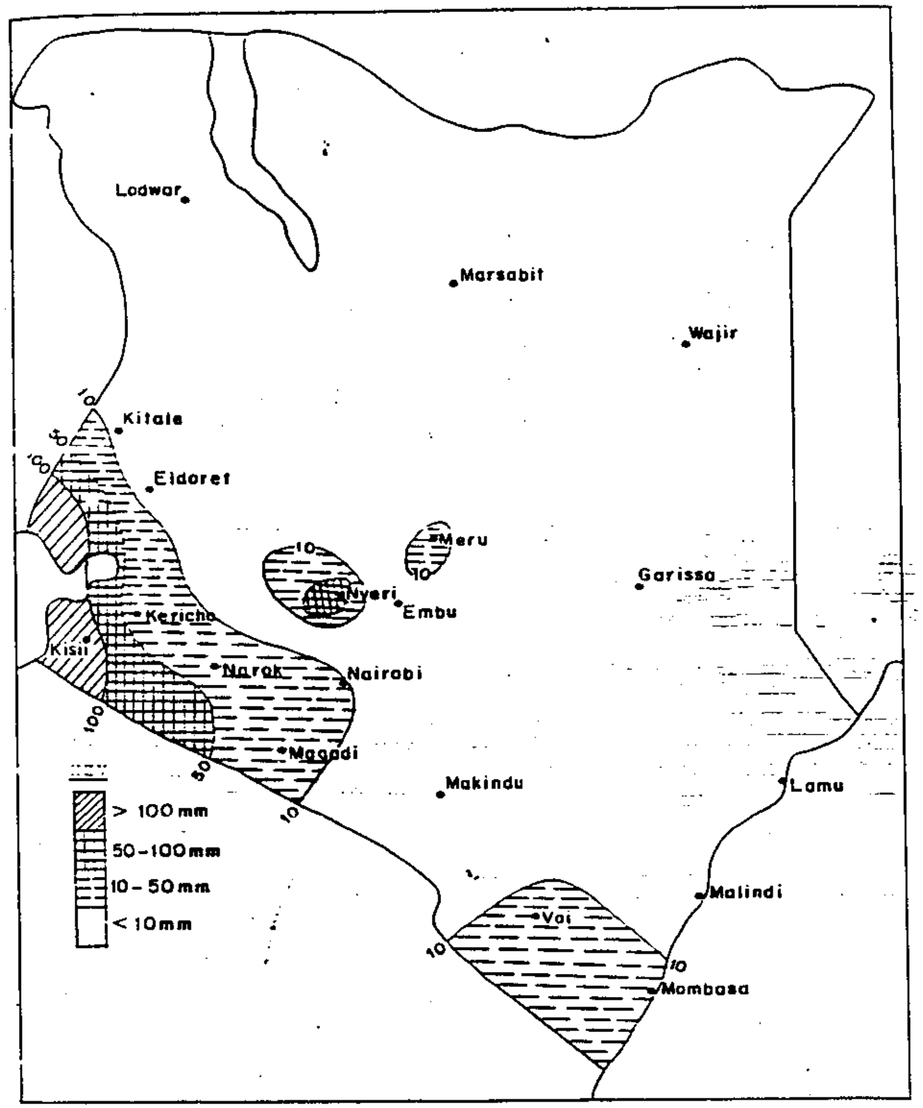

Fig. 2b: January, 1976 Rainfall Distribution in mm.

