Aerial Observations of the East African Low-Level Jet Stream

JOHN E. HART
Department of Astro-Geophysics, University of Colorado, Boulder, CO 80309

G. V. RAO
Department of Atmospheric Science, St. Louis University, St. Louis, MO 63156

HENRY VAN DE BOOGAARD
National Center for Atmospheric Research, Boulder, CO 80307

JOHN A. YOUNG
Department of Meteorology, University of Wisconsin, Madison, WI 53706

JOHN FINDLATER
Meteorological Department, Nairobi, Kenya

(Manuscript received 30 May 1978, in final form 14 September 1978)

ABSTRACT

This paper describes observations of the East African low-level jet stream obtained during June and July 1977 with a long-range research aircraft. We present results based on the real-time display of data on board the aircraft during the research flights. The jet stream core was located at about 40°E between 1 and 2 km altitude. The jet had a very sharp horizontal shear layer to the west of the core, with less pronounced shear to the east extending out over the ocean. Although flowing persistently from the south, it experienced a strong diurnal change over land. In addition, other changes in structure on a longer time scale were observed. This article presents the kinematic and thermal structure of the jet, and the low-level flow further upstream. Based on these data, the estimated cross-equatorial water vapor flux across the equator was found to be much higher than previously thought.

1. Introduction

As early as 1945, pilots flying at low levels into the northern part of East Africa reported moderate turbulence and buffeting of the aircraft from relatively strong winds. In 1963, with increased pilot balloon observations and aircraft flights over northeastern Kenya, the strong low-level winds were again brought to meteorological attention. It was subsequently determined that this strong low-level wind was the more obvious component of large-scale cross-equatorial flow that was very pronounced in the Northern Hemisphere's summer months. With special data gathered during the International Indian Ocean Expedition in 1963–64, the general climatology of the wind systems in that part of the world became better known. Ramage and Raman (1972) produced an atlas giving details of the circulation features.

In the past decade Findlater (1969a,b, 1971) paid special attention to the climatology of the general circulation over the Indian Ocean and Eastern Africa. The synoptic studies reported in these important articles were based primarily on daily pibal and rawinsonde stations, and documented the presence of a persistent low level southerly jet, which we shall call the "East African low-level jet". This low-level trans-equatorial air current flows from the Southern to the Northern Hemisphere during the southwest monsoon with a mean speed of typically 25 kt near the equator, although much higher wind speeds in excess of 70 kt have been observed during surges in the jet.

In addition to the synoptic studies, Findlater (1972) reported some aerial explorations in the landward flank of the jet betwen Nairobi and Kiunga, Kenya. These were made with a single-engine aircraft with limited range and minimal recording of data. Nevertheless some of the complex details of the jet structure were revealed for the first time. The jet appeared to be multi-cored, indicating the possibility of instability or interaction with small-

0027-0644/78/1714-1724$05.50

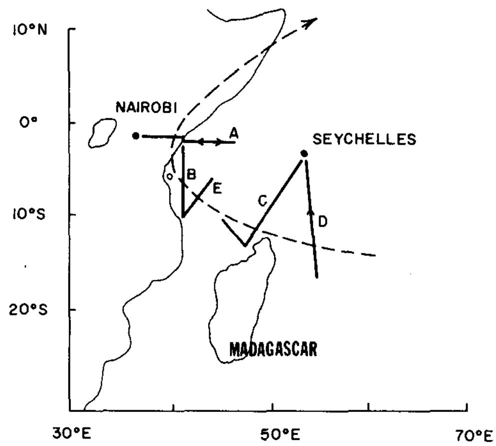


FIG. 1. Flight tracks (solid lines) as described in Table 1. The dashed line delineates the mean position of the jet axis for July from Findlater (1971).

TABLE 1. Electra flights during MONEX 77.

Flight no.	Date	Track*	Time** (GMT)
1	9 June 1977	A	0300, 0804
2	11 June 1977	A	0340, 1040
3	15 June 1977	A	0405, 1115
4	17 June 1977	B	0300, 0935
5	19 June 1977	B (to 3°S)	0310, 0940
6	22 June 1977	C (to Mahé)	0358, 1055
7	23 June 1977	D	0500, 1034
8	26 June 1977	C (to Nairobi)	0754, 1441
9	28 June 1977	A	0255, 1005
10	29 June 1977	A	1500, 2100
11	30 June 1977	A	1255, 1740
12	3 July 1977	E	0340, 1030
13	4 July 1977	A	0355, 0815

* From Fig. 1.
** The first column pertains to take-off, the second to landing.

scale convective and shear turbulence. The main core was observed to move from day to day, perhaps in response to fluctuations in upstream conditions. These aerial observations demonstrated the degree of complexity which can exist on the landward side of the jet. Prior to our present study there was little evidence for what occurs off the coast, and the data which were taken over land gave only a qualitative picture of the phenomena occurring there, with incomplete quantitative information regarding the diurnal cycle, the questions of instability and turbulence around the core, interactions with transverse mountain-sea-breeze circulations, etc. The main purpose of this paper is to describe our measurements relating to these and other phenomena.

2. The aircraft experiment

The Lockheed Electra (Model L-188C) leased and operated by the National Center for Atmospheric Research[1] was based in Nairobi, Kenya (1°S, 37°E) during the main experiment. Two of the thirteen flights were based at Mahé, Seychelles (5°S, 55°E). Thermodynamic, air motion (from vane and inertial navigation system signals), radiation, cloud particle and aerosol data were recorded digitally on magnetic tape at the dual turbulence rate (20 samples per second). These raw data tapes are processed on the NCAR computer, which produces a set of calibrated and edited output data tapes in a format described by Kelley and Lackman (1976). During the flights an on-board minicomputer generates 7 s averages of latitude, longitude, pressure altitude, horizontal wind (relative to ground based coordinates), potential temperature, radiometric surface temperature and dew point. These latter data form the basis of the results reported in this paper. The calibrations and bias removals performed on board in real time are not as sophisticated as those done at NCAR with the raw data tapes. We expect the analyses presented here would be altered in only a minor quantitative sense had the final output digital data been used instead of the real-time in-flight data.

