The Easterly Jet Stream in the Tropics*

By P. KOTESWARAM, Meteorological Office, Calcutta Airport

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Abstract

It is shown that in summer an easterly jet stream overlies southern Asia in the high troposphere with core near 15° N. This current is quasi-geostrophic. Below the level of strongest winds temperatures decrease from right to left across the current looking downstream; above the level of strongest wind (150–100 mb) the reverse is true. Distribution of cloudiness and precipitation in the lower monsoon correspond to that noted in association with westerly jet streams in the temperate zone: precipitation downstream from the region with the highest winds to left of the axis, upstream to the right.

The foregoing holds on individual days and climatically during the monsoon season as a whole. Since an easterly jet stream is observed only over southern Asia (and Africa), but not over the Pacific and Atlantic oceans, it is suggested that the current originates in connection with the large-scale arrangement of land masses and oceans, and with the elevated heat source of the Tibetan plateau.

Introduction

Numerous writers have studied high tropospheric jet streams as an important part of the general circulation. During the last decade jet streams have been located and described in various parts of the world. Progress has been most satisfactory in middle and high latitudes, while in the tropics the high location of jet streams and scarcity of data has retarded research. Several attempts have been made to locate and study westerly jet streams in the tropics. CHAUDHURY (1951) constructed a cross-section along 75° E based on data from the winter of 1946. YEH (1950) has analyzed the jet over China. The author (1953) has studied location and characteristics of the jet stream over India and Burma during the cool season; he also computed mean vertical motions (1954). RIEHL (1954) has pointed out the intermittent existence of a westerly jet stream in the central tropical Pacific during summer.

Easterly winds in the high troposphere have presented many puzzling features. Mean upper wind charts prepared by VENKITESHWARAN (1950) for India and surroundings show a wide belt of easterlies in the high troposphere and stratosphere over India during summer. Strong winds from the east have been noted over southern India in summer during periods of weak monsoon when pilot balloons could be followed to great heights. With the aid of these winds KRISHNA RAO (1952) inferred the existence of an easterly jet stream and constructed a vertical cross-section. KRISHNA RAO and GANESAN (1953) pointed out that these winds may reach 110 mph during July and August in the tropopause layer. FROST (1952) noted that at Aden the easterlies reach an average maximum of 70 knots between 150 and 100 mbs in summer. DAVIS and SAMSON (1952) noted winds of similar strength over Nairobi which they attributed to an easterly jet stream near the equator. They found that

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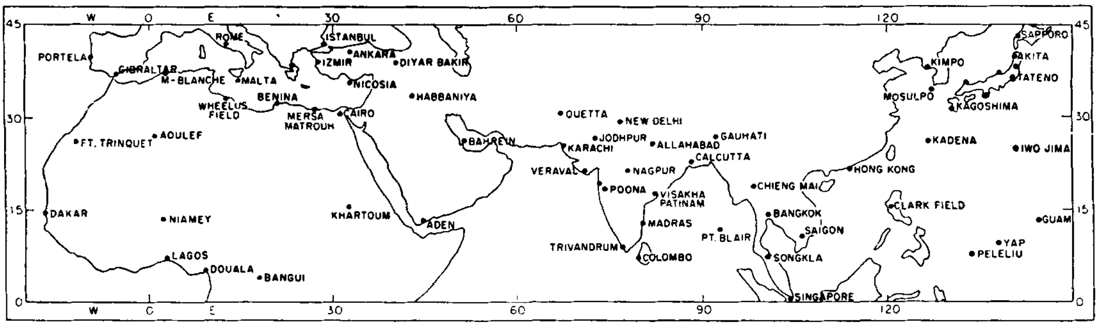

Fig. 1. Radiosonde and Rawin stations used in analysis.

the easterlies reach highest speeds during December—February and July—September, both dry seasons at Nairobi. Austin (1953) further analyzed the rawin observations at Aden, and Hay (1953) those at Singapore and Hongkong. The latter found that high-level easterlies prevail throughout the year at Singapore and in summer at Hongkong. They attain speeds of 90 knots at Singapore and 80 knots at Hongkong but the thickness of the layer of strongest winds is confined to a few thousand feet. Clarkson (1956) made a statistical analysis of Singapore winds; he finds them remarkably constant in direction; speeds occasionally reach to 100 knots in August and September. He also observed that the high-level meridional flow is strongest from north at the peak of the summer monsoon season; the reverse occurs during the winter monsoon.

While all these observations confirm the existence of strong easterlies in the high troposphere in some parts of the tropics, they do not necessarily indicate the existence of jet streams, since this requires strong lateral as well as vertical shear. The first welldocumented case study of an easterly jet stream (Alaka 1955) was made in the Caribbean where such currents are rare but where a good network of rawinsonde stations exists. Alaka found an easterly current with central speed of 75 knots. The current was confined to the region of the southern Bahamas and Florida; the strongest winds were situated near 200—150 mb. Alaka thought that this current had originated in middle latitudes and appeared at the southern periphery of a subtropical high after curving around this cell. A similar case has been discussed by Newton and Carson (1953) in connection with the formation of summer shearlines over the United States.

Since strong easterlies are frequent over southern Asia and eastern Africa, but rare over the Pacific and Atlantic Ocean areas, it was considered appropriate to study the high-tropospheric flow of the tropics over Asia and Africa with a view to jet stream analysis and an understanding of the upper wind circulation in these regions and their interaction with the large-scale circulation feature of the lower troposphere—the summer monsoon. The main features of the analysis are presented in this paper. Fuller details are available in a research report of the Department of Meteorology, University of Chicago (1956).

Data Utilized and Methods of Analysis

A survey as just indicated requires good rawin coverage. Unfortunately, daily analysis with radiosonde data alone is unreliable in the tropics since instrumental errors often have the same magnitude as synoptic differences. Radiosonde data averaged for the whole summer of 1955, however, give a fairly representative picture of the high-tropospheric flow pattern. Establishment of rawin stations at Madras, India, and in Thailand has been very useful, though one would wish for a still closer network. Collection of data from many sources is always difficult; in this respect the daily northern hemisphere data published by the U.S. Weather Bureau since July 1955 have proved very helpful. Data for India have been obtained from the Indian Daily Weather Report.

