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African monsoons, Part 2: Synoptic-scale wave disturbances in the intertropical convergence zone over north Africa

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सार - प्रस्तुत शोध-पत्र में अफ्रीका की मानसून के इस भाग में उत्तरी ग्रीष्मकालीन ऋतु के दौरान उत्तरी अफ्रीका के उष्णकटिबंधीय क्षेत्र में तरंग विक्षोभों के मलस्थान, संरचना, विकास और संचरण के अनेक पहलुओं के विषय में चर्चा की गई है। कुछ निश्चित अवरोधक परिसीमा अवस्थाओं के कारण वास्तविक तंरग विक्षोभों के विश्लेषण से यह पता चला है कि अटलाटिंक महासागर में, उत्पन्न होने वाले ये तरंग विक्षोभ आगे चलकर हरीकेन तूफान के रूप में परिवर्तित हो जाते हैं। यद्यपि अफ्रीका के मध्य क्षोभमंडलीय पूर्वी जेट से संबद्ध क्षेत्रीय पवन माध्य के क्षैतिजीय उर्ध्वधरीय अपरूपण, गतिकीय अस्थिरता उत्पन्न करने में सहायक होते हैं, तथापि इसका मुख्य कारण उत्तरी अफ्रीका के पूर्वी और मध्य भाग के पर्वतीय भागों में अप्रगामी तरंग पर मध्य अक्षांशीय पछुआ हवाओं की बृहत् आयामी बैरो क्लीनिक तरंगों का पड़ने वाला प्रभाव ही है, क्योंकि ऐसा प्रतीत होता है कि मारा और इथोपियन पर्वतों के मध्य सूडान की नील नदी की घाटी में अंतः उष्णकटिबंधीय अभिसरण क्षेत्र में तरंग विक्षोभ की उत्पत्ति को यह प्रभाव ही प्रेरित करता है। इस शोध पत्र में विक्षोभ के बनने, उनके विकसित और संचरित होने में भौतिक प्रकियाओं के संभावित महत्व के बारे में भी बताया गया है।

ABSTRACT. In this part, the paper discusses several aspects of the origin, structure, development and movement of wave disturbances over the North African tropical zone during the northern summer. Analyzing the cases often actual wave disturbances which later in their life cycles developed into hurricanes over the Atlantic, it finds that though the horizontal and vertical shear of the mean zonal wind associated with the mid-tropospheric easterly jet over Africa satisfies the condition of dynamical instability under certain restrictive boundary conditions, it is the influence of a large-amplitude baroclinic wave in mid-latitude westerlies upon a stationary wave in the mountainous region of the east-central north Africa that appears to trigger the birth of a wave disturbance in the intertropical convergence zone over the Nile valley of Sudan between the Marra and the Ethiopian mountains. Physical processes likely to be important in the formation, development and movement of the disturbances are pointed out.

Key words – African wave disturbances, ITCZ over north Africa, Stationary wave over Africa, Tropical-midlatitude interaction.

1. Introduction

The monsoon circulation over north Africa, the climatology and seasonal characteristics of which was presented in Part 1 of this study (Saha and Saha, 2001b), is often perturbed by wave disturbances which form in the Intertropical Convergence Zone (ITCZ) over the latitude belt, 5° N- 20° N, during the northern summer and move westward. Early studies of these disturbances, which were hampered by acute shortage of surface and upper air data, described them as cloud lines, squall lines, or even disturbance lines (Hamilton and Archbold, 1945; Eldridge, 1957). But, as satellite cloud and infrared imagery and a better network of observations became available to aid analysis from about the mid-sixties of the last century, several studies (Carlson, 1969a,b; Burpee, 1972; Rennick, 1976) suggested that these are synoptic-scale wave disturbances that form along the boundary zone between the hot dry Saharan air in the north and the cool humid air of oceanic origin in the south. According to observational study of Carlson (1969b), these waves have a mean zonal wavelength of about 2000 km, a pressure amplitude of 2-3 hPa, a frequency of one wave every 3.2 days and a westward phase velocity of 10-20 knots. The

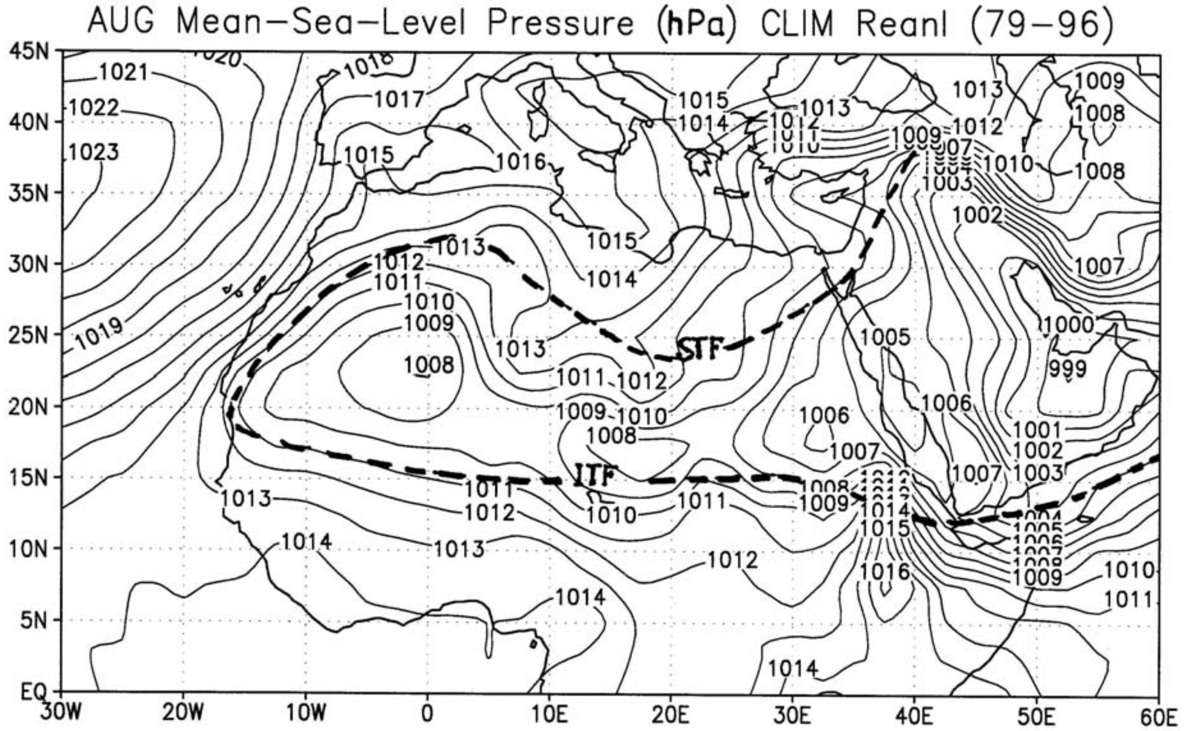
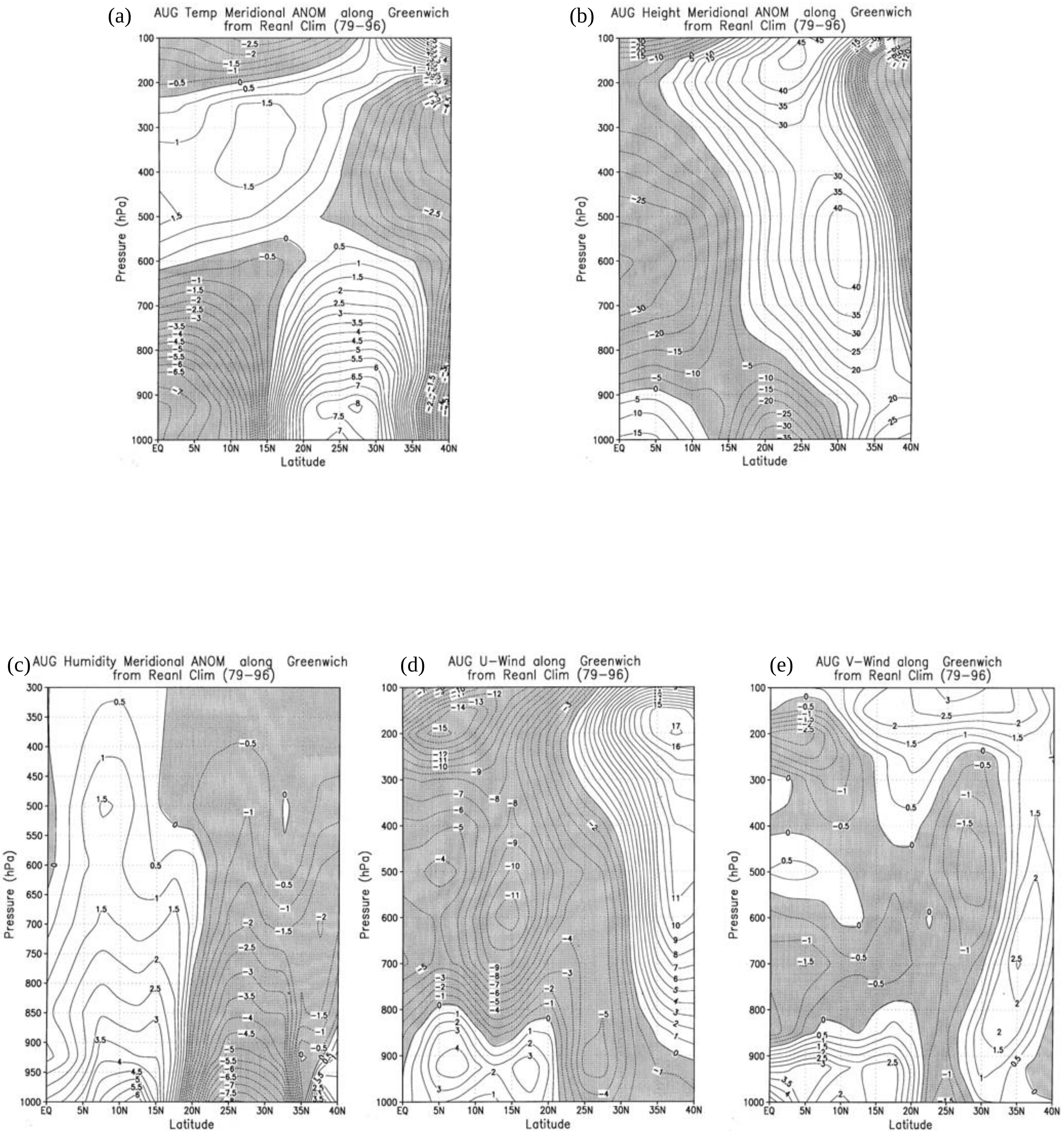