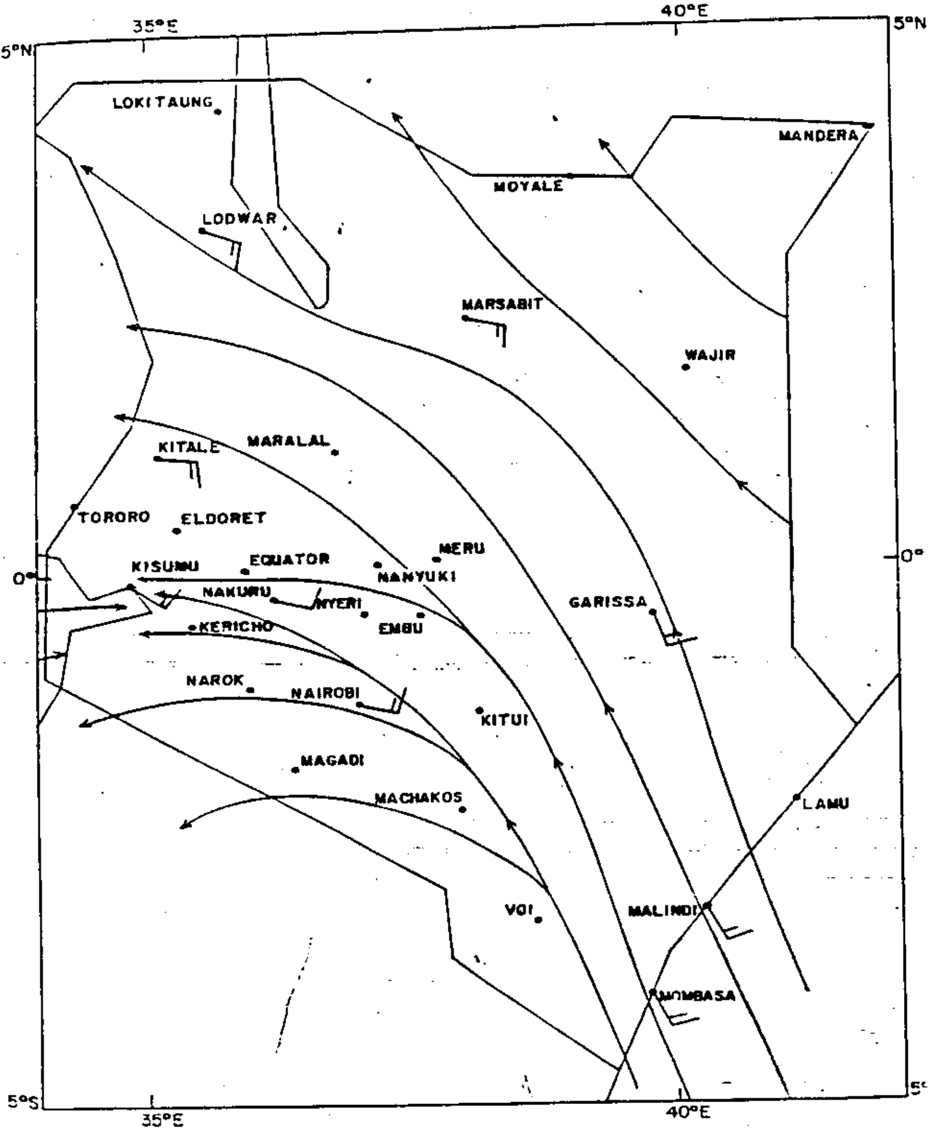

Fig. 2c: 850-mb level Mean April 1976 Wind Flow.
Units are knots, one full barb equal to 10 knots.

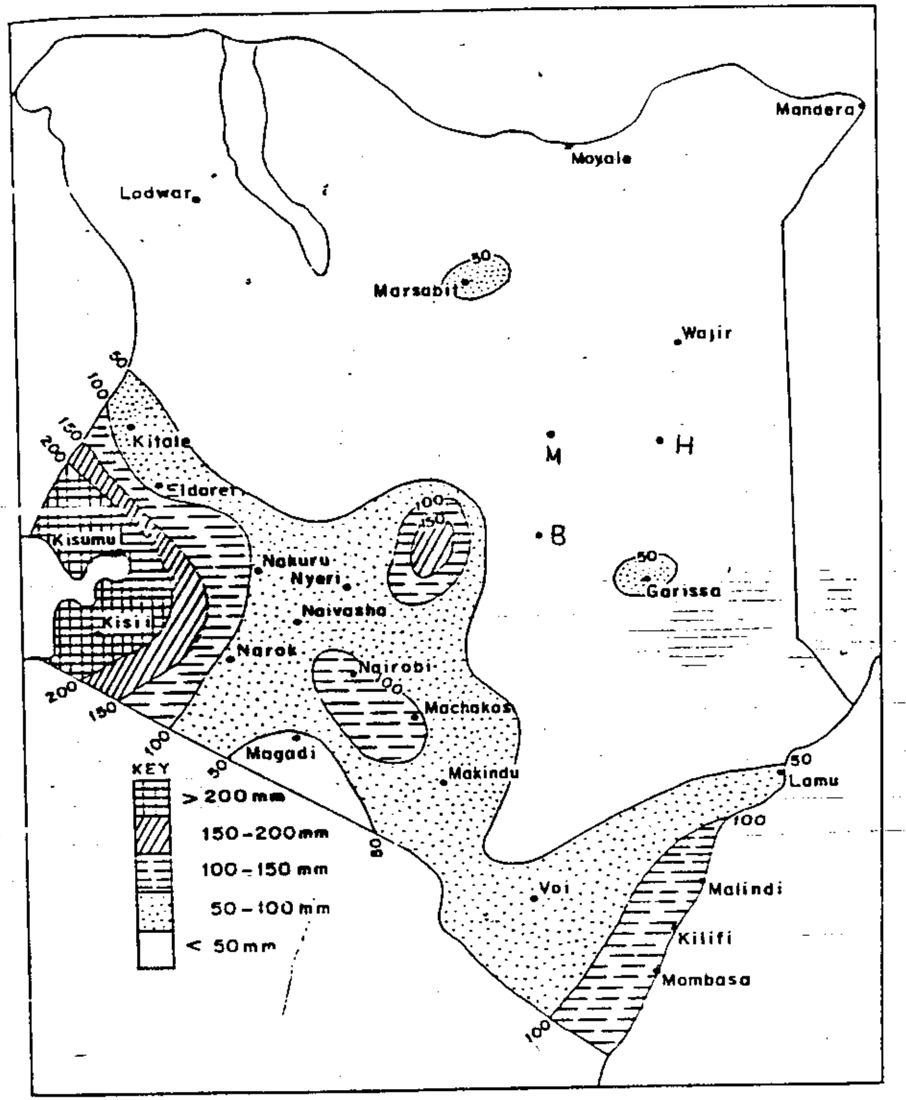

Fig. 2d: April, 1976 Rainfall Distribution in mm.
The rainfall stations M,B and H are respectively
Muddo Gashe, Balambala, and Habaswein. None of these

the east coast of Lake Victoria stretching from about 4½°S to about 1°N. This low-level convergence is associated with the lake breeze and upslope flow from the western side of the highlands and upslope flow from the eastern side. There is another low-level convergence area to the north of Lake Victoria associated mainly with Mt. Elgon. As will be shown later these convergence zones are also associated with very strong moisture convergence and strong vertical temperature gradients. On the eastern slopes of the highlands, we notice strong upslope and weak coastal southeasterlies. Maximum wind speeds of 10.6 m/s on the eastern slopes and 10.3 m/s above the highlands.