The area studied covers the tropics from the equator to 40° N, and from 20° W to 150° E.

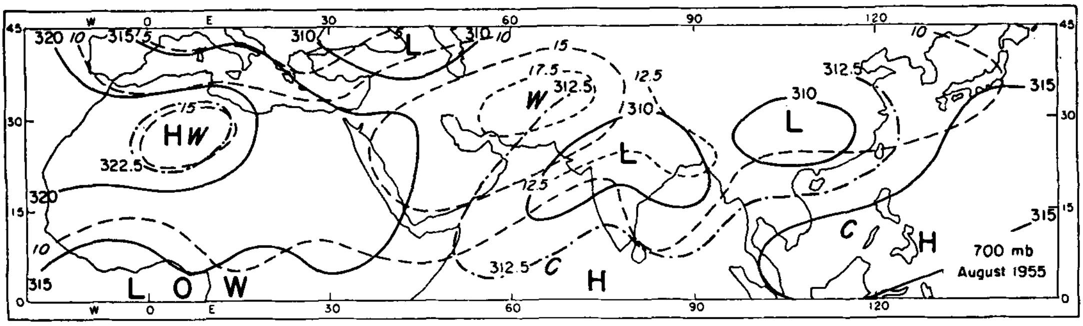

Fig. 2 a.

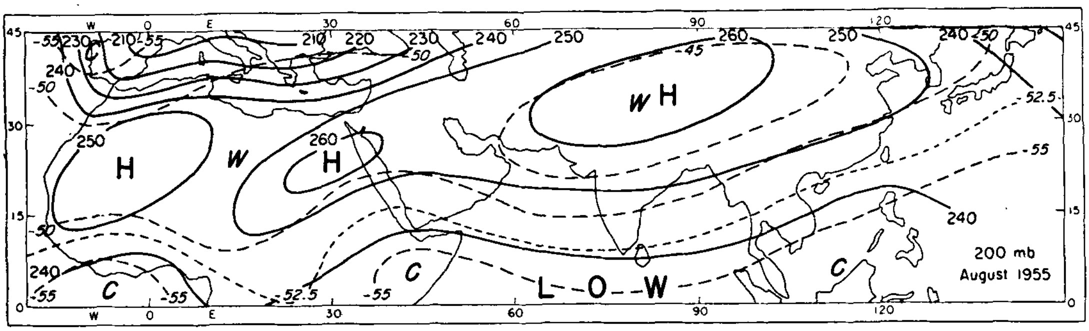

Fig. 2 b.

Fig. 2 a and 2 b. Mean isotherms (°C, dashed) and contours (10's m, first digit omitted at 200 mb) for August 1955 at 700 mb and 200 mb.

Fig. 1 shows the rawin and radiosonde stations in this area. The following types of analysis were performed.

- Vertical time section
- Horizontal space-time sections
- Stream lines on isobaric surfaces
- Isotachs on isobaric surfaces
- Vertical cross-sections

Techniques used in preparation of these analyses are well known and need not be repeated. Time sections were made for as many stations as possible; the sections extended over the whole summer of 1955. They are as valuable for analysis of jet stream maxima as for features such as passages of wave troughs and closed circulations. A horizontal space-time section was constructed for the Indian area at 40,000 feet projecting each rawin station at its appropriate parallel; the purpose of the section was to observe the relations between the southwest monsoon and the high-tropospheric flow patterns.

For reasons already indicated, streamline analysis was preferred to constant pressure analysis. With an adequate number of stations streamlines give a reliable picture of the broad flow patterns. No attempt was made to draw streamlines with the isogon technique; for this the network of stations was not sufficiently dense. Isotach analysis was carried out at 300 200 and 100 mb.

Structure of the Tropical Troposphere in Summer

Climatology of upper winds: Most prominent in the lower troposphere is the equatorial trough which migrates as far as latitudes 20—25° N over the Asian-African continent during the northern summer; it is accompanied by the spectacular summer monsoon of southern Asia. A broad westerly current overlies the Arabian Sea, Bay of Bengal and the Gulf of Siam. Occasionally it reaches across the South China Sea to the western Pacific. This current—called southwest monsoon in

India and Indian westerlies farther east—extends to 10,000—20,000 feet, occasionally 30,000 feet. It is a persistent feature of the general circulation over southern Asia from June to October.

PALMER (1951, 1953) concluded after a study of the Marshall Island region that the equatorial westerlies in the low levels merely represent a statistical mean of individual westerly currents connected with westward moving cyclones and that they do not form a branch of the general circulation. RIEHL (1954), on the other hand, pointed out the great steadiness of the westerly component of the Indian monsoon. It should be mentioned here that the low latitude westerlies are confined to southern Asia and parts of equatorial Africa; they do not appear as a persistent current anywhere else. Thus any model of the general circulation must account for this special location.

In the high troposphere, a train of cyclonic and anticyclonic vortices tends to progress westward at least over the western Pacific (RIEHL, 1948) and over the Atlantic. Over the Asian monsoon region such vortices occur only rarely; high-level winds are generally easterly south of the Himalayas and westerly to their north. Similar cells also exist over the deserts of Africa and Arabia.

Mean Flow during summer: As an illustration of the mean flow pattern during summer Fig. 2 gives mean contours and isotherms at 700 and 200 mb for August 1955 over tropical Asia and Africa. These two levels generally represent the flow patterns in the lower and upper tropospheres respectively. Noteworthy is the existence of a Low over India and farther east at 700 mb, while to the west no such Low can be found. The surface heat lows which generally extend from northwest Africa to northwest India are shallow and restricted to the layer below 700 mb. Aloft a high is located over these regions; this high extends to the tropopause. Over the Asian monsoon region the subtropical anticyclone builds only above 500 mb. This anticyclone overlies the Tibetan plateau and probably extends to southwestern China.

Most striking at 200 mb is the concentrated contour gradient north of the African cell indicating a westerly jet over the Mediterranean. We note a similar though weaker gradient south of the Asian subtropical high, which *suggests an easterly jet stream over southern Asia.* The easterly gradient reaches its highest value between 150 and 100 mb; here the strongest easterlies will be located.

