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A seasonal air transport climatology for Kenya

C. K. Gatebe,[1,2] P. D. Tyson,[3] H. Annegarn,[4] S. Piketh,[3] and G. Helas[5]

Abstract. A climatology of air transport to and from Kenya has been developed using kinematic trajectory modeling. Significant months for trajectory analysis have been determined from a classification of synoptic circulation fields. Five-point back and forward trajectory clusters to and from Kenya reveal that the transport corridors to Kenya are clearly bounded and well defined. Air reaching the country originates mainly from the Saharan region and northwestern Indian Ocean of the Arabian Sea in the Northern Hemisphere and from the Madagascan region of the Indian Ocean in the Southern Hemisphere. Transport from each of these source regions show distinctive annual cycles related to the northeasterly Asian monsoon and the southeasterly trade wind maximum over Kenya in May. The Saharan transport in the lower troposphere is at a maximum when the subtropical high over northern Africa is strongly developed in the boreal winter. Air reaching Kenya between 700 and 500 hPa is mainly from Sahara and northwest Indian Ocean in the months of January and March, which gives way to southwest Indian Ocean flow in May and November. In contrast, air reaching Kenya at 400 hPa is mainly from southwest Indian Ocean in January and March, which is replaced by Saharan transport in May and November. Transport of air from Kenya is invariant, both spatially and temporally, in the tropical easterlies to the Congo Basin and Atlantic Ocean in comparison to the transport to the country. Recirculation of air has also been observed but on a limited and often local scale and not to the extent reported in southern Africa.

1. Introduction

Many studies of transport processes in the atmosphere, particularly long-range transport and horizontal and vertical mixing of aerosols and trace gases, have been undertaken over the last three decades [*Pitty*, 1968; *Schürtz*, 1980; *Prospero et al.*, 1981; *Persson et al.*, 1987; *Muhs et al.*, 1990; *Crutzen and Andreae*, 1990; *Watson et al.*, 1990; *Levine*, 1991; *Fishman et al.*, 1991; *Moody et al.*, 1991; *Dorling et al.*, 1992; *Pickering et al.*, 1992, 1994; *Krishnamurti et al.*, 1993; *Swap et al.*, 1993; *Franzen et al.*, 1994]. Most were undertaken in order to understand higher than anticipated concentration of aerosols and trace gases in remote environments. Atmospheric transports over southern Africa and adjacent oceans have been studied extensively as part of the Transport and Atmospheric Chemistry Near the Equatorial Atlantic/Southern African Fire-Atmosphere Research Initiative (TRACE A/SAFARI) investigations conducted in the austral spring of 1992 [*Garstang et al.*, 1996; *Swap et al.*, 1996] and in subsequent investigations [*Tyson et al.*, 1996a, b, c; *Sturman et al.*, 1997; *Tyson and D'Abreton*, 1998].

The transport of aerosols and trace gases over Kenya is currently under investigation. Previous studies of atmospheric transport over East Africa as a whole are of general meteorological nature and relate to local and larger-scale monsoon circulations [*Findlater*, 1968; *Fraederick*, 1972; *Kiangi et al.*, 1981; *Okeyo*, 1987; *Anyamba*, 1983, 1990; *Mukabana*, 1992; *Ininda*, 1995]. Of particular interest is the work of *Findlater* [1968] on monthly mean wind variations at 11 Kenyan stations at altitudes of 0.9, 1.5, 2.1, and 3 km above mean sea level. Findlater demonstrated the gradual wind change from northeasterlies in January to easterlies in March, southeasterlies in July, and back to easterlies again in November. The change was observed to occur first at low levels before rising to midlevels. The northeasterly monsoon was noted to divide into two streams on entering Kenya. One stream curves to become easterly and flows between the highlands of Kenya and Ethiopia. The other becomes northerly and flows over the relatively flat areas to the east of 38°E. Both of these branches were found to coexist on any one day, but often, one is more strongly developed than the other. In northwestern Kenya, persistent easterly winds prevail throughout the year at all levels in the lower troposphere.

Prior to determining actual aerosol transport, it will be useful to establish an air transport climatology for Kenya, as has been done for southern Africa [*Tyson et al.*, 1996a]. In this paper, such a climatology is developed at the synoptic scale using Lagrangian kinematic trajectory modeling.

