

African monsoons Part 1: Climatological structure and circulation

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सार — अफ्रीका महाद्वीप और उसके समीपवर्ती महासागरों में प्रायः मानसून ऋतु की चरम अवस्था के समय फ़रवरी और अगस्त के महीनों में समय-माध्य मौसम वैज्ञानिक क्षेत्रों की संरचना और विशेषताओं का अध्ययन करने के लिए हाल ही के (1979-1996) एन.सी.ई.पी./एन.सी.ए.आर. पुनः विश्लेषित डाटा सैटों का उपयोग किया गया है। इस महाद्वीप के विभिन्न भागों के कटिबंधीय और दक्षिणी उपखंडों की उर्ध्व संरचना का इसकी समीपवर्ती महासागरी तथा भौगोलिक दशाओं एवं द्रोणियों और रिज का मानसून के बनने और वर्षा के वितरण तथा संबद्ध शुष्क और नम क्षेत्रों पर पड़ने वाले विशेष प्रभाव का पता चलता है। उर्ध्व परिसंचरण से दो गोलाद्वों की उष्णकटिबंधीय मानसून और उपउष्णकटिबंधीय मरुस्थलों के बीच परस्पर आश्रित संबंधों का पता चलता है। इस शोध-पत्र में अफ्रीकी मानसून से संबंधित कुछ प्रमुख विशेषताओं जैसे भूमध्यरेखीय क्षेत्रों में दोहरी द्रोणियों के बनने एवं ऋतुओं के बदलने के अनुसार उनके आकार में आने वाले परिवर्तनों के बारे में चर्चा की गई है तथा विश्व में अन्य किसी स्थान पर इसी तरह की पाई गई भूआकृतियों के साथ तुलना भी की गई है।

ABSTRACT. A recent (1979-1996) NCEP/NCAR reanalysis dataset is utilized to study the structure and characteristics of the time-mean meteorological fields over the continent of Africa and surrounding oceans during February and August when the seasonal monsoons are normally at their peak intensity. The vertical structure, revealed in zonal and meridional sections over different parts of the continent, bring out the dominant influences of the neighbouring oceans and topography in the formation and distribution of monsoon troughs and ridges and associated dry and wet zones. Vertical circulations reveal a symbiotic relationship between the tropical monsoons and the subtropical deserts of the two hemispheres. Some salient features of the African monsoons, such as the formation of double equatorial troughs and their movement following change of season, are discussed and compared with similar features observed elsewhere over the world.

Key words – African monsoon, Climatology, Comparison with other monsoons.

1. Introduction

Africa is a continent with large ecological diversity. Here, on one side, there are the equatorial rainforests and regions of heavy precipitation which sustains life and activities of bulk of the African population and, on the other, there exist the great Saharan and the Namib-Kalahari deserts where little or no rain falls and are therefore, too dry and arid to sustain any large-scale habitation or vegetation. Though the people of Africa have come to live with this diversity the importance of monsoons to import the much-needed rainfall for agriculture and other activities was realised a long time ago. As a result of the several studies undertaken during the last few decades, we have now a better knowledge of

the climatology of Africa including the space-time distributions of climatic elements (Kendrew, 1953; Thompson, 1965; Griffiths, 1972), the atmospheric circulations and flow patterns associated with weather over the different parts of the continent (Soliman, 1958; Johnson and Morth, 1960; Flohn 1960) and the origin, development and movement of disturbances that affect not only the climate of Africa but also occasionally form the starting mechanisms for development of Atlantic hurricanes.

However, notwithstanding commendable progress made in our study of African monsoons, there are a few problem areas which appear to require further study. For example, there remains considerable uncertainty regarding

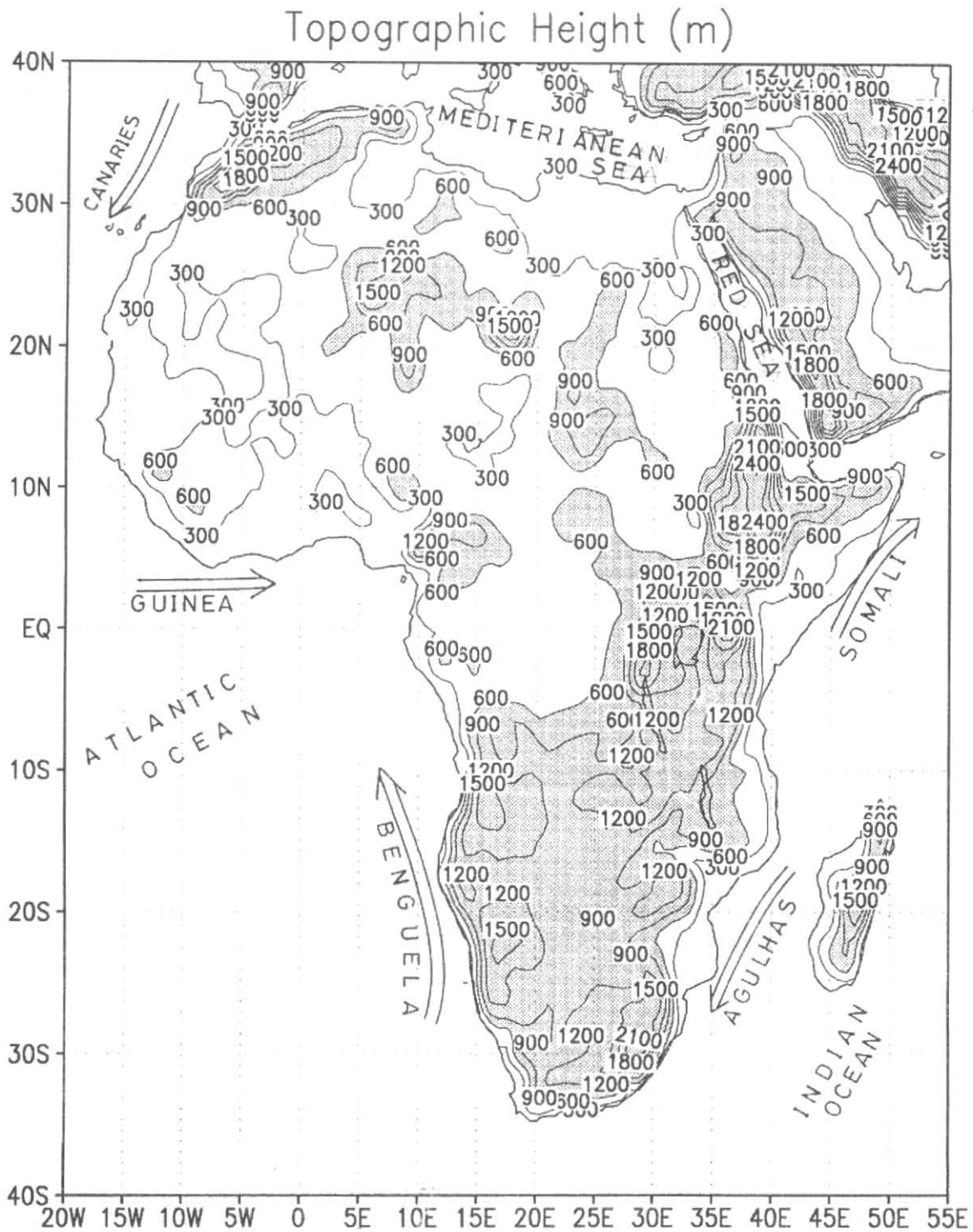


Fig. 1. Topography of Africa and ocean currents around the continent. Height above 500m above sea level are shaded. Double-shaft arrows show directions of ocean currents

the structure and properties of the monsoon troughs that form over different parts of the continent and the adjoining oceans. Some of the specific questions often asked are:

- (i) Are there one or two equatorial troughs over Africa in any season?
- (ii) Do oceans play any role in the formation of troughs and ridges and their seasonal movements?
- (iii) What is the role of orography in monsoon circulation over the continent?
- (iv) Is there any functional relationship between the deserts and the monsoons over the continent?
- (v) How does the African monsoon compare with monsoons over other parts of the globe, such as the Asian and the Australian monsoons?

Such questions call for an in-depth study of the problems with a reliable dataset and analysis. Attempts are made in the present study to look into some of these questions, using an 18 year (1979-1996) mean climatology based on National Centers for Environmental Prediction(NCEP)/ National Center for Atmospheric Research(NCAR) reanalysis (Kalnay *et al.*, 1996). Data used relate to the peak summer monsoon months of February and August over the southern and the northern parts of Africa respectively.

The paper is divided into two parts. Part I deals with the climatology of Africa and discusses some of the salient features of the time-mean meteorological fields over the continent and the surrounding oceans. It examines the vertical structure of the atmosphere over the region with special reference to the formation of troughs and ridges, the influence of ocean currents and topography on tropospheric circulation and formation of dry and wet zones. Some aspects of the vertical circulation which suggest a link between monsoons and deserts are also discussed. Finally, some of the salient features of the African monsoons are compared with their counterparts over some other parts of the globe.

Part 2 looks into the problem of the genesis, development and movement of monsoon disturbances over the African continent.

2. Physical features and environment

Important among the physical factors that appear to have bearing on the climate of Africa are its geographical

location, land-sea configuration, oceanic environment and topography. Though the continent, as a whole, lies across the equator and extends to the subtropical belts of both the hemispheres, it is only the eastern part (east of about 12° E) of the continent that has this latitudinal dimension. The western part of the continent lies between about 5° N and 37° N. Needless to state, because of its geographical location, the eastern part of the continent receives maximum solar radiation throughout the year, half-time over its northern part and half-time over the southern part. The oceanic environment of the continent consists of the Atlantic ocean to the west, the Indian ocean to the east and the Mediterranean Sea to the north. Some minor waterways such as the Red Sea, the Gulf of Suez and the Suez canal form its northeastern boundary with Asia. An important aspect of Africa's oceanic environment is the presence of cold and warm ocean currents that condition the air mass flowing over them through air-sea interaction. These include the cold Benguela current of the southern Atlantic which causes intense upwelling along the coast of southwestern Africa and the cold Canaries current of the northern Atlantic that washes the shores of northwestern Africa. These ocean currents form part of the subtropical anticyclones of the two hemispheres. A warm ocean current flows along the Guinea coast during both February and August. The warm Agulhas current of the Indian ocean flows by the side of southeastern Africa along the Mozambique channel during southern summer. During the northern summer, the cold Somali current of the Arabian Sea causes intense upwelling along the coast of eastern Africa. Africa has a very uneven topography, especially between its western and eastern parts. Barring a few high grounds and isolated low mountains near its southern and northern coasts, western Africa has few orographic barriers. By contrast, eastern Africa from Ethiopia to South Africa is highly mountainous. The average altitude of the mountains ranges that lie between about 30° E and 35° E may be around 2-3 km above MSL. Most of the central and western parts of southern Africa consist of the high plateaux of Namibia, Botswana and Angola, the average height of which may be about 1.5 to 2.0 km above NSL. To the north of these plateaux and west of the eastern mountains lies the vast Congo-Zaire river basin of very low elevation which extends northward across the equator. A map showing the above-mentioned physical features and environment is presented in Fig. 1.

3. Climatological fields at the lower boundary

The climatological fields over Africa and its surrounding oceans, showing the distributions of temperature pressure/height, wind, humidity and precipitation at surface, during February and August, as revealed by reanalysis, are as follows:

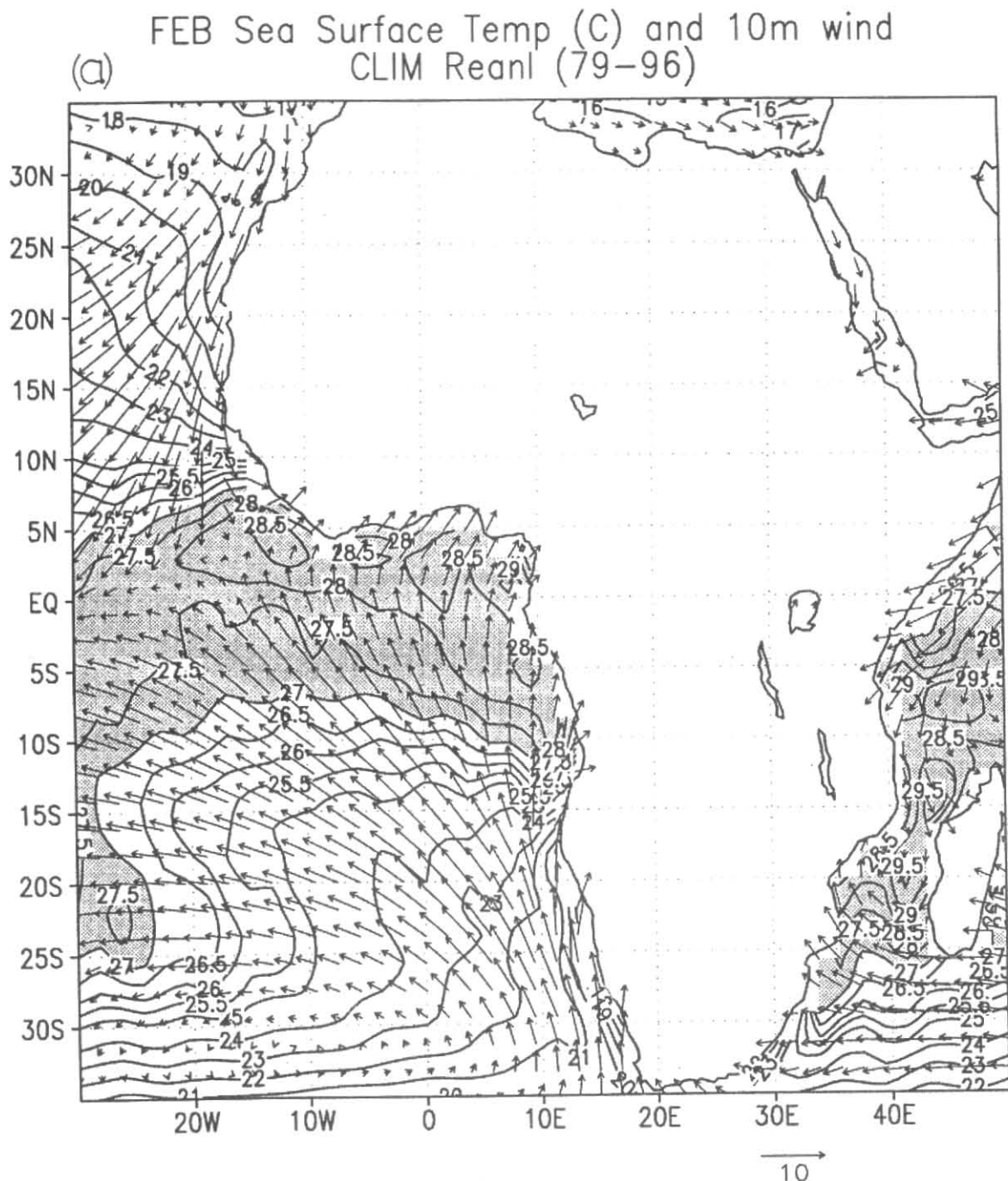
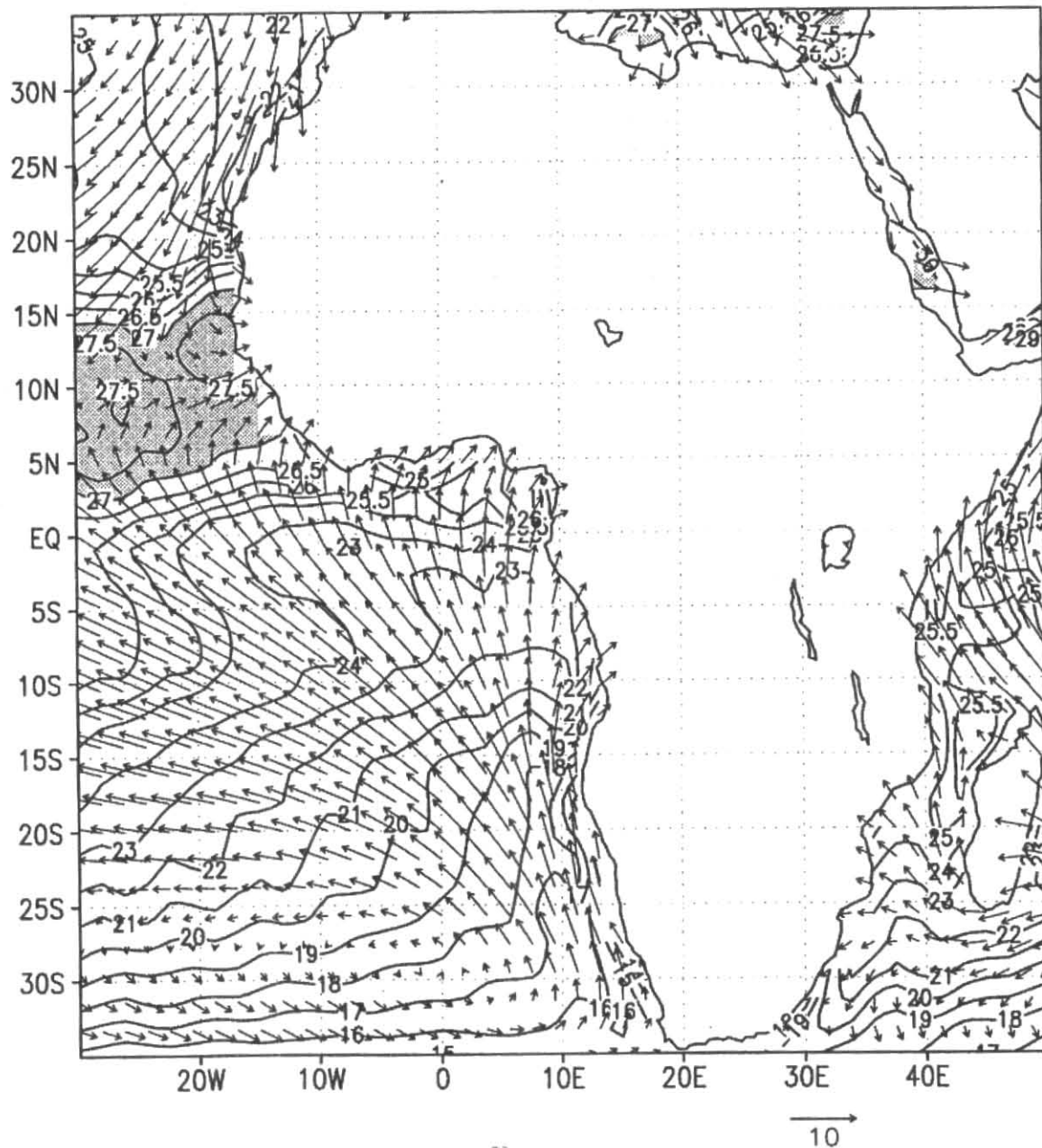