Mean temperature field and "intertropical front": In the low troposphere isotherms are concentrated off the Arabian coast, because of juxtaposition of desert air (T_c) and monsoon air or equatorial westerlies (E_m). The discontinuity between these airmasses has been given various names, such as intertropical front, equatorial convergence, etc. RAMANATHAN and BANERJI (1931) and SAWYER (1947) have studied this discontinuity. The former postulated a nose-like structure of the "front" since the steep lapse rate in the desert air would result in lower temperatures aloft than in the monsoon air. SAWYER utilized this structure to explain thunderstorms over northwest India. However, since the anticyclone over Arabia and Iran is associated with low-tropospheric divergence and descent, small temperature lapse rates are often observed in the desert air well above the surface layer with the result that temperatures remain higher in desert than in monsoon air. Above 300 mb the isotherms in Fig. 2 extend east-west with lower temperatures toward the equator. Thus the "nose" structure of the "ITF" is quite doubtful. In the low troposphere there is frequently a stable inversion where T_c overlies E_m; weather along the "front" then consists in stcu above the monsoon layer as often experienced at Karachi.

Over India the equatorial trough, locally called "monsoon trough", extends from western Pakistan to the head of the Bay of Bengal. The monsoon curves around this trough from the Bay of Bengal into northern India and the Himalayan foothills, resulting in the well-known monsoon circulation. No thermal contrast is observed in the trough, though there is a slight decrease of temperature from north to south.

Since the monsoon trough produces most summer precipitation over India, many Indian meteorologists have pictured it as a warm front type discontinuity, relying upon the slightly higher temperatures of the easterlies north of the trough. The easterlies are called "turned monsoon air" (*EmT*) (ROY 1946) or tropical maritime air from the far east (MALURKAR 1950, DESAI 1951 a). Many attempts

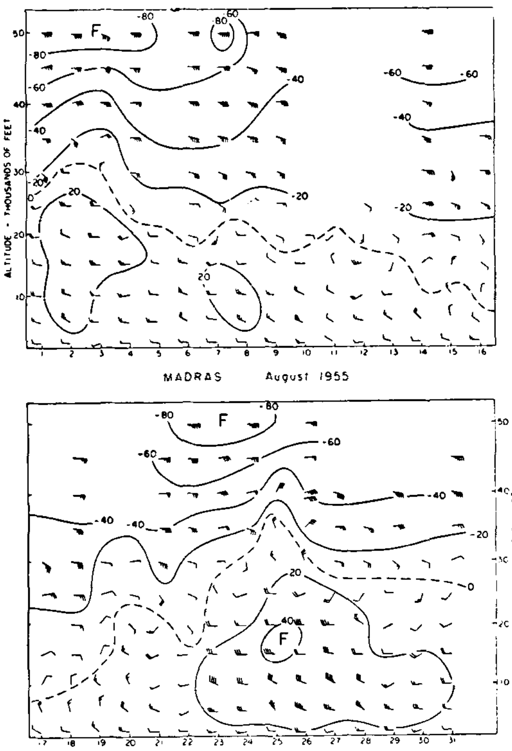

Fig. 3. Vertical time section of upper winds at Madras for August 1955, Easterly speeds negative. Short barb 5 knots, long barb 10 knots, pennant 50 knots.

to explain Indian weather with "fronts" have resulted from this assumption. The ITF which BJERKNES (1933) had terminated at the Himalayas was extended through the monsoon trough by DESAI (1951 b). Without repeating the well-known arguments about non-existence of fronts in tropical regions, it would suffice to speak of a convergence zone.

High Tropospheric Jet Stream

The mean flow pattern just described has indicated strong easterlies at high levels along the southern margin of Asia. In order to determine whether these winds are concentrated in jet streams, daily analysis up to 100 mb was undertaken for July and August 1955. As mentioned earlier, low latitude data are still scarce and high level ascents are missing on many days. Nevertheless, sufficient evidence remains to demonstrate the existence of a core of easterlies near 15° N. This current forms off the east coast of China and extends through India and Arabia at least as far as the Sudan. A second current appears to start near 10° N along the African west coast; it must dissipate over the eastern Atlantic since it is not observed in the Caribbean or along the Guiana coast of South America.

Time sections: Time sections of the following rawin stations have been examined, for the following stations: New Delhi (28° 35′ N, 77° 12′ E), Calcutta (22°39′N 88° 27′ E), Bombay (19° 05′ N, 72° 53′ E) and Madras (13° N, 80° 11′ E). Similar data do not exist at lower latitudes over India,[1] but the time section for Singapore (1° 22′ N, 103° 59′ E) has been looked into for comparison. Fig. 3 gives the time section for Madras for August 1955. Zero speed is marked with a dashed line, easterlies with negative sign and westerlies with positive sign. Observations are mostly for 0300 Z, supplemented by 1 500 Z data when the former were missing.

The following features have been noted:

1) Winds are mostly easterly at New Delhi up to 50,000 feet, but speeds rarely exceed 30 knots even at the top of the troposphere.

2) At Calcutta, monsoon westerlies predominate in the lower levels during the better part of the month. These westerlies frequently reach 20,000 feet, occasionally 30,000 feet. The high-tropospheric current is easterly and fairly steady with occasional ondulations. Easterly winds increase between 30,000 and 50,000 feet, where speeds of 30—50 knots are regularly attained.

3) Lower westerlies and upper easterlies are more steady at Bombay than farther north. The surface of separation lies generally near 20,000 feet, though with ondulations. As at Calcutta, the easterlies build between 30,000 and 50,000 feet, where speeds reach 60—70 knots.

4) Madras is the southernmost station in this series. Here also, the monsoon westerlies generally have a depth of 20,000 feet and occasionally they extend to 30,000 feet. The speed of the westerlies is greater than farther north; speeds as high as 40 knots are attained. In the upper easterlies 60—80 knots are reported at 50,000 feet. The flow in the high troposphere is quite steady, more so than near the ground; there are, however, some interruptions of the rapid easterly flow, as from August 7 to 9.

[1] A rawin station has been started at Trivandrum in September 1956.

