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A kinematic estimate of the large-scale motion fields over West Africa during the special observation period of WAMEX

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ABSTRACT

The kinematic method has been employed in this study to estimate the large-scale fields for horizontal divergence, relative vorticity and vertical motion over West Africa during the Special Observation Period (14 July to 15 August 1979) of WAMEX. The procedure is simply to generate a multiple stations array (with the horizontal length scale $\leqslant 1000$ km) covering the entire area for a least-squares-plane approximation of the windfield. That this technique is practicable has been demonstrated by its being able to reproduce some of the recognized synoptic scale features over the region for the study period.

1. Introduction

It has been shown by Sherman (1952) that both the horizontal divergence and relative vorticity fields are of synoptic importance since the horizontal divergence can be related to the vertical motion (hence convection), while the relative vorticity is connected to the intensity of the disturbances. At present, various methods are in use for computing these quantities, some of which are kinematic, planimetric, adiabatic, vorticity, and numerical (Bellamy, 1949; O'Brien, 1970; Harwood, 1981; Pedder, 1981). The choice of an appropriate technique depends to a large extent on the quality and quantity of the wind data (Smith, 1971; Lateef, 1967).

In this present study, the kinematic method has been used to evaluate the motion fields over continental West Africa, an area bounded by latitudes 4°N and 16°N and longitudes 18°W and 16°E. The use of the kinematic method is important because it is not based on an assumption about the nature of the atmospheric circulation except the hydrostatic relationship (Kung, 1972; 1973). The procedure employed here is a variant of the least-squares-plane method described by Kung (1972) and Pedder (1981). The utility of this scheme is largely based on its simple mathematical formulation and also it is found practicable for the sparse upper air station network existing over the study area. Adoption of this technique is reliable because it incorporates a scheme which removes unrepresentativeness in the wind data field. The bulk of the wind analyzed consisted of the 1200GMT observations from some 14 upper air stations located within the region (see Fig. 1) and collated during the Special Observation Period (14 July to 15 August 1979) of the West African Monsoon Experiment (WAMEX). These data sets have been published earlier by Balogun (1982).

2. Flow of the analysis scheme

In the rectangular coordinate system, the horizontal wind divergence, relative vorticity, and vertical p-velocity are defined as:

$$\nabla_{\mathrm{H}} \cdot V = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} - \left[\left(\frac{\bar{v}}{R} \right) \tan \bar{\phi} \right], \tag{1}$$

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + \left[\left(\frac{\bar{u}}{R} \right) \tan \bar{\phi} \right], \tag{2}$$

$$\omega_{\mathrm{p}} = \omega_0 - \int_{p_0}^{p} (\nabla_{\mathrm{H}} \cdot V) \mathrm{d}p, \qquad p < p_0, \tag{3}$$

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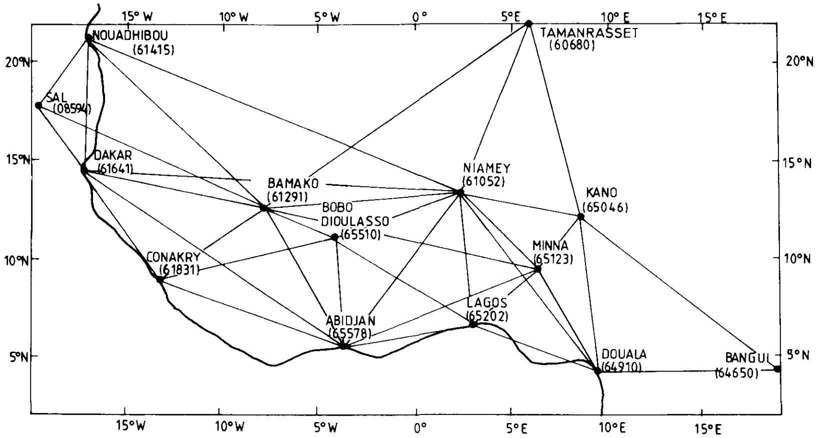

Fig. 1. Area of this study showing the layout of upper air stations for least-squares-plane estimations (the WMO Station Identification Number are indicated in the brackets).

