On the Observed Diurnal Oscillation of the Somali Jet

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27 April 1979 and 6 August 1979

ABSTRACT

The time mean and diurnal oscillation of the Somali jet are examined, using as a data base a high-resolution time series of pilot balloon soundings for two sites in northeast Africa. The diurnal mode is found to contain a significant amount of the total amplitude of the jet. In association with this oscillation, the level of maximum wind varies considerably during the course of a day. A multi-cored jet structure is observed during the afternoon. Other interesting structural variations of the jet are discussed. Hypotheses are ventured to provide explanations for the observed behavior of this low-level jet.

1. Introduction

In the recent decade, a number of studies have shed light on the understanding of a major component of the Asian summer monsoon: the East African, or Somali, low-level jet (Findlater, 1969, 1971; Hart *et al.*, 1978). This jet forms on the western boundary of a broad cross-equatorial current of moisture-laden air which feeds directly over the Indian peninsula during the southwest monsoon.

This low-level jet has been found to exhibit variability over a broad range of time scales. Annually, the jet undergoes a complete life cycle as the Asian monsoon circulation, in which it is imbedded, evolves. After retreating into the southern Indian Ocean during the winter monsoon, the jet axis progresses steadily to the northwest as the summer monsoon circulation develops. By June the low-level jet axis is located directly over the horn of northeast Africa (Fig. 1). Pronounced variations in the behavior of the jet are also present on time scales related to synoptic disturbances in the Southern Hemisphere (Findlater, 1977). The Somali

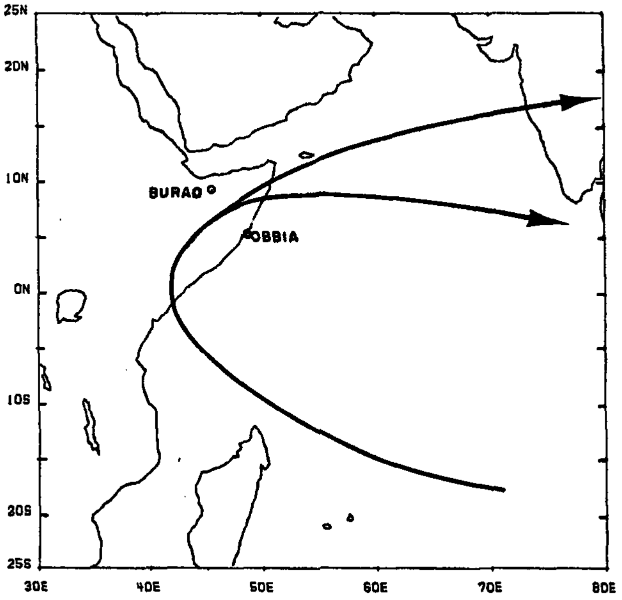

FIG. 1. The position of the axis of the low-level Somali jet at the 1 km level, for June, following Findlater (1971).