Over Lake Victoria the model simulations show a strong low-level divergence due to the relatively higher pressure zone developed over the lake than over the land because of the differential heating between water and land during this time. The results above are consistent with the theory of the development of lake breeze circulations and observations over this region (Section 3). Observations here show strong weather activity over the Kenya highlands and generally clear skies over the lake. The reverse situation takes place at night with the development of the mainly convergent land breeze which causes thunderstorms over the lake at night.

The combination between the lake breeze and the upslope flow from the western side results in increased wind speeds which enhance the convergence over the Kenya highlands with the consequence of increased convection. In general the low-level flow is convergent mainly due to two factors i.e. friction and convergence between lake breeze/upslope flow from the western and upslope flow from the eastern side of the highlands. It should be noted that the strength of the convection over the highlands depends on the intensities of the lake breeze and the two upslope flows - from west and east of the highlands. The intensities of these mesoscale flows depend strongly on the radiative heating and the large-scale heat and moisture convergence.

The low-level convergence is noticed up to the 700 mb level especially above the highlands. However, at 500 mb level the winds are generally week and divergent. Thus it is clear that the mesoscale phenomena (lake breeze and upslope flows) are shallow systems that influence strongly the evolution and maintenance of deep convective clouds. These convective clouds transport heat, moisture and momentum to great depths into the upper atmosphere and also recirculate heat, moisture and momentum into their environment through lateral mixing and adiabatic warming.

In Fig. 3b, the vertical velocity profile is presented. The figure shows a low-level maximum in vertical velocity at 700 mb and an upper level maximum at 300 mb and a minimum at 500 mb. Since vertical velocity is coupled to latent heating, it is expected that there is strong condensational warming betwen 850 mb and 550 mb and also between 400 mb and 200 mb. The simulations of the vertical velocity are consistent with those of the horizontal wind field which show convergence in the lower and upper layers of the troposphere and divergence in the middle troposphere. The double peaked profile in vertical motion supports strong mid-tropospheric convection. Okeyo 1990 (this issue) using a two-dimensional numerical model simulated deep, mid-tropospheric cumulus clouds over the Kenya highlands during late afternoon. Hack et al (1983) showed that a double peaked large-scale vertical velocity produces a pronounced enhancement of middle-level convection. The strength of the convection depends on the strength of the vertical velocity itself. (Yanai et al (1976) however showed that deep convection was better correlated to upper-level vertical motion than to low-level peaks in vertical velocity profile. In general, however, it is evident that convection is coupled to the vertical motion field. In models of mesoscale or convective-scale nature, vertical velocity must be properly computed if convection has to be correctly monitored.

ii) Moisture and precipitation

In Fig. 3c the relative humidity filed at 850 hPa from experiment MM1 is illustrated. The figure shows that there is a strong concentration of moisture above the Kenya highlands, along the west coast of the Indian Ocean and on the eastern shores of Lake Victoria. We however notice drying on the eastern slopes of the Kenya highlands indicating that the Indian Ocean sea breeze is limited to small distances inland. The figure further shows that there is drying on the centre, southern and northern sides of Lake Victoria. These illustrations are in agreement with the centres of convergence and vertical updrafts. The moisture or momentum convergence here is due to mesoscale convergence which is strongest over the highlands.

Fig. 3d shows the 12-h accumulated rainfall from experiment MM1. The salient features include: precipitation maxima over the highlands and areas to the north and north-eastern Kenya. As is evident from the figure, most precipitation is associated with mesoscale convergence of momentum and moisture as discussed above. The highest rainfall of 2.7 cm over the Kenya highlands is associated with the convergence between the moist Lake Victoria breeze and the upslope flows from the west and east of the highlands. The other precipitation maxima are associated with high ground as shown in Fig. 1 (physical features). These results are compatible with observational analysis discussed in Section 3.

b) The effect of latent heating on the mesoscale systems over Kenya (MM2)

In this section the influence of latent heat from cumulus convection on the mesoscale systems over Kenya is discussed by comparing the results from passive moisture scheme (MM2) to those from the control experiment (MM1).