Several flight tracks (vertical projections of aircraft path) were flown. These are shown in Fig. 1, along with the climatological jet axis from Findlater (1971). The flight times and tracks flown are listed in Table 1. Eighty-six hours of flight data were recorded, the equivalent of about 35 000 km horizontal distance. Most data operations were at altitudes rang-

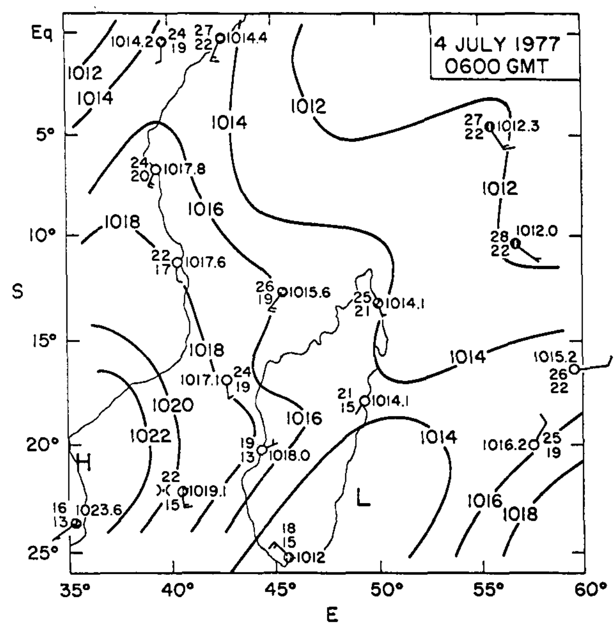
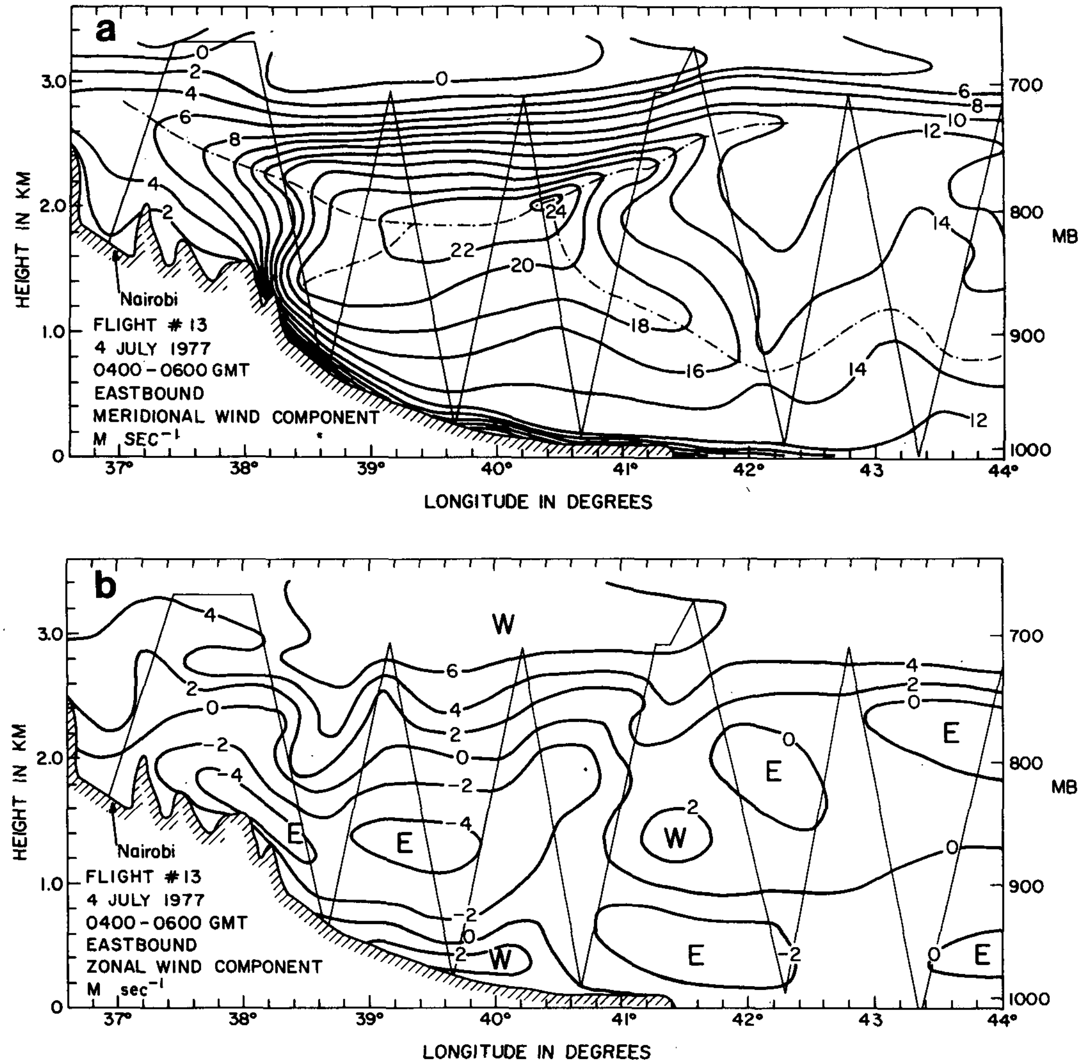


FIG. 2. Surface map for 4 July 1977.

[1] NCAR is sponsored by the National Science Foundation.



ing from the surface to 3 km. Several cross sections were made by flying essentially across the jet at approximately constant latitude. Most of the flights along track A left Nairobi eastbound just before dawn, about 0300 GMT (0600 local Nairobi time), and crossed the jet before the onset of any substantial convective activity. On the longer flights (up to ~7 h), the return westbound leg crossed the main jet core about midday during substantial convective mixing. In addition track A was followed for one night flight (10) and one late afternoon flight (11). On all flights three "standard" maneuvers were made:

1) A forward "sawtooth" (see Fig. 3a) wherein the aircraft made successive descents and ascents (typically at 500 ft min^{-1}) in an effort to get a large amount of data in the height-(along-track) plane.

2) A "ladder" pattern wherein the aircraft flew several 10 min level legs stacked on top of each other at different altitudes. These were intended to provide profile data on radiation and on horizontally averaged turbulent fluxes over the same geographical location.

3) A forward "staircase" similar to maneuver 2 except that the level legs were flown sequentially along the flight track.

The upstream oceanic inflow region was investigated on flight numbers 6, 7, 8 and 12. Flight numbers 4 and 5 (as well as 12) were performed to investigate the downstream evolution of the jet as it crossed from ocean to land. Portions of flights 4, 5 and 10 contained short north-south tracks over land and ocean for midday boundary layer evolution measurements. On these flights the standard maneuvers as described above were employed.