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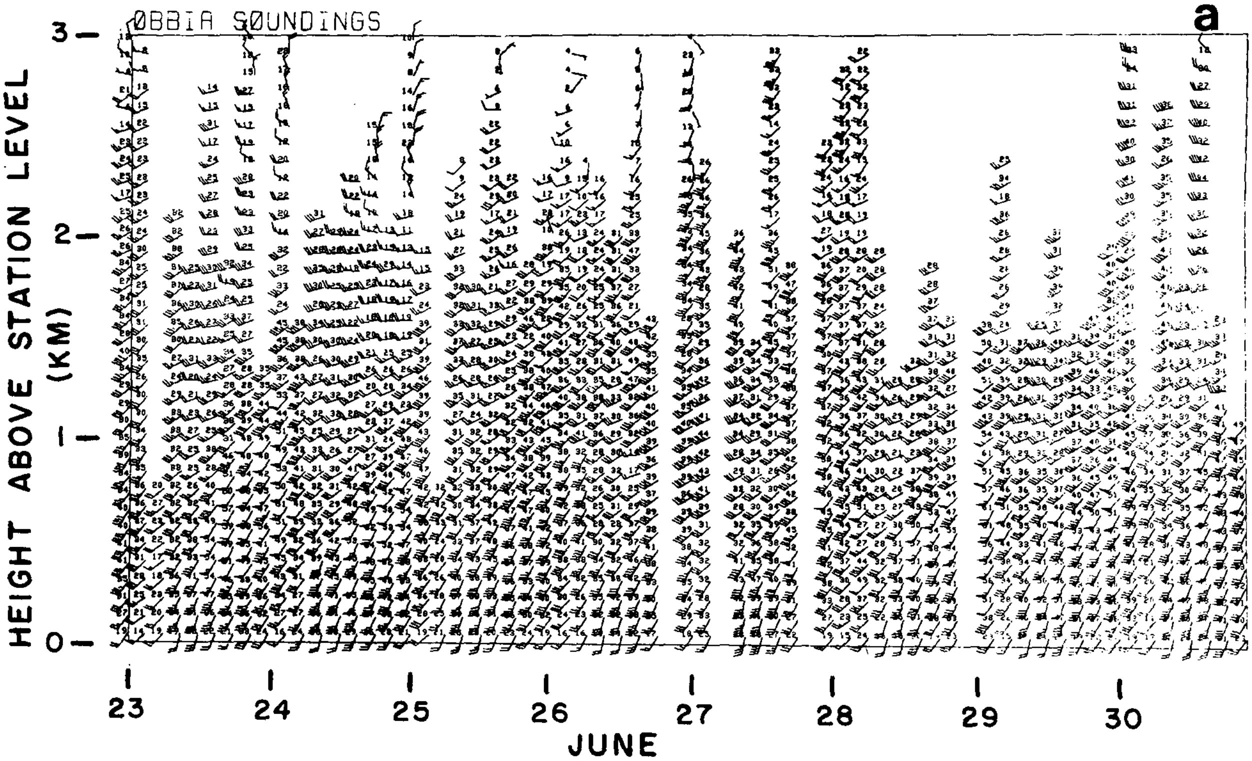


FIG. 2a. Time section of pilot balloon soundings taken at Obbia from 0000 GMT on 23 June–2100 GMT on 30 June 1977. The interval between successive observations is 3 h. One full barb represents 5 m s^{-1}, a half barb 2.5 m s^{-1}. Triangles represent a wind speed of 25 m s^{-1}. Local time precedes Greenwich time by 3 h.