Fig. 2(a). Mean sea surface temperature ($^{\circ}\text{C}$) and 10m-wind (ms^{-1}) over the oceans around Africa during February

(i) *Sea surface temperature (SST)*

The distributions of sea surface temperature around Africa along with the 10m height winds above the sea surface during February and August are shown in Figs.2

(a&b) respectively. The outstanding features of the distributions are the following: In February [Fig. 2(a)], extremely cold SSTs appear over the Atlantic near the coasts of southwestern and northwestern Africa with a warm region in between near the equator. The

(b) AUG Sea Surface Temp (C) and 10m wind
CLIM Reanal (79-96)Fig. 2(b). Mean sea surface temperature ($^{\circ}\text{C}$) and 10m-wind (ms^{-1}) over the oceans around Africa during August

Mediterranean Sea to the north is cold. In the Indian ocean, a warm regime appears near the coast of southeastern Africa around the island of Madagascar. In August [Fig. 2(b)], there appears to be a general northward shift in the locations of the cold and warm

SSTs over the Atlantic. The cold SST near the southwestern coast of Africa now appears to have intensified and extended to the equator or even beyond. The warm belt over the equatorial Atlantic now lies between 5°N and 10°N . The cold SSTs off the coast of

(a) FEB Temp 925 hPa (C) CLIM Reanl (79-96)

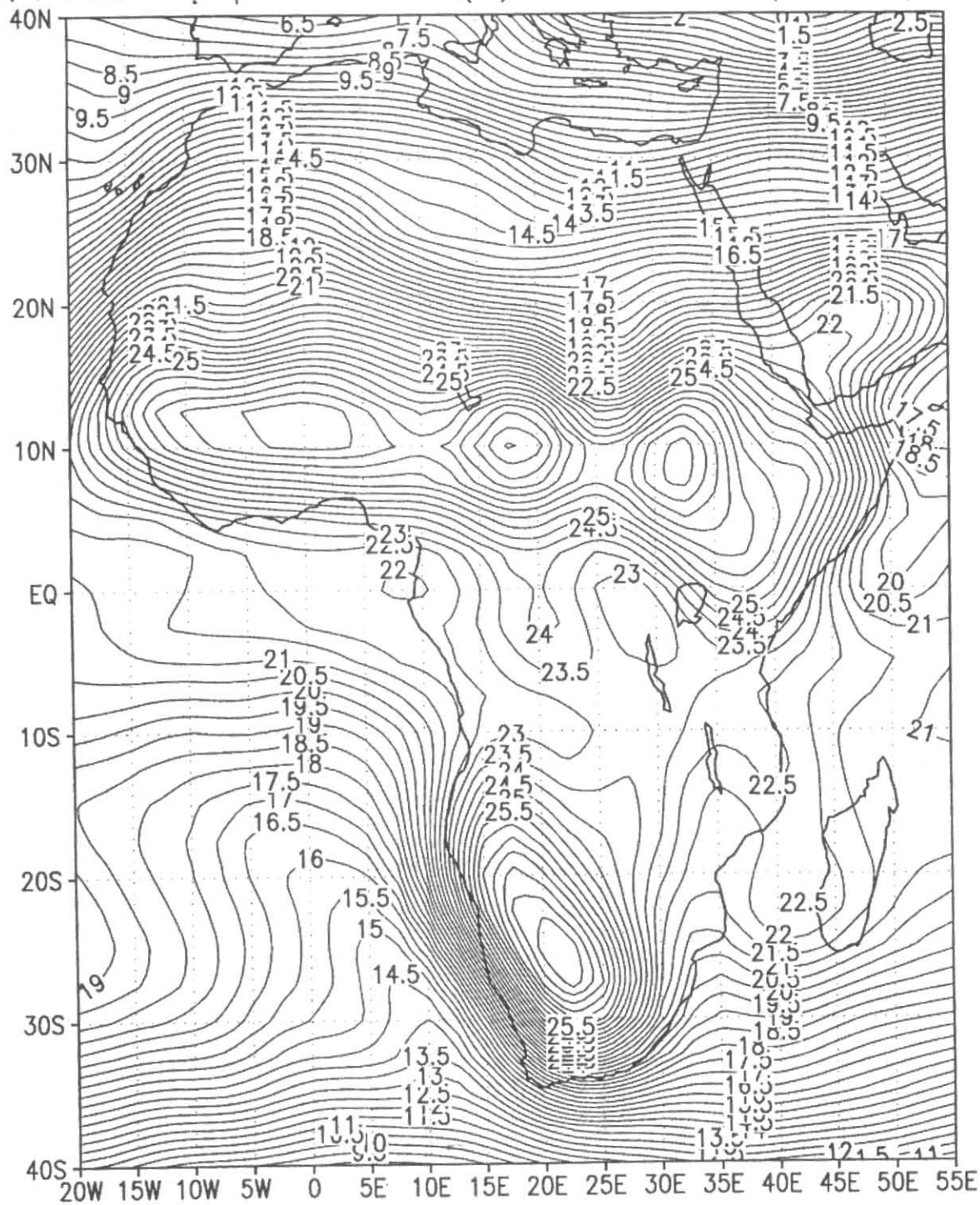


Fig. 3(a). Mean temperature (°C) distribution at 925 hPa over Africa and surrounding oceans during February

(b) AUG Temp 925 hPa (C) CLIM Reanal (79-96)

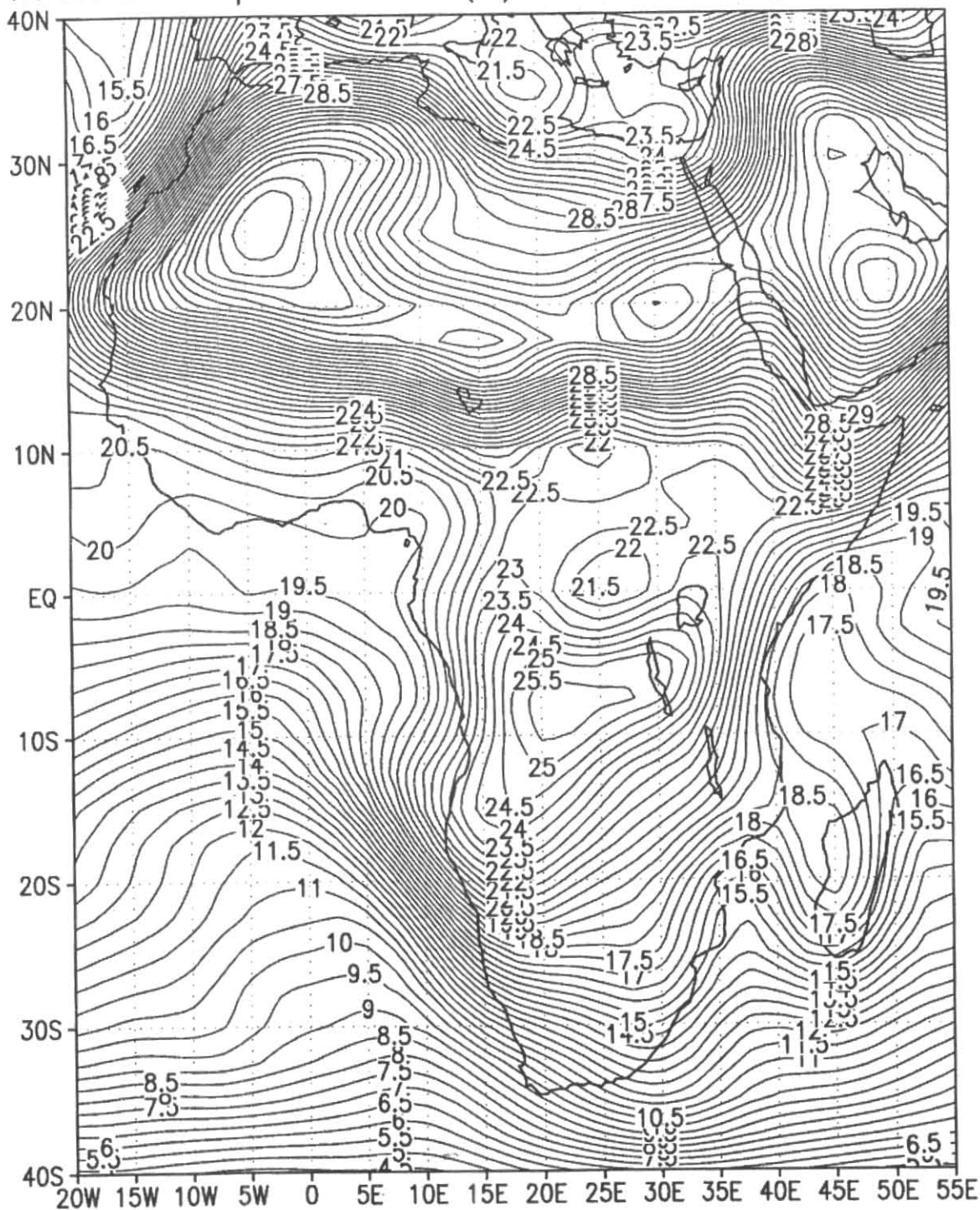


Fig. 3(b). Mean temperature ($^{\circ}\text{C}$) distribution at 925 hPa over Africa and surrounding oceans during August

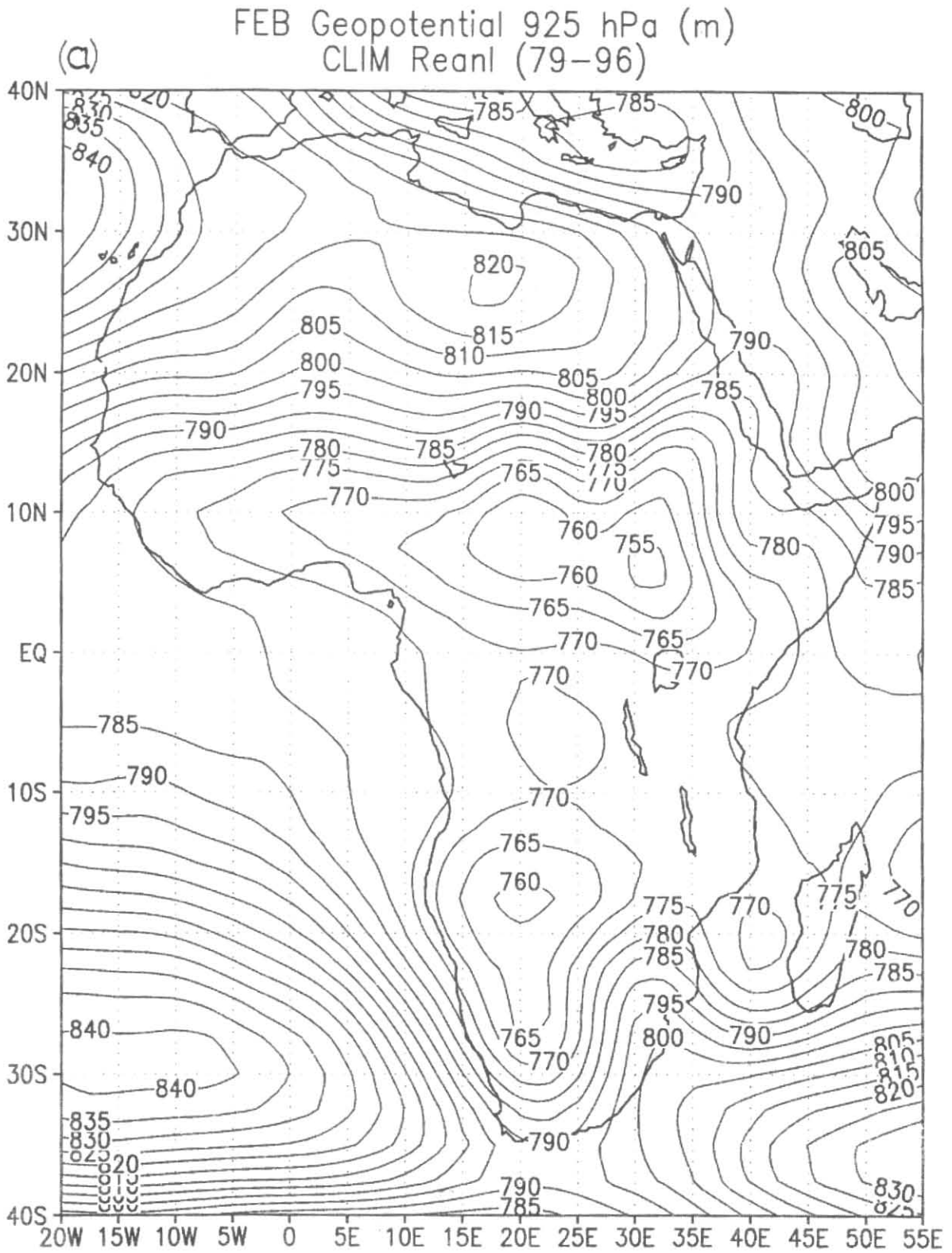


Fig. 4(a). Same as in Fig.3(a), except for isobaric height (gpm)

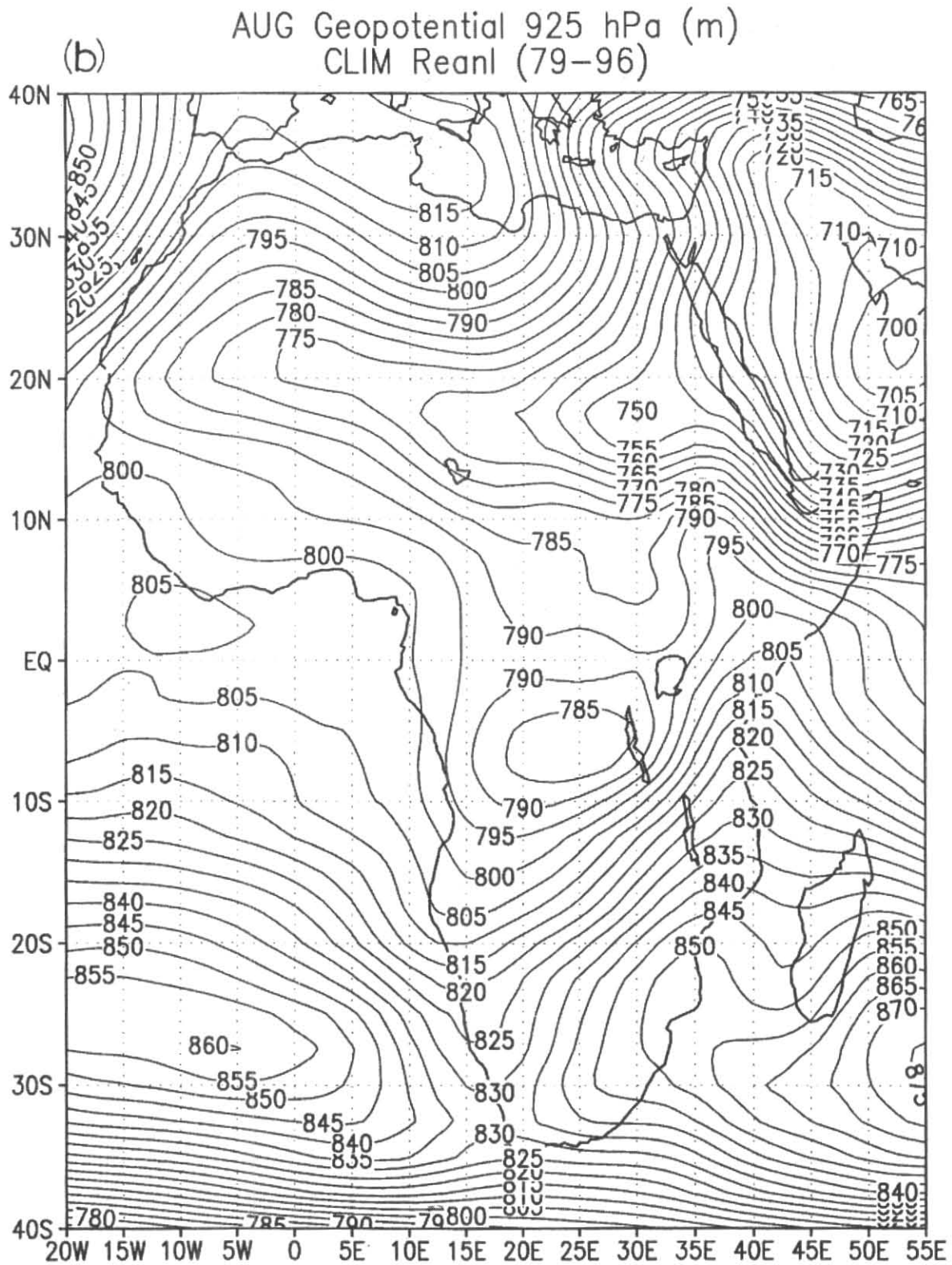


Fig. 4(b). Same as in Fig.3(b), except for isobaric height (gpm)