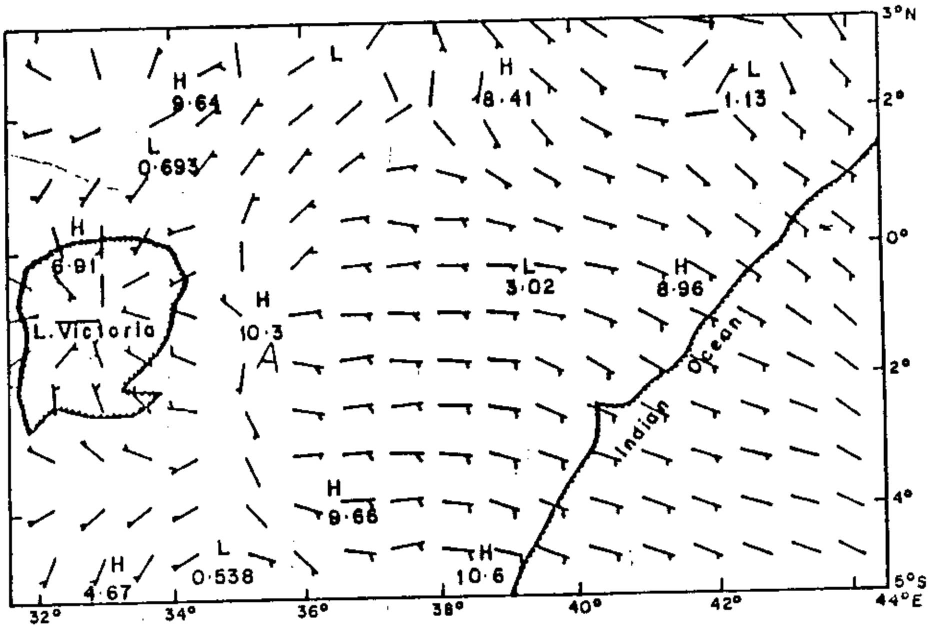

Fig. 3a: Vector wind field at level $\sigma = 0{\cdot}98$ at 1800h (dry season). Maxima and minima are given in m/s. A is a point over the highlands above

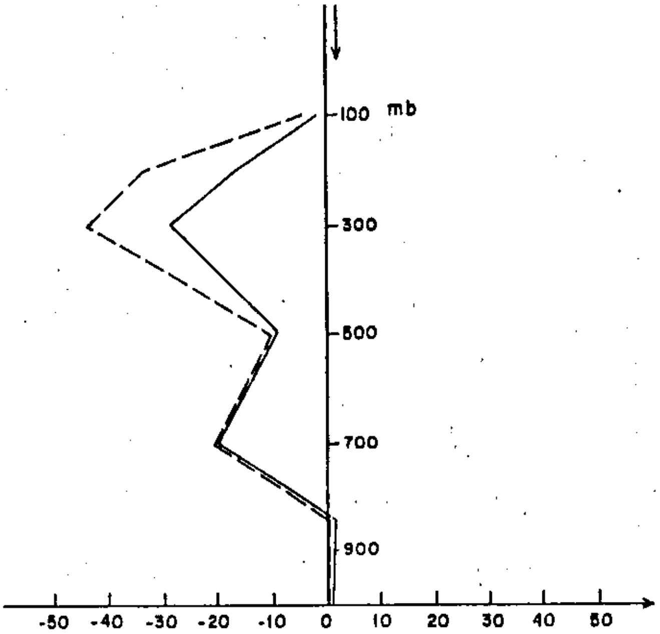

Fig. 3b: Vertical velocity profiles above point A at 1800h local time. Units are μb/s, approximately cm/s. Solid line (dry season). Dashed line (wet season).

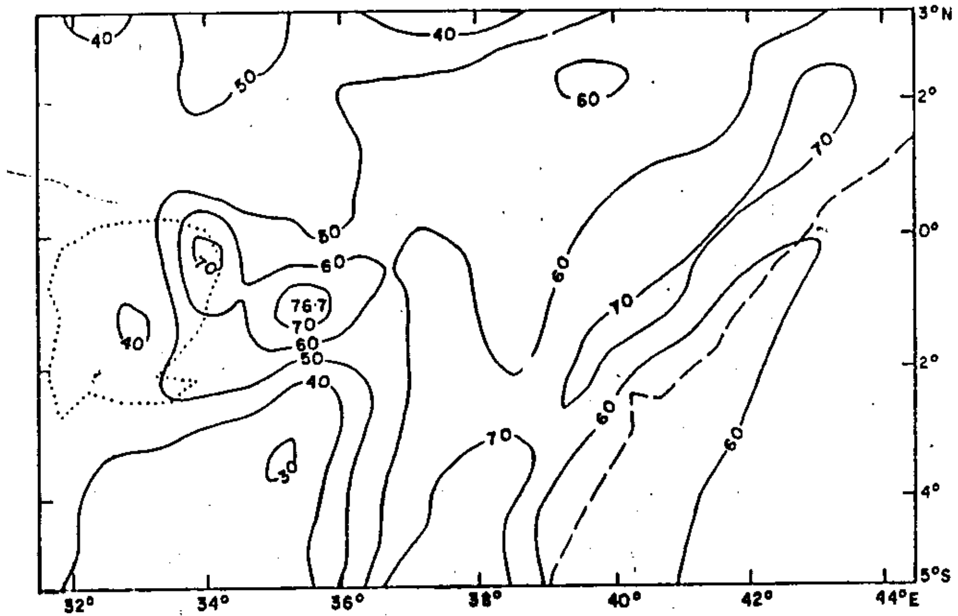

Fig. 3c: Relative humidity at 1800h local time at 850 mb (Dry season). Contour interval is 10%.