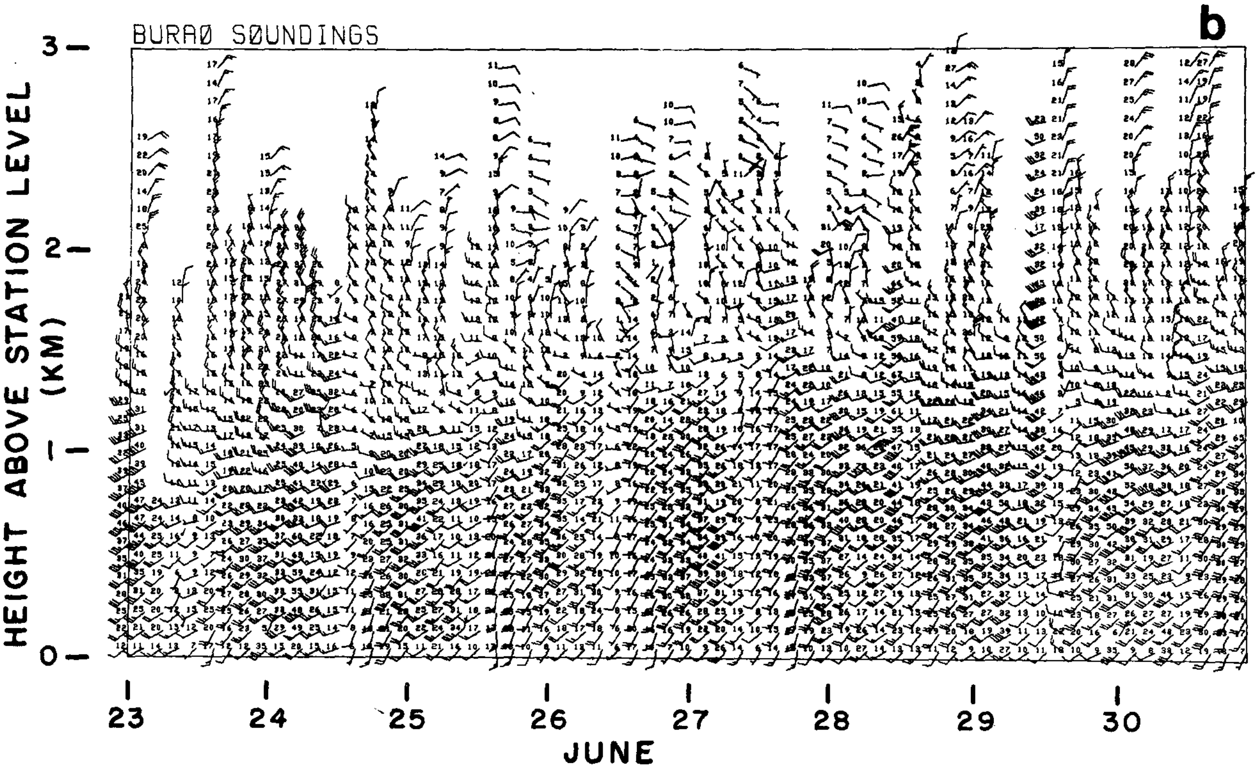


FIG. 2b. As in Fig. 2a except for Burao.

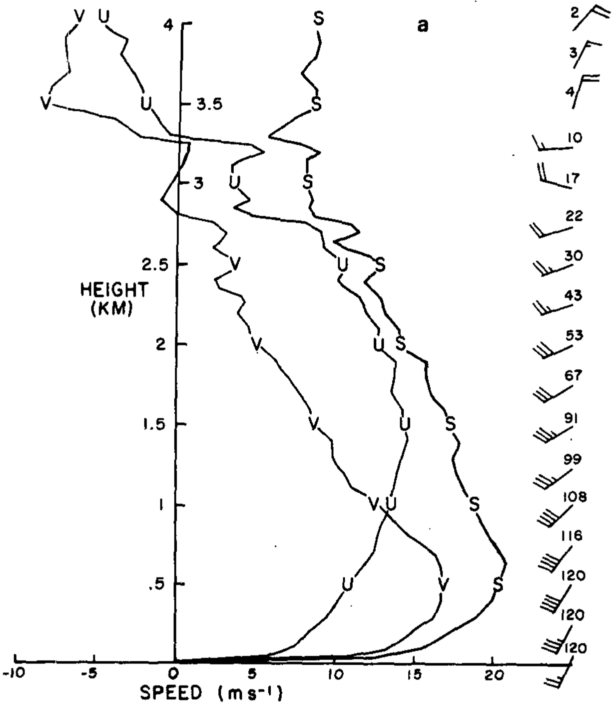


FIG. 3a. Vertical profiles of the zonal (u) component, the meridional (v) component, and the total wind speed (s) at Obbia. Wind vectors indicate wind speed and direction at 250 m intervals, commencing at 250 m. The lowest vector is at a height of 50 m. The number plotted above each vector is the total number of observations available at that level.

jet also exhibits interesting diurnal fluctuations of both wind speed and direction. This diurnal oscillation is also evident in the height of the jet core, which will be shown to vary from over 1 km to as little as 250 m above the earth's surface in 3 h.

2. Description of the data

A large problem in the description of this jet and its variability has been the lack of a reliable observational network. Observations are not only sparsely distributed in space, but also infrequently taken in time. However, a data set of unprecedented accuracy and observational density for the region became available during the Monsoon 77 experiment. Part of the U.S. contribution was the operation of a set of upper air stations by a team of observers from Florida State University, with the cooperation of the Meteorological Service of Somalia (Krishnamurti *et al.*, 1977). Recorder pilot balloon soundings, with a time spacing of 30 s, were taken twice daily during a 28-day period commencing 6 June. During an intensive observation period between 23 June and 3 July soundings were taken at each station at 3 h intervals.