where R and $\bar{\phi}$ represent the earth's mean radius and the mean latitude over the area considered. The horizontal gradients of the windfield contained in eqs. (1) and (2) can be estimated as coefficients (constants) by fitting the wind data (zonal and meridional components) to a plane surface using the least-squares-plane method, i.e.,

$$u(x, y) = u_0 + a_1 x + a_2 y, \tag{4}$$

$$v(x, y) = v_0 + b_1 x + b_2 y, \tag{5}$$

where,

$$a_1 = \frac{\partial u}{\partial x}, \quad a_2 = \frac{\partial u}{\partial y},$$

$$b_1 = \frac{\partial v}{\partial x}, \quad b_2 = \frac{\partial v}{\partial y}.$$

The least-squares-plane method as described by Pedder (1981) was modified by forming a multiple stations array from different combinations (minimum of 3) of the 14 upper air stations within the West African region as shown in Fig. 1. In grouping these stations together, a horizontal length scale $\leqslant 1000$ km was used to identify the stations to be located within a particular array so as not to smooth out features that are characteristic of the synoptic scale disturbances over the area. For each combination of the upper-air stations identified in Fig. 1, the coordinates of latitude and longitude at the array center have been obtained as the simple geometric mean from the individual station's values. The positions of the geometric centers of the 70 different combinations of the stations formed over the area is shown in Fig. 2. The gradients of the windfields obtained at these points were then used to estimate the kinematic quantities in eqs. (1), (2), and (3). To reduce the effect of random observing error, arrays consisting of more than 3 stations were taken to be more reliable. The value obtained at each of the geometric centers in Fig. 2 is an approximation over an area of about 200 km radius. These point values have then been smoothed subjectively over the study area in order to produce the horizontal motion fields. The significance of this method is that more representative data points are generated over the study area so as to improve the quality of the kinematic analysis. The technique developed here is a variant of the scheme used by Kung (1972, 1973) for estimating the vertical motion field over North America.

Above the 500 hPa level, the observation error of wind velocity increases rapidly with height and as such an adjustment of the profiles of these kinematic fields was deemed necessary to minimize the pressure bias error. The correction factor employed is the same as derived by Pedder (1981), which is stated as

$$(\nabla_H \cdot V)_c = \frac{\omega_t}{(p_0 - p_t)}, \tag{6}$$

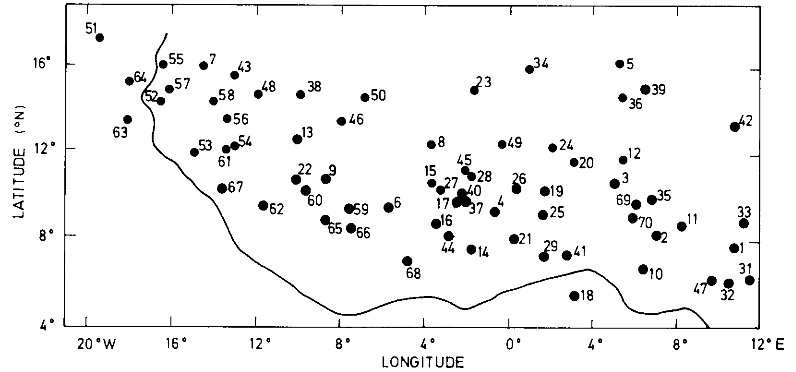

Fig. 2. Distribution of the geometric centers (mean latitude and longitude) of the different stations' arrays (see text for details).

where the subscript $_c$ indicates a correction to the actual divergence estimates. The subscripts $_0$ and $_t$ represent the surface and tropopause values respectively. The quantity evaluated in eq. (6) was then subtracted from the previously estimated values of the divergence and recomputed in eq. (3) to obtain a realistic vertical velocity profile, i.e., a precondition that the vertical p velocity, is zero both at the surface and at the tropopause, which was taken as 100 hPa in this case (O'Brien, 1970; Kung, 1972; Pedder, 1981).

Using the daily 1200GMT soundings from the Special Observation Period of WAMEX, values of these kinematic quantities have been estimated at each of the 70 representative points (geometric centers) over West Africa at the standard pressure levels. The averages for the period were plotted as the mean fields.

3. Results and discussion

Shown in Figs. 3, 4, and 5 are the mean kinematic fields; horizontal divergence, relative vorticity, and vertical p velocity respectively, over West Africa for the Special Observation Period. These fields have been computed using the procedure discussed in Section 2 above and at the following pressure levels: 1000 hPa, 850 hPa, 700 hPa, 500 hPa, 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa, and 100 hPa. A level-by-level study of the fields reveals prominence of certain tropospheric features, some of which supported observed synoptic surface weather patterns during the period.