The climate of Kenya is dominated by the annual cycle of the latitudinal migration of the Hadley cells and Intertropical Convergence Zone (ITCZ) over the region, following the annual movement of the Sun [*Newell et al.*, 1972; *Okeyo*, 1987; *Asnani*, 1993]. The ITCZ being a zone of confluence of northeasterly and southeasterly trades is mainly associated with rain. The Sun is approximately overhead in East Africa at the end of March and again at the end of September, so the heat trough can be expected to be most effective about a month later, i.e., late April/May and late October/November. The so-called

[1]Institute of Nuclear Science, University of Nairobi, Nairobi.
[2]On leave at Climatology Research Group and Schonland Research Center for Nuclear Sciences, University of Witwatersrand, Johannesburg, South Africa.
[3]Climatology Research Group, University of Witwatersrand, Johannesburg, South Africa.
[4]Schonland Research Center for Nuclear Sciences, University of Witwatersrand, Johannesburg, South Africa.
[5]Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany.

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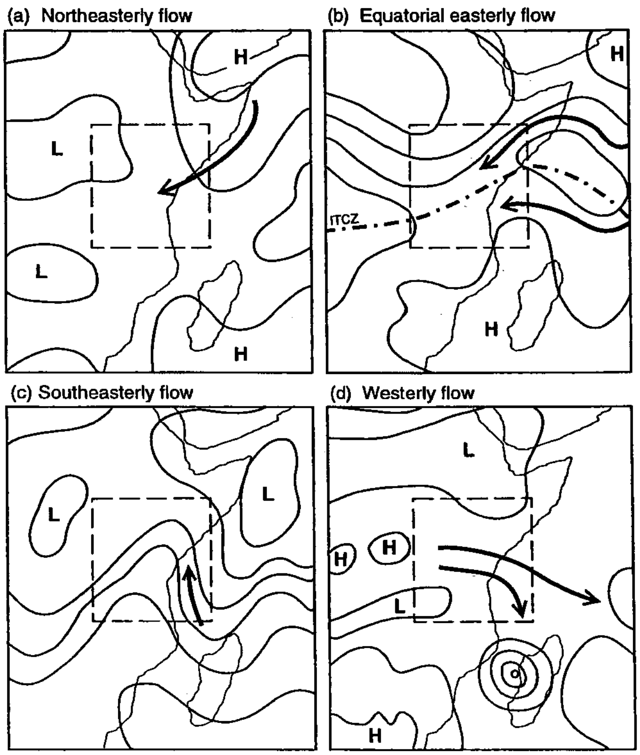

Figure 1. Major synoptic circulation types over Kenya and eastern equatorial Africa: (a) northeasterly flow associated with the Arabian Ridge of high pressure, (b) equatorial easterly flow associated with the equatorial Intertropical Convergence Zone (ITCZ), (c) southeasterly flow associated with a ridge of high pressure over east Africa, (d) westerly flow associated with a ridge of high pressure over the Congo and low pressure or tropical cyclones in the southwestern Indian Ocean.

long-rain season lasts from roughly March to May and the short rains from late October to early December [*Kiangi et al.*, 1981]. However, the local variations, because of topography and the presence of the large lakes, introduce such significant modifications that the seasons cannot be said to follow the classical (ITCZ) pattern with enough correlation to make this approach a practical one [*Griffiths*, 1969]. The diurnal variation of precipitation is largely determined by the mesoscale flows, the synoptic scale flows, and the interaction between the mesoscale and the synoptic scale flows [*Asnani and Kinuthia*, 1979; *Asnani*, 1993]. On a longer timescale the annual cycle of circulation changes is modulated by east-west adjustments in the zonal Walker circulation associated with El Niño-Southern Oscillation (ENSO) [*Cadet and Diel*, 1984; *Cadet*, 1985; *Ininda*, 1987; *Nyenzi*, 1988; *Ogallo*, 1988]. Variability of the general circulation patterns on seasonal and longer timescale similarly influences transport [*Charney*, 1975; *Charney and Shukla*, 1981; *Barnet et al.*, 1991; *Gordon and Hunt*, 1991; *Asnani*, 1993].

2. Data and Methodology

Daily synoptic charts for 1200 UTC at 850 hPa in Kenya were examined for the 5-year period 1971–1975. The period was chosen because of the availability of a wide coverage of continuous upper air data in Kenya and the region. Circulation types were then grouped into similar patterns and named according to the major synoptic feature(s) associated with each. Four major representative types were identified: northeasterly flow, equatorial easterly flow, southeasterly flow, and westerly flow (Figure 1).