This study will examine the time mean, as well as the diurnal oscillation, contained within the time series of pilot balloon soundings for the sites Obbia (5.24°N, 48.28°E, 12 m) and Burao (9.20°N, 45.25°E, 1043 m). Obbia is situated on a flat coastal plain, which rises only 12 m in 1 km, while Burao is located inland and to the north at an elevation of over 1 km, in steeper terrain. Fig. 2 illustrates sample time sections of soundings for each of these two stations during the intensive observation period. Variations of the wind speed on a time scale of longer than one day are noticeable at Obbia (Fig. 2a) in the wind maxima of 23–24 and 29–30 June. At Burao (Fig. 2b), the diurnal oscillation is clearly visible in both the wind speed and direction.

For each pilot balloon ascent, the values of the zonal (u) and meridional (v) wind components, as well as the total wind speed (s), are computed at 50 m intervals in the vertical by fitting a cubic spline to the data. This spline is the unique function which interpolates the data while minimizing the integral of the square of the curvature along the fitted curve (Forsythe *et al.*, 1977). This allows the time mean and the diurnal oscillation of the jet to be extracted at each level.

3. The time mean jet

The time mean vertical profiles of the u and v components of the wind and the wind speed at each observation site are shown in Fig. 3. Immediately evident in each is the pronounced low-level wind maximum occurring ~600 m above the surface. A striking feature associated with this maximum is the strong vertical wind shear in the lowest 100 m. The

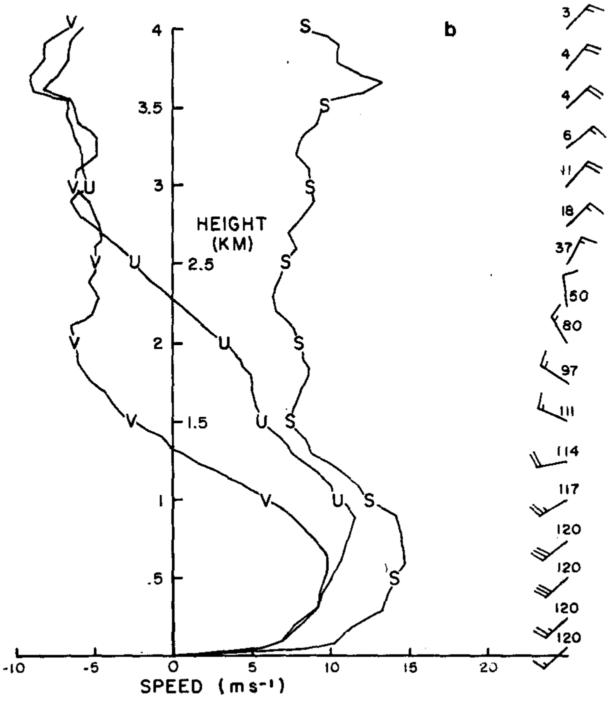


FIG. 3b. As in Fig. 3a except for Burao.