Fig. 1. Mean Sea Level (MSL) pressure (hPa) distribution over north Africa during August, showing approximate locations of the Intertropical Front (ITF) and the Subtropical Front (STF) as suggested by Soliman (1958)

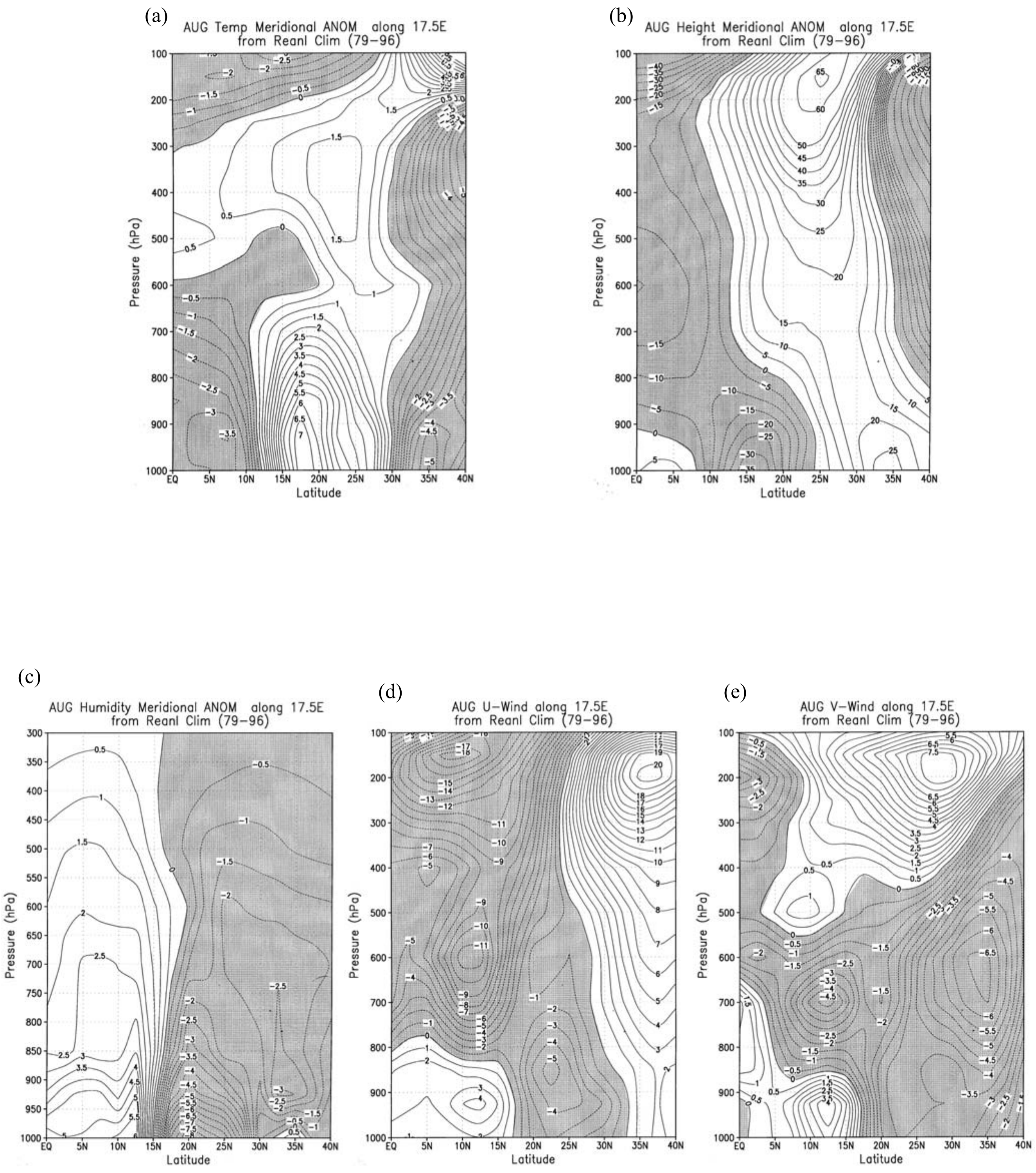
Global Atlantic Tropical Experiment (GATE) which was conducted over the eastern Atlantic close to the coast of west Africa in 1974 also led to further studies on the structure and energetics of these disturbances (Reed, *et al.*, 1977; Norquist, *et al.*, 1977). The fact that several of these disturbances moving out over the Atlantic ocean later developed into hurricanes might also have spurred research into these disturbances.

The above-mentioned studies, especially those of Carlson (loc.cit.) and Burpee (1972), contributed greatly to our knowledge and understanding of the formation, development and movement of these disturbances. However, despite great advances made, uncertainties appear to remain in several areas. One of these relates to the source region of these disturbances. While most of the above-mentioned studies sought to relate these disturbances to the midtropospheric easterly jet which extended all the way from east to west across tropical north Africa, Carlson (1969b) found that the majority (80% or more) of the disturbances originated in a mountainous region east of about 10° E. Burpee (loc.cit.) who carried out detailed power-and cross-spectral analysis of available upper-air data over Africa also concluded that normally these waves originated over the region between Fort Lamy (15° E) and Khartoum (32° E). Another uncertainty is the source of energy for the formation and growth of these disturbances. While some (Rennick, 1976) emphasize a barotropic mechanism related to the existence of the midtropospheric easterly jet, others (Burpee, 1972; Norquist *et al.*, 1977) emphasize almost equal contributions from barotropic and baroclinic conversions of energy. Little is known about the possible effect of condensational heating. Further, even a tentative model of the zonal-vertical circulations associated with these disturbances is not yet available.