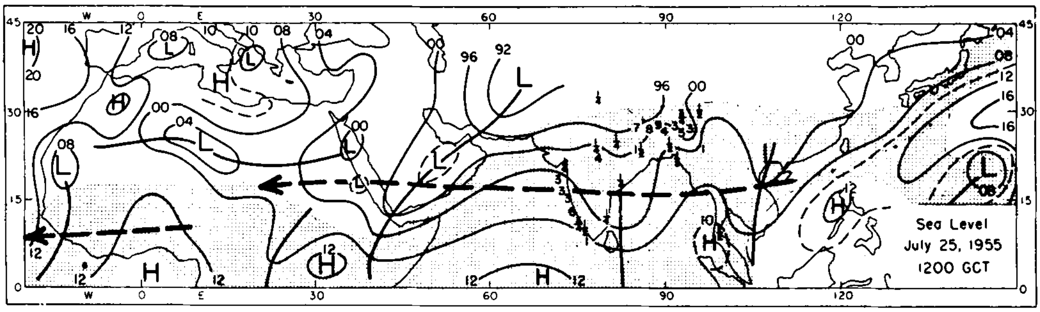

Fig. 4 a. Sea leval isobars (mb. first two digits omitted) July 25, 1955. Clouded area shaded. Figures over India and neighbourhood indicate 24 hours rainfall in inches.

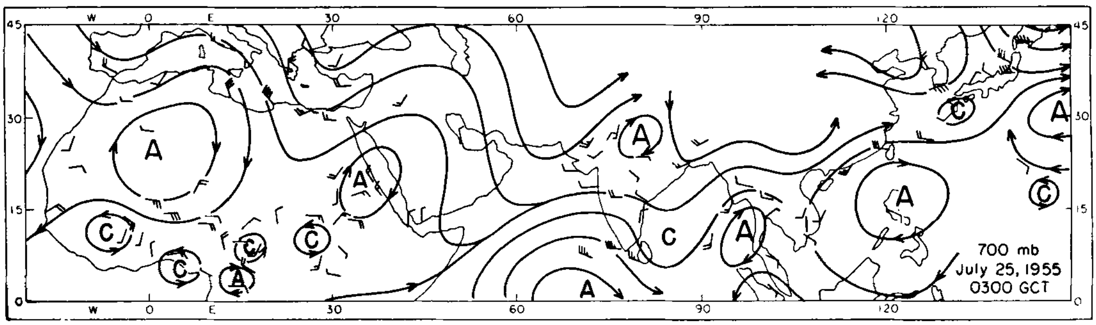

Fig. 4 b. Streamlines at 700 mbs, July 25, 1955.

The time sections indicate that the speed of the easterlies increases with decreasing latitude at the highest tropospheric levels. Singapore lies far off the longitude considered but its time section affords an interesting comparison with those of India. Here also, there are lower westerlies. These are generally confined below 15,000 feet; during part of the period they are not present. As over India steady easterlies blow in the upper troposphere and speeds as high as 80—90 knots occur. Speeds however are variable, ranging from 20 to 80 knots at 50,000 feet.

The situation of July 25, 1955: On this day the observations were reasonably complete and the upper wind structure was quite definite, with easterly speeds above 100 knots. The flow pattern as standard isobaric levels upto 100 mbs have been examined. Fig. 4 shows surface isobars, also streamlines at 700 and 200 mb. Isotachs have been drawn at 200 mb.

a) Wind structure: At the surface (Fig. 4 a) we observe a series of "heat lows", situated roughly along latitude 20° N; the easternmost of the lows lies over western Pakistan near 30° N. A monsoon trough is not present over India. The situation is one which is locally described by the statement that the monsoon trough lies close to the Himalayas. The flow over India and farther east is mainly westerly. A southwesterly current extends off the Asiatic coast to Japan and then merges with the temperate westerlies. The equatorial westerlies are strong in the Arabian Sea.

At 700 mb (Fig. 4 b) the situation over Africa and Arabia looks quite different. The surface heat lows have given way to subtropical anticyclones. In contrast, the westerly flow persists over Asia, and a pattern of well marked troughs and ridges in the westerlies is discernible.

The low latitude westerlies are replaced everywhere by easterlies at 500 mb. The African and Arabian cells persist and new ones appear over Iran, India and the Phillippines. The configuration of the easterlies is wavy, with an apparent "wave length" of 25° longitude over the North Indian Ocean and the western Pacific.

The subtropical anticyclones arrange them-

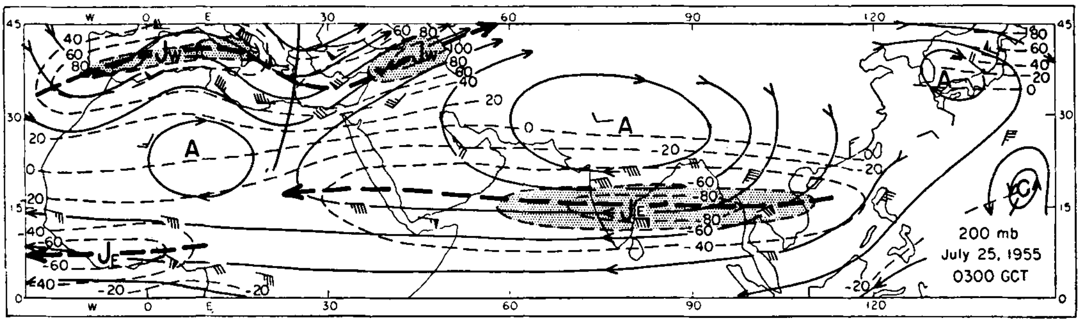

Fig. 4 c. Streamlines and isotachs 200 mbs, July 25, 1955. Jet axis marked heavy and wind maxima shaded.

selves roughly along 25° N at 300 mb over the Asian and African continents as the easterly flow in the lower latitudes increases in speed and becomes less wavy. North of the anticyclones, a well marked westerly current overlies the Mediterranean and Iraq, with characteristics of a jet stream. Such a current is also observed over northern Japan.