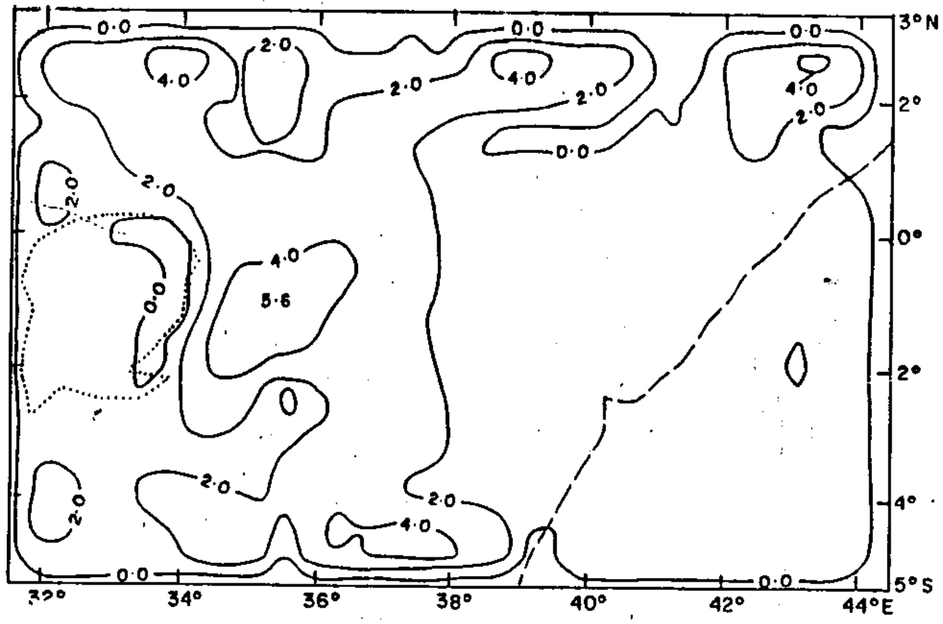

Fig. 3d: Total rainfall for dry season (control) at 1800h local time. Contours are values of P = ln (R + 0.01) + 4.6 where R is in cm. Values of P equal to 2.0, 4.0 and 5.6 correspond to rainfall amounts of 0.064 cm, 0.54, and 2.70 cm respectively.

Results show similarity of solutions at 12h local time (6h of model run). This similarity indicates that the evolution of mesoscale circulations is not significantly affected by the latent heating during the early stages and supports the hypothesis that convective instability of the tropical atmosphere is the major mechanism in the early development of the clouds. However, as the insolation intensifies in the late afternoon and the vertical motions become stronger, latent heating plays a greater role in enhancing the development.

The difference in PBL winds (Fig. 4a) indicates larger, more intensive circulation when latent heating is present at 1800 h (12 h model time) local time. This is consistent with the results of previous researchers such as Anthes et al (1982) and Anthes et al (1983). Cumulus convection also produces a warmer upper troposphere over most of the Kenya highlands (Fig. 4b) with a maximum difference of 2°C occurring over the region of maximum precipitation and at the level of upper level velocity maximum. This is much less than the difference realised in extra-tropical cyclone by Anthes et al (1983) which was 8.9°C. In the lower troposphere, the simulation with latent heating is colder in most coastal areas and the highlands. The lower layers above the lake and the ocean are however, warmer due to the effect of warmer compensating subsidence.

Fig. 4~~b~~c shows that the lower layers are drier in the simulations with latent heating than from the passive moisture scheme over the points of maximum convection and is more moist elsewhere. These results confirm the hypothesis that cumulus convection affects the environment through lateral mixing and adiabatic warming. They also confirm the theory that cumulus convection transports heat and moisture to the middle and upper troposphere thereby warming and moistening those levels while cooling and drying the lower troposphere through the convective eddy flux terms $\overline{\omega' T'}$ and $\overline{\omega' q'}$. Both these terms transfer energy upwards and tend to stabilise the cloud environment.

c) The role of orography on mesoscale and convective-scale systems (MM3)

In this section we discuss the results from a model run assuming flat terrain (MM3) and compare these these results with those simulations from the control experiment (MM1).

Fig. 5a illustrates the wind field difference (MM1 - MM3). The figure shows the strength of the upslope flows at 1800 h local time. In Kenya, the high frequency of thunderstorms/ hailstorms is associated with high ground and Lake Victoria breeze and with the convergence between the mesoscale and synoptic-scale flows (Asnani and Kinuthia, 1979). Chaggar (1977) however, argues that it is difficult to relate the patterns of thunderstorms to synoptic and climatological features whereas the association of thunderstorms with high ground and the convergence zones is well illustrated in East Africa. Hills (1978) found that the organisation of rainfall in East Africa is clearly related to oceanic and orographic influences.

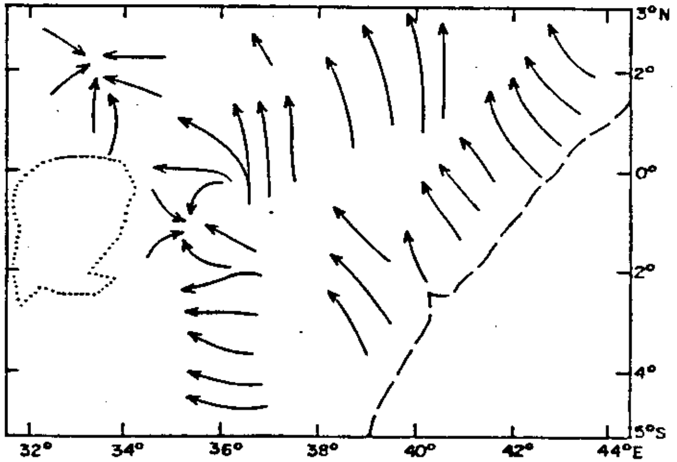

Fig. 4a: : Difference wind field at 1800h local time (control and passive moisture) at σ = 0.965.