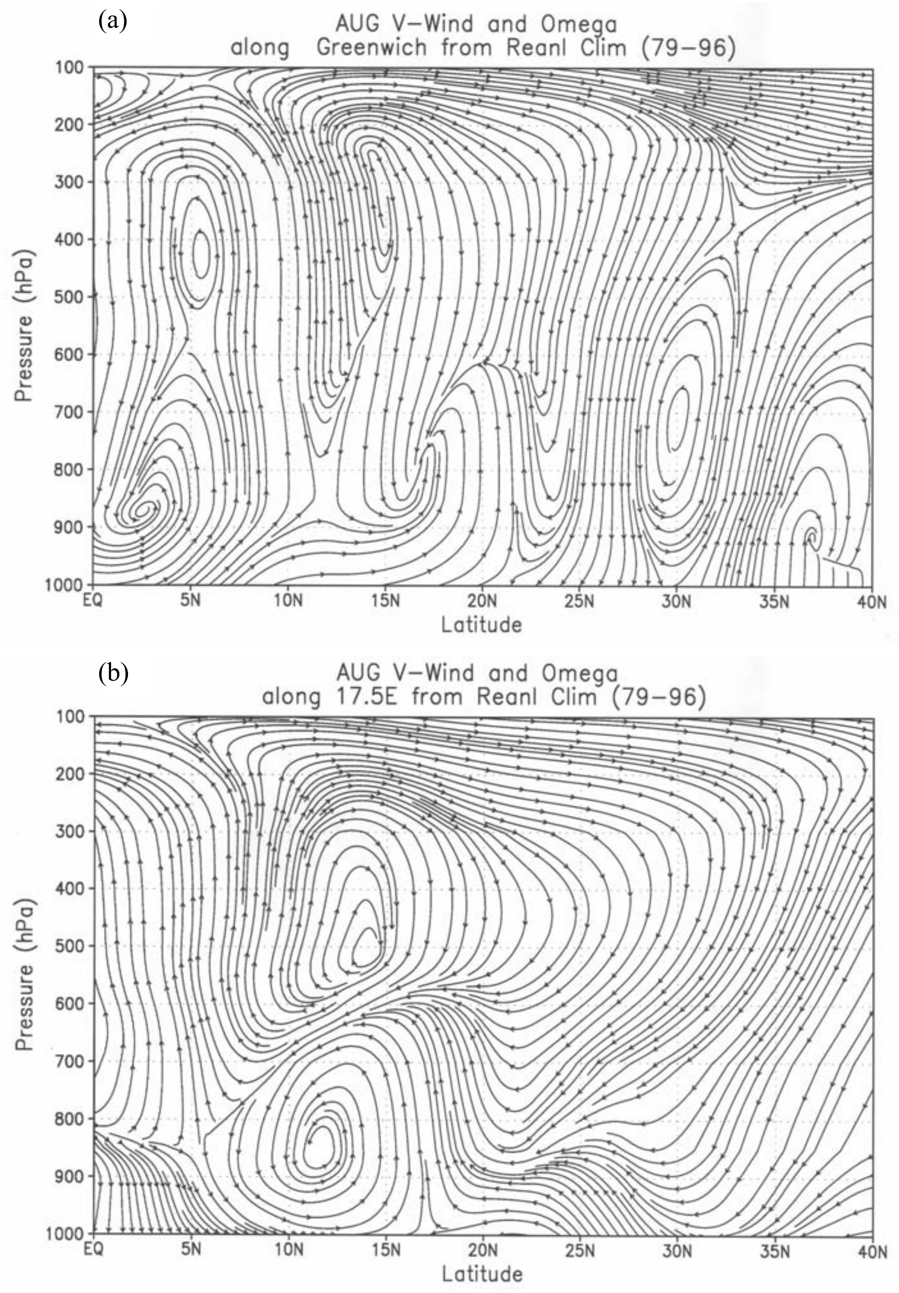
In the present study, we look into some of these problems by first re-examining, using Reanalysis (Kalnay *et al.*, 1996), some aspects of the climatology of north Africa in an attempt to find out what special conditions, if any, might exist over its east-central part to make it so sensitive to formation of wave disturbances. In particular, we examine the structure of the equatorial trough and its associated convergence zones over different parts of the large heated continent in an effort to identify in what way the conditions over east-central Africa differ from those over western Africa. The effort leads us to find the



Figs. 2(a-e). Distributions of meridional anomalies (deviation from the meridional mean) of (a) temperature, (b) isobaric height, (c) specific humidity, (d) zonal and the (e) meridional components of the wind along the Greenwich meridian, from Reanalysis



Figs. 3(a-e). Distributions of meridional anomalies (deviation from the meridional mean) of (a) temperature, (b) isobaric height, (c) specific humidity, (d) zonal and the (e) meridional components of the wind along longitude 17.5° E, from reanalysis



Figs. 4(a&b). Meridional-vertical circulation along: (a) the Greenwich meridian and (b) longitude 17.5° E

presence of a stationary wave in the ITCZ in the mountainous region of east-central Africa. Further investigation reveals that it is the frequent interaction of this stationary wave with midlatitude baroclinic waves that may trigger the birth of synoptic-scale wave disturbances in the ITCZ. The mechanics of this interaction and several other issues relating to African wave disturbances are dealt with in the sections that follow.

2. The Intertropical Convergence Zone (ITCZ) over Africa

Over tropical oceans, the ITCZ appears where the tradewinds from the two hemispheres meet in a warm narrow trough of low pressure, generally known as the equatorial trough, in the summer hemisphere. The situation over a large continent such as Africa appears to be different, in that, instead of a well-defined narrow

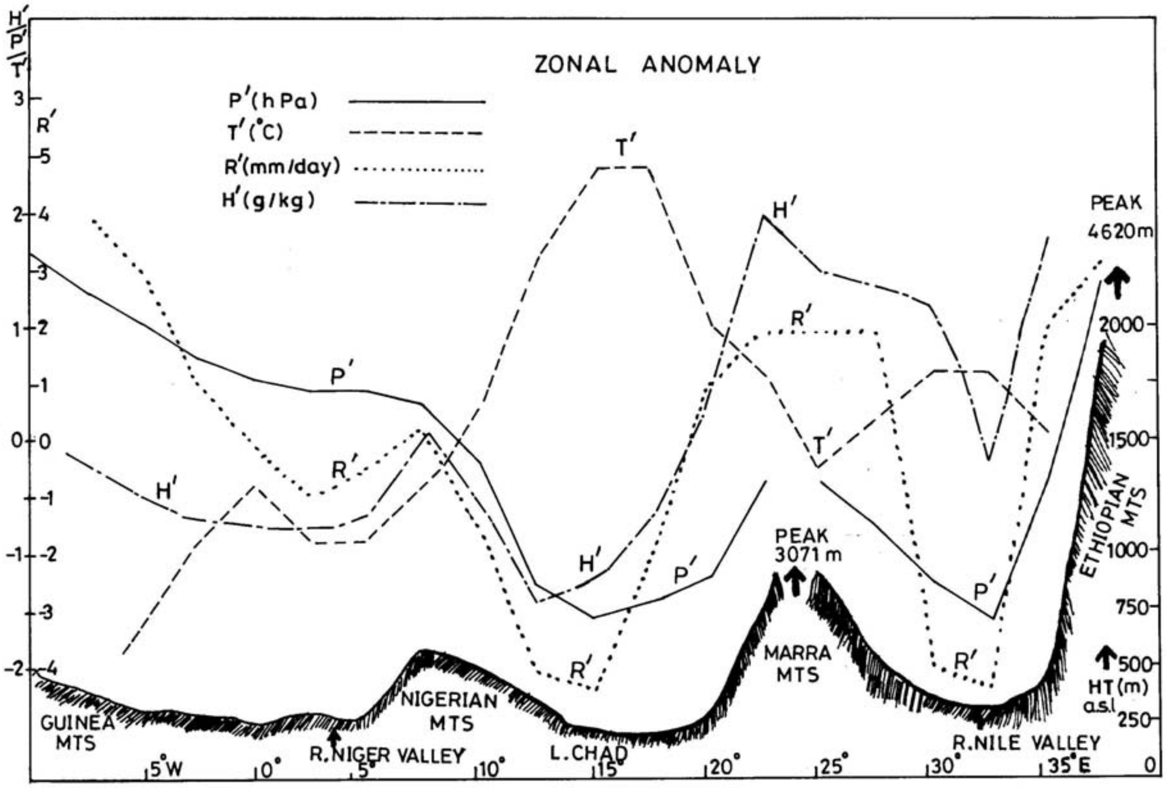


Fig. 5. Mean zonal anomaly (deviation from the zonal mean) of MSL pressure (*P*), 925 hPa temperature (*T*), 925 hPa specific humidity (H) and Precipitation (R) over the latitude belt, 10° N- 15° N, during August. Topography is shown by hatching

trough of low pressure confined within a few degrees of latitude, a large-scale 'heat low' develops over the continent covering several degrees of latitude during the northern summer. Ordinarily, the powerful 'heat low' circulation appears to prevent the cool humid tradewinds from the neighbouring oceans from meeting directly to produce a single convergence zone, as they appear to do over the neighbouring ocean. A question that has often been asked and debated relates to the location of the ITCZ in relation to the center of the 'heat low' or the equatorial trough which passes through it. Soliman (1958) who studied the problem almost half a century ago discounted the idea of an ITCZ over Africa and proposed that instead of a single ITCZ, there are two frontal zones, one along the southern boundary of the thermal belt which he called the Intertropical Front (ITF) and the other along the northern boundary which he called the Subtropical Front (STF). According to him, both the fronts are baroclinic zones with the baroclinicity varying with season, that at ITF becoming maximum and strongly correlated with the upper-air easterly jetstream in summer and that at STF becoming maximum and strongly correlated with the westerly jetstream in winter. The approximate locations of these fronts, as proposed by Soliman are marked in Fig. 1 which shows the August Mean Sea Level (MSL) pressure distribution over northern Africa from Reanalysis. One may note that these so-called fronts are widely separated from each other over the western part of Africa (west of about 10° E) and also over the extreme eastern part bordering western Asia but are very close to each other over the central part between longitudes about 10° E and 30° E. While we discuss the structure and properties of the atmosphere associated with the two fronts further in the present study, we conclude that it is the ITF which appears to play the role of the ITCZ over Africa. However, as we show in what follows, there are significant differences in the structure and characteristics of the ITCZ between the western and the central parts of north Africa due to differences in oceanic and orographic influences on the heat low circulation.