The 200-mb chart (fig. 4 c) indicates intensification of both easterly and westerly currents with two well marked anticyclones over northern Africa and the Himalayan plateau. Wind speeds exceed 100 knots in the westerlies and 80 knots in the easterlies. Concentration of the easterlies into a narrow current is clearly seen from 300 mb upward. At Bangkok (13° N) the speed is 69 knots compared to 47 knots at Chiengmai (18.5° N) and 32 knots at Songkla (7° N). One also notes equatorward flow in the "entrance" region (Hongkong 360°, 15 knots) and poleward flow in the "exit" region (Bahrein 140°, 27 knots).

The 100-mb pattern is similar to that at 200 mb except that the westerly current weakens between these two surfaces, while the easterly current strengthens, at least to about 150 mb. At Bangkok 102 knots is reported. At Aden the highest speed occurs at 48,000 feet (81 knots); then there is a rapid upward decrease to 38 knots at 53,000 feet. The center of the easterly current lies roughly along 15° N. It starts building over the South China Sea. The greatest strength is attained over southern India, while over Africa the current is weakening. The core of the easterlies appears to lie at a somewhat higher altitude in the eastern portions (Bangkok 55,000 feet) than in the western part (Aden 48,000 ft).[2]

b) Thermal Structure: The thermal pattern, as that of the winds, resembles the mean charts described earlier. At 700 mb the warmest air is located over Arabia, Iran and western Pakistan; the strongest temperature gradient is found over the Arabian Sea. At 500 mb the warmest air is situated in the subtropical ridge near 25° N. The 300-mb pattern resembles that at 500 mb except that temperature gradients on both sides of the subtropical ridge are stronger. At 200 mb, the temperature gradient over southern Asia is still well marked. In contrast, the gradient has reversed over northern Africa and Japan indicating that the 200-mb surface lies above the strongest westerlies.

The thermal pattern at 100 mb is spectacular. The temperature field has reversed in the easterlies in accord with the wind observations. A belt of very cold air extends from the Palau Island across Thailand and central India to Arabia and upper Egypt. Another cold pool starts near the coast of equatorial Africa and reaches into the Atlantic. Analysis of the 100-mb temperature field over the Atlantic and Pacific Oceans and over Central America indicates that this pool of coldest air is confined to the equatorial zone over the rest of the globe. It is only over the Asian-African continents that it appears at

[2] Songkla (7° N) reports 100 knots at 50,000 feet. This speed is considered doubtful because speeds are only 40 to 50 knots at 45,000 and 55,000 feet. The report has been omitted from the analysis.

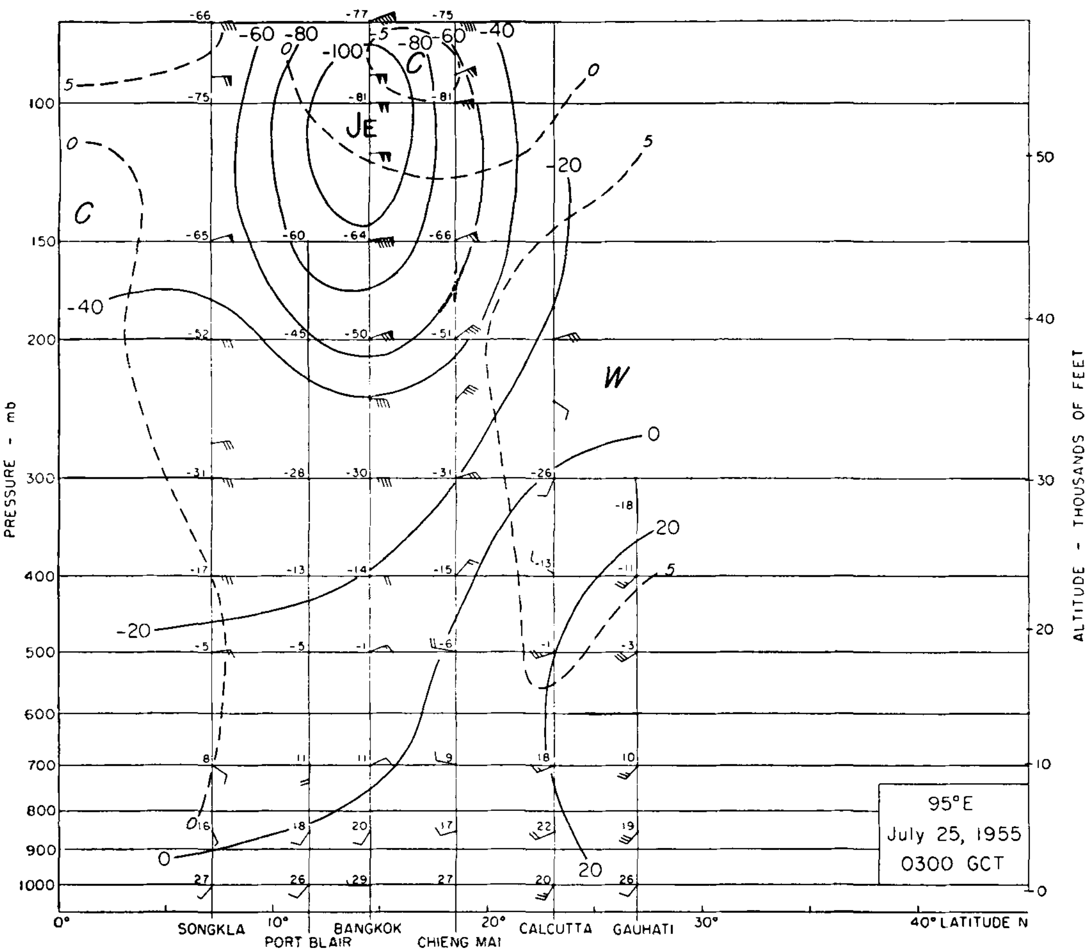

Fig. 5 a. Vertical cross-section of wind and of temperature anomaly (°C) from the mean tropical atmosphere along 95° E July 25, 1955. Isotachs solid, east components marked negative. Isolines of temperature anomaly dashed. Double dashed line is tropopause.

higher latitudes in association with the concentrated easterly current.

c) Vertical cross-sections: Vertical cross-sections have been constructed along six meridians over Asia and Africa. Isotachs and isanomals of temperature from the mean tropical atmosphere (SCHACHT 1946) have been drawn. Fig. 5 presents the vertical section along longitudes 95° E and 45° E. The following features are observed:

At 145° E only one jet stream is present—north of 45° N in the westerlies. An easterly maximum is noticed near 30° N at 100 mb and is probably part of the stratospheric easterly circulation which is known to reach at least 50 knots, often more, in the lower stratosphere (RIEHL 1948).