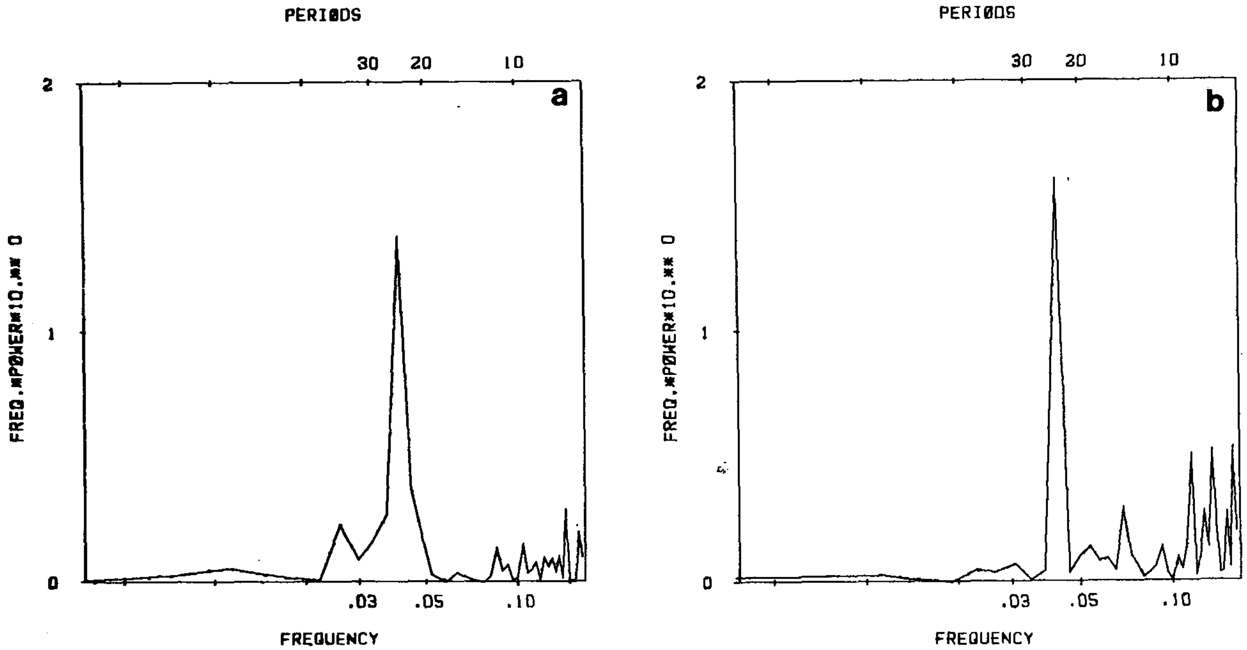


FIG. 4. Power spectra of the total wind speed at the level of maximum mean wind for Obbia (a) and Burao (b). The abscissa is log frequency, and the ordinate is frequency times power. Periods are given in hours.

wind direction veers with height at both locations, with the southwest wind turning most rapidly to northeast at ~3 km MSL in either case. At heights >3 km MSL the soundings are quite similar; however, below this level some differences appear. Most noticeable is the stronger time mean maximum wind at Obbia, which is ~21 m s^{-1} during the observation period.

4. The diurnal oscillation

The power spectra of the total wind speed, at the level of mean maximum wind, are illustrated in Fig. 4 for each location. The strong peak corresponding to the diurnal mode is apparent in both cases. There appears to be little evidence for a strong semidiurnal mode at this level for either location.

The diurnal evolution of the wind speed profiles for the lowest 2 km is illustrated in Fig. 5. As Burao (Fig. 5b) strong composite wind speeds are found during the night, gradually increasing to over 20 m s^{-1} at 750 m by dawn. Immediately after sunrise, wind speeds increase rapidly near the ground, while decreasing in strength aloft. This adjustment reaches an extreme by late afternoon, when the wind speed is essentially constant with height above a shallow surface shear layer. The shallow maxima and minima seen in the profiles between 0600 and 1200 GMT may be related to individual features of the separate soundings (see Fig. 2b). After sunset, the wind speed decreases at the surface as the nocturnal jet maximum begins to reform aloft. At Obbia (Fig. 5a) the jet attains its greatest speeds at night as well, although the highest wind speed (25 m s^{-1} at 750 m) is observed at midnight. Immediately after sunrise, wind speeds decrease rapidly at 500 m, while the wind speed at 250 m undergoes a corresponding increase. This produces a wind speed maximum-minimum pair which increases in amplitude and propagates upward throughout the day. The maximum then strengthens during the evening and night to form the 750 m nocturnal wind maximum. A secondary wind maximum is evident at 1.5 km during the afternoon, giving the jet a multicored structure.