(a) FEB Wind 925 hPa (m/sec) CLIM Reanal (79-96)

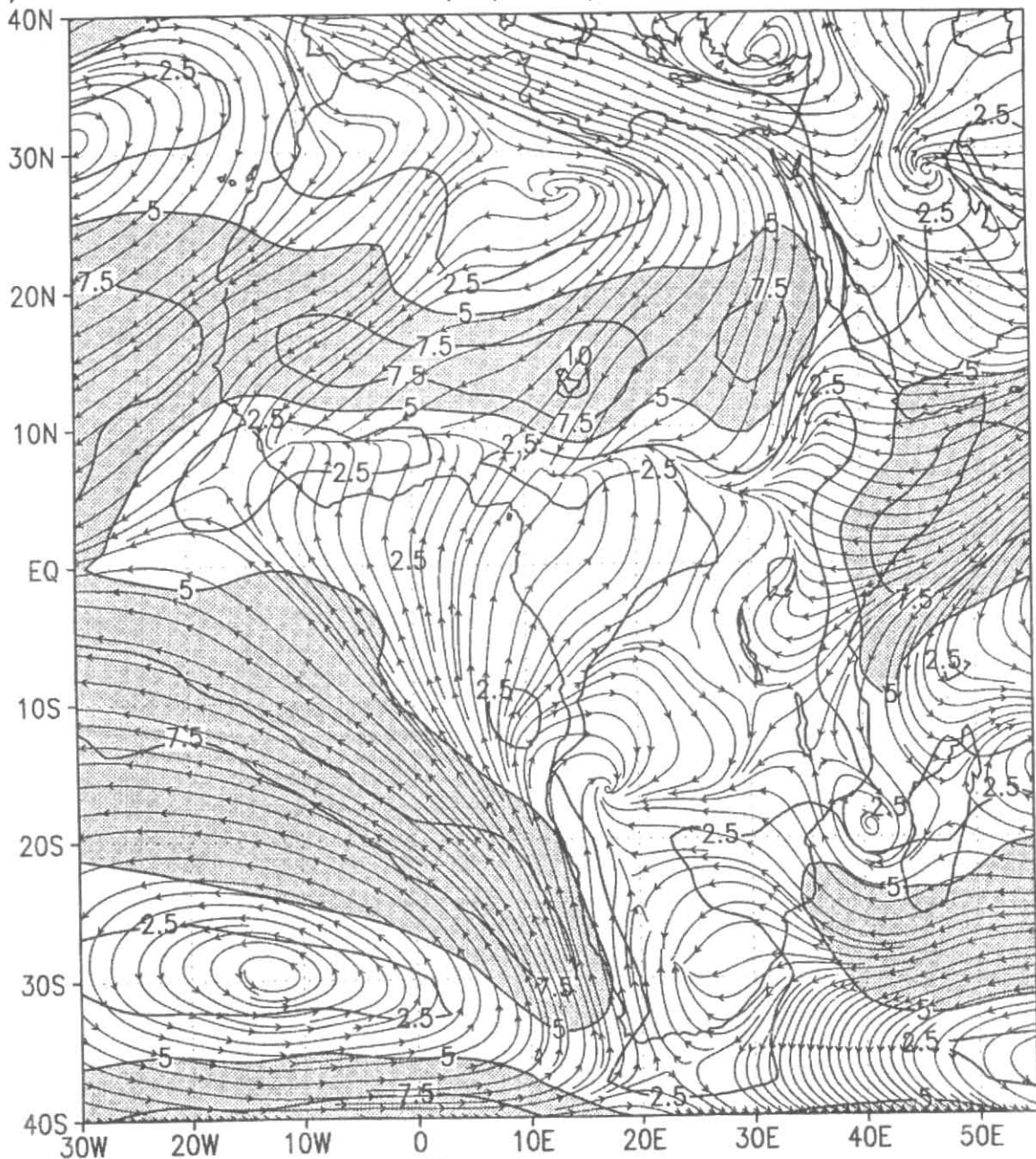


Fig. 5(a). Same as in Fig. 3(a), except for streamline-isotachs (ms^{-1})

northwestern Africa persist. The Mediterranean Sea is relatively warm. The warm area near the coast of southeastern Africa has disappeared. A new area of cold SSTs appears near the Somali coast over the western Indian ocean.

(ii) *Temperature, pressure/height and wind*

In view of the highly uneven topography of Africa, the fields of these variables are presented at 925 hPa, a pressure surface about 1 km above m.s.l., in Figs. 3, 4 and

(b) AUG Wind 925 hPa (m/sec) CLIM Reanal (79-96)

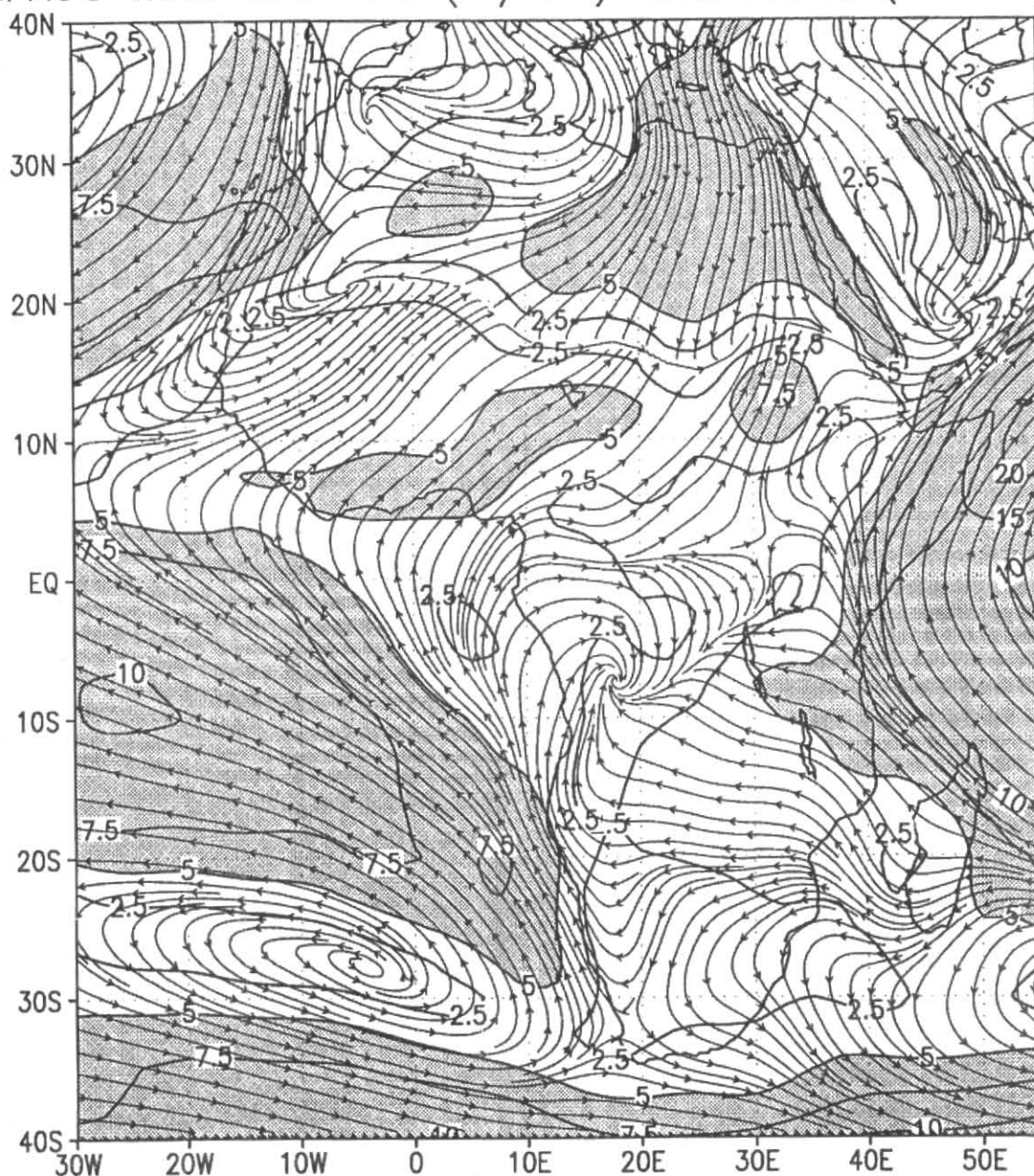


Fig. 5(b). Same as in Fig. 3(b), except for streamline-isotachs (ms^{-1})

5 respectively for the months of (a) February and (b) August.

The climatological fields presented in Figs. 3(a&b), 4(a&b), and 5(a&b) show significant seasonal changes in their locations and intensities over both the African continent as well as the surrounding oceans. While there

appears to be a general northward shift as the season changes from February to August, the changes appear to be more complex over the continent than over the oceans. In February with the Sun in the southern hemisphere, a series of well defined 'heat low' circulations develops over southern Africa and adjoining southern Indian ocean between about 15° S and 20° S. An intense high pressure

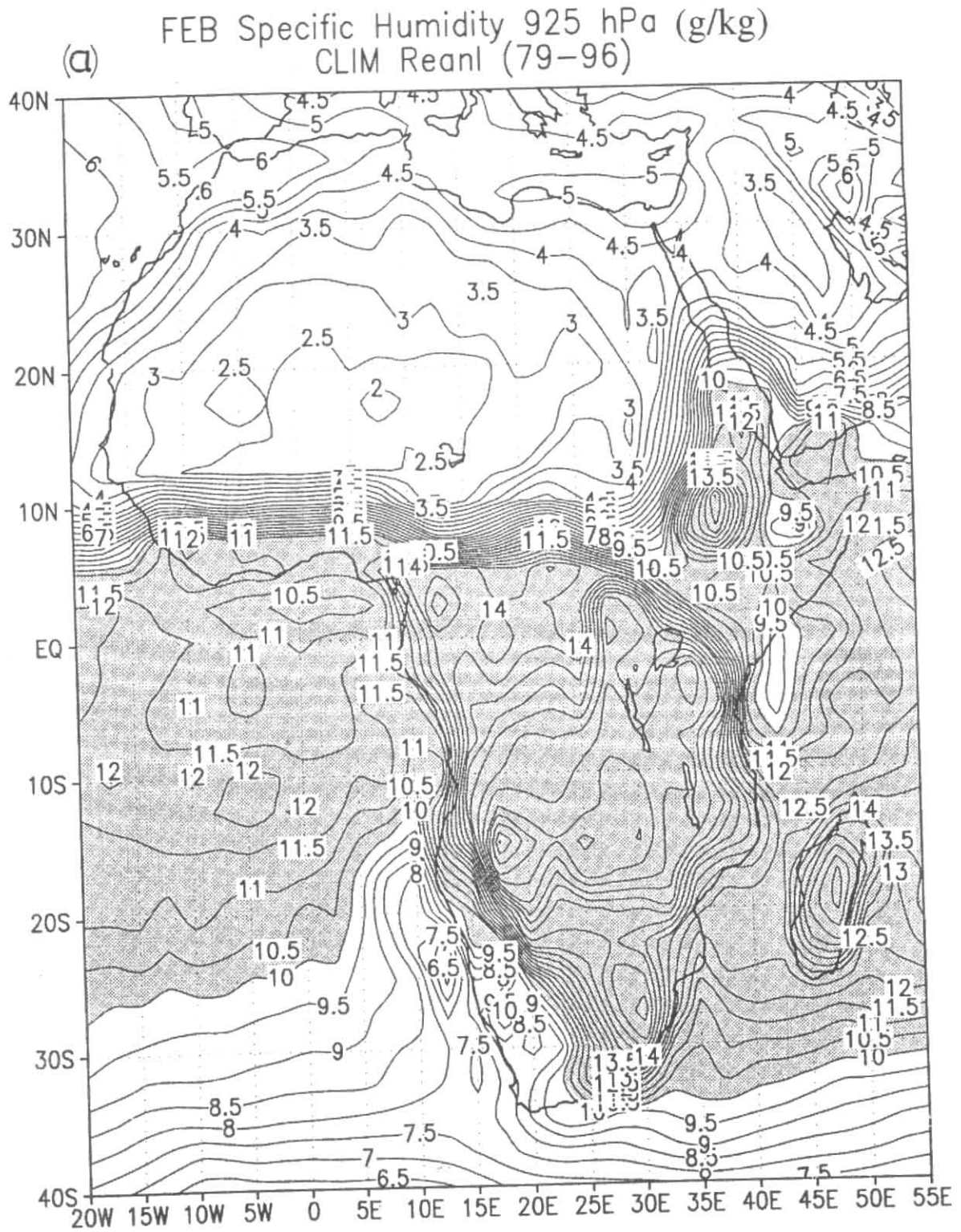


Fig. 6(a). Same as in Fig.3(a), except for specific humidity (g/kg)

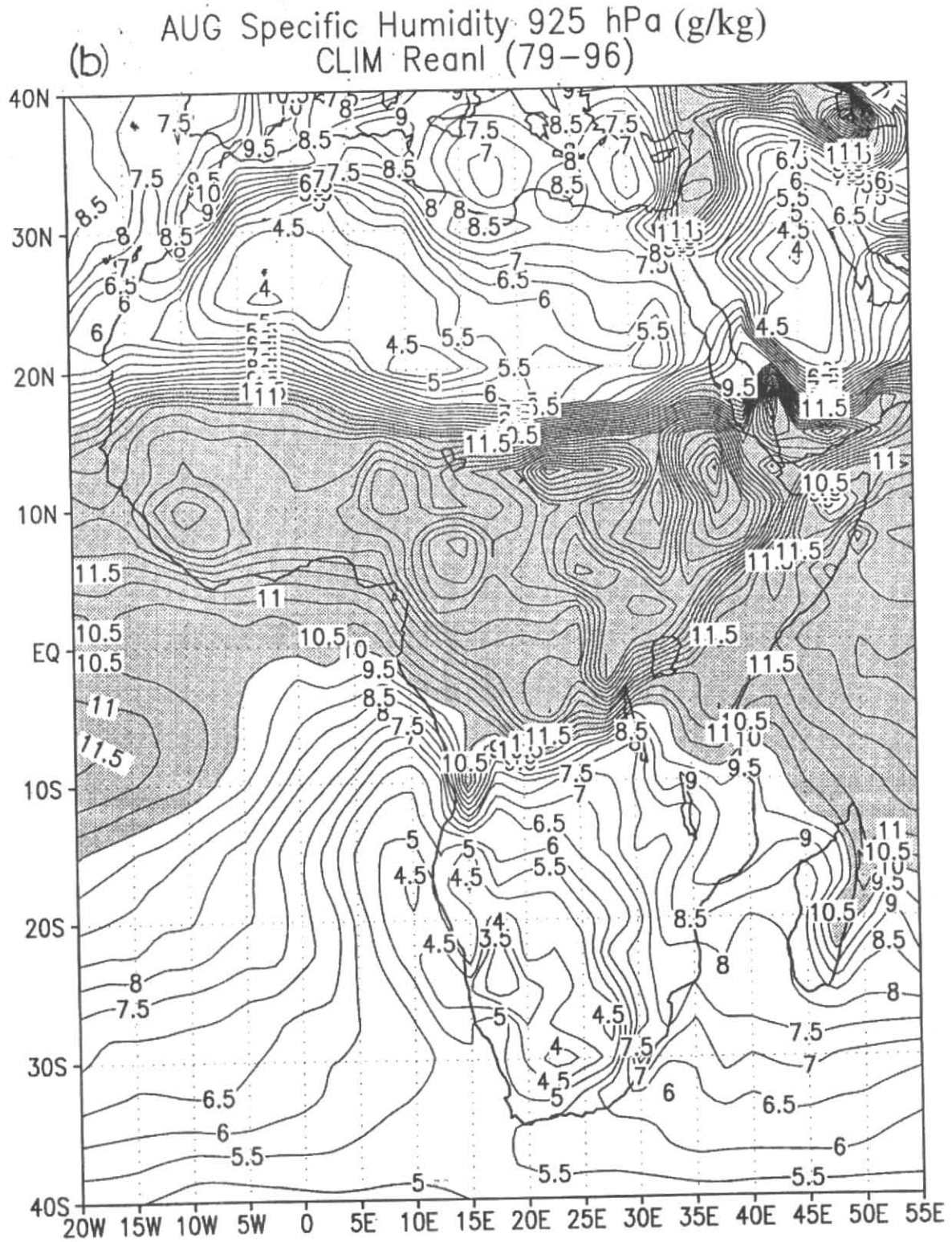


Fig. 6(b). Same as in Fig.3(b), except for specific humidity (g/kg)