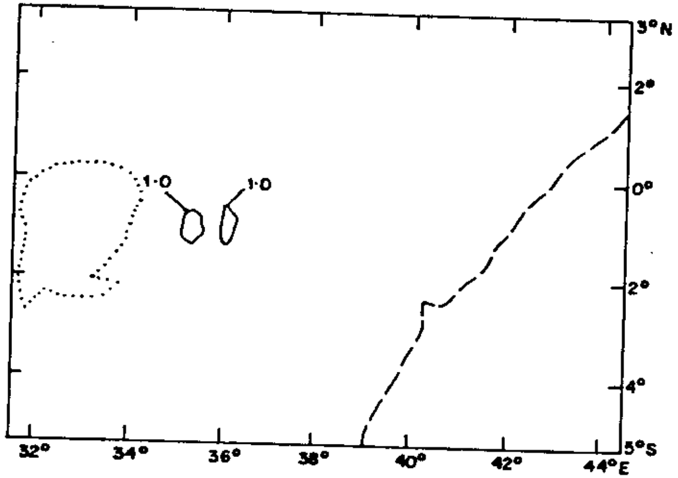

Fig. ~~4.7b~~ 4b: Same as ~~4.7a~~ 4a but for temperature at upper levels (σ = 0.35). Contour interval is 1°C.

Temperature difference field (not shown) indicates strong temperature difference in the lower layers, revealing that high ground is an important factor in modifying the atmospheric temperature at least in the planetary boundary layer (PBL).

Fig. 5b illustrates the relative humidity field at 850 mb from experiment MM3. The figure shows that maximum moistening is simulated along the coasts of Lake Victoria and Indian Ocean. These maxima are associated with lake/sea breeze convergence zones as noted by previous researchers (Gentry, 1950, Gentry and Moore, 1954, Hsu, 1969, and Pielke, 1974). In the control case, most of the moistening is simulated above the Kenya highlands at the zone of maximum updraft. Overall the control case shows more precipitation than the flat case. Fig. 5c shows the rainfall field for MM3. Most rainfall is realised along the coasts of Lake Victoria and the Indian Ocean in agreement with the relative humidity field. These results indicate the effect of orography in concentrating and transporting moisture to great depths aloft.

d) <u>Large-scale influence (MM4)</u>

In this section the results from an experiment using a more moist sounding and different temperature profile for the wet season are discussed and compared to the results from a dry season (MM1). The results from this experiment are qualitatively similar to those from MM1. Some differences however occur in the magnitudes which show slightly stronger flow for wet season (Fig. 6a) than for dry season. This is perhaps associated to increased convection which influences its mesoscale environment through lateral mixing and adiabatic warming.

The major difference between these experiments is however noticed in the vertical velocity profiles (~~compare Fig. 6b and~~ See Fig. 3b). The two figures illustrate strong differences in magnitudes although the vertical structures are qualitatively similar. Like in the case of MM1 the vertical profile has two maxima at 700 mb and 300 mb and a minimum at 500 mb. As discussed earlier, latent heating is coupled to vertical velocity. Therefore for higher magnitudes of vertical velocity we expect stronger convection and more precipitation. Krishnamurti et al (1983) showed that mesocale convergence is an important factor when considering rainfall rates. Since rainfall parameterization is posed as a two-parameter problem: a mesoscale convergence and moistening parameter, it follows that during the wet season when the ITCZ is passing over Kenya, we get increased convection due to increased moisture following the ITCZ. We therefore get more active weather and increased precipitation during this season.

Krishnamurti et al (1983) also showed that the mesoscale convergence parameter has a higher magnitude during disturbed weather than during other times.

Fig. 6b shows that simulated rainfall for wet season is more than that for dry season (compare Fig. 6b and ~~Fig. 6c and~~ Fig. 3d). The two figures however illustrate similar patterns of rainfall occurence during both these seasons indicating that mesoscale and convective-scale features are paramount in influencing the rainfall pattern. This result shows that over Kenya and indeed over most of the tropical regions where cumulus convection is an important aspect of weather activities, mesoscale convergence seems to be a more significant mechanism in deciding when and where convection occurs.

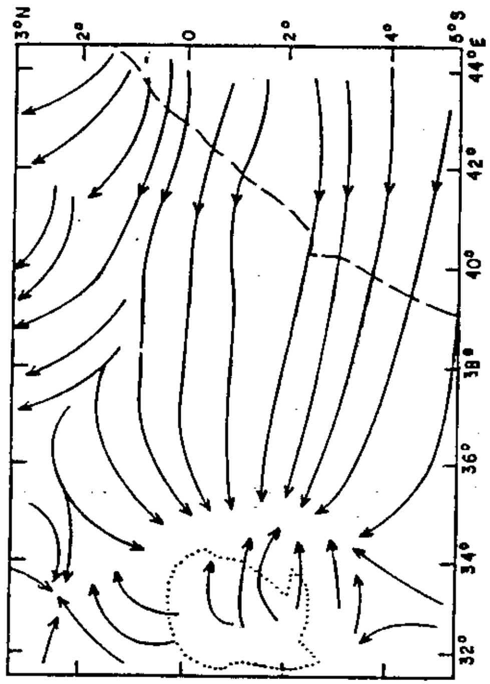

Fig. 5a: Difference Windfield (control and flat cases) at 1800h local time at σ = 0.965.