Anomaly charts for the entire period (Fig. 6) are obtained by subtracting the time mean profiles of the *u* and *v* wind components and the total wind speed (as shown in Fig. 3) from the corresponding 3 h composite profiles (as shown in Fig. 5). In each of the stations, the maximum amplitude of the wind speed anomaly is in excess of 10 m s^{-1}. This amplitude is especially noticeable at Burao, where the mean wind speed does not exceed 15 m s^{-1} at any level. At dawn, a 1 km speed maximum is present in the anomaly fields for each site. The wind speed anomaly decreases sharply with time immediately afterward, with the strongest negative anomalies occurring at the level of mean maximum wind speed. This large negative anomaly occurs at Obbia in the early afternoon, and at Burao in the late afternoon and early evening. Both stations show a positive maximum anomaly at the surface at

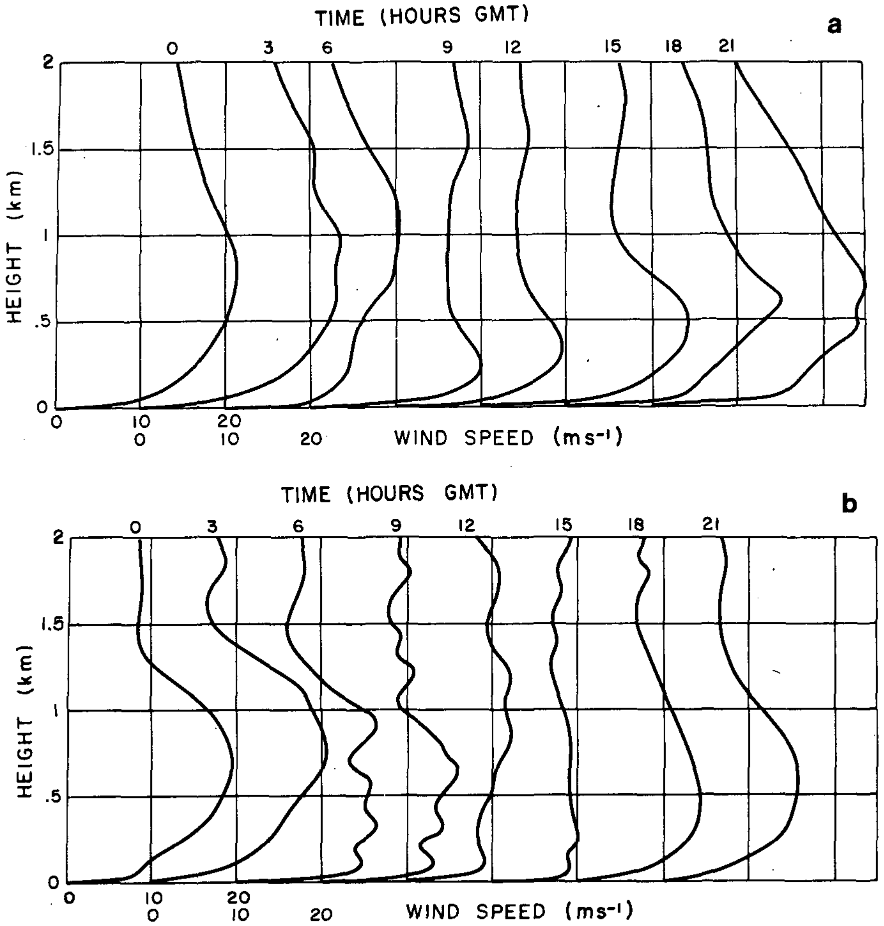


FIG. 5. Composite 3 h profiles of the wind speed at Obbia (a) and Burao (b). The abscissa is a staggered scale of wind speed, beginning at zero for each profile. The ordinate is height above the ground in kilometers.