(a) FEB Precipitation (mm/day) CLIM Reanal (79-96)

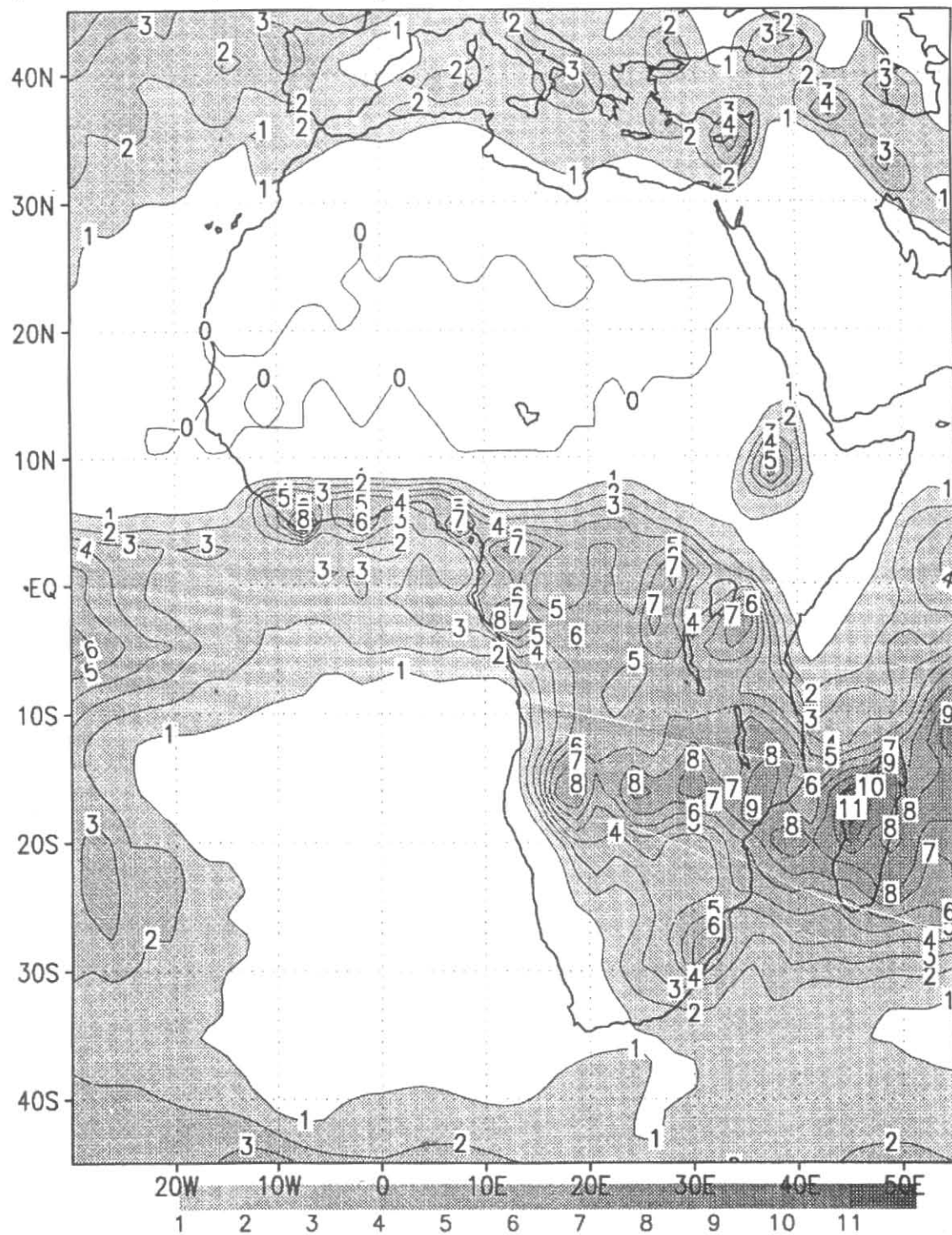


Fig. 7(a). Same as in Fig.3(a), except for precipitation (mm/day)

(b) AUG Precipitation (mm/day) CLIM Reanal (79-96)

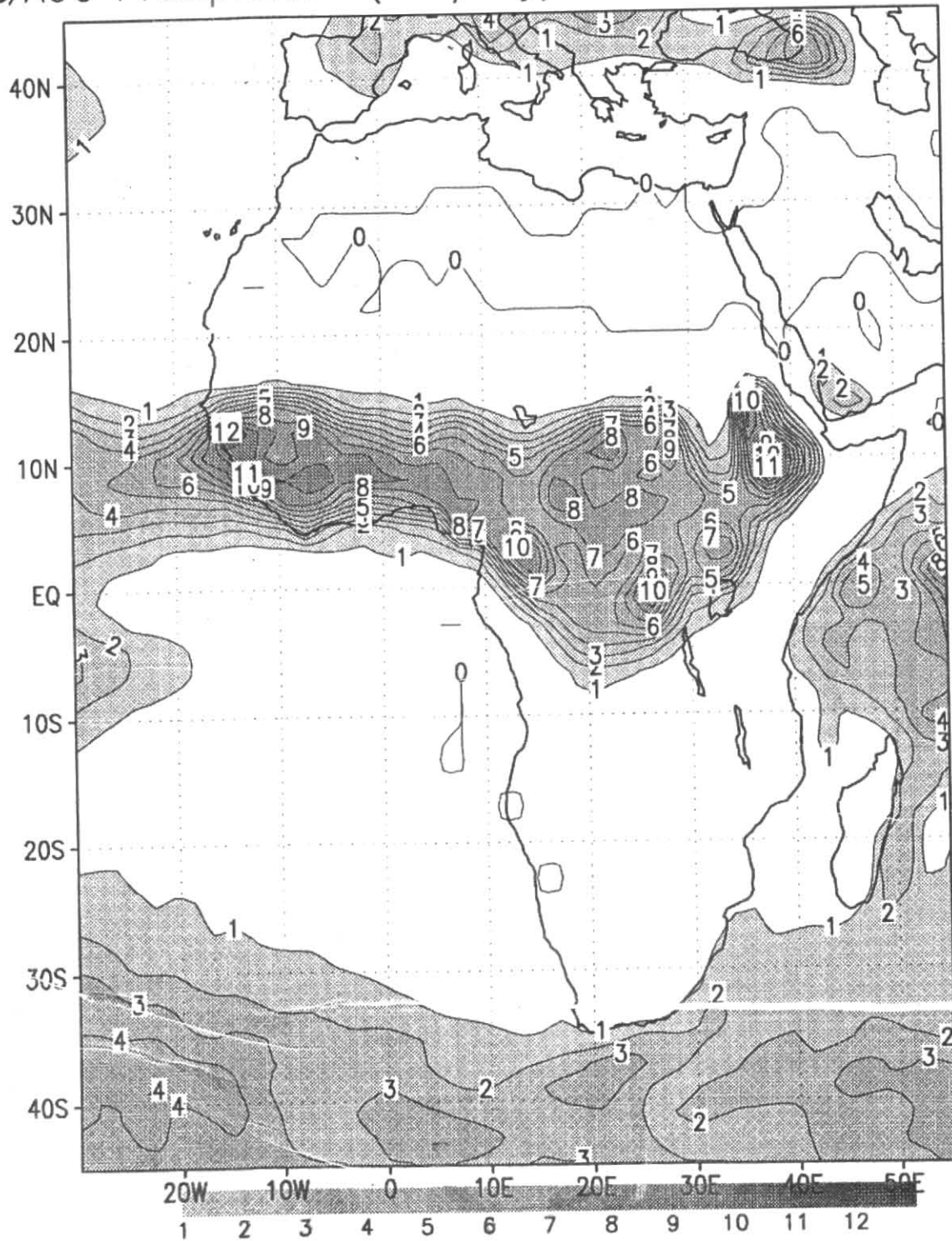


Fig. 7(b). Same as in Fig. 3(b), except for precipitation (mm/day)

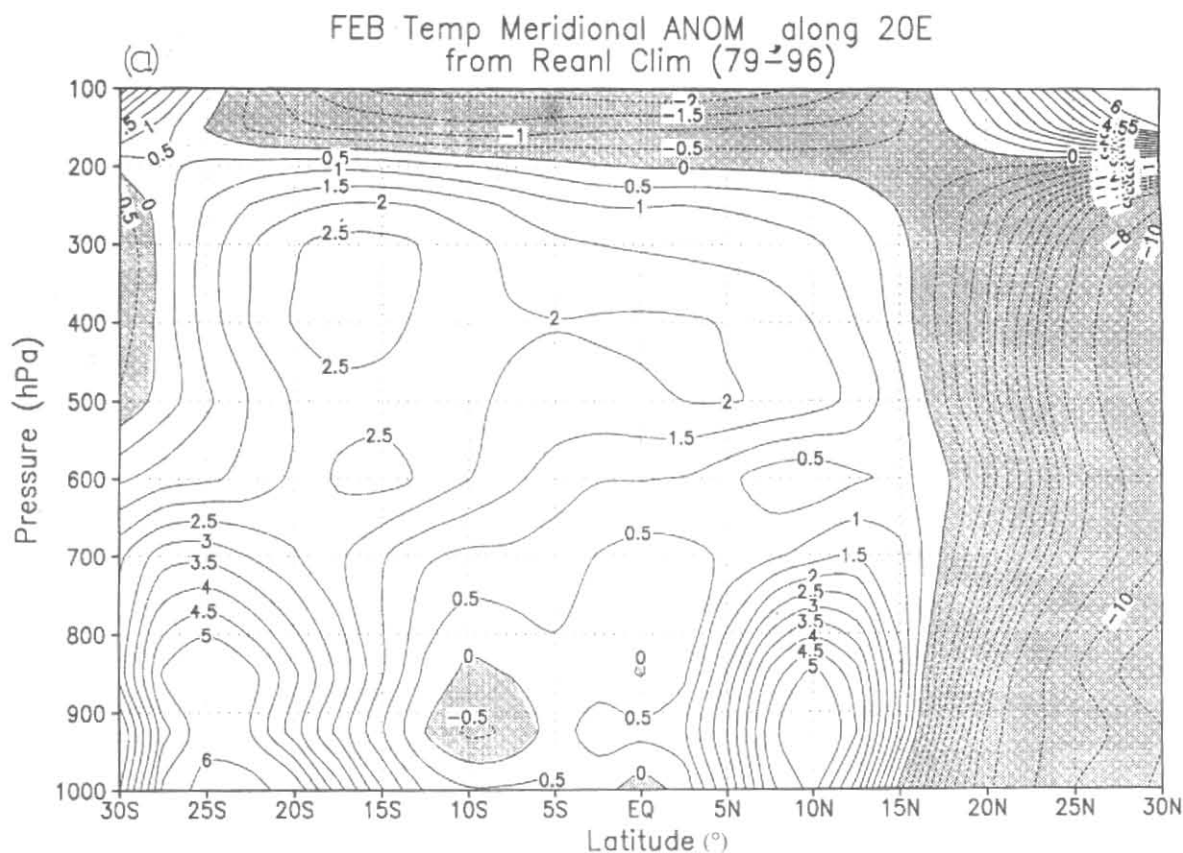


Fig. 8(a). Meridional-vertical section showing meridional anomaly (deviation from meridional mean) of temperature ($^{\circ}\text{C}$) along 20° E longitude during February

area associated with strong northeasterly trades appears over the subtropical belt of northern Africa. However, an interesting fact is that in this month a 'heat low' circulation with well-marked convergence of the trades of the two hemispheres also appears to the north of the equator along about 10° N. Thus, two 'heat lows' are located, one on either side of the equator and are separated from each other by a wedge of 'cold high' pressure ridge located between the equator and about 10° S. Over the Atlantic ocean, the NE and the SE trades of the subtropical anticyclones meet directly along a warm equatorial trough of low pressure along about 5° N. In the Indian ocean, besides a 'heat low' circulation over the Mozambique channel, a cyclonic circulation also appears in a warm zone northeast of Madagascar. As the season changes from February to August, the southern hemisphere 'heat lows' weaken or disappear. In fact, it is only the 'heat low' over the western part of southern Africa that survives and moves equatorward to be located between 5° S and 10° S. On the other hand, the northern hemisphere 'heat low' circulation intensifies and its

trough moves northward to a latitude between about 20° N and 25° N. Thus, in August also, two 'heat lows' appear over continental Africa, one on either side of the equator, and they are separated by a ridge of 'cold high' pressure lying between the equator and about 10° N. Over the Atlantic ocean, the subtropical anticyclonic circulations on both sides of the equator strengthen and move northward. As a result, the cold Benguela current which forms part of the southern hemispheric circulation pervades the whole southeastern Atlantic and, even before reaching the equator, branches off in two directions, one veering eastward to form equatorial westerlies over central and equatorial Africa and the other turning westward to cross the equator and converge into the warm monsoon trough over western Africa and warm equatorial trough over the Atlantic along about 10° N. Thus, in both the seasons, it is the cold equatorial westerlies diverging from the Benguela ocean current area which appear to provide the main monsoon air currents, as southwesterlies to northern Africa and as northwesterlies to southern Africa.

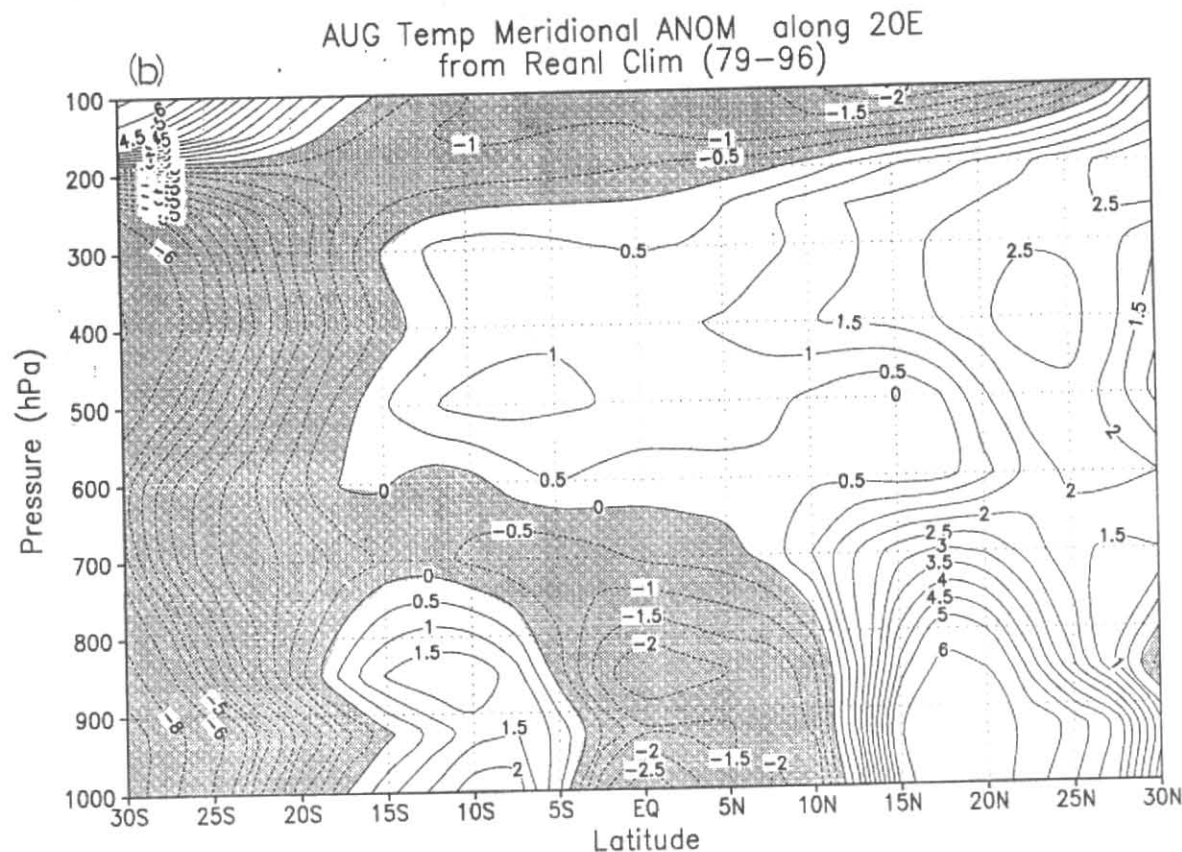


Fig. 8(b). Meridional-vertical section showing meridional anomaly (deviation from meridional mean) of temperature ($^{\circ}\text{C}$) along 20°E longitude during August

(iii) Specific humidity

The distributions of moisture over Africa and the surrounding oceans for February and August are shown in Figs. 6 (a&b) respectively. The salient features are the following:

In February, the continent of Africa north of about 10°N appears to be extremely dry with humidity values falling to about 2 g/kg over the Saharan desert. However, a localized region of high humidity exceeding even 15 g/kg appears over the eastern mountains of Ethiopia. In general, equatorial and southern parts of Africa appear to be very humid. A humidity maximum of 19.5 g/kg appears over Angola and another of 17.5 g/kg over equatorial east Africa. Humidity over the Atlantic ocean appears to be generally less than that over many parts of Africa at 925 hPa . A maximum of about 12 g/kg appears over the central and western parts of the southern Atlantic. This may be compared with an extremely dry region off the coast of Namibia where a humidity as low as 6.5 g/kg

is registered. However, relatively higher humidity appears over the Indian ocean off the coast of Mozambique with a maximum of 16.5 g/kg centered over Madagascar.