The stratospheric easterlies near 30° N are also found at 125° E. In addition another easterly maximum appears over the Philippines, probably the beginnings of the current which extends across the whole of southern Asia. Concentration of easterly kinetic energy takes place only above 250 mb in a layer about 10,000 feet thick.

At 95° E—Fig. 5 (a)—we observe the core with easterly speeds above 100 knots, described earlier. Again the current is hardly in evidence below 200 mb. Temperatures decrease from right to left across the current, looking downstream, below the core if the Port Blair report which evidently does not fit is omitted. Above the core the temperature field reverses.

The picture at 75° E is similar to that at

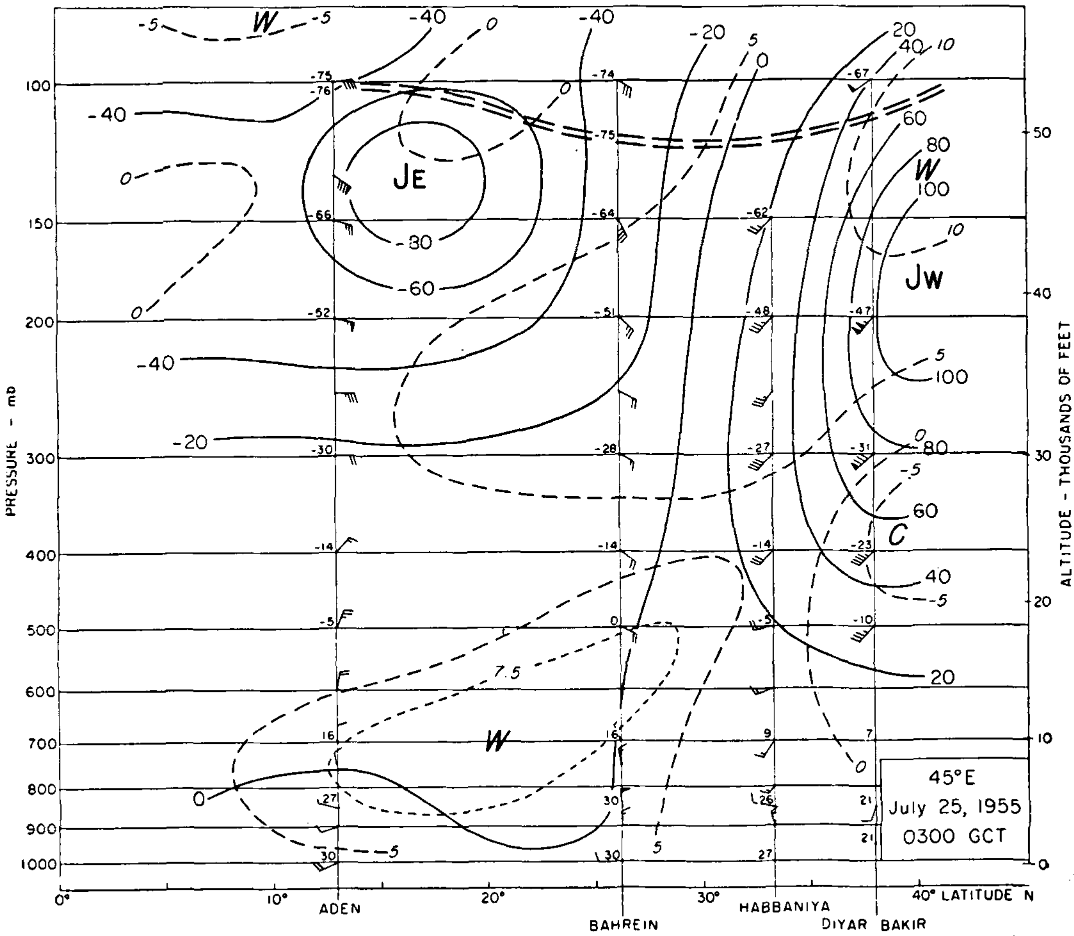

Fig. 5 b. Vertical cross-section of wind and of temperature anomaly along 45° E, July 25, 1955.

95° E both as regards wind and temperature structure. A 100 knot center could be inferred though direct evidence is lacking as the Madras ascent broke off at 200 mb. On the previous day a maximum of 89 knots had been reported at 100 mb.

We enter the decaying portion of the easterly current near 45° E—Fig. 5 (b). The core speed still exceeds 80 knots, however; the latitude of the core is the same as farther east but its altitude is about 7,000 feet lower. We observe the equatorward portion of a westerly current near 40° N. Large temperature gradients are encountered. In the lower and middle troposphere temperatures decrease poleward north of 25° N; above a transition layer with indifferent temperature field near 300 mb we find the warmest temperatures in the north with a gradual decrease southward—the pattern conducive to decrease of the westerly and increase of the easterly current with height. Above 100 mb we see still another reversal in the region of the easterly current. Thus the temperature fields associated with both easterly and westerly jet streams are particularly well brought out by this section.

At 30° E the easterly current has diminished further in intensity. The core speed is only slightly above 60 knots, and highest speeds occur between 200 and 100 mb. The temperature field resembles that at 45° E; the double jet stream regime is still in evidence.