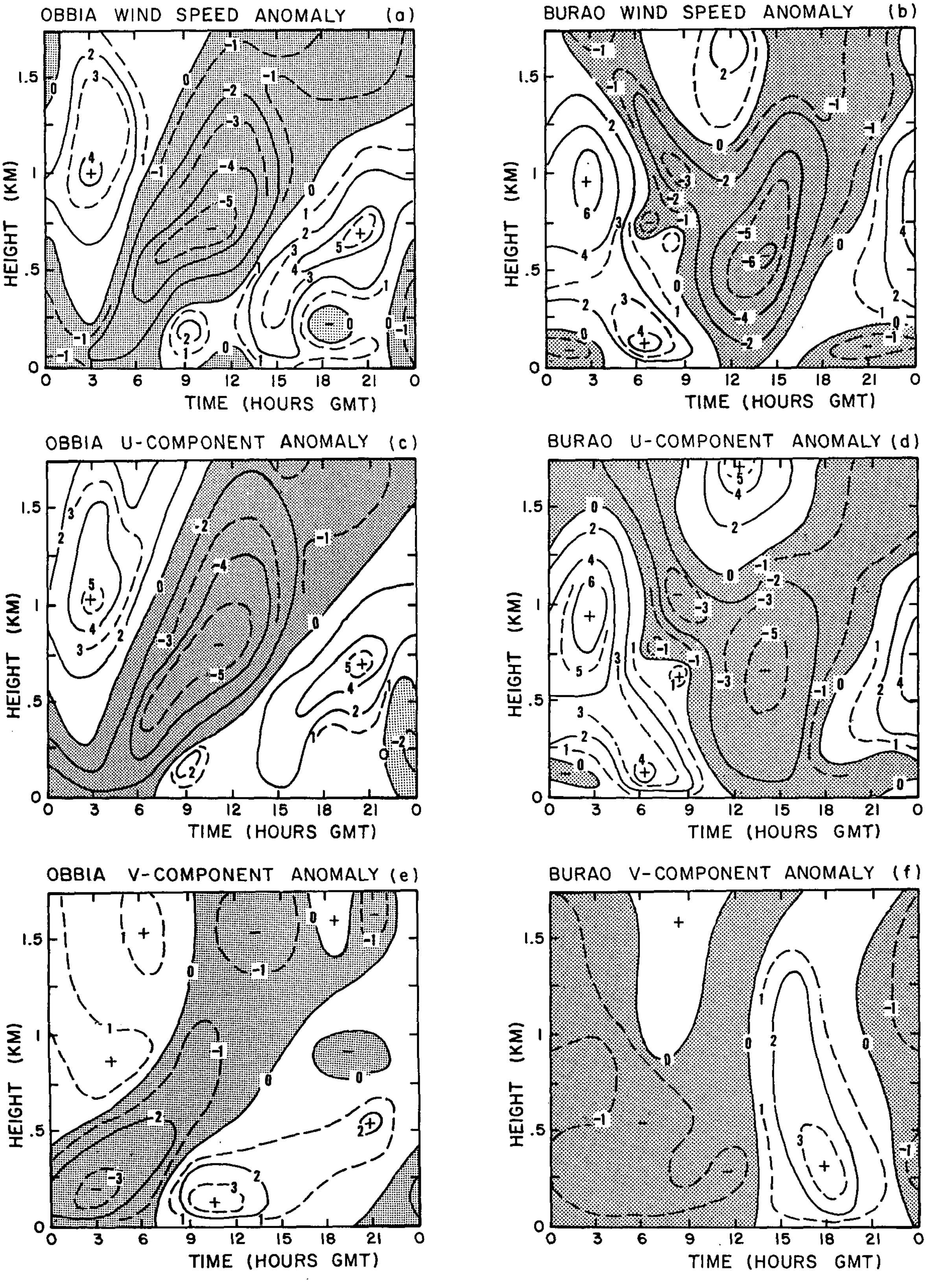
midday, with a secondary maximum in the evening. This agrees quite well with observations taken upstream at Garissa, Kenya (0.48°S, 39.63°E, 128 m), where similar behavior of the surface winds was noted (Findlater, 1977). Although similarities in the amplitude and phase of the diurnal cycles at each location are evident, significant differences are also present. This is especially true of the vertical propagation of the maximum-minimum pair at Obbia (Figs. 6a, 6c and 6e), which is absent at Burao. It is interesting to note that the maximum amplitude of the diurnal oscillation of the meridional wind component is realized within the lowest 500 m, unlike the zonal component which has its maximum amplitude well above this level.