3. Review of the data

a. Synoptic background

The 1977 aerial reconnaissance program began with the first flight on 9 June 1977 and concluded

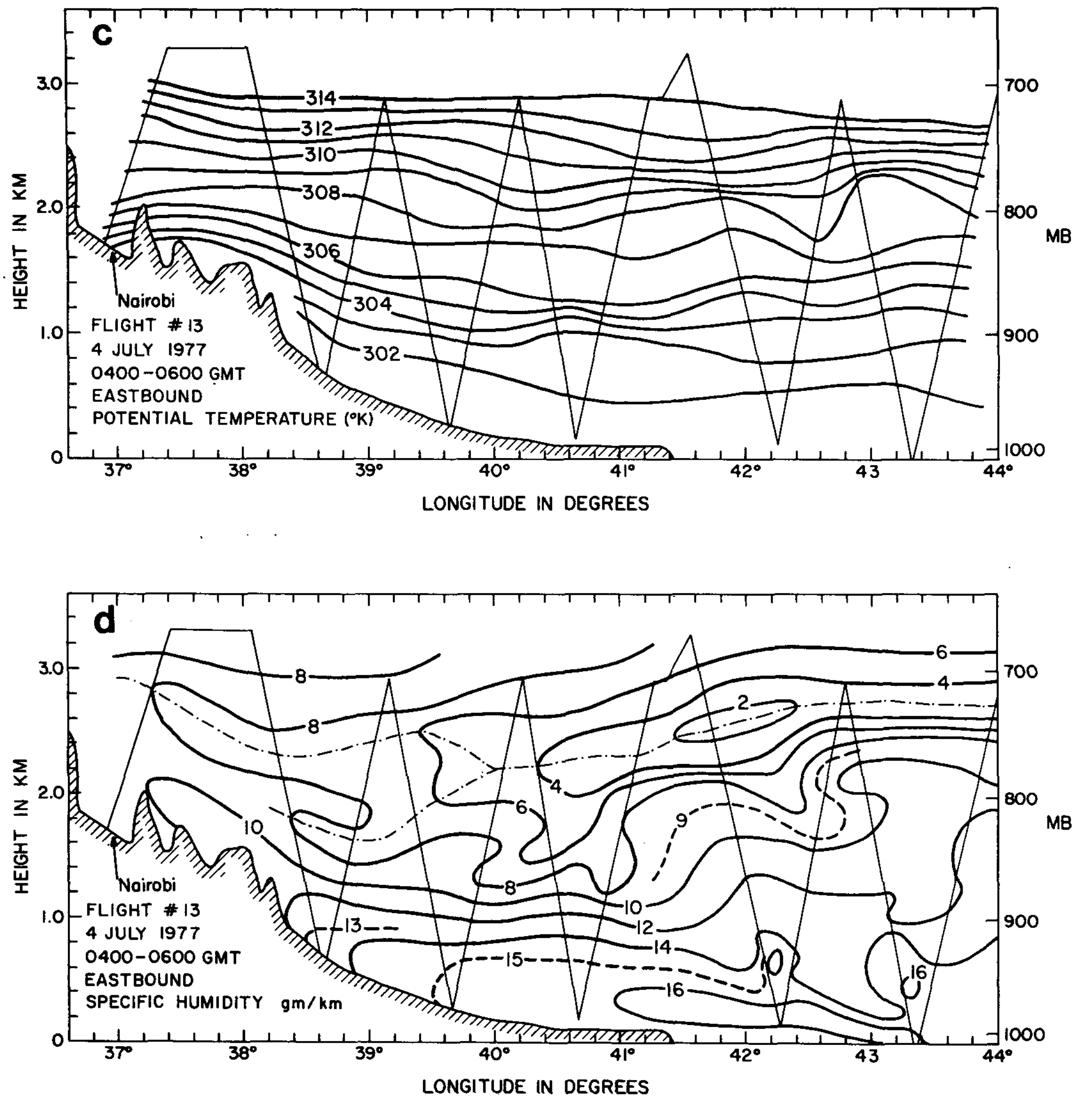


FIG. 3. The early morning cross section of 4 July 1977. The light sawtooth line shows the flight path in height-longitude coordinates. The vertical projection is approximately track A of Fig. 1. (a) Meridional (southerly) wind (m s^{-1}), (b) zonal (westerly) wind (m s^{-1}), (c) potential temperature (K), (d) specific humidity (g kg^{-1}).

with the thirteenth flight on 4 July 1977. Over the western Indian Ocean and eastern Africa one usually finds ridges in the pressure field, one along the East African coast and a second one east and northeast of Madagascar. The former ridge is a characteristic feature in the northern summer while the latter undergoes significant synoptic variation. The flow is driven by the meridional pressure gradient which experiences inertial turning near the equator, and is blocked by the Kenya and Ethiopian highlands.

Fig. 2 shows a representative sea level pressure chart for 4 July 1977. To the south note the high-pressure cell (20°S, 35°E) and the low-pressure center directly east of the high. As these systems travel eastward, the divergent flow from the high extends northward up the Mozambique channel to eventually strengthen the East African jet. On the last days of the aerial reconnaissance the jet was particularly strong. Speeds as high as 24 m s^{-1} were registered at 0500 GMT, at 800 mb altitude, near 2°S, 40°E on both 3 and 4 July 1977. We present this latter case first because of the strong and distinct jet structure and its representativeness of the other days.

b. The cross section of 4 July 1977

On 4 July a flight was made along track A departing Nairobi about dawn (0655 LT). Fig. 3 presents analyses of meridional wind component v, zonal