Trajectory flow patterns were then determined for specific months dominated by the different circulation types. Ten-day backward and forward trajectories starting at Mount Kenya were calculated over the 3-year period 1991–1993 for January, March, May, and November using European Center for Medium-Range Weather Forecasts (ECMWF) operational analyses of the 6 hourly, three-dimensional (3-D) wind field data at various pressure levels. The ECMWF operational analyses of the 3-D wind field are available globally every 6 hours at 31 levels, of which 13 below 500 hPa are used. *Bengtsson* [1985a] gives a description of the ECMWF data assimilation system. *Pickering et al.* [1994, 1996], in a comparison of trajectory methods and global data sets, find the ECMWF-generated fields to yield the best current trajectory results. Each transport pathway is calculated over a 10-day period using the *D'Abreton* [1996] model. The model is based on the principle of Lagrangian advection with u, v, and w wind components at a given time, and atmospheric layer and grid used to compute a new downstream (upstream) location of an air parcel at a later (earlier) time. This procedure is then repeated to produce a forward or backward trajectory over 10 days. Vertical velocities are determined from nonlinear mode initialization, which permits the diabatic as well as the adiabatic processes, which influence vertical motion, to be taken into account.

Daily clusters of five trajectories at latitudes and longitudes 1° apart, with the centroid at Mount Kenya (0.1°S, 37.2°E), were calculated for the initial levels of 700, 600, 500, and 400 hPa for the 4 months in each of the years. Since ECMWF data are available on 2.5° × 2.5° latitude-longitude grid [*Bengtsson*, 1985b], Mount Kenya is taken as a representative of the entire country. The merit of Mount Kenya lies in its location next to the equator, second highest mountain in Africa (5199 m) and an isolated feature in what can be considered as a remote environment in central Kenya. It is also in an area that has been known climatologically to experience monsoon winds at different times of the year. Matched back and forward trajectories were grouped according to similarities. Six major types of transport to Kenya were identified according to source area: from the northwest Indian Ocean, from the southwest Indian Ocean, anticyclonic Saharan transport, in the Atlantic westerlies, circum Kenyan transport, and localized transport within Kenya. Likewise, six major transport modes from Kenya were delimited: equatorial easterly transport to the Congo and Atlantic Ocean, recurved easterly transport to the Arabian Penisula, northwesterly transport to the southwest Indian Ocean, northeasterly transport to the northern Indian Ocean, southwesterly transport to the central interior Africa, and return circulation to Kenya.

3. Results and Discussion

3.1. Synoptic Flow Patterns

Four synoptic circulation types dominate airflow over Kenya (Figure 1). The first is the northeasterly flow type, in which the 850 hPa pressure field is dominated by a ridge of high-pressure field over the Arabian Penisula producing northeasterlies over Kenya. The easterly flow type occurs with the equatorial convergence of northeast and southeast trade winds over the eastern equatorial region of Africa. The southeasterly flow type

Table 1. Monthly Percentage Frequency of Synoptic Circulation in Kenya

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
NEF	90.3	85.8	54.8	4.7	0.0	0.0	0.6	0.0	0.0	0.0	34.7	72.9
EEF	6.4	10.6	25.1	24.7	0.6	0.7	0.6	1.9	2.0	11.6	35.3	23.9
SEF	2.6	2.1	20.0	70.7	99.4	99.3	98.7	98.1	98.0	88.4	28.7	3.2
WF	0.6	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0

NEF, northeasterly flow; EF, equatorial easterly flow; SEF, southeasterly flow; WF, westerly flow.

results from a ridge extending from the south toward Kenya. The fourth type is the westerly flow type in which the pressure fields exhibit a ridge from the Congo eastward and low pressure or tropical cyclones in the southwestern Indian Ocean.

Winds with an easterly component dominate the Kenyan tropics [*Anyamba*, 1990]. However, analysis of the synoptic flow patterns during the 5-year period studied reveals that the northeasterly monsoons are most prevalent from December to April, with the highest frequency of occurrence (90%) during January (Table 1). The southeasterly monsoon dominates from April to October, with nearly all the days from May to September, showing at least 88% southerly/southeasterly flow. Direct easterly flow is dominant during November (35%). March is a transitional month between northeasterly and southeasterly monsoons; November is transitional between southeast and northeast monsoons. These two months have highest relative frequencies of easterlies into Kenya. These results confirm the earlier studies of *Findlater* [1968] and *Kiangi et al.* [1981].