5. Interpretation and conclusions

An understanding of the dynamics behind the diurnal change of the Somali jet is complicated because of the many scales of motion that combine in the region. Krishnamurti *et al.* (1976) showed that the broad-scale monsoon forcing, arising from differential land-ocean heating, is essential to the formation of this cross-equatorial jet. They further showed that the removal of the beta effect drastically altered the wind field of the region. Local topography was similarly shown to be important through the removal of the East African and Madagascar mountain ranges.

Transients in the strong Southern Hemisphere winter westerlies also affect the wind and pressure fields for the region. This generally occurs on a time scale somewhat greater than 24 h (Rao *et al.*, 1978; Hart *et al.*, 1978).

Coupled with these are such local effects as mountain slope winds, sea breeze circulations and the diurnal variation of convective stability. A separate discussion on the individual contributions to the diurnal oscillation by each of these phenomena is, at best, difficult with only two observation sites available. There is, however, no evidence of the passage of a sea breeze front at the coastal station Obbia. It has been found observationally that the



OBBIA WIND SPEED ANOMALY (a)

BURAO WIND SPEED ANOMALY (b)

OBBIA U-COMPONENT ANOMALY (c)

BURAO U-COMPONENT ANOMALY (d)

OBBIA V-COMPONENT ANOMALY (e)

BURAO V-COMPONENT ANOMALY (f)

FIG. 6. Wind anomalies as a function of time at Obbia and Burao. The abscissa for each map is time in hours, and the ordinate is height (km). The contour interval is 2 m s^{-1}. Shaded regions indicate negative anomalies. Small-scale variations with an amplitude <1 m s^{-1} were not considered significant and were omitted from these analyses: (a) wind speed anomaly at Obbia; (b) wind speed anomaly at Burao; (c) u-component anomaly at Obbia; (d) u-component anomaly at Burao; (e) v-component anomaly at Obbia; (f) v-component anomaly at Burao.

surface temperatures over land for the region increase 18°C during the morning (Hart *et al.*, 1978). Thus, the effect of the localized land-ocean heating contrast should be present in the pressure field and, consequently, the wind field. This is supported by the direction change of the low-level wind at Obbia, which backs to a slightly inland component during the morning and early afternoon, and then veers slightly offshore during the evening and night. Upstream from this region in coastal Kenya, Findlater (1972) observed a pronounced seabreeze front. It is also in this region that the axis of the low-level jet is observed to cross the coast (Findlater, 1971). Thus, some interaction between the jet and a sea breeze circulation normal to the jet axis should be expected.

Probably the most important contribution to the diurnal change of the Somali jet is eddy transport of momentum out of the jet core by dry convection and turbulence. The lower atmosphere would tend to become destabilized during the day by strong shortwave radiational warming of the ground, and stabilized at night due to longwave cooling of the ground. From aerial flights through the jet, Hart *et al.* (1978) found a dry adiabatic lapse rate at midday through the diffuse jet up to an altitude of nearly 2 km. This is certainly indicative of strong convective and turbulent mixing, and suggests a corresponding transport of momentum downward below the jet core and upward above the jet core.

This is evident between 0300 and 1500 GMT at Burao (Fig. 5b), where the well-formed nocturnal jet deteriorates to a 2 km deep layer of 8–10 m s^{-1} winds above a shallow surface shear layer. An interesting example of the diurnal oscillation is illustrated at Obbia (Fig. 5a) where, beginning at 0600 GMT, a pair of maxima appear in the jet above and below the 750 m level of the nocturnal wind maximum. By early afternoon, the 750 m winds have decreased in intensity as momentum is transported away from the jet core. The resulting low-level wind maximum, which is only 250 m above the ground at midday, continues to strengthen throughout the day, and propagates vertically upward. This may be attributed partially to restabilization in the lowest surface layers due to radiational cooling in the late afternoon.

Further explanation of the diurnal change of the Somali jet will be the topic of a future paper. This paper will use as a data set the results of an upcoming field experiment in Somalia to be conducted jointly by Florida State University and Louisiana State University.

Acknowledgments. This work is supported by the National Science Foundation under Grant ATM 78-19363. Computations were carried out on Florida State University's Cyber 73 and Cyber 74 computers. The author would also like to thank Dr. T. N. Krishnamurti for his encouragement throughout the preparation of this work.

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