3.1. The mean horizontal divergence fields

At the 1000 hPa level shown in Fig. 3a, it is observed that the motion field over the entire area is divergent, particularly so in the northern and eastern parts. However, a weak convergence is also noticed around the central part. The divergence field at the 850 hPa level (Fig. 3b) is similar to the pattern near the surface, except that in this case, the area of convergence is seen to be more restricted to the coastal belt. The net divergence at the lowest layer indicates an outflow from the region. The diverging low-level flow field and the associated mid-tropospheric subsidence is consistent with the almost rainless condition within the region at the peak of the summer monsoon, from mid-July to about mid-August (see Obasi, 1965; Adefolalu, 1972; Omotosho, 1988).

Within the middle troposphere at about 700 hPa, the mean field is changed considerably from the patterns observed at the lower layers. In Fig. 3c, the mean field for the areas lying east of longitude 5° W is convergent. As such, the centers of divergence in the lower troposphere correspond to convergence around the middle troposphere. Though a weak divergence is observed in the north-western section. The distribution for 500 hPa is shown in Fig. 3d. The mean field is such that it portrays this level as the level of non-divergence (LND), especially in the areas east of longitude 10° W. The 400 hPa field shown in Fig. 3e, has features similar to those of the 500 hPa field.

At the upper troposphere (see Figs. 3g-j), it is observed that the net flow is convergent. This

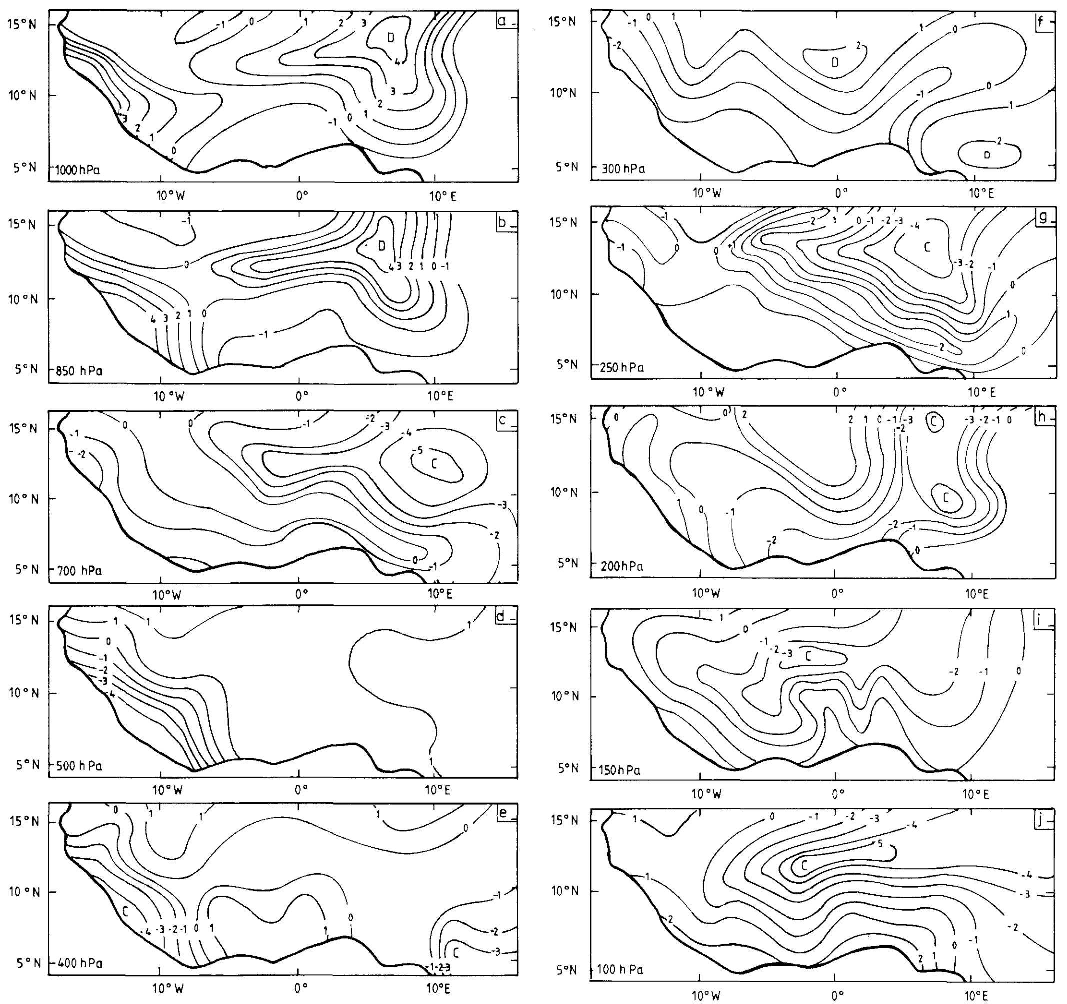

Fig. 3. Horizontal divergence fields ($10^{-6}\,s^{-1}$) over West Africa for the Special Observation Period.

appears reasonable since the upper level convergence largely compensates for the outflow in the lowest layers.