In August, there appears to be a general northward shift of the humidity fields like the fields of the other variables. A belt of high humidity with a maximum of about 14.5 g/kg now appears between the latitudes 5°N and 15°N . Northward of this belt, the humidity drops rapidly to a value of about 4 g/kg over the Saharan desert. South of the equator, humidity values are high between the equator and about 5°S with a maximum of about 14 g/kg located over the eastern part of Zaire. Southward of this belt, humidity drops rapidly to reach a minimum of about 3.5 g/kg over south Africa- Namibia region.

Over the Atlantic, the warm equatorial trough located north of the equator appears to have the highest humidity of 12.5 g/kg with values decreasing both northward and southward. The humidity values are generally low along the Benguela current flowing off the

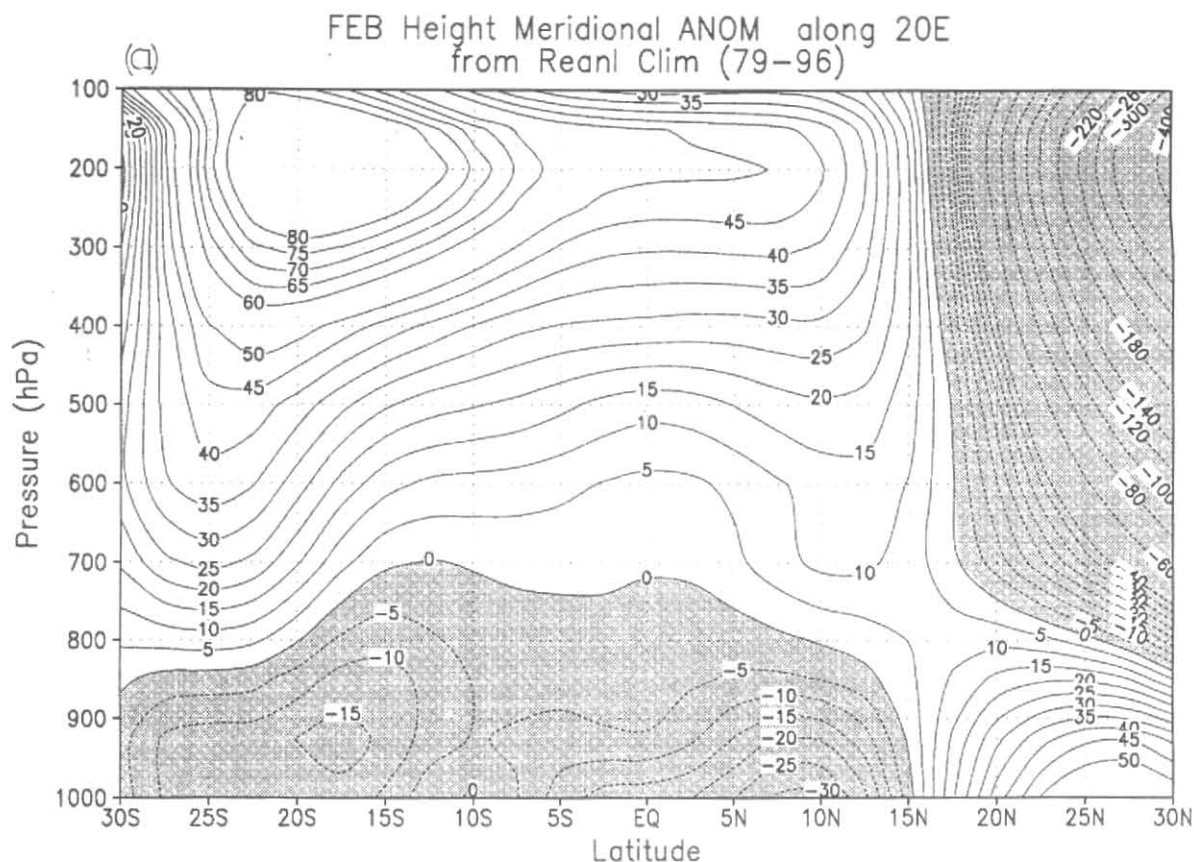


Fig. 9(a). Same as in Fig. 8(a), except for height (gpm)

southwestern coast of Africa. The Indian ocean off the east coast of Africa appears to be relatively a little more humid but here also a maximum of about 13 g/kg may be found a few degrees on either side of the equator.

(iv) Precipitation

The climatological distributions of precipitation over Africa and neighbouring oceans are presented in Figs.7 (a&b) for February and August respectively. In February, the main precipitation belt north of the equator is along the southern coast of western Africa with amount of precipitation decreasing sharply north of about 7° N. In the southern hemisphere, the main precipitation belt appears between the equator and about 20° S with a maximum of about 8 mm/day between about 10° S and 20° S. But a rainy area with a maximum of 5-7 mm/day also appears in a narrow belt north of the equator over Congo, Zaire and neighbouring Uganda. It is noteworthy that the maximum precipitation belt over southern Africa extends eastward to join up with an area of moderate to

heavy precipitation over the southwestern Indian ocean with a maximum of about 10 mm/day over Madagascar. A localized area of light to moderate rainfall appears over the Ethiopian highlands. Elsewhere over the continent and surrounding oceans there is little rain in February. Even in the warm equatorial trough over the Atlantic, the registered rainfall amount hardly reaches 3 mm/day. In August, a clear northward shift of the rainbelts is noticeable. The belt of heavy rain along the southern coast of west Africa now lies between the coast and 15° N with a maximum fall of about 10-12 mm/day along about 10° N. The belt appears to extend eastward all the way to Ethiopia where some of the heavier falls are registered in the mountainous regions of Ethiopia, Uganda and Zaire. The belt of heavy rain over the southern part of west Africa also appears to extend westward over the equatorial Atlantic ocean and join up with the rainbelt associated with the warm equatorial trough along 10° N. We checked the reliability of the above-mentioned distributions of the model-generated rainfall by comparing them with those of observed (simulated) rainfall reported by several workers

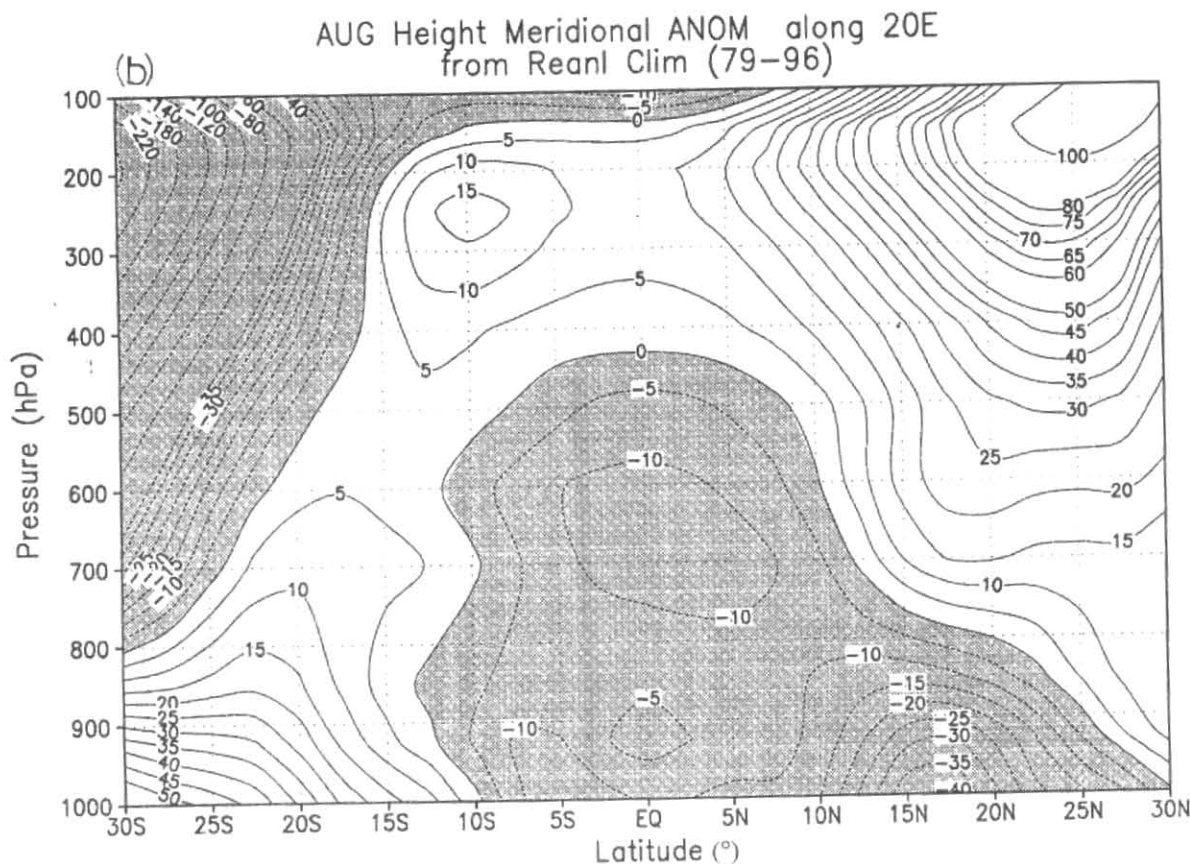


Fig. 9(b). Same as in Fig. 8(b), except for height (gpm)

(Xie and Arkin, 1996) and found that the agreement between the two was close, except over a few data-sparse areas such as oceans where the amounts only differed at a few locations.

4. Upper-air structures—vertical sections

We studied the upper-air fields over Africa and surrounding oceans at all the standard pressure surfaces, but are unable to show them all for lack of space. We, therefore, decide to present their essential features only in vertical sections along a few selected meridians representing broad longitudinal bands over the region. In this way, we could study the structure of the trough-ridge system and other related parameters over the different parts of the continent. The meridians selected are: 35° E for eastern Africa, 20° E for central Africa and the Greenwich for western Africa. We also studied the vertical structure of the equatorial trough zone over the Atlantic ocean along 20° W. However, lack of space does not permit us to present the vertical structure of the fields

of all the variables along all the selected meridians. We, therefore, show in Figs. (8-10) the vertical profiles of the meridional anomaly (departure from the meridional mean) of the fields of temperature, isobaric height and specific humidity respectively during (a) February and (b) August along 20° E only, a meridian which passes through the central parts of Africa. Figs. (8-10) would appear to show the following:

(i) Temperature [Figs. 8(a&b)]

In February Fig.8(a), two warmest anomalies appear in the lower troposphere, one in the northern hemisphere at about 10° N and the other in the southern hemisphere at about 25° S, with a cold anomaly in between at about 10° S, all extending vertically to about 650 hPa. A warm anomaly appears between about 15° S and 20° S in the upper troposphere of the southern hemisphere between about 450 hPa and 300 hPa. Very cold anomalies appear in the northern hemisphere to the north of about 15° N from surface to about 200 hPa. In August, there is a

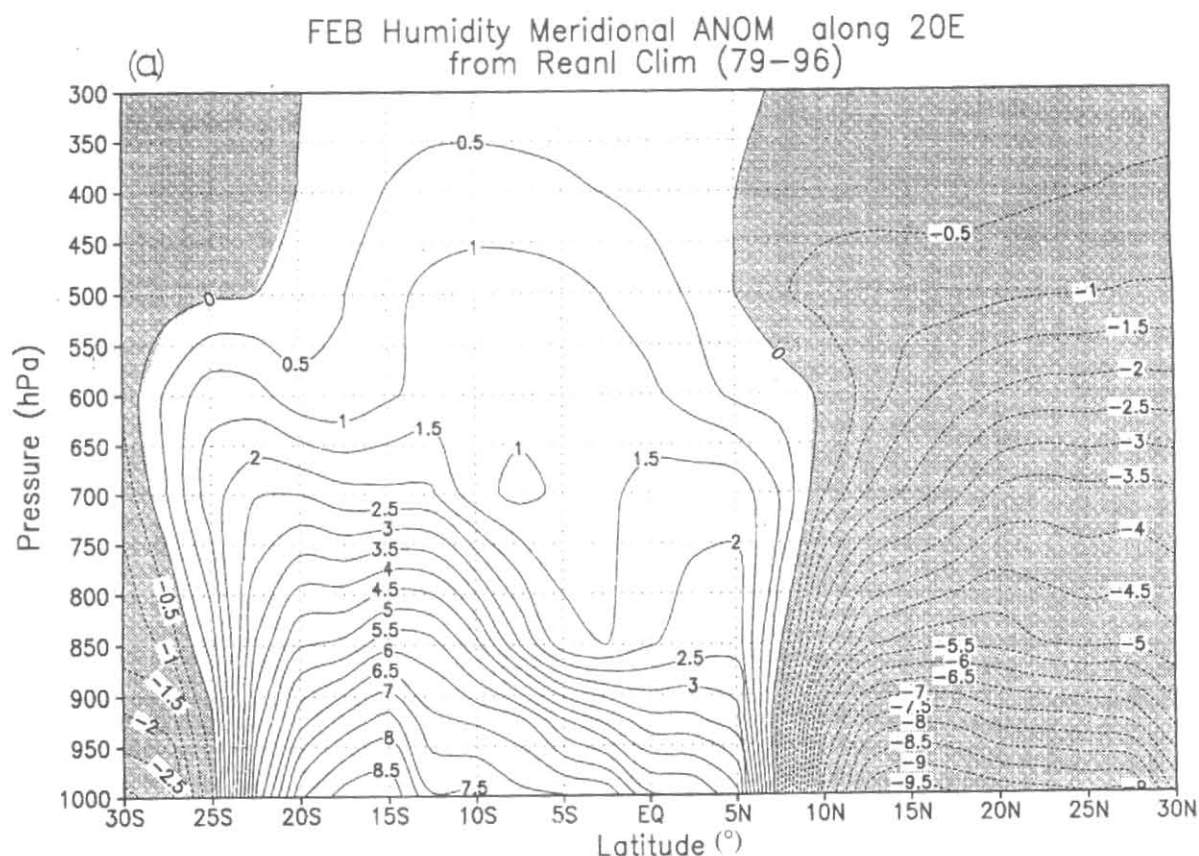


Fig. 10 (a). Same as in Fig.8(a) except for Specific humidity (g/kg)

general northward shift of the warm and cold anomalies. The warmest anomalies in the lower troposphere are now located at about 20° N and 10° S with the equatorial cold region between 5° S and 10° N, all extending to about 650 hPa. The troposphere to the south of about 20° S appears to be very cold.

(ii) *Isobaric height [Figs. 9(a&b)]*

The height anomaly profile in February Fig.9(a) shows the locations of two lower-tropospheric troughs, one in the northern hemisphere at about 10° N and the other in the southern hemisphere at about 20 - 25° S, both tilting equatorward with height up to about 700 hPa. A weak ridge of height anomaly appears around 10° S. The anomaly field appears to reverse with height. In August Fig.9(b), the anomaly fields at all levels of the atmosphere appear to have shifted northward. The lower-tropospheric trough in the northern hemisphere is now between 15° N and 20° N and that in the southern hemisphere lies around 5° S, both tilting southward with height. A weak ridge of

height anomaly appears over the equator. Here, also, there appears to be a general reversal of the anomaly field with height.

(iii) *Specific humidity [Figs.10(a&b)]*

The February humidity anomaly field [Figs. 10(a&b)] shows concentration of high humidity between about 7° N and 25° S, with two maxima, the stronger in the southern hemisphere at about 15° S and a weaker one in the northern hemisphere at about 5° N. In August [Fig.10(b)], the high humidity belt appears to have shifted northward and now lies between about 10° S and 15° N. The northern-hemispheric maximum lies between 5° N and 15° N, while the maximum south of the equator lies between the equator and 5° S.