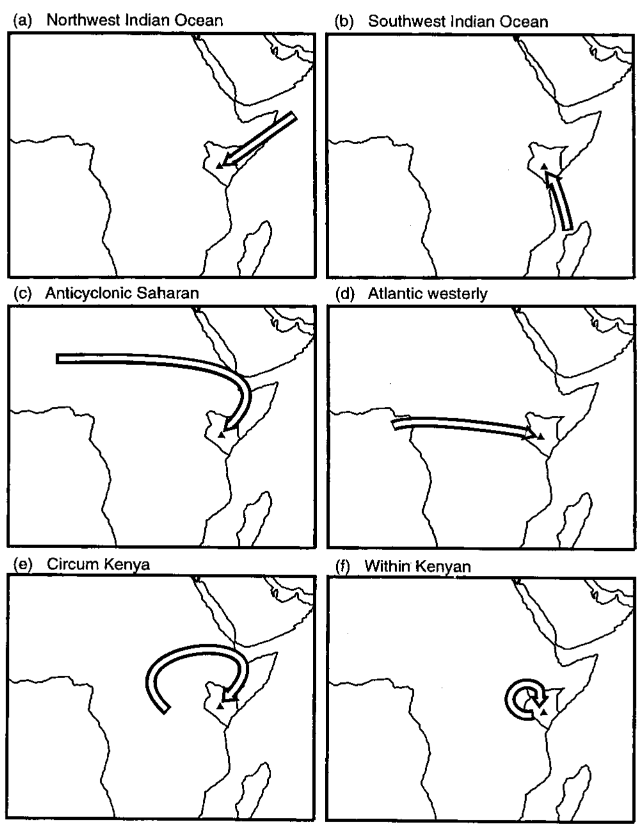

Figure 2. Predominant atmospheric transport modes conveying air to Kenya as determined by back trajectory modeling ending at Mount Kenya (triangle): (a) from the northwest Indian Ocean, (b) from the southwest Indian Ocean, (c) anticyclonic Saharan transport, (d) in the Atlantic westerlies, (e) circum Kenyan transport, and (f) localized within Kenyan transport.

Westerly flow is observed in January, February, and November but with frequencies not exceeding 2%. Unstable westerly currents are observed occasionally at lower and middle levels of the atmosphere over East Africa [*Forsdyke*, 1949, 1960; *Thompson*, 1965; *Nakamura*, 1968; *Harangonzo and Harrison*, 1983; *Kiangi and Temu*, 1984; *Davis et al.*, 1985; *Murakami and Sumathipala*, 1989]. The seasonal cycle of the different flow types has been used to define the optimum months to undertake trajectory analysis for determining air transport characteristics to and from Kenya over 20-day periods.

4. Transport Patterns

Back trajectory analysis to show the maximum frequency, 10-day transport corridors to Mount Kenya reveals transport modes more complicated than the simple circulation typology suggests (Figure 2). Northeasterly and southeasterly transport from the northwestern and southwestern Indian Ocean corresponds to their seasonal monsoon airflow counterparts (Figures 2a and 2b). Likewise, anticyclonic Saharan transport is a prominent feature (Figure 2c), and a westerly transport mode is evident (Figure 2d). Near-closed anticyclonic transport occurs around Kenya at different spatial scales (Figures 2e and 2f). The frequencies of transport modes are given in Table 2 for different months and levels in the atmosphere.

Northwest Indian Ocean and anticyclonic Saharan transport appears to be dominant at all levels in the months of January and March when northeasterlies and northerlies are most prevalent. It is at these times that Kenya is under strong influence of the Arabian and Azores semipermanent anticyclones of the Northern Hemisphere. Southwestern transport is most dominant in May in line with the period when southeasterlies are dominant in Kenya. Atlantic westerly transport is an upper troposphere phenomenon in January, March, and November. The two anticyclonic circulations are evidently absent in the medium levels in the month of November and only appear at 400 hPa. During this month, Kenya is under the influence of both the northeasterlies and the southeasterlies converging over the region.

Air transport away from Kenya, as determined from clustered forward trajectory analysis, reveals six major modes (Figure 3). The equatorial easterly to the Atlantic Ocean and the recurved easterly to the Arabian Penisula appear dominant in January, March, and November. This implies that the air transport to Kenya either as northerly, northeasterly, or easterly over the same period exits mainly to the Atlantic and Saudi Arabia. During the month of May air transport, which is mainly from the southern western Indian Ocean, exits mostly to the Atlantic Ocean. Return circulation to Kenya, though not