3. Meridional structure of the ITCZ

Due to differences in land-sea configuration and the presence of the Mediterranean sea to the north and the

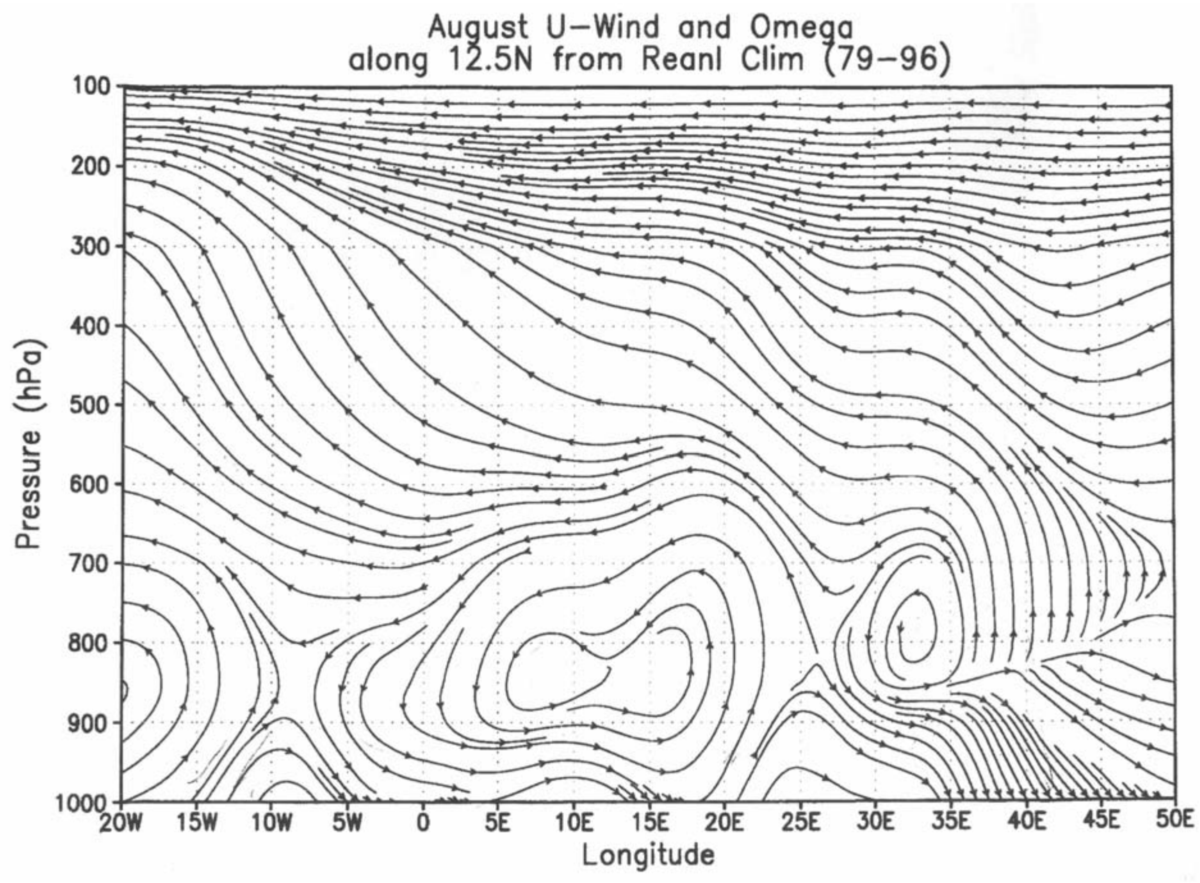


Fig. 6. Mean August zonal-vertical circulation in the stationary wave along 12.5° N

Atlantic ocean to the west and south, the oceanic influence on the heat low circulation over the western part of north Africa during the northern summer differs considerably from that over the central part, as suggested by Fig. l. The differences are reflected in the meridional distributions of anomalies of (a) temperature, (b) isobaric height and (c) specific humidity and those of (d) the zonal component (*u*) of the wind and (e) the meridional component (*v*) of the wind along the meridians, the Greenwich and 17.5° E, presented in Figs. 2 and 3 respectively. They show significant differences in the location and structure of the equatorial trough, warm and cold anomalies relative to it and the reversal of the temperature and height anomaly fields with height. It is not difficult to see that most of these differences between the two parts arise from significant differences in land-sea thermal contrast and the influence of the low-level anticyclonic circulation over the Mediterranean sea. Significant differences also appear in the vertical circulation fields, presented in Figs. 4(a&b) which show that while there is only one well- defined zone of strong upward motion south of the equatorial trough along the 17.5° E meridian, there are as many as three latitudinal zones of upward motion along the Greenwich meridian in the lower troposphere, one to north of the equatorial trough and two to south. However, despite these differences, there are some significant similarities between them over the tropical zone which need to be pointed out. These are: (*i*) there exist strong meridional temperature gradients in the lower and the upper troposphere along both the meridians; (*ii*) the equatorial trough of low pressure along both the meridians tilts equatorward with height in the lower troposphere; (*iii*) the zonal wind (*u*) in both has a strong horizontal and vertical shear; and (*iv*) an easterly wind maximum with a mean strength of about 11 metres per second appears at about 600 hPa a few degrees equatorward of the equatorial trough, besides the upper-tropospheric easterly jetstream at about 150 hPa. which appears further south.

4. A stationary wave in the ITCZ over north Africa

Recent investigations (Saha and Saha, 2000, 2001a) on wave disturbances over the monsoon regions of India and Australia suggest that these disturbances have a

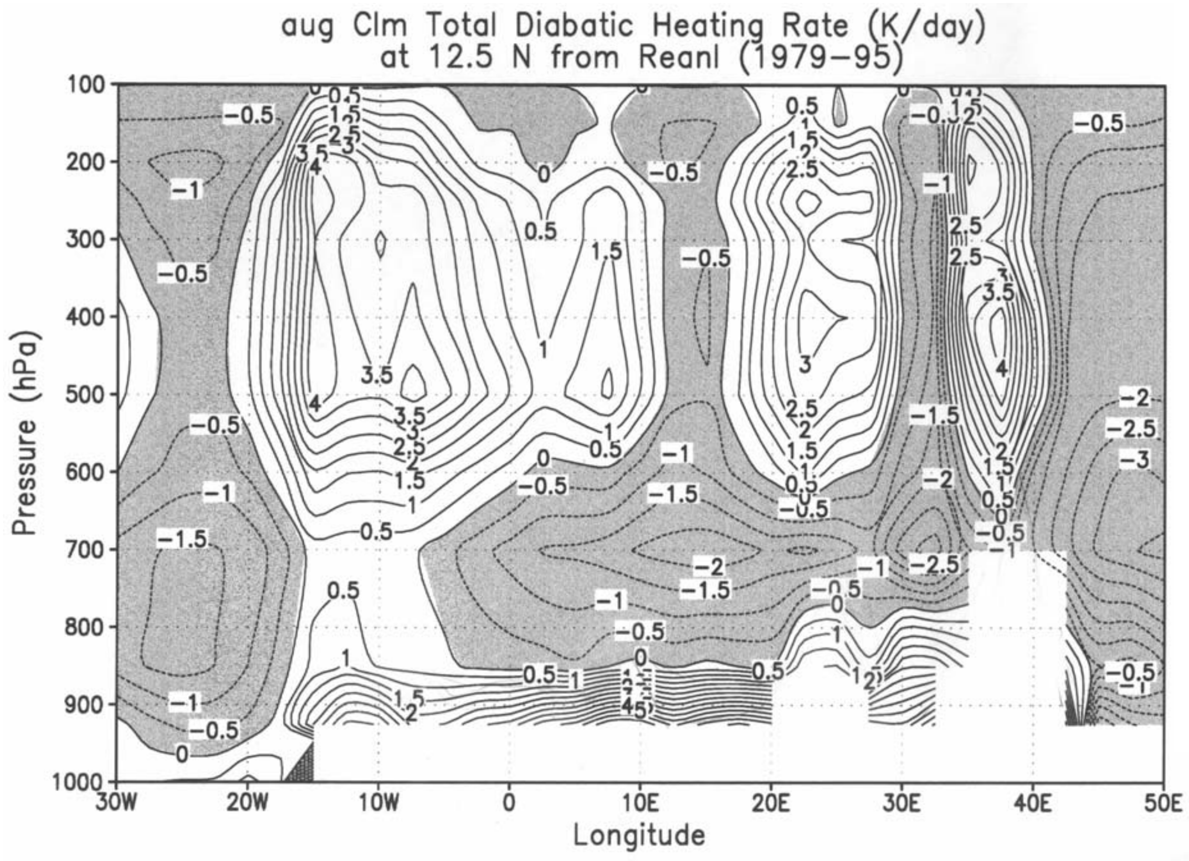


Fig. 7. Vertical distribution of total diabatic heating rate (K/day) along 12.5° N during August