5. Vertical circulations

By suitably combining the horizontal and vertical components of the wind along a few selected latitudes and

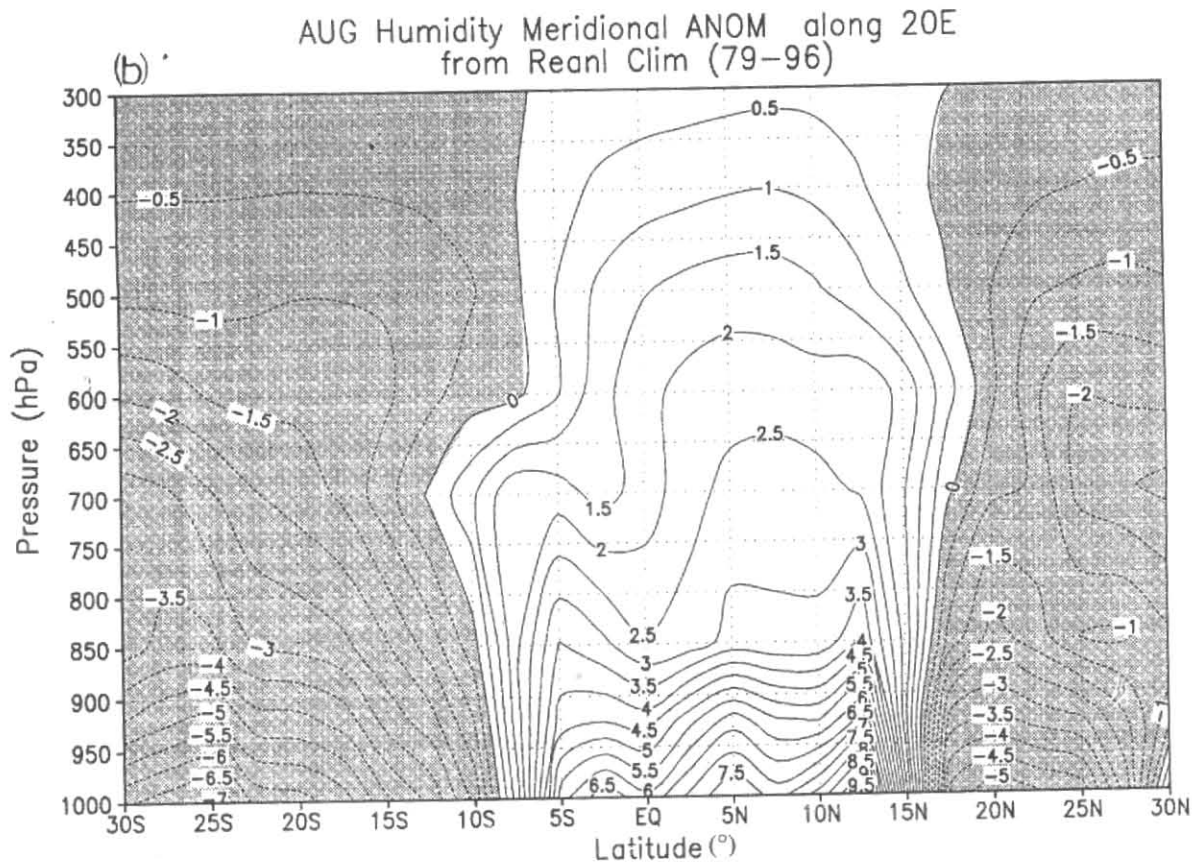


Fig. 10(b). Same as in Fig.8(b) except for Specific humidity (g/kg)

longitudes, we constructed approximate resultant streamlines to study the vertical circulations along those latitudes and longitudes. Since the average vertical velocity component of the wind is nearly two orders of magnitude smaller than the horizontal components (u, v), we multiplied the computed vertical velocity by a factor of 100, before combining with the horizontal components. From amongst the several latitudinal and longitudinal sections studied by us, we present only three, one zonal along the equator and the other two meridional along 20° E and the Greenwich meridian, in Figs. 11, 12 and 13 respectively, during (a) February and (b) August. Together, they appear to furnish a wealth of information regarding the various aspects of the monsoon circulation over Africa as pointed out below:

(i) *Zonal circulations along the equator [Figs. 11(a&b)]*

The February equatorial section Fig. 11(a) shows how the easterlies below about 700 hPa descend strongly over the southeastern Atlantic ocean over the cold

Benguela current region from where the low-level equatorial westerlies start their journey inland. The equatorial westerlies confined to a layer below about 800 hPa generally descend over the land, except for weak ascents over the Gabon coast and near 25° E, till they meet the mountains of eastern Africa between 30° E and 35° E where they also meet the easterlies from the Indian ocean side to rise strongly over the mountains. This orographic lifting of moist oceanic air carried by the westerlies and the easterlies leads to heavy precipitation over the mountainous region of eastern Africa, noted in section 3. It is no wonder, therefore, that most of the largest lakes of Africa, such as Lake Victoria, Lake Albert and Lake Edward in the equatorial region and so many others to both north and south, such as Lake Tana in Ethiopia. Lake Tanganika and Lake Nyasa in the south are located in the cradles of these mountains. Heavy rainfall on these mountains feeds such mighty rivers as the Nile which flows through the desert region to the north and the Congo-Zaire which flows westward to the Atlantic ocean. These rivers and their tributaries carry large volumes of water required for irrigation and other

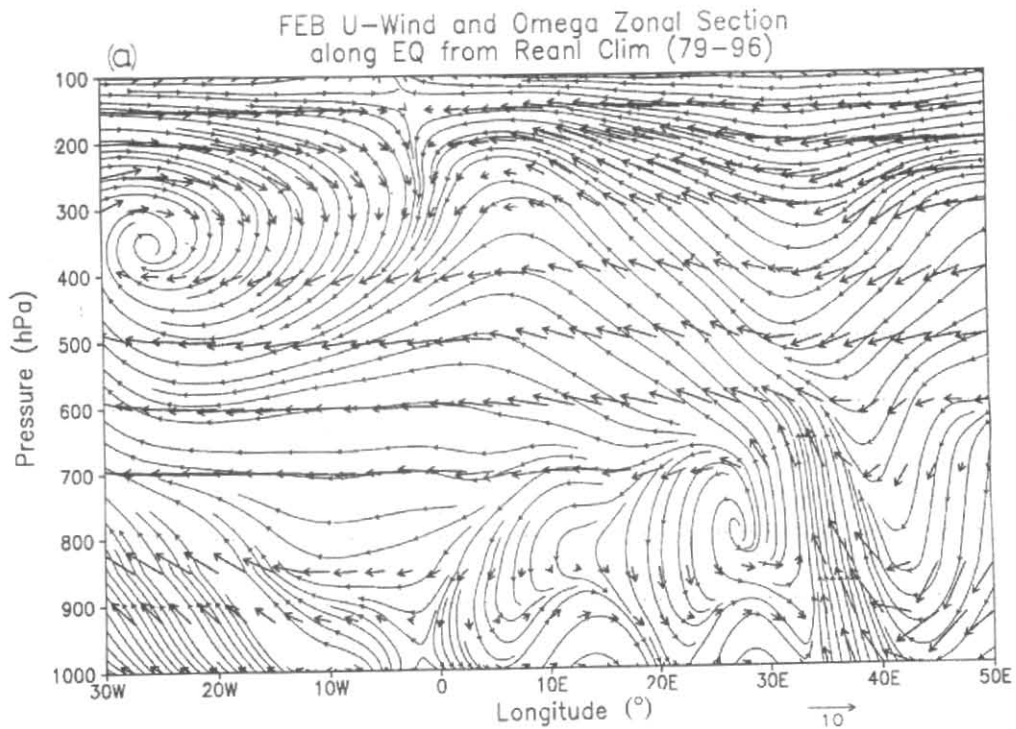


Fig. 11(a). Zonal-vertical circulations along the equator during February

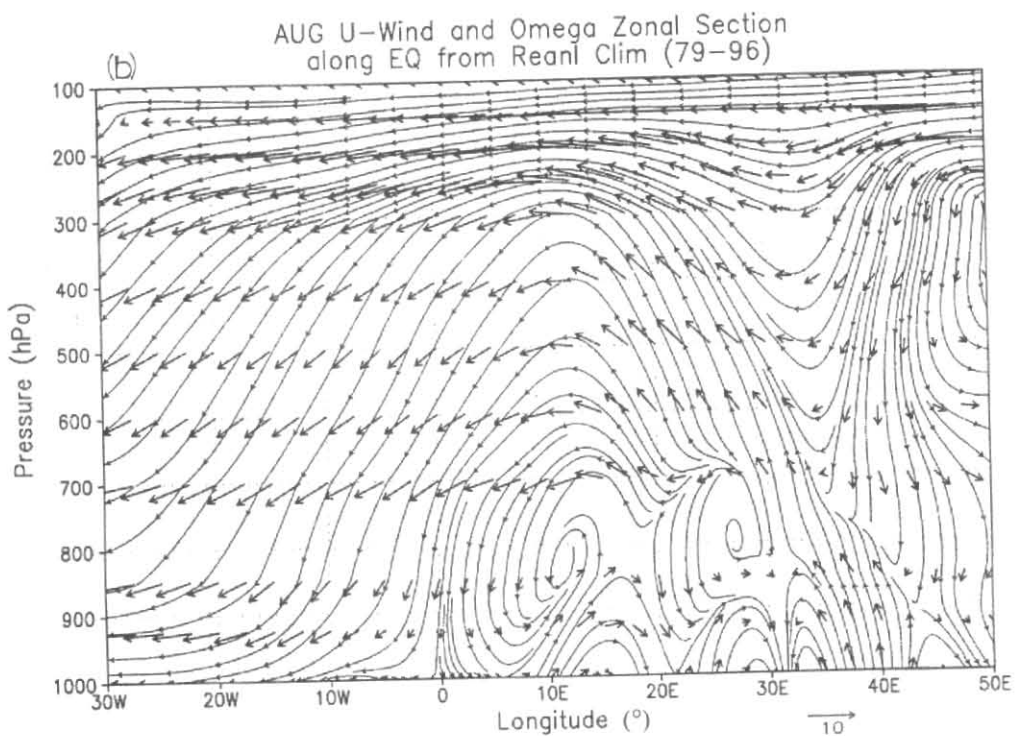


Fig. 11(b). Zonal-vertical circulations along the equator during August

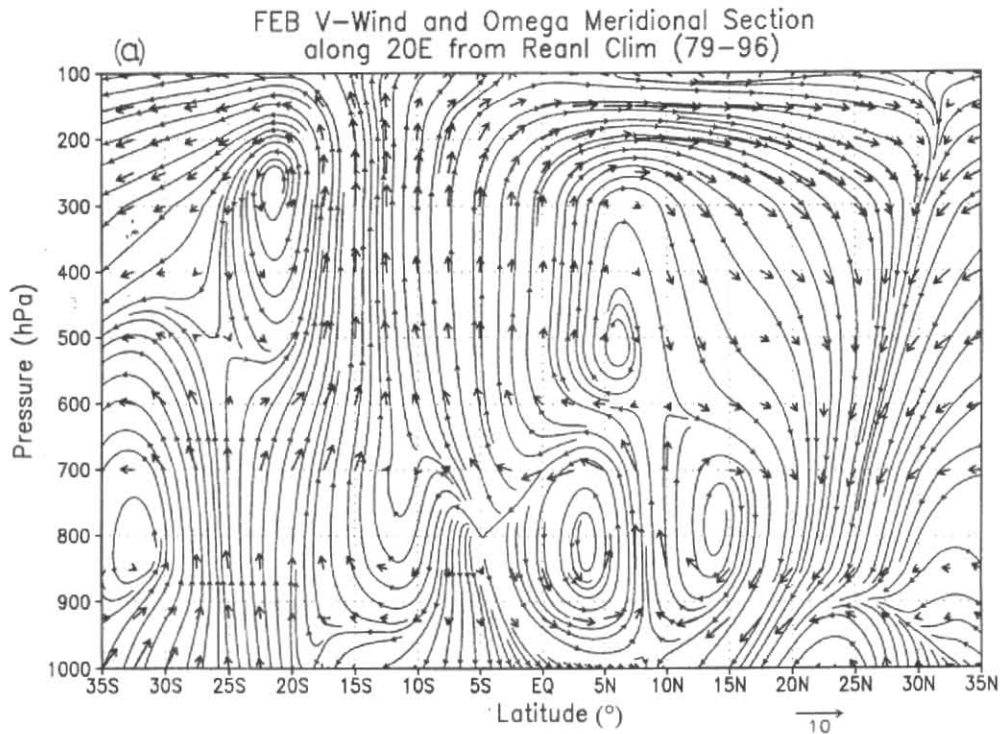


Fig. 12(a). Meridional-vertical circulations along 20° E meridian during February

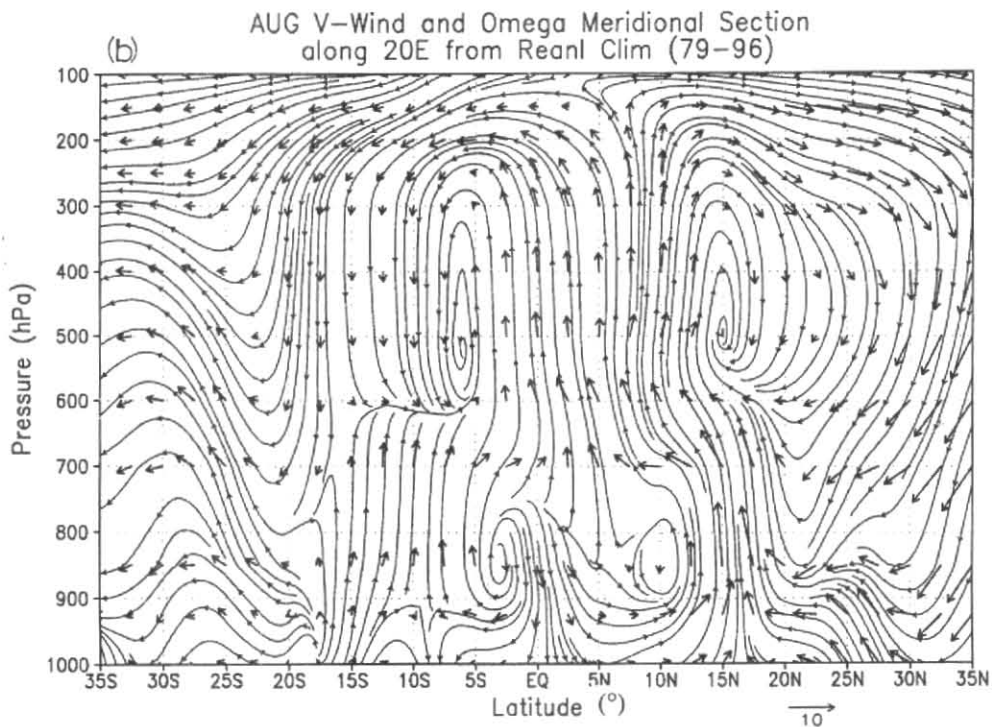


Fig. 12(b). Meridional-vertical circulations along 20° E meridian during August

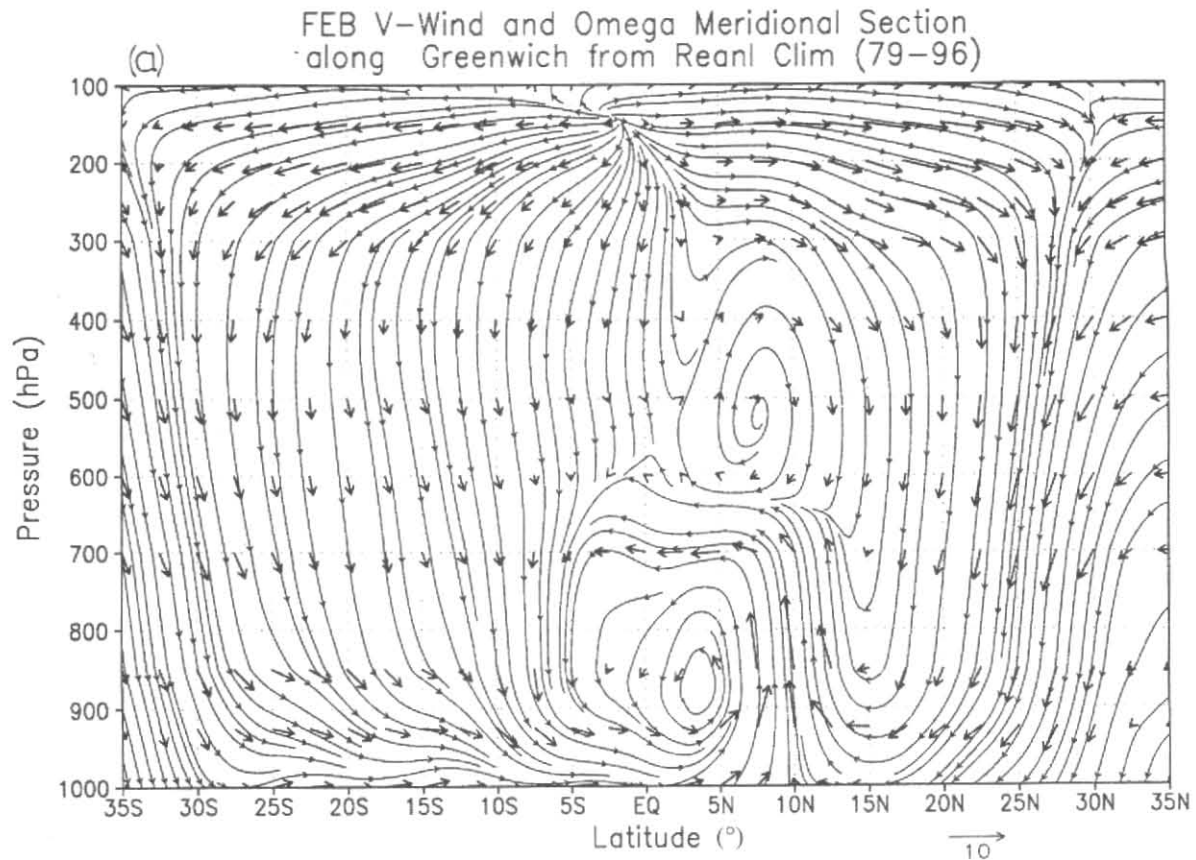


Fig. 13(a). Same as in Fig. 12(a), except along Greenwich meridian

purposes. Fig. 11(a) further shows that while the easterlies from the the Indian ocean in the middle and upper troposphere extend westward to about the Greenwich meridian, westerlies prevail west of this longitude above about 350 hPa. The August equatorial section Fig. 11(b) shows that the low-level equatorial westerlies originating from the Benguela ocean current region still continue to blow inland as far as the eastern mountains, as in February, and that there is little significant change in upper air circulation east of the Greenwich meridian. However, west of the Greenwich meridian, the upper-tropospheric westerlies disappear and the easterlies descend steeply over the ocean.