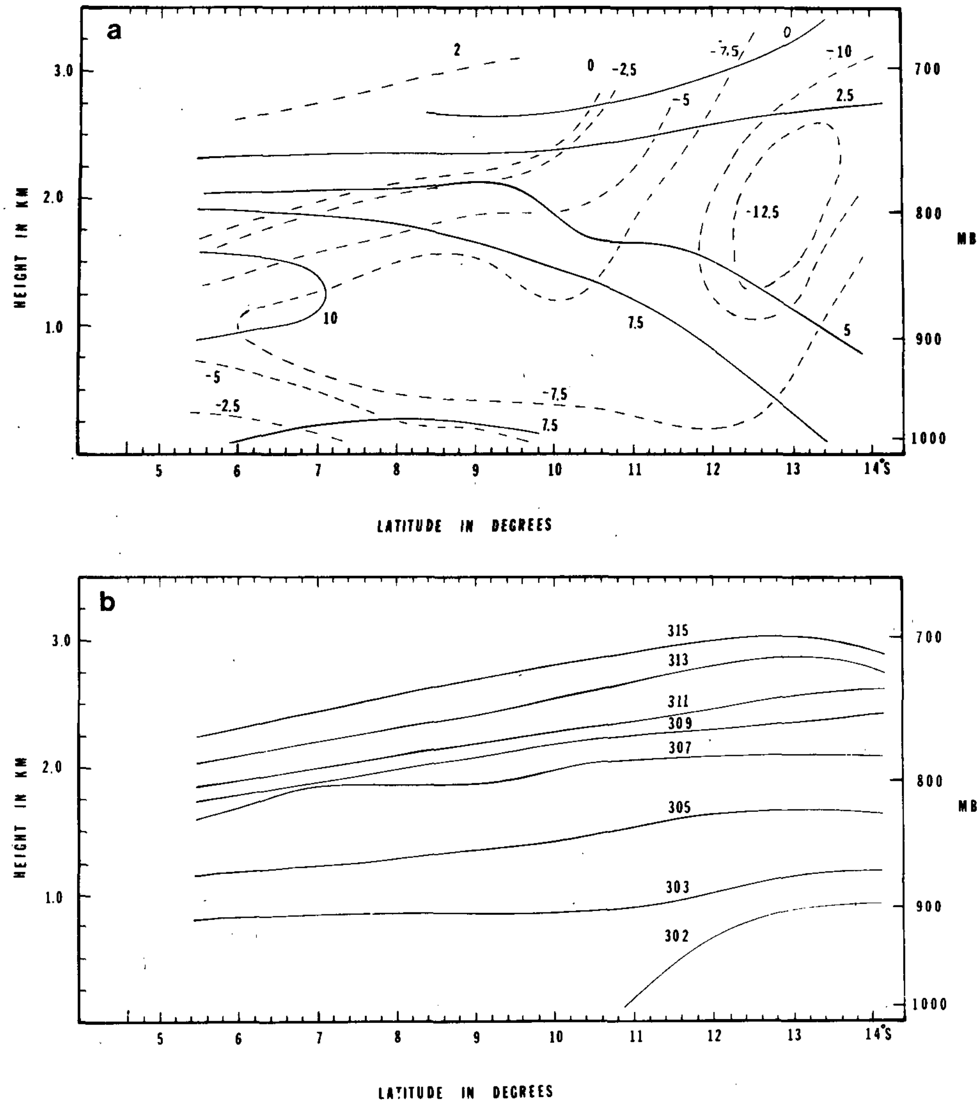


FIG. 4. Data from "inflow region", Flight 7, along track D of Fig. 1. (a) The meridional (southerly) component (solid contours) and the zonal (westerly) component (dashed contours) of the wind (m s^{-1}); (b) the potential temperature field (K).

wind component u, potential temperature θ and specific humidity q for the eastbound leg of the flight. As this flight began at dawn, there was little convective activity over land and the jet flow was relatively laminar except for the region just above the ground (altitudes < 200 m) and for some weakly turbulent regions of relatively high vertical shear above the core of the jet (at 2.5–3.0 km).

Fig. 3a shows a well-defined jet core near its normal inland position. One can see rather strong lateral shear to the left of the single jet core, with less pronounced shear on the oceanic side. The vertical structure contains extremely high shear in a shallow layer just above the ground and moderately high shear above the jet in a region of slightly enhanced vertical stability (see Fig. 3c). The Richardson number

$$\mathrm{Ri} = \frac{g\partial \ln\theta/\partial z}{|\partial \mathbf{v}/\partial z|^2}$$

in this upper region was slightly less than 1 and some weak "cobblestone" turbulence was encountered. Level runs in such regions were made during several flights to estimate the turbulent fluxes and the integral scale for the turbulence. Throughout most of the jet, there were quite high velocities associated with very smooth laminar flow. The transverse (zonal) wind component showed easterly flow (onshore) within and below the jet core, with westerly (offshore) flow above. Fig. 3c shows that the air was almost linearly stratified with slight increases in stability above and below the jet core at 1.8 km. A stable layer above the jet was found in most flights. There is a slight tendency for the isentropes to tilt upward from east to west. Baroclinicity is not marked for this near-equatorial location. Fig. 3d indicates the expected fact that the air in the jet, especially in the lower levels over the ocean, is quite moist. There is a general decrease of humidity with height, and there is a conspicuous core of dry air aloft over the coast.

The virtual potential temperature distribution implied by Figs. 3c and 3d together would also show isopleths sloping upward toward the west below the jet core. From the hydrostatic law this implies that the zonal component of the pressure gradient force would become directed opposite to the direction of the zonal wind, suggesting an indirect transverse circulation; in fact, the $u(x,z)$ distribution in Fig. 3b is consistent with cool, dry air rising upslope between 38 and 39°E, and subsidence of relatively warm, moist air west of 41°E at altitudes just above the ground.

Another implication of the virtual potential temperature distribution would hold further to the south: the thermal wind would be such that the southerly flow decreased with height. Thus, it seems plausible that the speed decrease above the jet core is partly influenced by upwind thermal wind structures advected toward the equator.

In summary, the early morning jet of 4 July 1977, at about 0500 GMT, contained a single core at 40°E at 1.8 km. There were strong shears above, below and to the west of the core, with weaker lateral shear on the oceanic side. A weak wind maximum is found at low levels (900 m) over the ocean away from the core, and appears to be a common characteristic of the broad cross-equatorial flow. There was a convectively disturbed region near the coast, accompanied by a local wind minimum, and cores of moist and dry air at low and high levels, respectively. Although there was usually little deep convective activity over the ocean, and none well inland, the coastal area was often a region of disturbed weather conditions.

c. The oceanic upstream region

There were three flights [on tracks C and D, (Fig. 1)] in the upstream region well east of the highlands. Because of synoptic fluctuations, these do not yield enough data to construct a composite picture, but do give some insight into the flow regime out over the ocean well upwind from the coast. Fig. 4 shows wind and potential temperature sections along track D. This track was the farthest east and probably gave the most representative sample of the oceanic inflow region. Most notable is the presence of a sloping inversion at about 2 km which caps a layer of air flowing from a southeasterly or easterly direction. The baroclinicity is stronger here, as expected for a region removed from the equator. There was fairly strong southerly flow near Seychelles possibly associated with some weather in this area. The speed maximum was relatively low (1 km), as was typical over the ocean away from the mountains. As the aircraft proceeded to the south, stronger easterly flow was encountered, with a weak core centered at about 12.5°S. This latitudinal change in wind direction and the existence of a modest oceanic speed maximum are broadly similar to the climatological analyses given by Findlater (1971). The decrease of zonal flow above the maximum (Fig. 4a) is consistent with the thermal wind distribution derived from Fig. 4b. Unfortunately, it was only possible to make one flight in this area during our experiment although considerable low-level turbulence and radiation data were obtained. We cannot say how representative this cross section is of the June–July regime, but the data do agree with the climatological mean core of 12.5 m s^{-1}, 110° for this area.