3.2. The mean relative vorticity fields

From Fig. 4a, the relative vorticity field at 1000 hPa is seen to be weakly cyclonic over the entire area. At 850 hPa, the pattern is also similar (Fig. 4b). The feature of the cyclonic vorticity that is present at the lowest levels is not now well understood; it could probably be as a result of lack of data over the region or smoothing associated with the analysis scheme. The relative vorticity field at 700 hPa in Fig. 4c shows centers of cyclonic vorticity both in the eastern and western parts with a small core of an anticyclone in the northern area. The closed cyclonic vortices seen about the level have been linked to the perturbations on the African Easterly Jet (AEJ) occurring as the African waves (Burpee, 1972; Adefolalu, 1985). The vorticity field at 500 hPa is found to be similar to the pattern at 700 hPa, although with weaker maxima and minima.

Near the 250 hPa level, the relative vorticity field is mainly anticyclonic. The upper level anticyclone noticed about this level during the

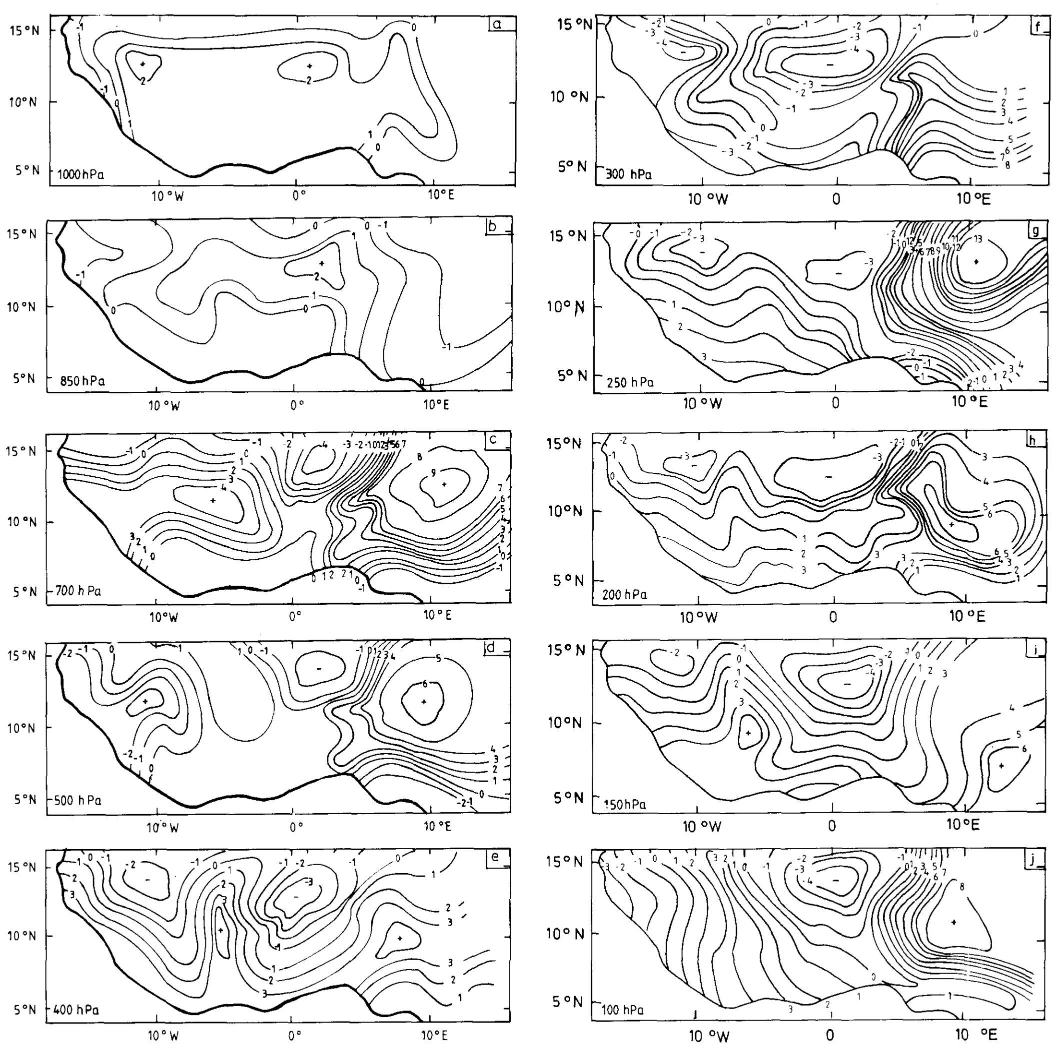

Fig. 4. Relative vorticity fields ($10^{-6}\,s^{-1}$) over West Africa for the Special Observation Period.

summer monsoon has been reported by Adefolalu (1985), and is associated with intensification of the Tropical Easterly Jet (TEJ) over the area. About this level, a strong core of cyclonic vorticity is observed around the northeastern part, which then appears as persistent up to the tropopause. The southwest area also indicates positive vorticity during the period. The wave-like circulation featuring at the upper levels can be ascribed to the TEJ, which generates a strong shear of the mean wind around its vicinity.

3.3. The mean vertical p velocity profiles

Shown in Fig. 5 is the distribution of the vertical p velocity profiles (from 1000 hPa to 100 hPa) within the West African region for the special observation period. These profiles are presented at some of the geometric centers selected in Fig. 2. Each of these profiles represents an approximate over area of about 200 km radius using wind data from the upper air stations in Fig. 1.

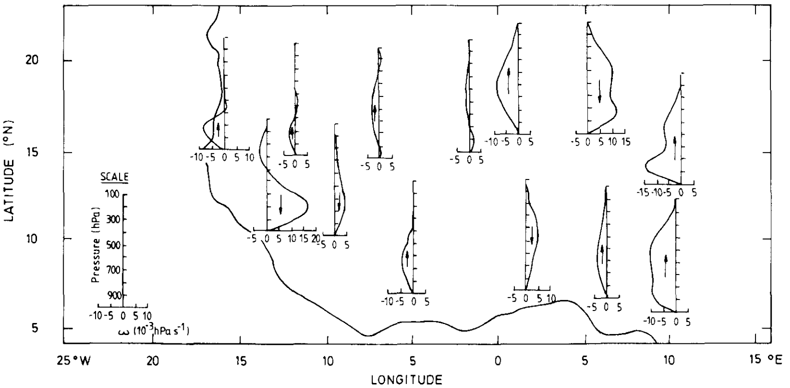

Fig. 5. Vertical motion field over West Africa obtained at some of the array centers in Fig. 2, for the Special Observation Period.