Table 2. Percentage Frequency of Air Transport to Kenya

	700 hPa	600 hPa	500 hPa	400 hPa
	January			
Northwest Indian Ocean	44	55	61	20
Southwest Indian Ocean	0	4	10	50
Anticyclonic Saharan	47	34	22	10
Atlantic westerly	0	0	0	12
Circum Kenyan	0	0	7	8
Within Kenyan	9	7	0	0
	March			
Northwest Indian Ocean	49	49	25	37
Southwest Indian Ocean	23	14	22	25
Anticyclonic Saharan	28	36	47	29
Atlantic westerly	0	0	0	6
Circum Kenyan	0	0	5	3
Within Kenyan	0	1	1	0
	May			
Northwest Indian Ocean	4	25	42	48
Southwest Indian Ocean	96	70	35	32
Anticyclonic Saharan	0	1	18	15
Atlantic westerly	0	0	0	0
Circum Kenyan	0	0	0	0
Within Kenyan	0	4	5	5
	November			
Northwest Indian Ocean	44	66	63	49
Southwest Indian Ocean	50	33	28	26
Anticyclonic Saharan	6	1	7	16
Atlantic westerly	0	0	2	5
Circum Kenyan	0	0	0	1
Within Kenyan	0	0	0	3

frequent, is nonetheless interesting (Figure 3f). Frequencies of occurrence of the different transport modes are given in Table 3.

5. Dominant Transport Fields

The flow of air into and out of Kenya in four different months and levels is shown in Figures 4–7. Analysis of the combined flow during the month of January (Figure 4) reveals that at the 700 hPa level, most air reaching Kenya flows anticyclonically from the Saharan region (56%). With increasing height, the proportion drops to 29% at 500 hPa and to 18% at 400 hPa. In contrast, the proportion coming in from the northeast Indian Ocean rises from 44% at 700 hPa to a maximum of 61% at 500 hPa. At all levels, air being transported from Kenya is at maximum toward the Atlantic Ocean. The greatest transport is at 700 hPa (69%). The second most important transport stream away from Kenya is that directed toward the Arabian Penisula (16%). In March (Figure 5) a similar picture is maintained, except that in lower levels the transport from southwest Indian Ocean area increases, as that from the Saharan region begins to decrease. Transport from Kenya remains predominantly toward the Congo Basin and the Atlantic Ocean. In contrast, during May the transport patterns, particularly in the lower troposphere, are markedly different. Transport from the Saharan region is absent or substantially diminished, whereas that in the southeast trades from the Southern Hemisphere increases significantly to reach 96% at 700 hPa (Figure 6). In November (Figure 7), transport of air to Kenya is mainly from the Madagascan region and from Kenya to the Atlantic Ocean. At the same time, outward transport toward the Arabian Desert increases significantly. Anticyclonic flow remains maximized in the tropical easterlies to the Congo and beyond at all levels and to the greatest extent in the lower troposphere (42% at 700 hPa). Transport to the southwest Indian Ocean in the region of Madagascar increases significantly at this time of the year.

The annual variation of transport in the three streams, accounting for the largest proportion of the total transport, is striking (Figure 8). The transport to Kenya shows more variability than that away from the country. In the latter case, the transport to the Congo Basin region and to the Atlantic Ocean is relatively invariant throughout the year, being greatest (~70%) in January and least (~40%) in November. In contrast, transport to Kenya from the Madagascar region is greatest (>90%) in May and least (zero) in January.

Integrating the lower-troposphere transport, from 700 to 500 hPa, allows the transport fields to be further simplified to advantage (Figure 9). The distinctive seasonal characteristic of transport to Kenya from the Saharan and Madagascan regions is clear; the relative constancy of transport from the northwest Indian Ocean region is likewise apparent. In the integrated transport from Kenya it is only the tropical easterly flow from the country to the Congo Basin and Atlantic Ocean that is important.

Measurements of the annual variation of the constituent elements of the aerosol loading at the remote Mount Kenya site are currently being made. Given knowledge of air trans-