Fig. 5 shows a section made from the west of Madagascar to Seychelles [track C, (Fig. 1)]. Of great interest was the extremely high lateral shear near 11°S. This seemed to be a result of the blocking of the southeasterly flow by the mountains of Madagascar, which causes a shadow zone about 200 km downstream from the tip of the island. As this shear line was crossed, all scientists were impressed by the sudden change in the sea state from dead calm to very active whitecaps. Surface winds were about 17 m s^{-1}. The atmosphere was again uniformly stratified although the distinct and continuous low-level inversion found near 2 km on flight 7 was absent. One other section of this type was made in the same area four days later. This was flight 8, on which very light winds ($|\mathbf{v}| < 8$ m s^{-1} all along the section) were encountered. The situation was quite anomalous, with very high static stability and strong directional backing of the wind vectors. Clearly, synoptic day-to-day fluctuations are important in this area of the southwest monsoon and indicate that further study over a more extended time is necessary. As the program concentrated on the cross-equatorial flow, only a limited study was possible in this important region.

d. Synoptic variability in the cross-equatorial flow

From the previous subsections we have shown how the upstream flow is modified as it passes Madagascar and flows northward along the east slope of the East African highlands. In numerous flights along track A (and along B as well) two types of variability were discovered: synoptic day-to-day variations in the structure of the jet as measured at the same local time, and diurnal variations. The former are thought to be associated with regional synoptic fluctuations, especially the pro-

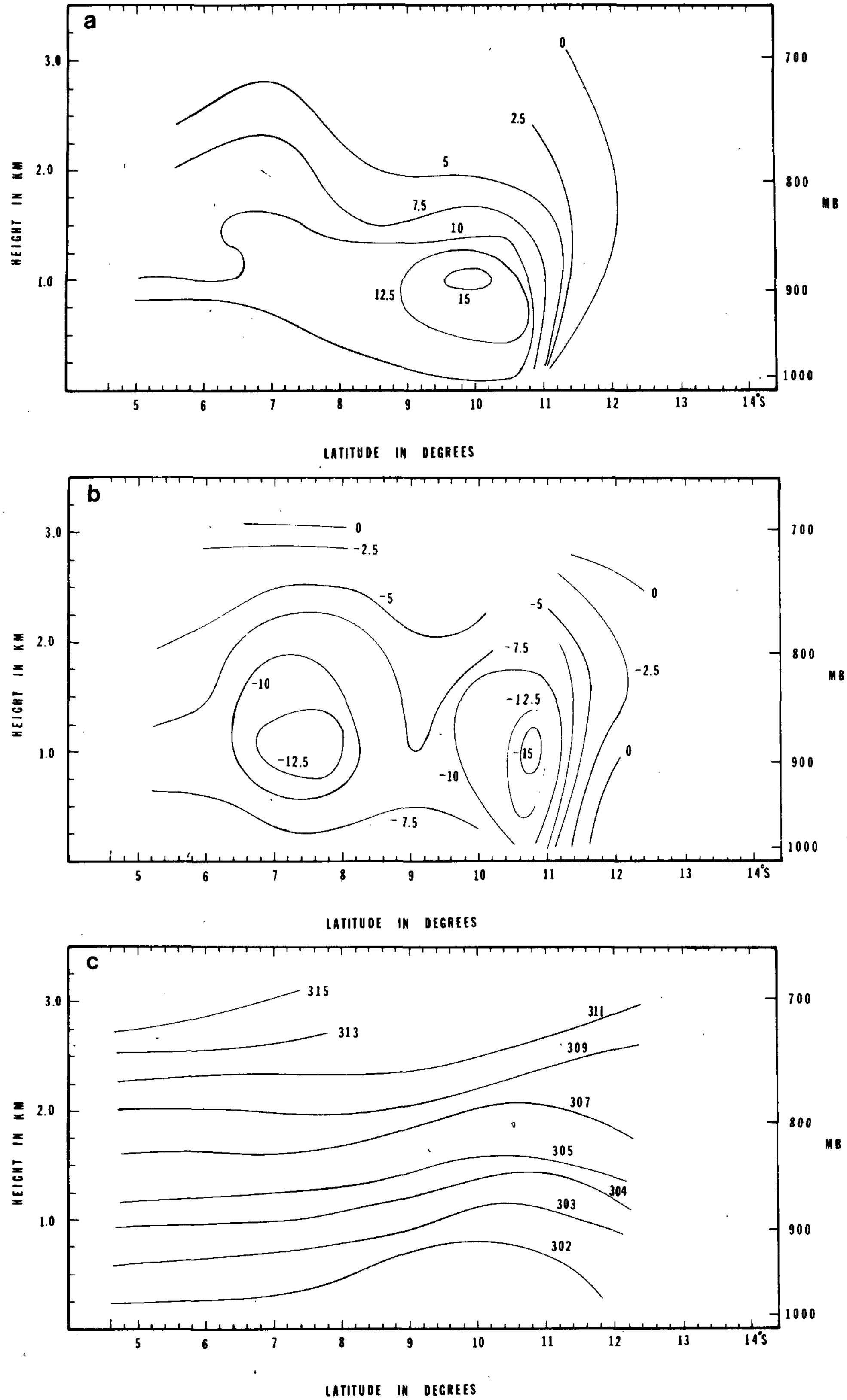


FIG. 5. Sections from Flight 6, track C, from west Madagascar to Seychelles. (a) The meridional wind ($m\ s^{-1}$), (b) the zonal wind ($m\ s^{-1}$), (c) the potential temperature (K).