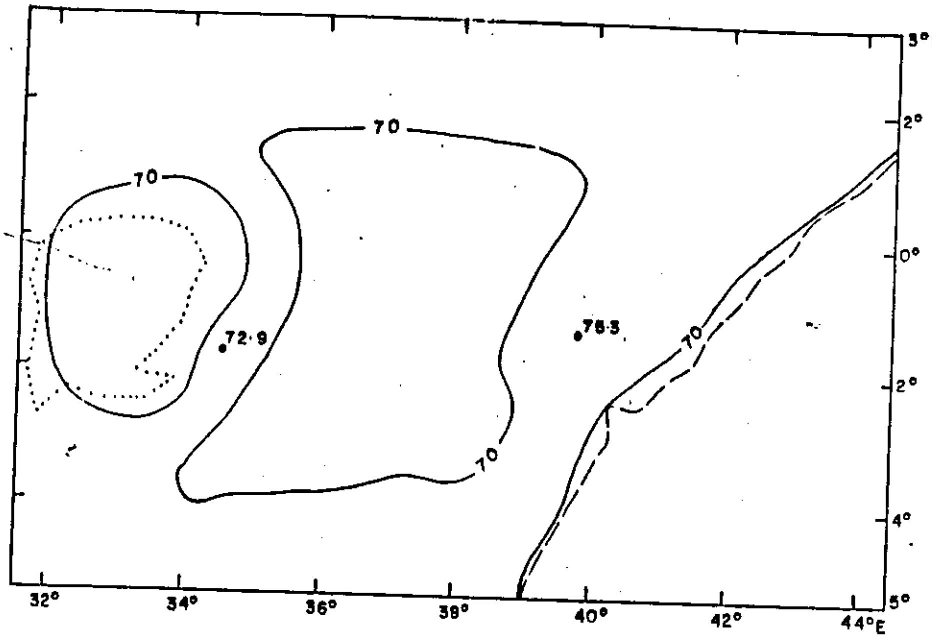

Fig. 5b: 850 mb Relative Humidity at 1800h local time (for flat case). Contour interval is 10%.

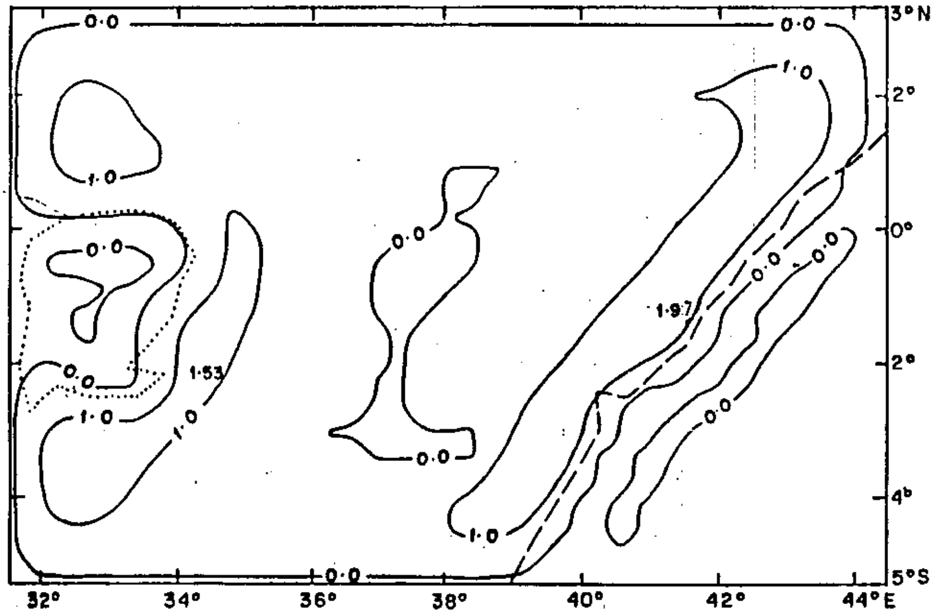

Fig. 5c: Total accumulated rain at 1800h local time for flat case. Contours are values of $P = \ln (R + 0.01) + 4.6$ where R is in cm. Values of $P = 1.0$, 1.53 and and 1.97 correspond to values of R equal 0.017, 0.036, and 0.062 cm respectively.