(ii) *Meridional circulations along 20° E [Figs. 12(a&b)]*

The meridional-vertical circulations along 20° E reveal the dominant presence of the Hadley circulations of the two hemispheres and the manner in which they co-exist with the monsoon circulations in the lower

troposphere. In February [Fig. 12(a)], two latitudinal belts of strong rising motion associated with monsoon cells in the lower troposphere are identified, one in the northern hemisphere around 10° N and the other in the southern hemisphere between about 15° S and 30° S. Strong descending motion occurs over the equatorial belt between about 5° N and 10° S below about 700 hPa. The Hadley cell of the northern hemisphere has a clockwise circulation centered at 500 hPa at latitude about 5° N, while that of the southern hemisphere has an anti-clockwise circulation centered at about 300 hPa near 20° S. The two cells have their common rising branch over a wide stretch of latitudes between about 5° N and 20° S in the upper troposphere above about 600 hPa. Lower down, the vertical motion field is largely modified by the presence of the monsoon cells which lift the Hadley cells in both the hemispheres. The strong upward motion in the southern hemisphere south of about 12° S by the combined effects of the monsoon and Hadley circulations is noteworthy, for it lifts the cool moist air of the

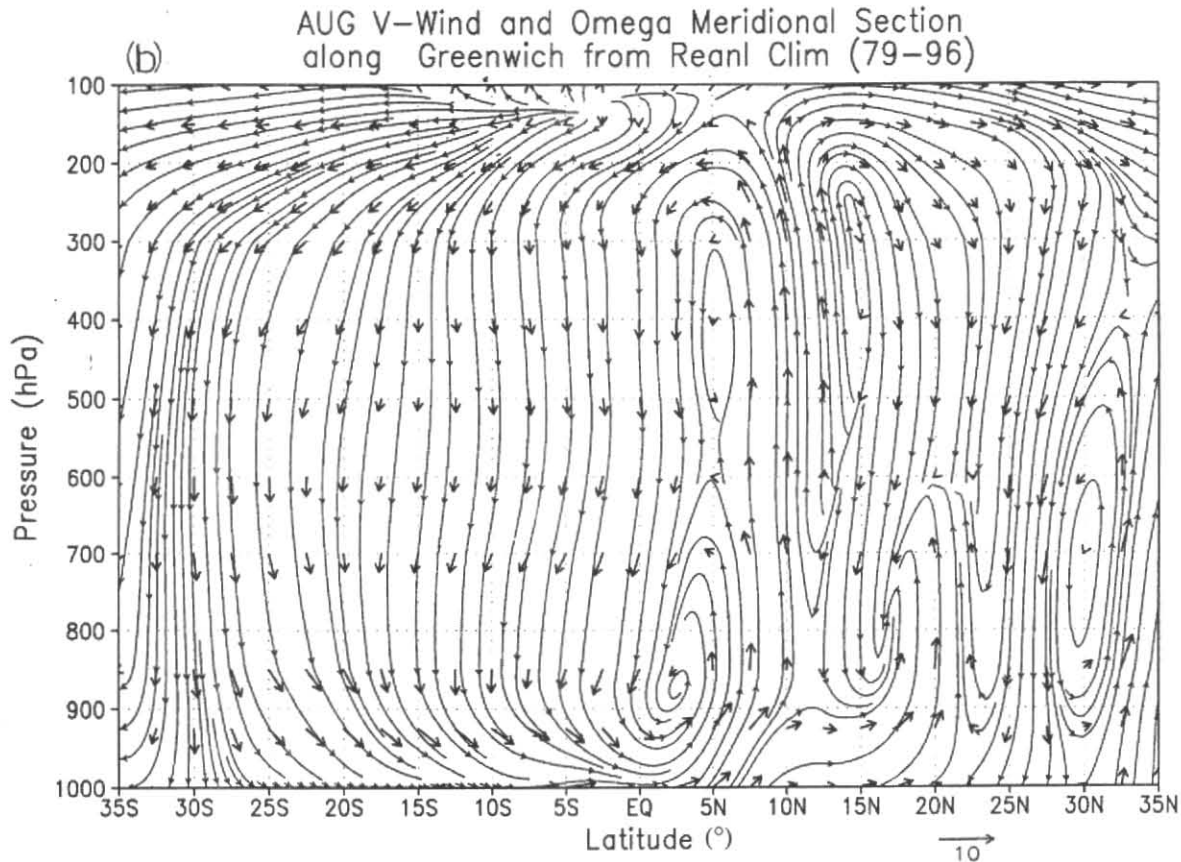


Fig. 13(b). Same as in Fig. 12(b), except along Greenwich meridian

equatorial westerlies which converges from the north to great heights for precipitation over the plateaux or mountains of Angola, Zambia and Tanzania. Some of the major rivers of southern Africa, such as the Zambesi and the Congo-Zaire and their several tributaries have their origin from these heavy precipitation area. In the northern hemisphere, strong descending motion occurs at all levels north of about 15° N. In August [Fig. 12(b)], there is a clear seasonal movement of both the monsoon and the Hadley cells towards the north. The northern and the southern hemispheric monsoon cells in the lower troposphere are now centered at 10° N and 3° S respectively. The corresponding Hadley cells are centered at 500 hPa at 15° N and 7° S respectively. Strongest upward motion are now in the northern hemisphere around 15° N. Strong descending motion occurs in the northern hemisphere to the north of about 20° N.

(iii) *Meridional circulation along the Greenwich meridian*

Figs. 13 (a&b) show the mean meridional circulation along the Greenwich meridian during February and

August respectively. In February [Fig. 13(a)], a monsoon cell with anti-clockwise circulation centered at about 850 hPa appears between the equator and 5° N. Its associated and elevated Hadley cell with clockwise circulation centered at about 500 hPa appears between about 5° N and 10° N. Their common rising branch lies between 5° N and 12° N. Strong descending motion occurs poleward of about 15° N in the northern hemisphere and over the entire oceanic area south of the equator. In August [Fig. 13(b)], strong descending motion is evident over the entire oceanic area south of the equator, as in February. However, the situation in the northern hemisphere, particularly over the land in western Africa, appears to be rather complex. Instead of a single monsoon cell with anti-clockwise circulation in the lower troposphere and an elevated Hadley cell with clockwise circulation aloft, three separate anti-clockwise circulation cells appear in the lower troposphere. one centered between the equator and 5° N, the second at about 15° N and the third at about 30° N. A single Hadley cell with clockwise circulation centered at about 350 hPa appears at about 15° N. The strong ascending branch of the Hadley circulation is now located between about 5° N and 15° N.

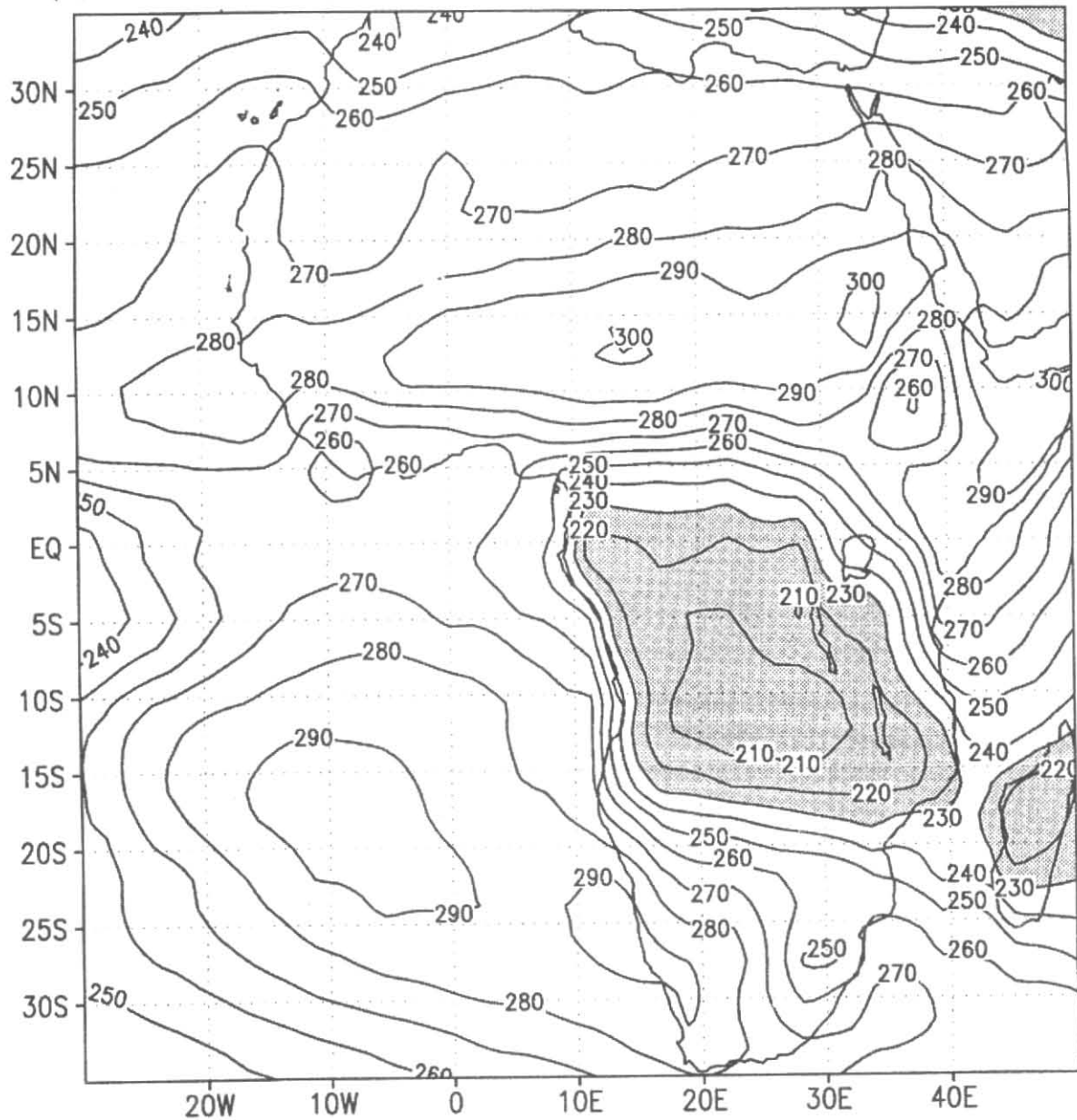
(a) FEB OLR (Watts/m²) CLIM Reanal (79-96)

Fig. 14(a). Fields of Outgoing Longwave Radiation (OLR) over Africa and surrounding oceans during February (unit: Wm^{-2})

6. Co-existence with deserts

One may have noted from Figs.12(a&b) that over tropical Africa, on both sides of the equator, the Hadley circulation is greatly modified by the presence of the monsoon circulation cell in the lower troposphere. The former is lifted by the latter and the two circulating in the opposite directions have a common rising branch along a

sloping surface of discontinuity at the monsoon trough zone, which lifts the converging cool moist tradewind air from the equatorial side to great heights for precipitation. But what happens to the region of the descending branch of the Hadley cell? Before looking into this question, it is important to point out that the seasonal movement of the monsoon trough and its associated rainbelt on either side of the equator covers only a few degrees of latitude. On

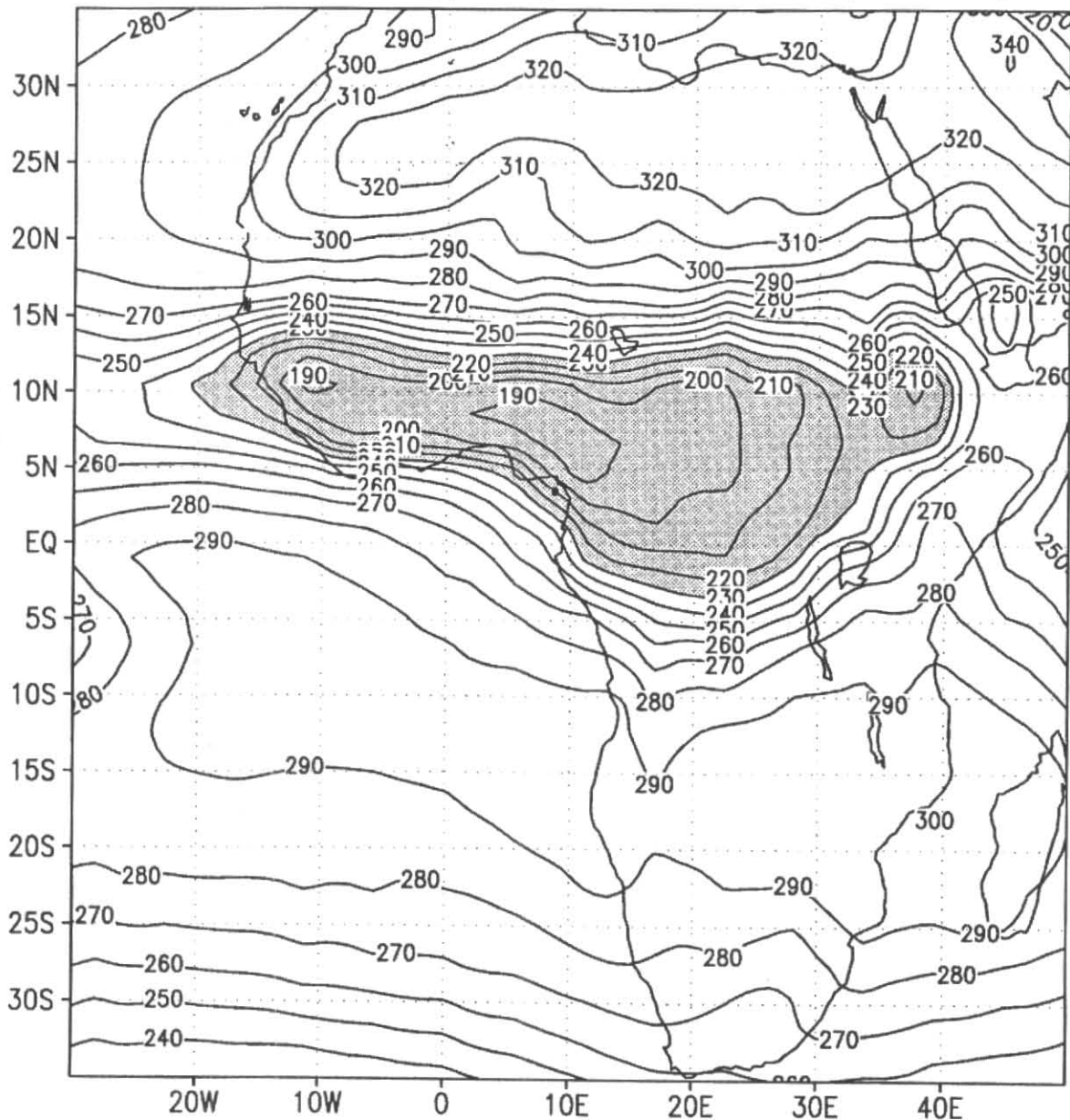
(b) AUG OLR (Watts/m²) CLIM Reanal (79-96)

Fig. 14(b). Fields of Outgoing Longwave Radiation (OLR) over Africa and surrounding oceans during August (unit: Wm⁻²)

the poleward sides of this equatorial rainbelts lie vast tracts of land which receive little or no rainfall during the year. Over Africa, the great Saharan desert in the north and the Namib-Kalahari desert in the south are in this category. It may be said that these deserts co-exist with the monsoons. In fact, Africa is not unique in this respect. Similar co-existence of deserts on the poleward sides of the monsoon belts are found over the other continents as

well, such as Asia, Australia and America. In a seminal contribution to the study of dynamics of deserts and drought over Sahel in Africa, Charney (1975) concluded that to maintain the radiative equilibrium of the atmosphere over a surface with high albedo, such as a sandy soil surface, against radiative heat loss, air must descend and that it is this descent or subsidence that leads to continued dryness and maintenance of the desert. He