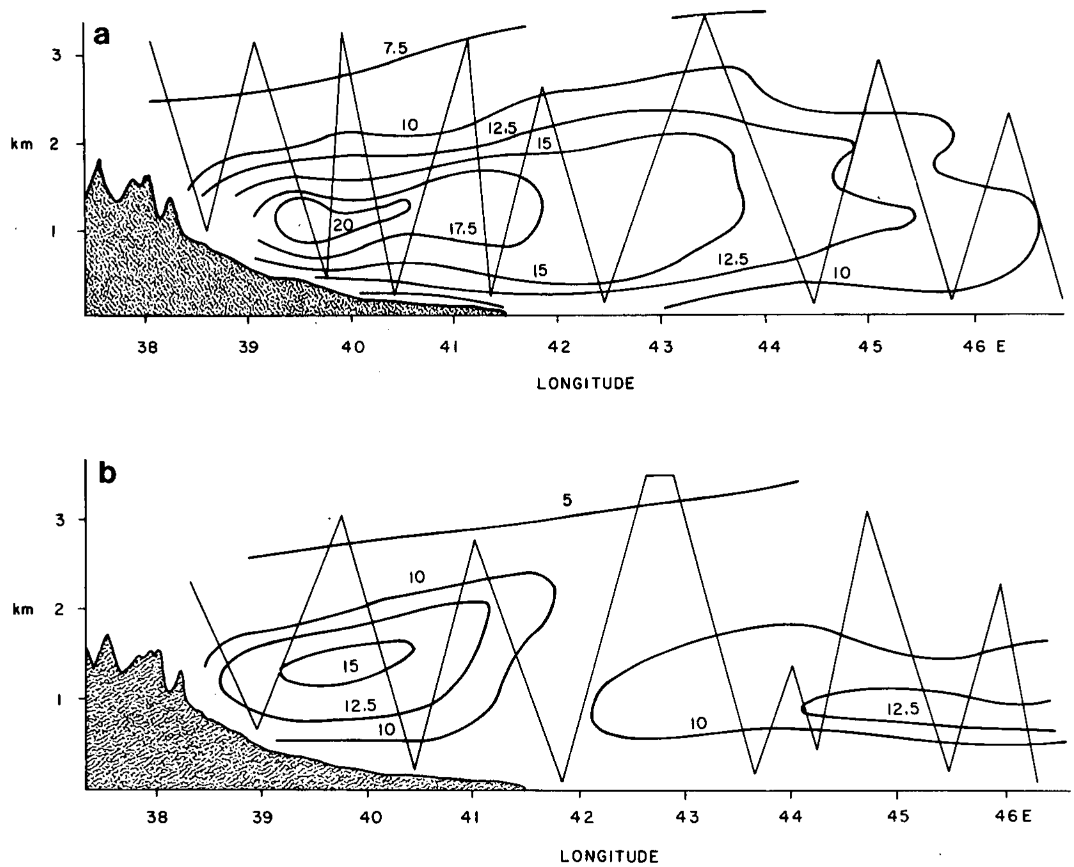


FIG. 6. Cross sections of wind speed (m s^{-1}) for additional flights across the jet at 2°S (track A). Both are eastbound runs and traverse the jet in early morning (typically beginning 0400 GMT, 0700 local Nairobi time). (a) 15 June 1977, (b) 11 June 1977.

gression of high- or low-pressure cells across the head of the Mozambique Channel that lead to surges up the channel (see Fig. 2). The latter are related primarily to strong convective mixing during the late morning and nocturnal radiative stabilization in the evening.

Fig. 6 shows the wind speed (dominated by the southerly component) along track A for two additional days (see also Fig. 3). These data were obtained on early morning eastbound runs between 0400 and 0600 GMT. The main jet core, although typically centered over about 40°E, can be found either to the east or west of this location on individual days. On some days (Fig. 6b) the overland portion of the cross-equatorial flow was separated from a secondary oceanic lower level wind maximum by a disturbed coastal region with a relative wind minimum. This phenomenon was not as pronounced on days in which the overland portion of the jet was extremely strong. On several days the low-level oceanic maximum was observed to be at the level of the tops of small cumulus clouds, and on one day when the convection was deep the oceanic low-level wind maximum was absent.

e. Diurnal fluctuations

Fig. 7 demonstrates the strength of the diurnal variations within the jet. It is seen that the convective mixed layer over land penetrates through the entire depth of the jet core. This is primarily an overland phenomenon associated with the strong thermal convection overland. Radiative surface temperatures typically increased from 22 to about 40°C between 0600 and 1100 LT. There is also downwind evolution of this mixed layer following the jet core as the air crosses the coast and flows northward over the strongly heated, dry sandy soil. This will be the main subject of a future paper.

4. Conclusions

From all flights along track A we have constructed a composite picture of the jet at 2°S. This was obtained by vector averaging wind data over boxes 50 mb deep and 1° longitude in width. Fig. 8 shows both components of the horizontal wind for eight early morning flights (plus one night flight). The structure is similar to that shown in Fig. 3 for 4 July, displaying the high lateral shear on the

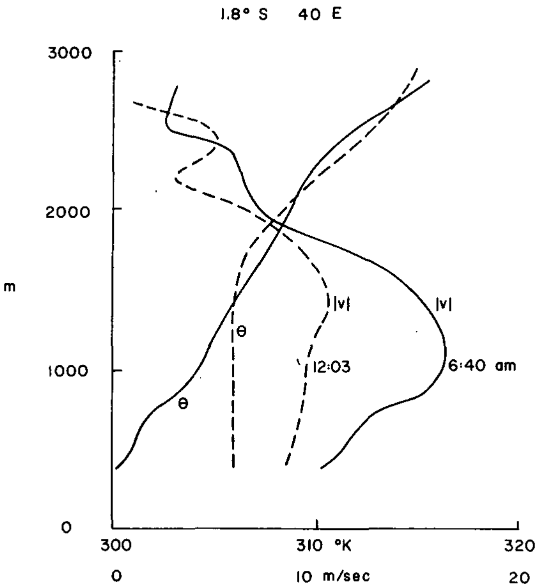


FIG. 7. Vertical soundings of potential temperature θ and wind speed $|v|$ over northeast Kenya. Solid lines represent data from an aircraft sounding at 0640, the dashed lines for 1203, both local Nairobi time.

western edge and a tendency for the level of maximum wind to slope downward from west to east in many cases. The highest speeds are found over land, where weak upslope flow is also observed. This composite jet is generally confined to heights less than 3 km. The structure is shallower and horizontally broader than Findlater's (1971) analyses for previous years. Fig. 9 shows the composite v component for six late morning (plus one late afternoon) flights. The strong winds over the ocean between 43 and 46°E are due to a bias toward one particular case of strong winds in the relatively few flights which extended further east than 43°E. Considerable mixing has nonetheless occurred over land; the jet core is higher and weaker and the vertical shear beneath is weaker. Analysis of the u velocity distribution for these data (not shown) yields a pattern similar to that in Fig. 8b, but with enhanced upslope component, of magnitude ~ 3.5 m s^{-1} in the region between 38 and 40°E, at 1 km.