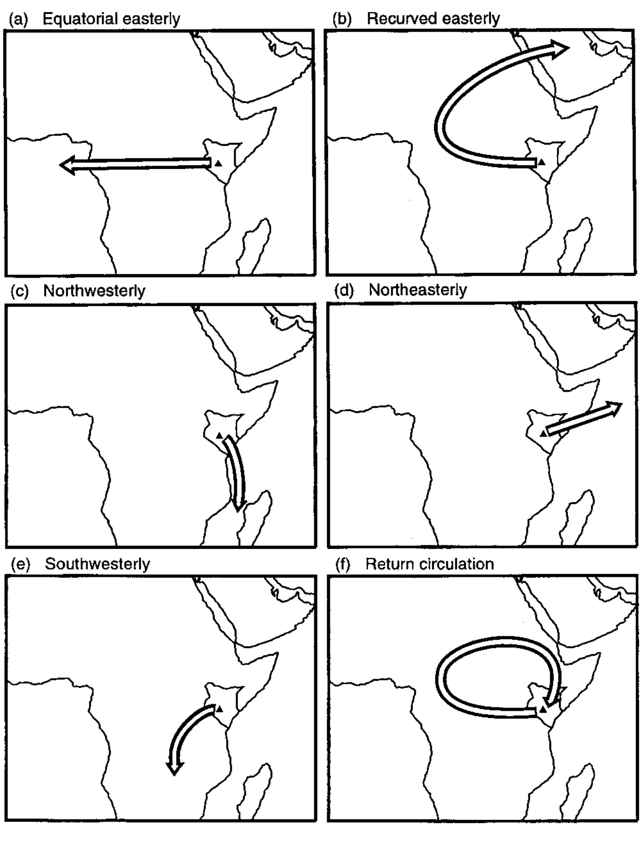

Figure 3. Predominant atmospheric transport modes conveying air from Kenya as determined by forward trajectory modeling starting from Mount Kenya (triangle): (a) equatorial easterly transport to the Congo and Atlantic Ocean, (b) recurved easterly transport to the Arabian Penisula, (c) northwesterly transport to the southwest Indian Ocean, (d) northeasterly transport to the northern Indian Ocean, (e) southwesterly transport to the central interior Africa, and (f) return circulation to Kenya.

Table 3. Percentage Frequency of Air Transport from Kenya

	700 hPa	600 hPa	500 hPa	400 hPa
		January		
Equatorial easterly	69	61	66	59
Recurved easterly	16	24	24	30
Northwesterly	4	5	1	0
Northeasterly	0	0	0	0
Southwesterly	7	7	6	9
Return circulation	4	3	3	2
		March		
Equatorial easterly	67	60	55	53
Recurved easterly	26	22	15	23
Northwesterly	0	6	8	3
Northeasterly	0	10	10	6
Southwesterly	6	0	4	1
Return circulation	1	2	8	14
		May		
Equatorial easterly	48	43	26	37
Recurved easterly	0	2	0	10
Northwesterly	37	36	35	26
Northeasterly	8	8	8	6
Southwesterly	7	11	31	21
Return circulation	0	0	0	0
		November		
Equatorial easterly	42	43	27	28
Recurved easterly	31	35	30	11
Northwesterly	4	9	14	27
Northeasterly	6	5	2	25
Southwesterly	10	8	26	3
Return circulation	7	0	1	6

port climatology and the source and sink areas of air reaching and moving away from the site, it should prove possible to quantify aerosol transport in the Kenyan region. More importantly, it will allow estimates of cross-equatorial hemispheric transfers of aerosols to be made for the first time over continental Africa. The simple technique used in this paper presents a further means of understanding the regional manifestation of the general circulation of the atmosphere and resultant inter-

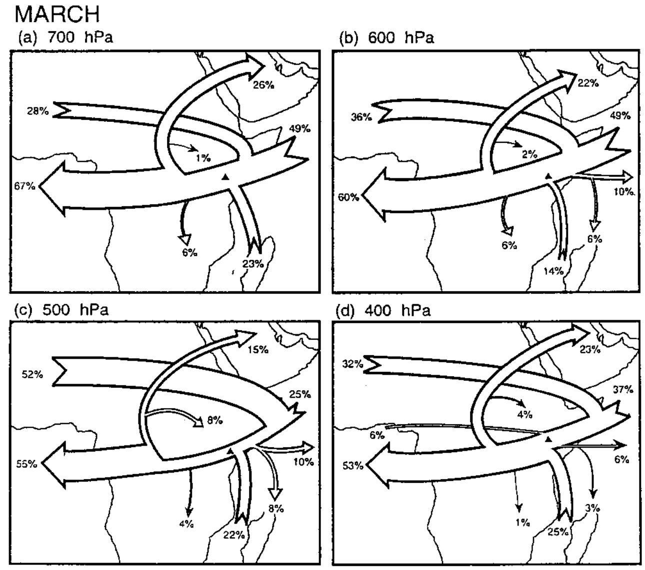

Figure 5. March air transport to and from Kenya at 700, 600, 500, and 400 hPa.

tropical large-scale regional transport of air, and the matter contained therein, over eastern equatorial Africa.