tendency to form in a zonal stationary wave in the ITCZ which is maintained over the region by land-sea thermal contrast and/or orography. In the monsoon region of Africa, therefore, we looked for the presence of a stationary wave along the ITCZ. Fig. 5 which shows the distribution of the zonal anomaly (deviation from the zonal mean) of MSL pressure, precipitation, 925 hPa temperature and specific humidity over the latitudinal belt, 10° N - 15° N, during August, in relation to the mean topography over the belt, appears to confirm our suspicion. It clearly reveals the presence of a well-defined stationary wave eastward of the Nigerian mountains in the fields of all the atmospheric variables examined, the mountains being associated with low temperature, high pressure, high humidity and heavy rainfall and the valleys/lowlands with high temperature, low pressure, extreme dryness and little or no rainfall. The stationary wave appears to have an average wavelength of about 1500 km and an amplitude of about 1.5 hPa in the pressure field and 1.5° C in the temperature field at low levels. Its vertical structure is shown in Fig. 6 which presents the mean zonal-vertical circulation along 12.5° N. It shows the low-level monsoon westerlies rising gently over the low Nigerian mountains, sinking over the Lake Chad area and then rising strongly against the slopes of the high Marra mountains. However, the current descends strongly on the leeside of the Marra mountains and over the Nile valley of Sudan only to rise strongly again along the steep slopes of the Ethiopian mountains. The wave pattern is also reflected in the upper-air easterlies over the belt. Since large-scale upward (downward) motion in the tropics indicates net diabatic heating (cooling) of the atmosphere, according to the approximate relationship, $Q = -C_p \sigma\omega$, where Q is the rate of diabatic heating, C_p the specific heat of dry air at constant pressure, σ the static stability parameter and ω the vertical *p*-velocity (Holton, 1979), we present in Fig. 7 the August climatological values of total diabatic heating rate along 12.5° N, from Reanalysis. It shows, inter alia, strong diabatic cooling over Lake Chad area as well as the Nile valley of Sudan but strong diabatic heating over the western slopes of the Marra and the Ethiopian mountains. There is little doubt that strong diabatic heating over the mountains is due to release of latent heat of condensation on the windward sides of the mountains, while strong diabatic cooling over the desert lowlands and valleys is due to net radiative heat loss.

5. Origin of African wave disturbances

Ever since African wave disturbances were discovered, there have been speculations regarding the origin and dynamics of these disturbances. Carlson (1969b) who first noted that the majority of them originated in the mountainous region of east-central Africa thought that they might arise from the effect of afternoon heating over mountain surfaces. Frank (1970) put forward the view that the mechanical lifting of the easterly airflow over the mountains of Ethiopia might be responsible for them. However, Burpee (loc.cit.) who carried out systematic power- and cross-spectrum analysis of available upper-air data over Africa discounted both these speculations, though his study confirmed the origin of these disturbances over east-central Africa. He applied the quasi-geostrophic theory of an internal baroclinic jet by Charney and Stern (1962) (who had applied it earlier to the polar-night jet) to the case of the midtropospheric easterly jet over Africa and showed that the horizontal and vertical shear of the mean zonal wind associated with the jet satisfied the condition of dynamic instability of the flow under certain strict boundary conditions, one of which stipulates that there would be no horizontal transports of heat and momentum toward the region of the midtropospheric jet through appropriately-placed vertical boundaries at the poleward and equatorward limits of the influence of the jet. In the absence of data, he assumed the validity of the restrictive boundary condition and attributed the origin of African wave disturbances to the dynamic instability of the midtropospheric easterly jet. However, the present study finds that this boundary condition is frequently violated in the real atmosphere when the midtropospheric easterly jet comes under the influence of the midlatitude disturbances of the two hemispheres and there are meridional fluxes of heat and momentum across the boundaries of the jet. In fact, the fluxes vary considerably during the period of such interaction leading to large variations in the stability of the jet. We discuss the mechanism of this interaction with the midlatitude baroclinic waves of the northern hemisphere in the section that follows.

6. Midlatitude forcing

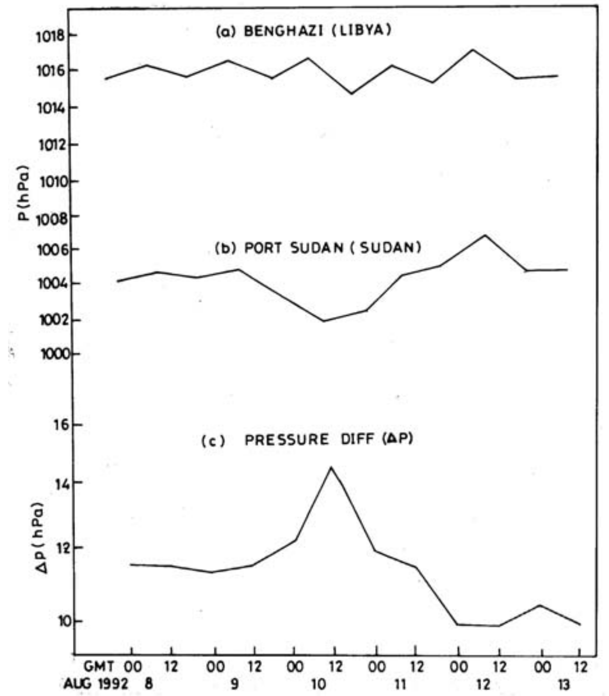
Over the subtropical belt of north Africa, the zonal anomaly of MSL pressure (Fig.1), say along 25° N, shows alternate sectors of high and low pressures of a stationary wave associated with the STF, the high pressures being generally over the cool ocean or land areas under oceanic influence and low pressures over the heated land. The stationary wave appears to have an average wavelength of about 4000 km and amplitude of 3 to 5 hPa over the land section. As part of this wave, the sphere of influence of the low-level anticyclonic circulation over the Mediterranean sea extends to lower latitudes, almost converging to the latitudes of the equatorial trough near 18° N over central north Africa, between about 10° E and 30° E. Needless to state, the stationary wave associated with the STF, though similar to that associated with the ITCZ, has a much longer wavelength and is more powerful than its tropical counterpart and baroclinically more akin to midlatitude baroclinic waves. It is, perhaps, because of this structural similarity that the stationary wave associated with the STF frequently interacts with the baroclinic waves that move eastward across southern Europe and adjoining Mediterranean sea.

Now, what happens when the stationary wave over north Africa interacts with the midlatitude baroclinic wave and how does this interaction affect the stationary wave in the ITCZ and lead to formation of a wave disturbance in it? We decided to examine this question by taking, instead of mean conditions, ten cases of wave disturbances which were born over Africa, moved westward and later in their life cycles developed into well-known hurricanes over the Atlantic. These were hurricanes: ANDREW (Aug,1992), LUIS (Aug,1995), EDOUARD (Aug,1996), ERIKA (Aug,1997), MITCH (Oct,1998), CINDY (Aug,1999), ALBERTO (Aug,2000), DEBBY (Aug,2000), GORDON (Sep,2000) and KEITH (Sep,2000). We obtained the particulars of these hurricanes from the official website of the U. S. National Hurricane Center at http://www.nhc.noaa.gov/pasall.html. There was no rationale behind the selection of these particular hurricanes except that their predecessor disturbances had to originate over Africa. We noted the date a particular wave disturbance left the west coast of Africa and worked backward in time over a period ranging from 7 to 8 days. In each case, we computed daily at 0000 and 1200 UTC the values of eddy kinetic energy and rates of barotropic and baroclinic energy conversions over an area bounded by latitudes, 0-30° N, and longitudes, 5° E-35° E, using the following expressions: Eddy kinetic energy,

$$K' = 1/(2\mathrm{g})\int_{0}^{P_0}\int_{A}\left(u'^2 + v'^2\right)\mathrm{d}A\mathrm{d}p \qquad (1)$$

Barotropic energy conversion,

$$\left\langle [K]\bullet K'\right\rangle = -(1/\mathrm{g})\int_{0}^{P_0}\int_{A}\ \left\{ [u'v']\partial[u]/\partial y + [u'\omega']\partial[u]/\partial p + [v'v']\partial[v]/\partial y + [v'\omega']\partial[v]/\partial p\ \right\}\delta A\delta p \qquad (2)$$



Figs. 8(a-c). Daily MSL pressure values at (a) Benghazi (Libya) and (b) Port Sudan(Sudan) and (c) pressure difference between them during period 8 through 13 August 1992