At the Greenwich meridian, a wind maximum of 40 knots persists at 15° N which may

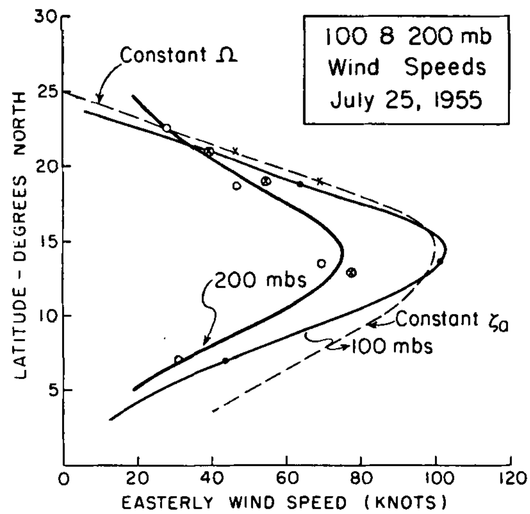

Fig. 6 a. Meridional profile of the east component at 100 mb and 200 mb using combined data from India and Thailand for July 25, 1955.

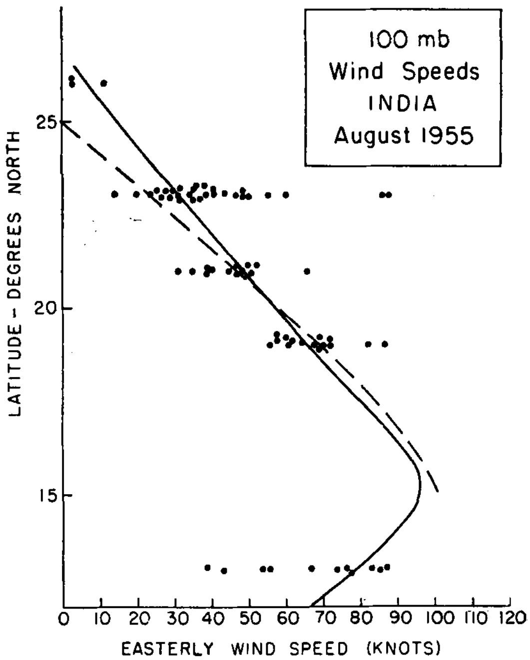

Fig. 6 b. Meridional profile of the east component at 100 mb for India using all observations for August 1955.

be a remnant of the Asian easterly current. A new core appears near 10° N with center at 200 mb. This current is also of limited thickness (about 15,000 feet), but the associated temperature field is complex and cannot be analyzed further in the present context.

d) Distribution of momentum and vorticity: Fig. 6 (a) shows meridional profiles of easterly wind speed at 200 and 100 mb using combined data from India and Thailand. The dashed line represents constant absolute angular momentum on the anticyclonic side assuming zero relative zonal velocity at 25° N, the latitude of equatorial trough and high tropospheric ridge line. On the cyclonic side, the dashed line represents constant absolute vorticity using the earth's vorticity at 15° N, the latitude of the core of the current, for the constant. The fit of the values at 100 mb, the level of strongest wind on the anticyclonic side, is quite good. In order to see to what extent constant angular momentum was observed over longer periods, a meridional wind profile was drawn at 100 mb using all rawin observations over India during August 1955 (Fig. 6 b). Dots represent individual observations, the full line is the mean speed profile and the dashed line is the same as in Fig. 6 a. The average anticyclonic shear amounts to nearly 4×10^{-5} sec^{-1}, while the mean value of the Coriolis parameter in the area considered is 5×10^{-5} sec^{-1}. Thus the mean wind distribution indicates nearly constant absolute angular momentum, or zero vorticity, on the anticyclonic side of the easterly core, quite similar to what is found on the anticyclonic side of mid-latitude westerly jet streams.

Lack of sufficient data prevents discussion of the wind distribution on the cyclonic side.

e) Vertical shear: We have seen during the analysis of the vertical cross-sections that concentration of easterly kinetic energy occurs only in a thin layer in the high troposphere. Fig. 7 shows vertical wind profiles for a number of stations situated close to the easterly core from longitude 120° E to 0°. In all of these profiles the easterlies increase, or the westerlies decrease, from the ground upward. The profiles are curved so that the strongest shear occurs just under the maximum speeds; the

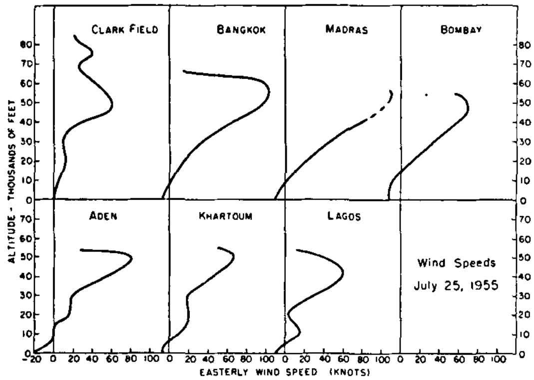

Fig. 7. Vertical profile of the east component at seven stations, July 25, 1955.

value of the strongest shear is 4—5×10^{-3} sec^{-1}. Above the level of strongest wind the profiles cannot be drawn with much accuracy due to lack of data. At some stations notably Bangkok and Aden, the upper shear greatly exceeds the lower one with values as high as 20×10^{-3} sec^{-1} at Bangkok. In contrast, the upper shear at Clark Field is very weak.

f) Rainfall and Cloudiness: Fig. 4 (a) shows the distribution of cloudiness over southern Asia and Africa at 1 200 Z, July 25, 1955, and rainfall in inches for the 24 hours ending at 0 300 Z, July 26, over India, Pakistan, Burma and Ceylon. The heavy dashed line marks the position of the easterly core. Concentration of cloudiness north of the core east of 75° E and south of the core farther west indicates the vertical currents associated with the core, i.e. ascent east of 75° E and descent west of this longitude north of the core and the reverse on the south side. Since, as noted earlier, the current is accelerating east of 75° E and decelerating farther west, a "direct" crosstream circulation is implied for the "entrance" zone of the current and an "indirect" circulation at the exit. Such a distribution of vertical circulation has previously been noted by the author and PARTHASARATHY (1954) in the mean westerly jet stream over India in the pre- and postmonsoon seasons. Since all of these results are in substantial agreement with findings in temperate zone jet streams, it follows that the type of vertical circulation pattern observed is independent of latitude or orientation of a jet stream. It also follows that there should be a close connection between fluctuations in the upper easterly current and fluctuations in the low-level monsoon. Before considering this subject we shall try to establish, using climatic data, to what extent the results of July 25, 1955, can be generalized for the summer monsoon season.