6. Conclusion

A climatology of air transport to and from Kenya has been developed using kinematic trajectory modeling. Significant months for trajectory analysis have been determined from a classification of synoptic circulation fields. Five-point back and forward trajectory clusters to and from Kenya reveal that the transport corridors, or plumes, to Kenya are clearly bounded and well defined. Air reaching the country originates mainly from the Saharan region and northwestern Indian Ocean of the Arabian Sea in the Northern Hemisphere and from the Madagascan region of the Indian Ocean in the Southern

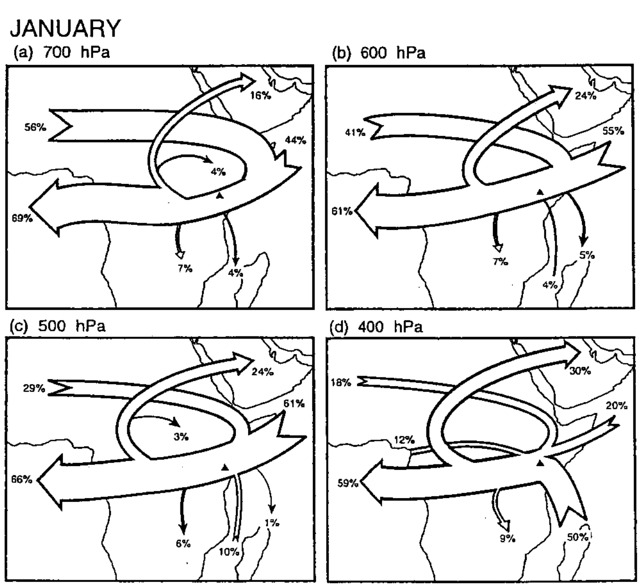

Figure 4. January air transport to and from Kenya at 700, 600, 500, and 400 hPa.

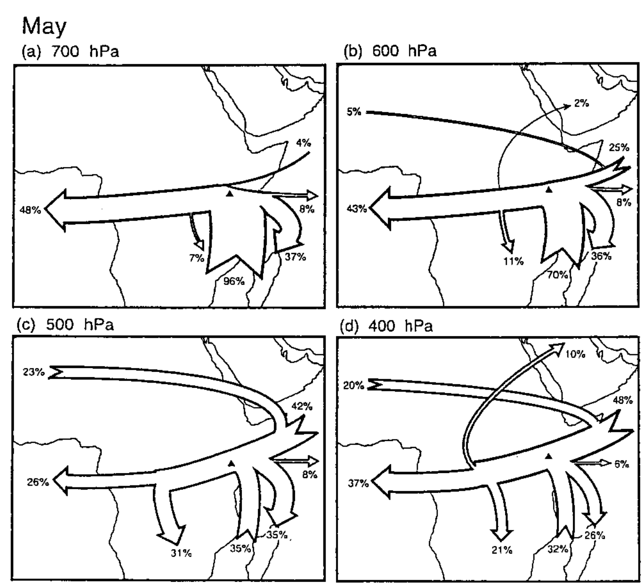

Figure 6. May air transport to and from Kenya at 700, 600, 500, and 400 hPa.

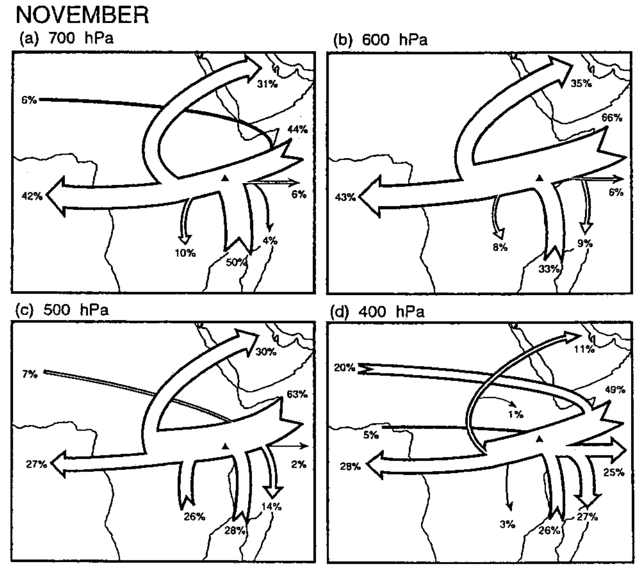

Figure 7. November air transport to and from Kenya at 700, 600, 500, and 400 hPa.