The vertical motion field over the area shows that during the period, there was mostly upward motion north of latitude 15° N, particularly from near the west coast up to the Greenwich meridian. In contrast, the mean vertical motion was downward (that is, subsidence) south of latitude 10° N. Noticeable also from Fig. 5 is a region of dominant convective activity in the area lying between longitudes 5° E and 10° E. During the northern summer, the West African region is characterized by a moist southwesterly current (which is of maritime origin) at the lowest layers forming a wedge underneath the very dry northeasterly wind blowing out of the Sahara desert from the Azores subtropical High Pressure system. The surface position of the transition between the moist and dry air masses is known as the Inter-Tropical Discontinuity (ITD)* line (Hamilton and Archbold, 1945). It should be noted that it is around this period of study (July/August) that the ITD line attains its maximum northward position over continental West Africa, which is at about latitude 22° N. Relative to the ITD position, the landmass lying behind its surface position had been demarcated into different weather regimes as shown in Fig. 6 by Balogun (1981), at the peak of the summer monsoon. From the figure, the area just north of latitude 15° N falls within a convectively active belt as zone C, whereas the area south of latitude 10° N is in the weather zone D. In zone D, the convective activity is inhibited since the zone is characterized by an inversion layer at about 850 hPa. Overall, there is a good matching between the vertical motion field in Fig. 5 and the weather zones shown in Fig. 6 over the West African region.

However, a comparison made between the vertical velocity profiles in Fig. 5 and the horizontal wind divergence fields in Fig. 3 reveals some disparities both at the western and eastern boundaries in the lower layers (1000 hPa and 850 hPa). For instance, the weak divergence around the northeastern part in Figs. 3a and b, does not match with the upward motion portrayed in the velocity profile for the same area. This is probably due to the subjective smoothing applied to the original divergence estimates, whereas the vertical velocity profiles represent point values.