The wind structures found in this work have important implications for the cross-equatorial water vapor flux. Pisharoty (1955) computed the northward flux of water vapor across an equatorial cross section covering from 42 to 75°E and from the sea surface to 450 mb. He compared that flux with the corresponding flux across a meridional cross section approximately along 75°E and stretching from the equator to 26°N. He found that the latter flux exceeded the former by a factor of 2–3. This finding

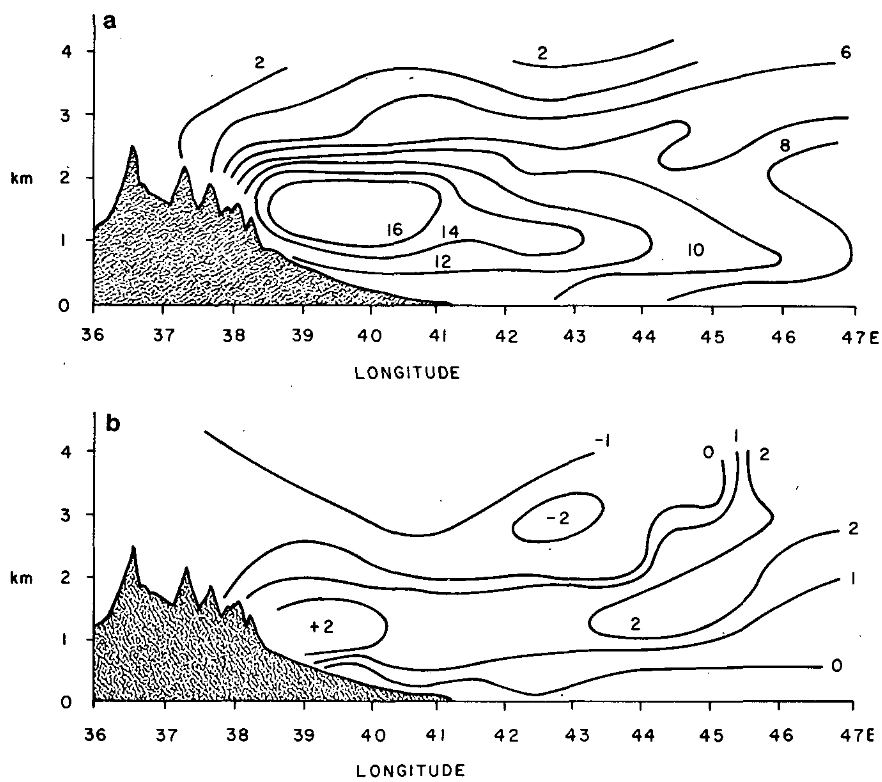


FIG. 8. Mean wind components (m s^{-1}) at 2°S obtained by compositing data from eight flights on track A at "night" (1900–0700 GMT): (a) southerly component, (b) easterly component.

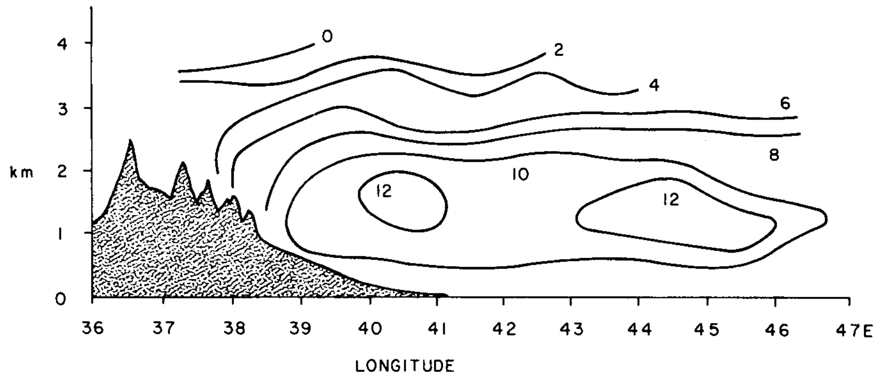


FIG. 9. Mean southerly wind component for six flights on track A during 0700–1900 GMT.

led to the conclusion that the bulk of the water vapor condensed over peninsular India came through evaporation over the Arabian Sea. Saha (1970) and later Saha and Bavadekar (1973) reexamined the calculation and used the Seychelles 1964 data (which apparently were unavailable to Pisharoty) and computed the quantity

$$F = g^{-1} \int_0^L \int_{450\ \mathrm{mb}}^{1000\ \mathrm{mb}} vq\, dldp,$$

where L covers the distance between 42 and 75°E. The quantity F was estimated to be 3.4×10^{10} tons day^{-1} for June 1974.

Fig. 10 shows the cross-sectional distribution of the quantity vqg^{-1} in units of 10^{-3} ton m^{-1} s^{-1} cb^{-1}. The maximum transport occurs in a low-level slab of air between 38 and 45°E. Pronounced values (>7.5) are confined to below 750 mb, decreasing above. This fact simply means that an accurate water vapor flux computation needs a good set of low-altitude wind and humidity observations. The previous investigations, including those of Saha and Bavadekar (1973), leaned heavily on the Seychelles data to compute this quantity. Present indications are that the estimates of vq based on Seychelles data for early June 1977 from the surface to 800 mb are about a third of those estimated from 43.5°E data shown in Fig. 10. A more comprehensive water vapor flux calculation will be presented in a future paper, after the final computer processed data become available.