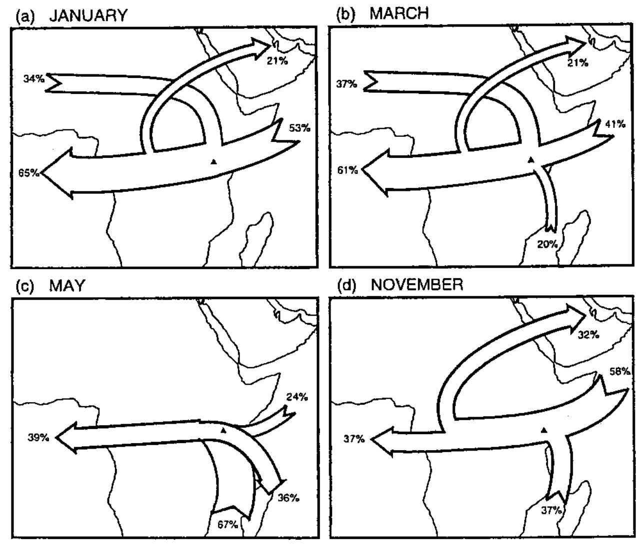

Figure 9. Integrated 700–500 hPa air transport to and from Kenya.

Hemisphere. Transport from each of these source regions shows distinctive annual cycles related to the northeasterly Asian monsoon and the southeasterly trade wind maximum over Kenya in May. The Saharan transport in the lower troposphere is at a maximum when the subtropical high over northern Africa is strongly developed in the boreal winter. Air reaching Kenya between 700 and 500 hPa is mainly from Sahara and northwest Indian Ocean in the months of January and March, which gives way to southwest Indian Ocean flow in May and November. In contrast, air reaching Kenya at 400 hPa is mainly from southwest Indian Ocean in January and March, which is replaced by Saharan transport in May and November. Transport of air from Kenya is invariant, both spatially and temporally in the tropical easterlies to the Congo Basin and Atlantic Ocean in comparison to the transport to the country. Recirculation of air has also been observed but on a limited and often local scale and not to the extent reported in southern Africa [*Tyson et al.*, 1996b].

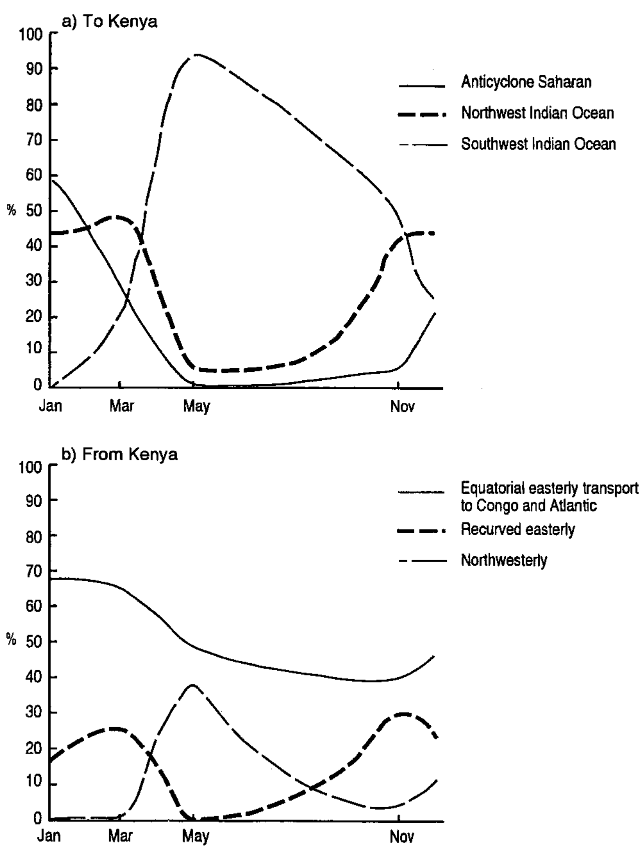

Figure 8. Annual variation of transport at 700 hPa in the three most significant streams conveying air to and from Kenya.

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H. Annegarn, Schonland Research Center for Nuclear Sciences, University of Witwatersrand, Johannesburg, P.O. Wits, 2050, South Africa.

C. K. Gatebe, Institute of Nuclear Science, University of Nairobi, P.O. Box 30197, Nairobi, Kenya. (e-mail: charles.gatebe@lion.meteo.go.ke)

G. Helas, Max Planck Institute for Chemistry, Biogeochemistry Department, P.O. Box 3060, D-55020 Mainz, Germany.

P. D. Tyson and S. Piketh, Climatology Research Group, University of Witwatersrand, Johannesburg, P.O. Wits, 2050, South Africa.

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