Baroclinic energy conversion,

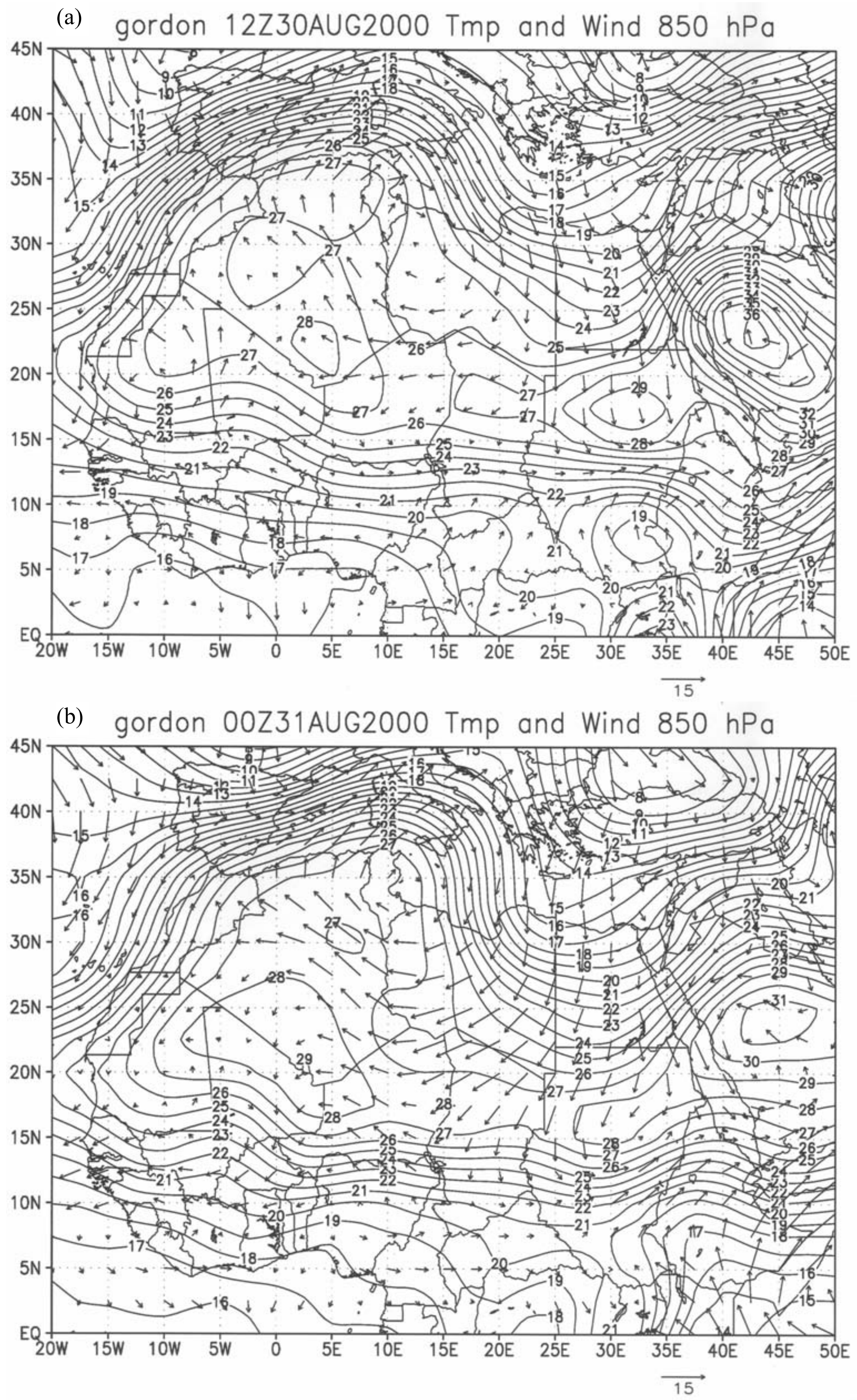
$$\langle P' \bullet K' \rangle = -(R/\mathrm{g}) \int_0^{P_0} \int_A (T'\omega'/p)\delta A \delta p \qquad (3)$$

where, u, v, ω are the three components of the wind (u positive to east, v positive to north and omega the vertical p-velocity), p is pressure, T is temperature (A), R is gas constant for dry air, g is acceleration due to gravity and A is area, K, K' and P' are zonal kinetic energy, eddy kinetic energy and eddy available potential energy respectively over the closed domain, the prime denotes a deviation from the zonal average indicated by square brackets, and the two terms within the angular brackets denote conversions from the first to the second and the other terms have their usual meanings.

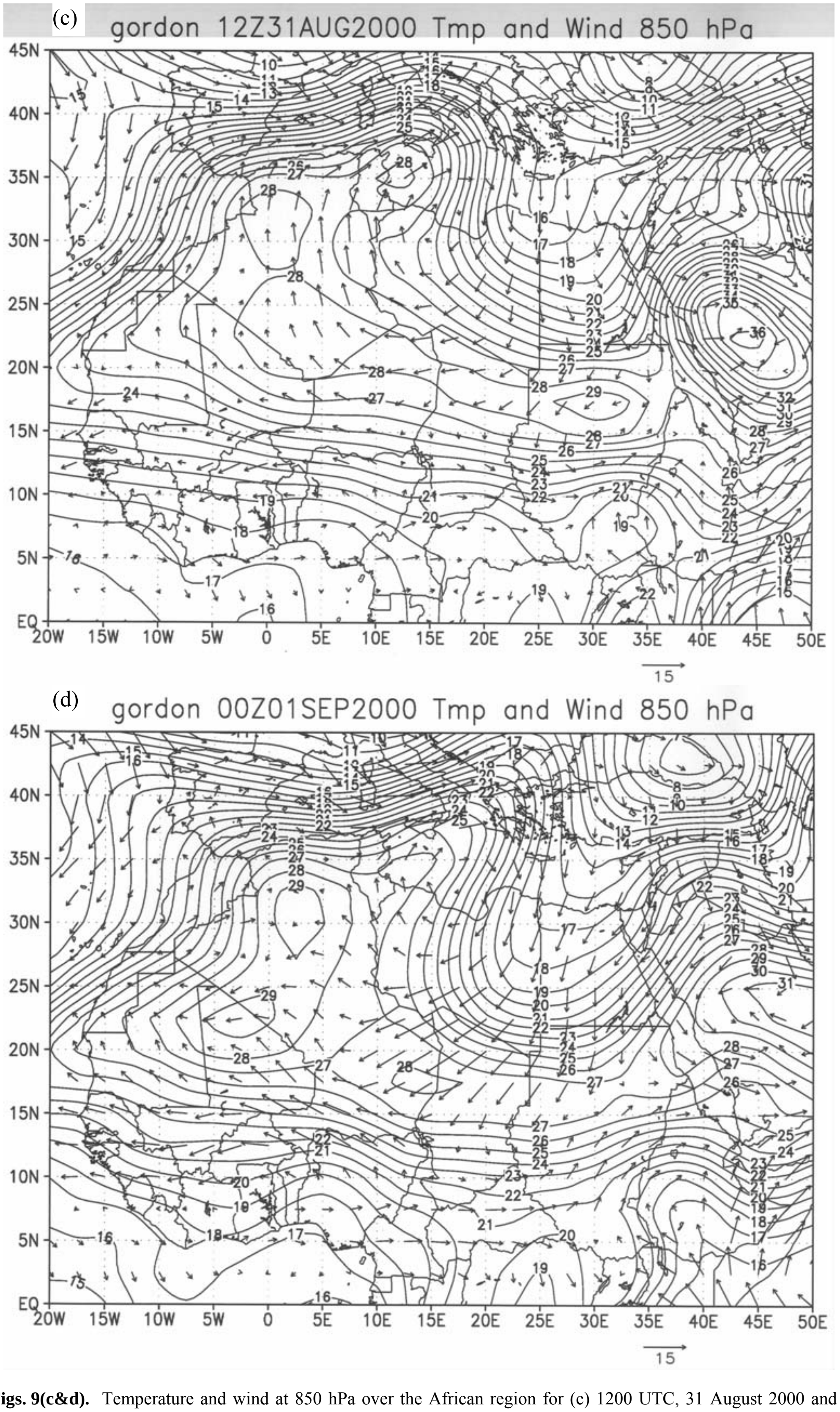
Additionally, we examined in each case the daily 0000 and 1200 UTC maps of wind and temperature distribution at 850, 500 and 200 hPa over a wider area extending from equator to 45° N and 20° W to 50° E with a view to noting the formation and tracking the movement of wave disturbances in different latitude belts over the African longitudes.

A detailed examination of the results of our study of the different cases reveals that in the formation of a wave disturbance in the ITCZ over Africa, there is a sequence of events that occurs in practically all the cases. Since it is not possible to present the findings of each case separately, we decide to describe this pattern taking a sample case of the wave disturbance which was traced to be the predecessor of hurricane GORDON in September 2000.

Three distinct stages could be identified in the interaction process: (*i*) Coupling/decoupling of the pressure systems between the STF and the midlatitude wave; (*ii*) Increase/ decrease of meridional fluxes of heat and momentum toward the ITCZ; and (*iii*) Development/ weakening of the stationary wave in the ITCZ. During stage (*i*), as a large-amplitude baroclinic wave in midlatitude westerlies moves eastward across the region of the Mediterranean sea, the lows and highs associated with it get successively superimposed on the stationary lows and highs associated with the STF. This results in a strengthening of the subtropical pressure systems when they are in phase with the corresponding pressure systems of the midlatitude wave and weakening when they are in opposite phase. For example, when the deep trough of a midlatitude wave arrives over Spain or adjoining western Mediterranean sea, it may link up with the corresponding 'heat low' trough over western Africa, forming an extended trough between the two latitude belts. At that time, the high pressure ridges of the two belts also get superimposed on each other. When the midlatitude trough moves away eastward and gets replaced by a high over Spain, the out-of-phase interaction leads to a weakening of the 'heat low' over western Africa. Similar coupling and de-coupling occur between the high pressure systems of the two latitude belts as well, causing periodic fluctuations in the strength of the stationary high pressure and its related anticyclonic circulation over subtropical central Africa. The 'heat low' over western Asia centered over Saudi Arabia also fluctuates in strength when it interacts alternately with the troughs and ridges of the midlatitude wave moving across eastern Mediterranean sea and adjoining western Asia. In stage (*ii*), following an in-phase interaction with a midlatitude wave, the pressure gradient between the subtropical high pressure over the Mediterranean sea region and the low-latitude equatorial trough over east-central Africa increases, allowing stronger northerly winds to blow to low latitudes. An example of this type of sudden strengthening of the pressure gradient is furnished in Fig. 8 which shows the daily MSL pressure values at 0000 and 1200 UTC at Benghazi (32.08° N, 20.27° E) in Lybia and Port Sudan (19.58° N, 37.22° E) on the Red sea coast and the pressure difference between them during the period, 8 through 13 August 1992, when an in-phase interaction occurred between a midlatitude wave and the subtropical front / equatorial trough leading to the formation of hurricane