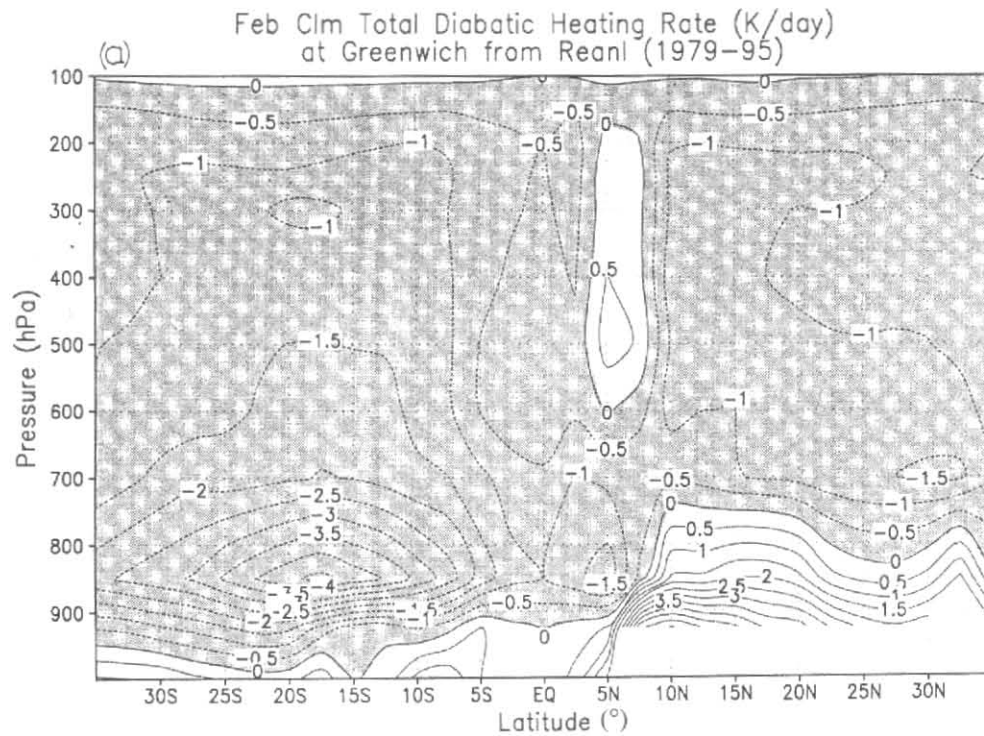


Fig. 15(a). Meridional-vertical section along the Greenwich meridian showing the distribution of total diabatic heating rate (K/day) during February

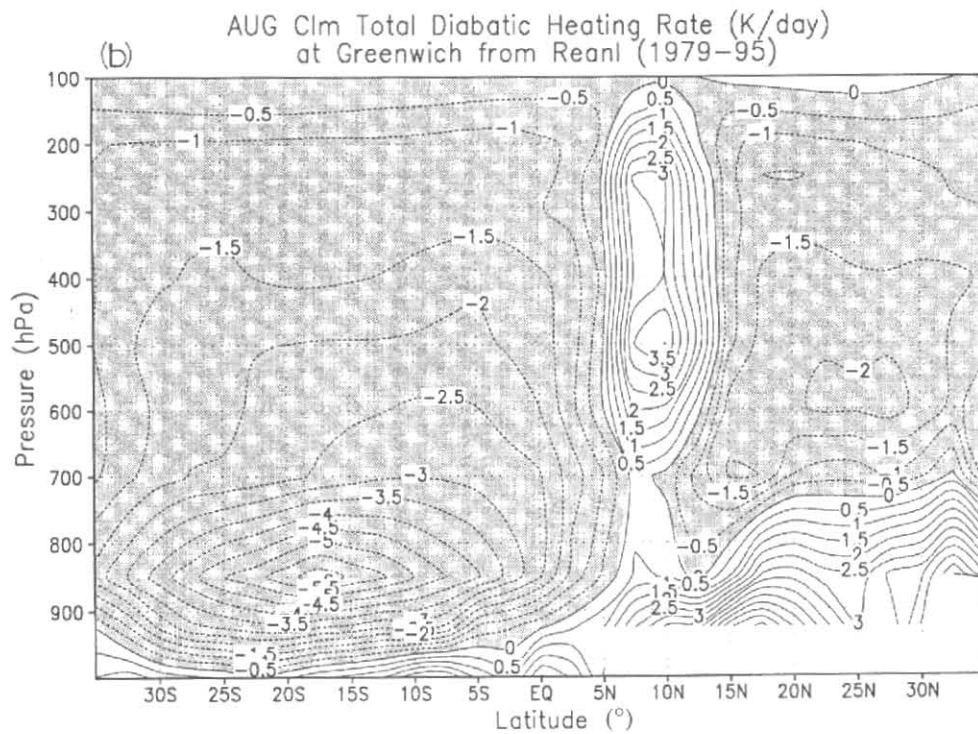


Fig. 15(b). Meridional-vertical section along the Greenwich meridian showing the distribution of total diabatic heating rate (K/day) during August

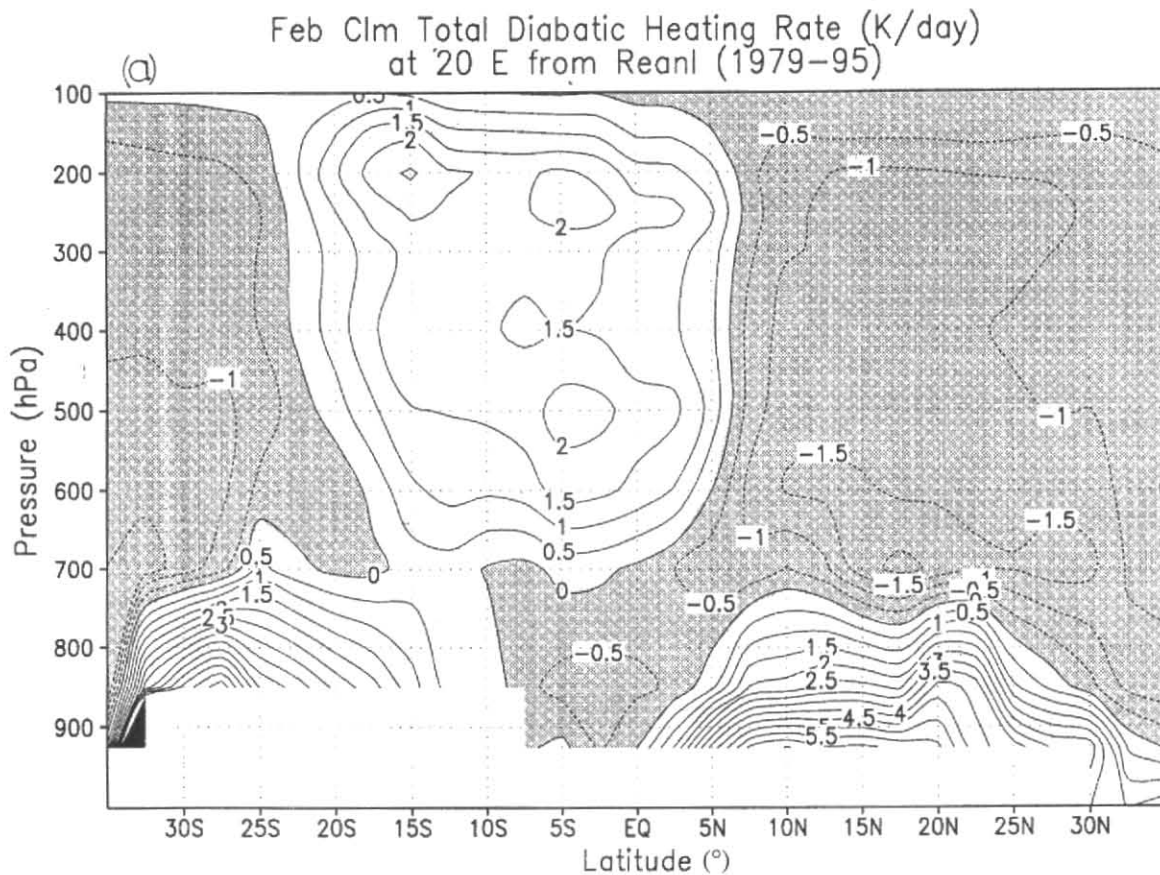


Fig. 16(a). Same as in Fig. 15(a), but along the 20° E meridian

also recognized the contribution made by the descending branch of the Hadley circulation to the desertification process but expressed the view that the impact of the radiative loss was the greater. Our qualitative analysis appears to confirm that both the processes might have been at work to create and perpetuate the deserts poleward of the equatorial troughs in Africa, in both the hemispheres. Figs. 14(a&b) which present the fields of the Outgoing Longwave Radiation (OLR) during February and August respectively show very high values of OLR over the regions where the Hadley circulations have their descending branches in both the hemispheres. The fields of total diabatic heating along the Greenwich meridian in Figs. 15(a&b) and along 20° E meridian in Figs. 16(a&b), which show strong diabatic cooling in the middle and upper troposphere over latitudes poleward of the locations of the equatorial troughs would seem to lead to the same conclusion.

7. Comparison with other monsoons

In several respects, monsoons over different parts of the continent of Africa and neighbouring oceans appear to

have their close analogues over other parts of the globe. For example, one may compare: (a) Western Africa with southern Asia; (b) Southern Africa with Australia and (c) Equatorial eastern Atlantic off western Africa with equatorial eastern Pacific off south America. The bases for these comparisons are the following:

(a) Western Africa with southern Asia

- (i) Both are in the northern hemisphere and have oceans to the south.
- (ii) Both experience rainy monsoons during the northern summer when 'heat lows' develop over the land and cool moist air from the ocean converge into them and rise in convection.
- (iii) The converging air currents are predominantly southwesterly to the south of the monsoon trough and northeasterly to the north, in both cases.
- (iv) Hadley circulation co-exists with and is lifted by monsoon circulation over both the regions.

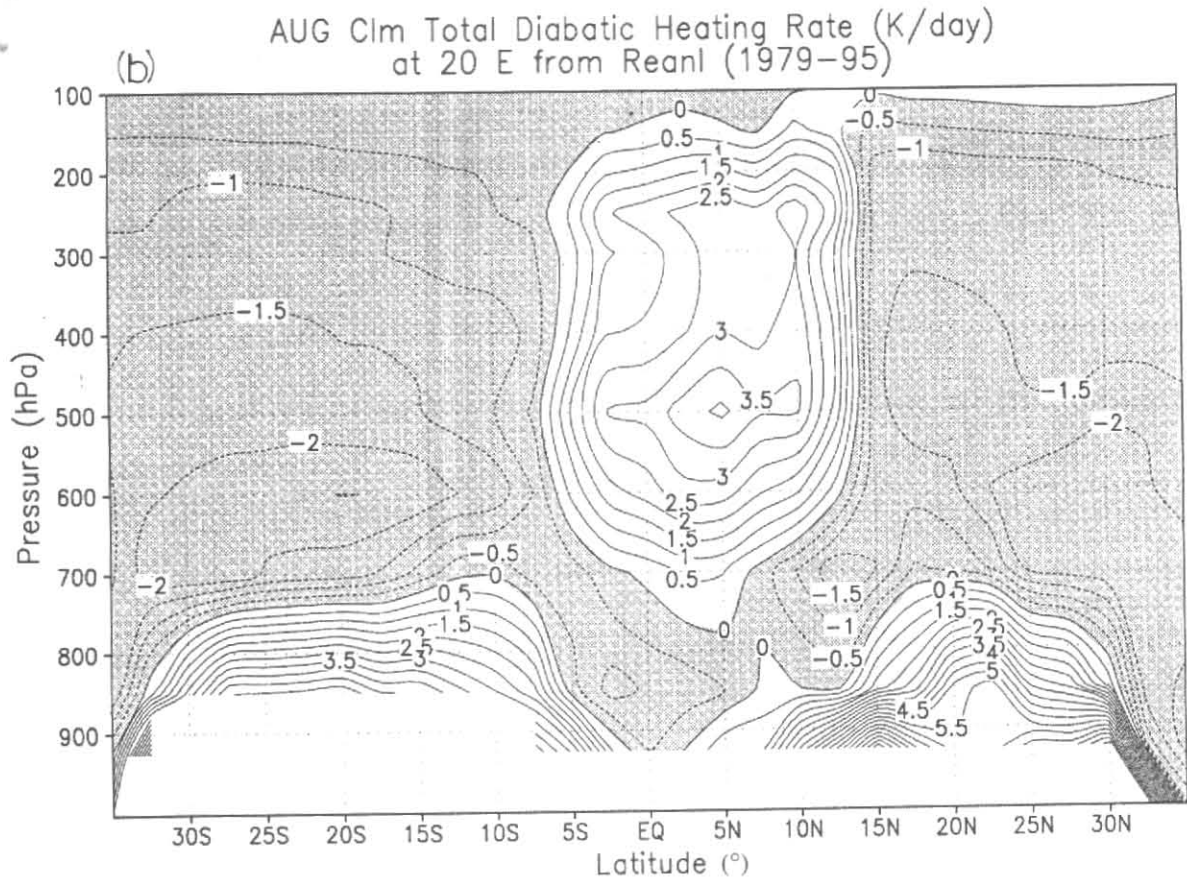


Fig. 16(b). Same as in Fig. 15(b), but along the 20° E meridian

- (v) Like the great Sahara desert in Africa, the great central Asian desert extending from Mongolia to western Asia lie to the north of the Asian monsoon belt.

However, important differences exist between the two in other seasons, especially during the northern winter. For example, when northern summer ends, the west African monsoon gets stuck and marks time near the Guinea coast because of the inhibiting effect of the cold ocean to the south, whereas, away from the influence of the Somali current in the Arabian Sea, south Asian monsoon withdraws southward almost upto the equator and the monsoon trough marks time near the equator till return of the next summer. In fact, during northern winter, two monsoon troughs are identifiable over the equatorial eastern Indian ocean, one on each side of the equator (Raman, 1965; Saha, 1973).

(b) *Southern Africa with Australia*

Despite the fact that unlike southern Africa, Australia has an ocean to the north and all around, there are several similarities between their monsoons, as stated below:

- (i) Both the landmasses are situated in the southern hemisphere.
- (ii) During the southern summer, 'heat lows' develop over the land and the tradewinds converge into them to rise in convection and yield monsoon rains.
- (iii) An elevated Hadley circulation cell co-exists with and is lifted by the monsoon circulation cell over both the regions.

- (iv) Like the Namib-Kalahari desert, the Great Australian desert lies poleward of the monsoon rainbelt.
- (v) The north-south oriented belt of heavy rain along the eastern African mountains appears to be similar to that along the Great Dividing Range and Blue mountains of eastern Australia.
- (vi) The role of the cold Benguela ocean current in African monsoon appears to be somewhat similar to that of the cold ocean current off western Australia in Australian monsoon.
- (c) *Equatorial eastern Atlantic with equatorial eastern Pacific*

These two ocean basins appear to be similar in following respects:

- (i) Both exercise dominating influence upon the weather and climate of neighbouring oceans and continents.
- (ii) Over both the oceans, the cold ocean surface south of the equator, maintained cold by powerful ocean currents does not permit the formation of an equatorial trough south of the equator, even during the southern summer.
- (iii) The lone equatorial trough confined to the northern hemisphere is associated with a warm ocean surface and executes a seasonal oscillation through a few degrees of latitude in the same hemisphere following the movement of the Sun.
- (iv) Disturbances forming at the equatorial trough over both the ocean basins generally move westward and often develop into hurricanes in the Atlantic/ typhoons in the Pacific.

8. Findings and conclusion

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

- (i) Differences in latitudinal extents and land-sea distributions between the western and the eastern parts of Africa give rise to different kinds of monsoons over these parts.
- (ii) The eastern part (east of about 10° E), spanning across the equator to the subtropical belts of both the hemispheres, experiences two

monsoons in a season (summer or winter), one north of the equator and the other south, as against the western part which gets only one.

- (iii) While tradewinds from both the Atlantic and the Indian oceans take part in the monsoon circulation in any season, the cold Benguela ocean current appears to play a key role in the formation of low-level equatorial westerlies, positioning of troughs and ridges and distribution of monsoon rains over the African continent.
- (iv) Meridional-vertical circulations across the central part of Africa appear to suggest that each hemisphere has its own Hadley circulation cell which is lifted by the monsoon circulation cell in the lower troposphere. The two cells circulating in the opposite sense meet and cooperate with each other to produce strong upward motion in the monsoon trough zone.
- (v) The appearance of the descending branch of the Hadley cell on the poleward side of the monsoon belt appears to suggest a symbiotic relationship between monsoons and deserts in Africa. Such relationships may also be found over several other parts of the globe.

In conclusion, it may be reiterated that:

- (i) The northern and the southern hemispheres have their own separate monsoons, except where cold oceans intervene to prevent the formation on any side of the equator.
- (ii) When summer ends in a hemisphere, its summer monsoon does not die out or follow the Sun to the other hemisphere, as popularly believed. Instead, it weakens and withdraws to a location near the equator where it marks time till the return of the next summer.
- (iii) When summer returns to the hemisphere, the monsoon trough strengthens and starts moving again to begin the next cycle.

Acknowledgements

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