The longitudinal profiles of water vapor and mass flux are intimately linked to the special dynamics of the cross-equatorial system. One-layer dynamical models (Hart, 1977) of the cross-equatorial flow predict $\bar{v}(x)$, the depth-averaged southerly wind as a function of longitude at 2°S, say. The physics of such models can include lateral friction, planetary and relative vorticity advection, and/or bottom friction. Fig. 11 shows $\bar{v}(x)$ as determined by composit-

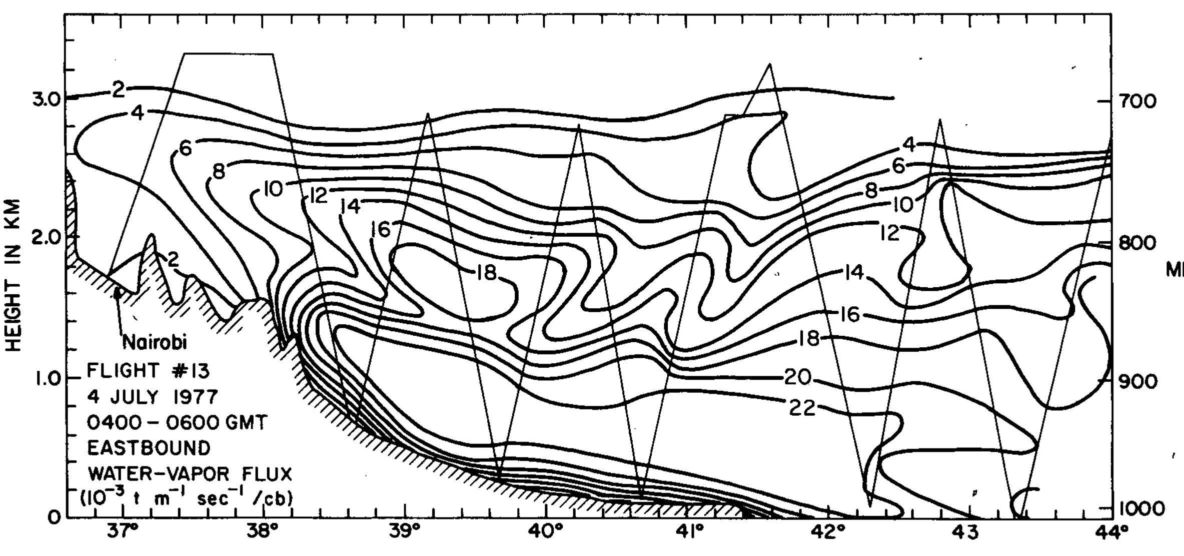


FIG. 10. Northward water vapor flux for flight 13 along track A.

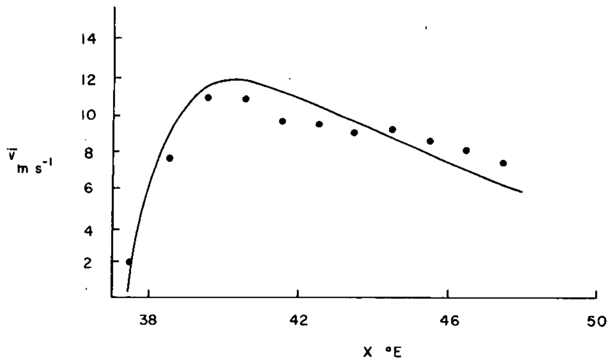


FIG. 11. Vertically averaged mean southerly wind component along track A for all flights (dots). The solid line is from a theoretical computation (see text).

ing all the cross-sectional data, and depth-averaging between the surface and 3.5 km. The solid line represents a prediction computed using a model which includes a rigid (free-slip) lid at 3 km, idealized meridionally invariant topography which rises from zero elevation at 41°E to 3 km at 37°E, linear bottom friction, and total absolute vorticity advection. Details of the model are given in Hart (1977, Section 3c). The favorable agreement suggests that the mean jet structure can be interpreted as having an inertial eastern shear layer [with scale $(-u_0/\beta)^{1/2}$ = 650 km for upstream inflow $u_0 = -10$ m s^{-1}] and a sharp frictional western shear layer near the highlands.

Although this simple model provides a framework for interpreting the mean jet, it doesn't address the interesting and very important fluctuations described in this paper. There are now sufficient data to study and construct parameterized models of the diurnal variations. The synoptic-scale fluctuations will require further study but are important for reasons mentioned in the Introduction. The low-level jet over Kenya can be fed either by the usual southeasterlies north of Madagascar or by occasional incursions of cold air moving up the Mozambique Channel from the south, and convecting vigorously over the warm sea. Flight 12 to the south along track E intercepted such a cold incursion which was associated with a strong jet over Kenya. Usually, however, the roots of the flow lie east of Madagascar.

Acknowledgments. We would especially like to thank all the members of the East African Meteorological Department, Nairobi, Kenya, for their open hospitality and enthusiastic assistance during this project. The flight and technical crew of the NCAR Electra deserves our greatest appreciation for their dedication and endless efforts toward successful and trouble-free operations during the experiment.

The participation of U.S. scientists in the field experiment was sponsored by the National Science Foundation, under Grant ATM 76-81097. During the preparation of this paper J.E.H. received support from NSF Grant ATM 76-17028, J.A.Y. from NSF Grant ATM 73-06635, and G.V.R. from NSF grant ATM-7720631. We also thank William Bolhofer for preparing Fig. 2 from data supplied by the East African Meteorological Department.

REFERENCES

Findlater, J., 1969a: A major low-level air current near the Indian Ocean during the northern summer. *Quart. J. Roy. Meteor. Soc.*, **95**, 362–380.

——, 1969b: Interhemispheric transport of air in the lower troposphere over the Western Indian Ocean. *Quart. J. Roy. Meteor. Soc.*, **95**, 400–403.

——, 1971: Mean monthly airflow at low levels over the western Indian Ocean. *Geophys. Mem.*, **16**, No. 115, 53 pp.

——, 1972: Aerial explorations at the low-level cross-equatorial current over Eastern Africa. *Quart. J. Roy. Meteor. Soc.*, **98**, 274–289.

GARP Special Report No. 21, 1976: Report of the planning for the Monsoon-77 experiment, Colombo, Sri Lanka, May 1976. World Meteorological Organization, 35 pp.

Hart, J. E., 1977: On the theory of the East African low-level jet stream *Pure Appl. Geophys.*, **115**, 1263–1282.

Kelley, N. D., and R. L. Lackman, 1976: Description of standard output data products from NCAR Research Aviation Facility Aircraft. NCAR Research Aviation Facility Bull. No. 9.

Pisharoty, P. R., 1965: Evaporation from the Arabian Sea and the Indian Southwest monsoon. *Proc. Symp. Meteorological Results International Indian Ocean Expedition*, Bombay, pp. 43–54 [Available from Pisharoty, Physical Research Laboratory, Almedabad, India.]

Ramage, C. S., and Raman, C. V. R., 1972: *Meteorological Atlas of the International Indian Ocean Expedition.* U.S. Govt. Printing Office.

Saha, K. R., 1970: Air and water vapor transport across the equator in the Western Indian Ocean during the northern summer. *Tellus*, **22**, 681–687.

——, and Bavadekar, S. N., 1973: Water vapor budget and precipitation over the Arabian Sea during the northern summer. *Quart. J. Roy. Meteor. Soc.*, **99**, 273–278.