Figs. 9(a&b). Temperature and wind at 850 hPa over the African region for (a) 1200 UTC, 30 August 2000 and (b) 0000 UTC, 31 August 2000, from Reanalysis



Figs. 9(c&d). Temperature and wind at 850 hPa over the African region for (c) 1200 UTC, 31 August 2000 and (d) 0000 UTC, 1 September 2000, from Reanalysis

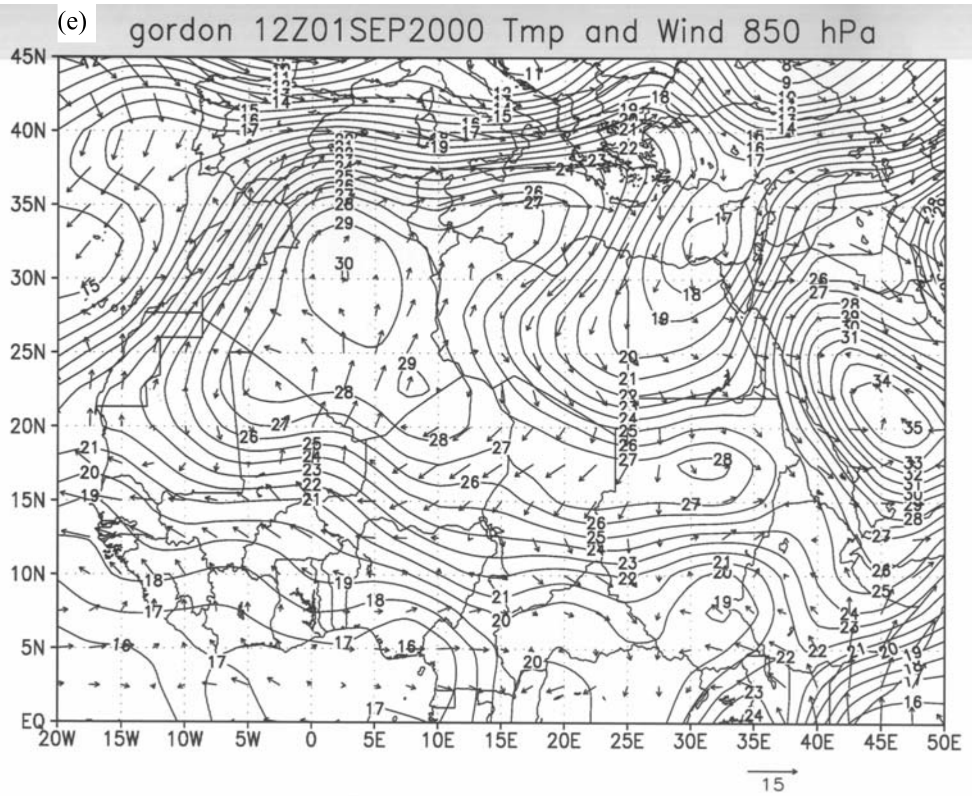


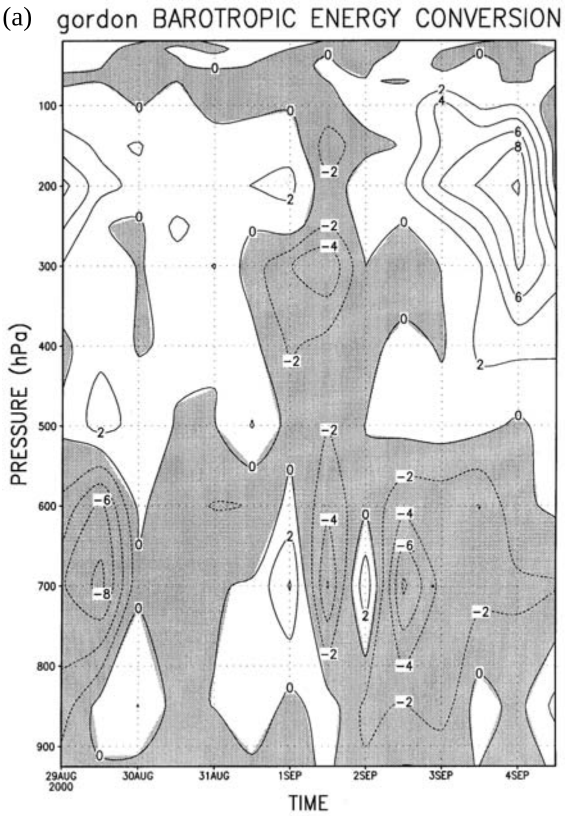
Fig. 9(e). Temperature and wind at 850 hPa over the African region for 1200 UTC, 1 September 2000, from Reanalysis

ANDREW's predecessor over east-central Africa at 0000 UTC on 10 August 1992. It shows a rapid increase in the pressure gradient between the two stations and implies a stronger equatorward flux of momentum from the subtropical belt to the tropics as a result of the interaction. Stage (*iii*) marks the period when heat and momentum flux from the north converges into the trough zone of the stationary wave, makes the airflow dynamically unstable and leads to the genesis of a wave disturbance as evidenced by an increase in eddy kinetic energy. We found this sequence of events following interaction of the north African subtropical front with a midlatitude baroclinic wave in all the cases examined. Some evidence of this sequence in the case of the birth of hurricane GORDON's predecessor is presented here. Figs. 9(a-e) which present the Reanalysis of wind and temperature at 850 hPa at five successive maptimes commencing 1200 UTC, 30 August and ending 1200 UTC, 1 September 2000 show how an in-phase coupling of the corresponding circulation systems and warm and cold sectors associated with the waves of the midlatitude and the subtropical belts culminated in the birth of a wave disturbance in the ITCZ over Sudan. Figs. 10 (a,b) present the daily computed values of the barotropic and baroclinic energy conversions for this case during the period 29 August through 4 September 2000. The daily computed values of the eddy kinetic energy during this period are presented in Fig. 11. It may be seen from Figs.10 and 11 that there was a large increase in eddy kinetic energy from both baroclinic and barotropic conversions during a period of 24 hours following the birth of GORDON's predecessor at 0000 UTC on 1 September 2000. Table 1 gives the particulars of the disturbances examined, their source of energy at birth, date and place of birth and the date they left the west coast of Africa.

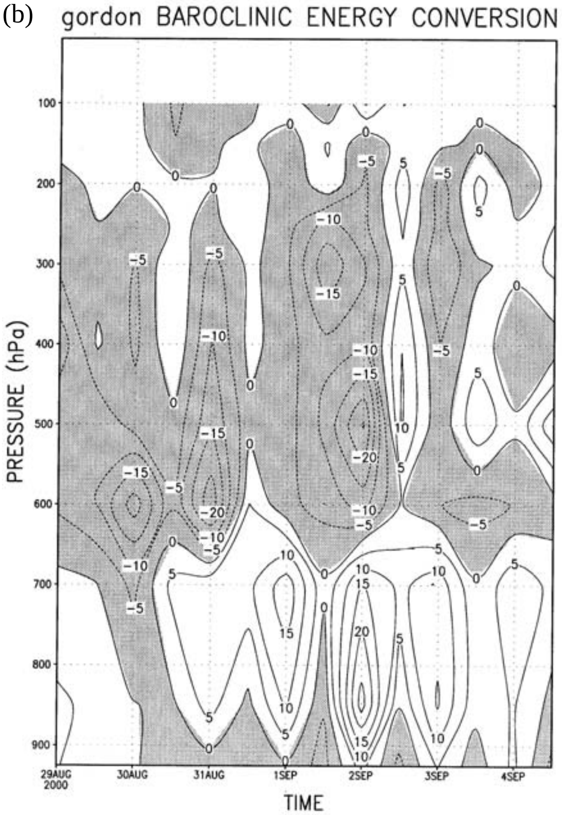
7. The mountain connection and wave structure and movement

In view of our finding that all the ten African disturbances examined originated over the Nile valley of Sudan which lies between two prominent mountain ranges, *viz*., the Marra in the west and the Ethiopian Highlands in the east, one may legitimately enquire if the

(a)



(b)



Figs. 10(a&b). Daily values of energy conversions over area, 0-30° N, 5° E-35° E, during the period 29 August through 4 September, 2000 (a) Barotropic and (b) Baroclinic. Unit 10^{-2} Wm^{-2}