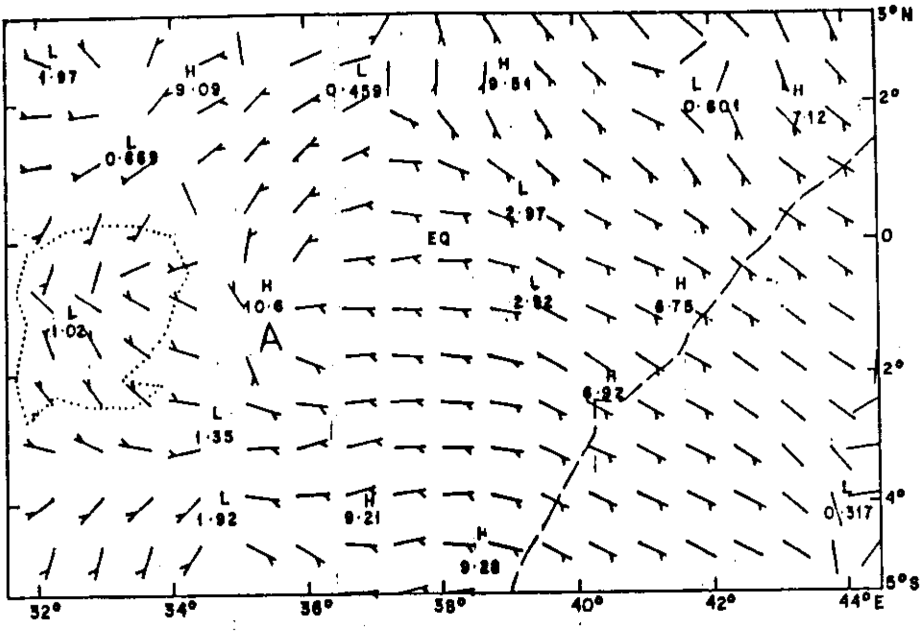

Fig. 6a: Vector wind field at 1800h local time at surface (wet season). Maxima and minima are given in m/s. A is a point over the highlands above which maximum convergence and updraft take place.

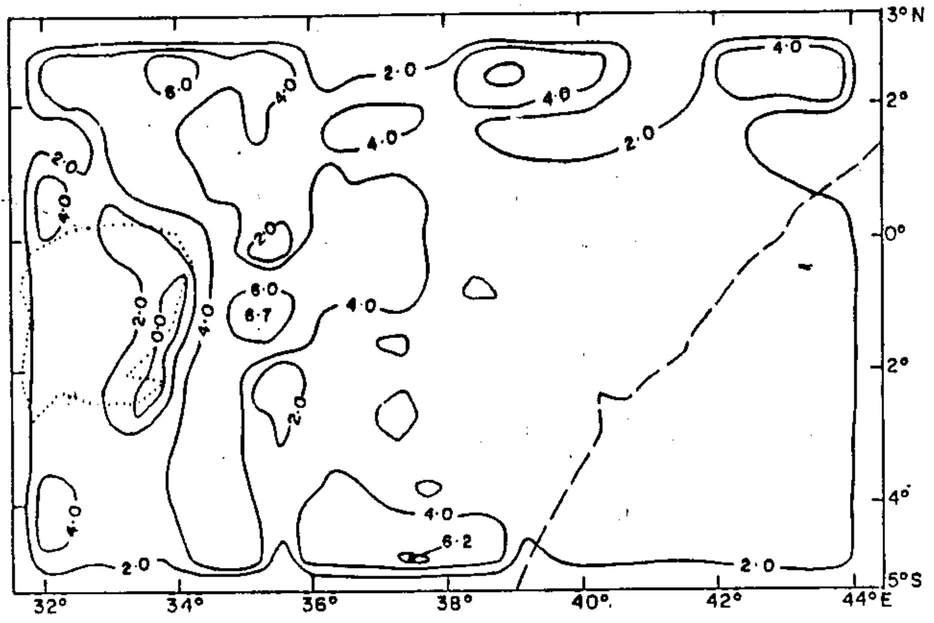

Fig. 6b: Total accumulated rainfall at 1800h local time (wet season). Contours as in Fig. 4.4f. Values of P = 6.2 and 6.7 correspond to rainfall amounts of 4.94 cm and 8.1[illegible] cm respectively.

5. SUMMARY AND CONCLUSIONS

This paper has described in general terms the mesoscale and convective-scale systems that influence the weather patterns over Kenya. Several sensitivity experiments have been done to isolate the impacts of these mesoscale and convective-scale phenomena on our weather.

The sensitivity studies show that in general weather over Kenya is generated locally by the mesoscale and convective-scale factors. The mesoscale and convective-scale factors of significance are lake/sea and land breezes, valley and mountain winds and thunderstorms, hailstorms and convective instability.

It has been shown that Lake Victoria breeze plays a very significant role on the development and maintainance of the hazardous weather over the Kenya highlands by supplying moisture and energy to the convergence zone over the highlands. Both observational and numerical results further show that valley and mountain flows have strong influence on local weather activities over Kenya. Indeed most of the rainfall especially over central Kenya is associated with valley and mountain winds. Results also show that latent heat produced from condensational heating has significant influence on the development of thunderstorms/hailstorms, lightning and flash flood hazards over Kenya. It is therefore important to incorporate condensational heating into any numerical model for accurate simulations of these weather hazards.

Additional results show that both the mesoscale and convective-scale systems have strong influence on the activities of the Intertropical Convergence Zone (ITCZ) over Kenya.

In comparing the numerical model results with the observational analysis it can be concluded that the numerical model used in this study can be efficiently used used as a forecasting tool for Kenya. It can further be concluded that this model can be used with great success to give early warning of meteorological hazards like thunderstorms/hailstorms, lightning and flash floods. These hazards are rampant in many parts of Kenya especially over the Kenya highlands. We however, need to do further research, incoporating the large-scale flow before the model can be applied operationally to forecasting and to give early warning of the meteorological hazards.

This study has an important bearing on the development of a forecasting numerical model for Kenya and also on early warning to residents and farmers living on areas which are usually affected by meteorological hazards. The model, with modification can be used to monitor many other meteorological phenomena such as pollution, drought etc.

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