3.4. The areal means of the kinematic fields

Figs. 7a, b, and c are reproduced as a summary of the circulation fields over the entire area for the same period. The divergence profile shown in Fig. 7a shows that at the lower levels, the flow field is divergent. This explains the break in the monsoon rains which occurs at about this period in West Africa. Over the area as a whole, the 500 hPa level corresponds to the level of non-divergence (LND). In the upper troposphere, the mean flow is convergent.

* The World Meteorological Organization has recommended this terminology over continental West Africa.

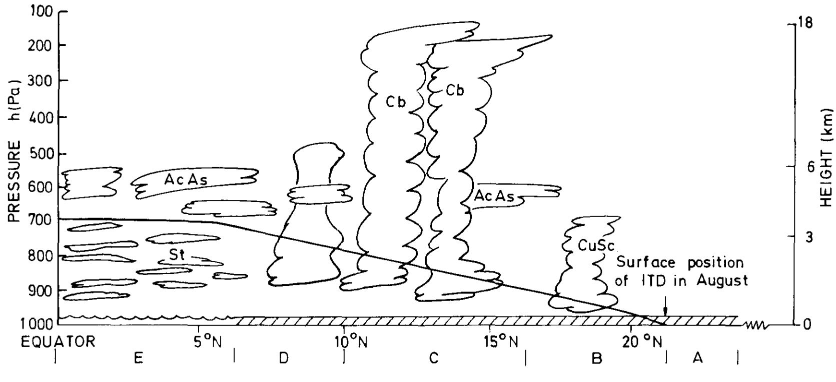

Fig. 6. Schematic representation of variations in monsoon depth and the different weather zones over the area (adapted from Balogun, 1981).

The relative vorticity profile shown in Fig. 7b indicates that the field is mainly cyclonic, with the upper troposphere being anticyclonic, especially between 300 hPa and 250 hPa. The upper level anticyclone is attributed to the prominence of the TEJ during the same period.

The vertical motion field in Fig. 7c for the period and over the area (particularly in the southern part) shows that the mean motion is subsidence. This reveals that during this period, little or no convective activity could take place as has earlier been reported by Adefolalu (1972) and Omotosho (1988).

4. Conclusions

A variant of the least-squares-plane method by Kung (1972) and Pedder (1981) has been used to investigate the large-scale motion fields over West Africa for the Special Observation Period of WAMEX. The method has been proved successful despite the rather sparse upper air station network existing over the region, since some of the observable synoptic features are indicated on the derived fields. This technique is also suggested as being dependable for routine weather analyses for the West African area.

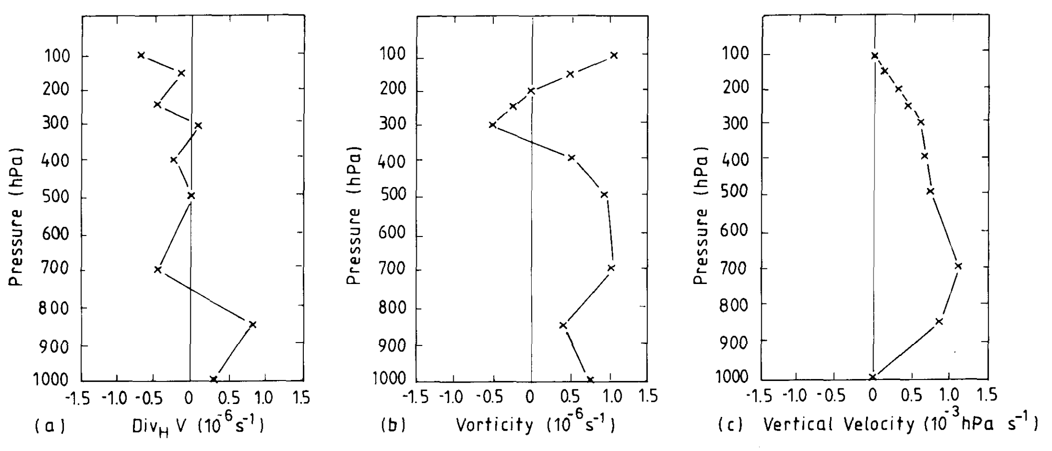

Fig. 7. Vertical profiles of areal averaged kinematic fields over West Africa for the Special Observation Period.

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