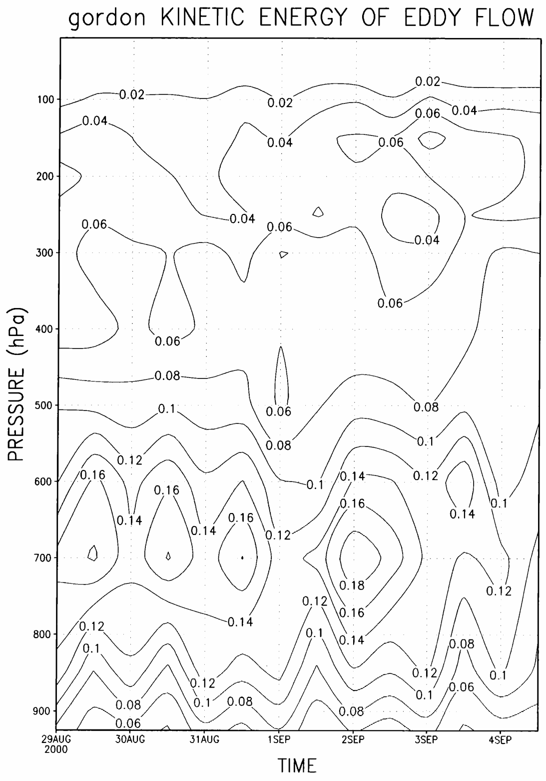


Fig. 11. Daily values of eddy kinetic energy over area, 0-30° N, 5° E-35° E, during the period 29 August through 4 September, 2000. Unit: 10^{-2} J m^{-2}

mountains have anything to do with the origin of the disturbances. There is little doubt that the stationary wave between the mountains and the lowlands over the region is maintained and governed by the principle of conservation of potential vorticity. Now, when, in the course of an in-phase interaction of the STF over north Africa with a midlatitude baroclinic wave, an increased equatorward flux of heat and momentum by the anticyclonic circulation over the east-central part of north Africa enters the trough zone of the stationary wave associated with the ITCZ, it may have the effect of amplifying the stationary wave and generating a transient disturbance. Further, the formation of the new disturbance in the stationary wave is accompanied by a shift in the area of low-level convergence, upward motion and rainfall from the east to the west of the trough axis. This shift appears to be consistent with the observations (Carlson, 1969a,b; Reed *et al.*, 1977) that in association with travelling wave disturbances over tropical north Africa, more rain falls to the west of the trough than to the east. After formation, the wave disturbance moves westward at an average speed of about 13 m/s. However, its amplitude, activity and speed of movement appear to undergo remarkable change as it moves westward. Eastward of about 10° E, its amplitude appears to be small, it yields little rain and it moves rather slowly. But, once it crosses this longitude, its amplitude increases and it moves faster. Also, the amount of rainfall associated with the disturbance appears to increase considerably as it moves over west Africa. As pointed out by Carlson (1969b), there could be several reasons for this change in wave structure and activity, such as meridional coupling of the wave with the west African ‘heat low’, greater convective instability of the lower troposphere, and increased moisture supply from the neighbouring Atlantic ocean. In Fig. 12, we present schematically an idealized model of the structure of the horizontal and vertical circulations and thermal patterns associated with a developing African wave disturbance. The schematics are self-explanatory. They appear to throw light on the physical processes responsible for development of the wave and its westward movement. In the development process, an increased low-level moisture convergence supported by strong upper-level warm divergence leads to strong penetrative convection and condensational heating

TABLE 1

Particulars of the wave disturbances, their source of energy(barotropic and/or baroclinic) at birth, date and place of birth and the date they left the west coast of Africa

Predecessor of hurricane	Source of energy		Date & place of birth	Date left west coast
	Below 600 hPa	Above 600 hPa		
ANDREW(1992)	Baroclinic	Both	10 Aug Sudan	14 Aug
LUIS (1995)	Both	Both	21 Aug Sudan	26 Aug
EDOUARD(1996)	Baroclinic	Barotropic	14 Aug Sudan	19 Aug
ERIKA(1997)	Both	Barotropic	26 Aug Sudan	31 Aug
MITCH(1998)	Both	Barotropic	5 Oct Sudan	9 Oct
CINDY(1999)	Both	Barotropic	13 Aug Sudan	18 Aug
ALBERTO(2000)	Baroclinic	Barotropic	31 Jul Sudan	3 Aug
DEBBY(2000)	Baroclinic	Barotropic	12 Aug Sudan	16 Aug
GORDON(2000)	Both	Barotropic	1 Sep Sudan	4 Sep
KEITH(2000)	Baroclinic	Baroclinic	13 Sep Sudan	16 Sep

to the west of the disturbance center, while increased low-level moisture divergence and upper-level cold convergence leads to strong subsidence and drying up of air to the east. We do not know with certainty what determines the westward movement of the disturbance. If the disturbance is treated as a pure Rossby wave, its phase velocity is westward and it will move rapidly westward in the vertically-averaged basic easterly wind over tropical north Africa. Some past studies (Saha and Saha,1993) have found that although maximum condensational heating occurs in the southwest quadrant of a tropical disturbance, it moves westward or even westnorthwestward. It is likely that increased condensational heating to the southwest of the disturbance center may strengthen the meridional-vertical circulation leading to stronger subsidence and adiabatic warming and rapid fall of surface pressure to the west/westnorthwest of the center. On the other hand, lack of condensational heating and upper-air cold advection may lead to a rapid rise of surface pressure to the east/southeast of the center. When such is the case, an isallobaric gradient across the center will force a westward movement.

8. Findings and conclusion

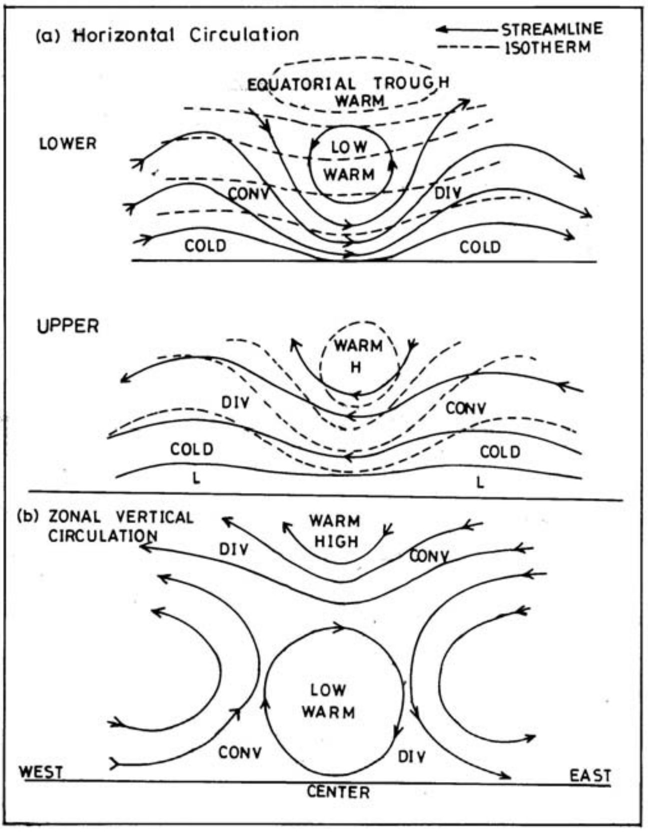
The findings of the present study may be smnmarized as follows:

(*i*) Oceanic and orographic influences on the heat low circulation over tropical north Africa during the northern summer appear to introduce large differences in the structure and properties of the equatorial trough and its related atmospheric circulation between the western and the eastern parts of the continent.

(*ii*) The land-sea thermal contrast over the subtropical belt maintains a zonal stationary wave which frequently interacts with baroclinic waves in midlatitude westerlies moving eastward across southern Europe and adjoining Mediterranean sea. The orography over the east-central part of tropical north Africa appears to produce a zonal stationary wave in the equatorial trough zone between about 10° E and 30° E.

(*iii*) During an in-phase interaction of the subtropical stationary wave with the midlatitude wave, an increase in the equatorward fluxes of heat and momentum leads to the development of the monsoon stationary wave over east central Africa. The increased flux convergence in the trough zone of the stationary wave enhances the dynamic instability of the flow over the region and leads to the formation of a wave disturbance.

(*iv*) A detailed study of ten cases of wave disturbances which later in their life cycles developed into hurricanes over the Atlantic showed that they were all born in the trough zone of the stationary wave over Sudan following interaction of the subtropical stationary wave with midlatitude baroclinic waves.



Figs. 12(a&b). Schematic showing an idealized model of the structure of the horizontal and vertical circulations associated with an African wave disturbance: (a) horizontal circulation (lower and upper levels) and (b) zonal-vertical circulation through the center of the distance. Symbols : H-High; L-Low

(*v*) There appears to be a major structural change when a wave disturbance forms in the ITCZ stationary wave. The area of low-level convergence, upward motion and rainfall shifts from east to west of the wave trough. In the upper troposphere, warm divergence appears to the west of the high pressure ridge and cold convergence to the east. After formation, the disturbance generally moves westward.

(*vi*) The amplitude, speed of movement and activity of an African wave disturbance appear to increase considerably as it moves westward of longitude about 10° E.

In conclusion, we should like to point out that in the present study, we did not consider any possible variation in the fluxes of heat, moisture or momentum from the south to the stationary wave zone, which might have affected the process of development and movement of African waves. Secondly, our selection of ten hurricane cases for study may appear to be rather arbitrary in that there could be many other such cases which could be studied. Also, we did not include any non-hurricane cases. We would urge for consideration of these aspects in any future study.

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