The easterly current related to rainfall over Asia and Africa in summer

Analysis of daily charts during the summer of 1955 has shown that easterly jet streams regularly exist over southern Asia and Africa during the summer monsoon season near 15° N. Assuming then, that the easterly jet is an average feature over this area during summer and that large scale ascent takes place north of the entrance and south of the exit region, we may examine the mean rainfall distribution over Asia and Africa with reference to the jet stream. Fig. 8 shows the average July rainfall and the average jet stream position. Rainfall data have been taken from HAURWITZ and AUSTIN (1944); for the Indian area charts published by the INDIA METEOROLOGICAL DEPARTMENT (1949) have been used. Over Asia, the rainy belt lies mostly north of the axis of the current, with

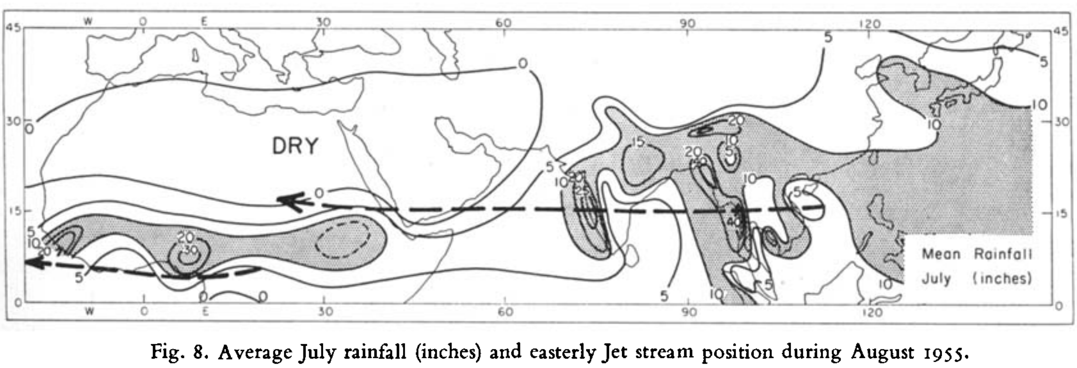

Fig. 8. Average July rainfall (inches) and easterly Jet stream position during August 1955.

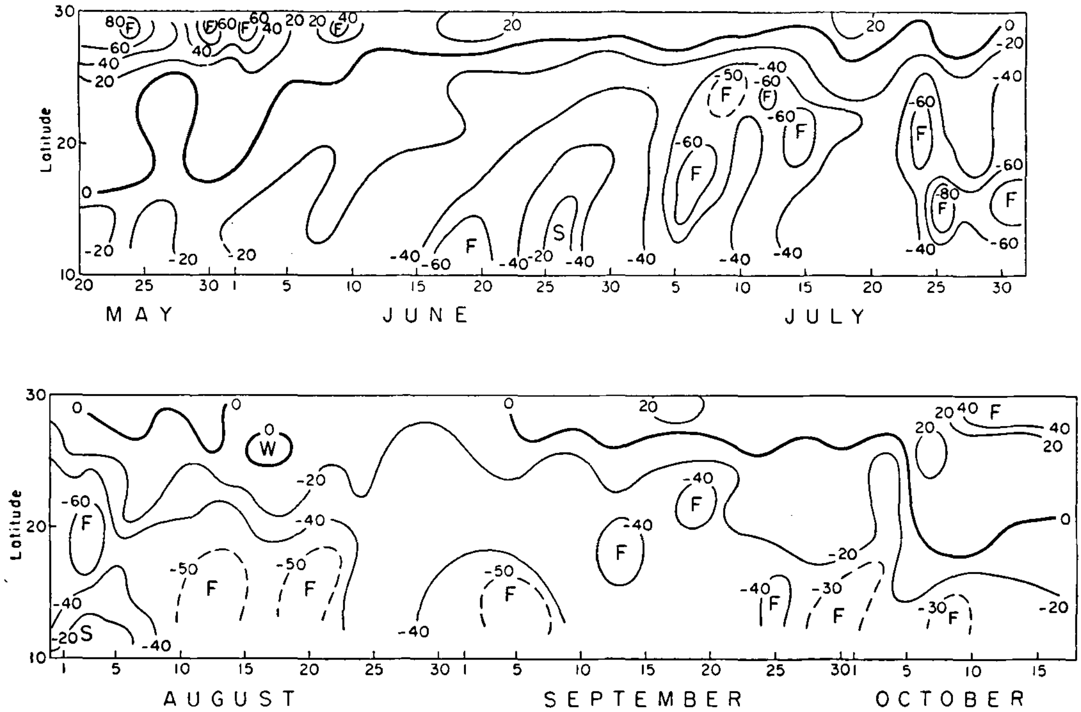

Fig. 9. Space-time section of 200 mb wind speed over India for the summer of 1955 (east components negative).

the exception of the mountainous west coast of India and the Tennaserim coast of Burma. But even along those coasts rainfall generally diminishes southward, as is well known. While interpreting the map, one should remember that the easterly current is not always in the accelerating stage over the Bay of Bengal; during periods when it decelerates in this region, there may be copious precipitation in the southern areas. The climatological distribution can be expected only to bring out the preponderant features. Since on most days the current accelerates east of the Indian Peninsula, the extensive rain areas over northeastern India, Burma and farther east are in accord with the large-scale ascent to be expected over these areas from the jet stream consideration.

West of the Indian peninsula the pattern is reversed. Here the current decelerates in the mean and large scale descent over the well-known deserts is the result. In fact, the deserts themselves may be attributed to this sinking in the higher levels in spite of intense surface heating. South of the axis of the current rainfall is confined to the region south of 10° N over Africa. Here, as noted in a previous paragraph, the principal upper-air feature probably is a new current forming at very low latitudes over Africa.

It thus appears that the easterly jet stream plays an important role in shaping the summer rainfall distribution over Asia and Africa, that it forms a part of the general monsoon system and that the monsoon in the low troposphere must be related to the high-tropospheric easterly current.

Fluctuations in the Monsoon Season

Burst of the monsoon: YIN (1949) has suggested that the monsoon bursts when the wintertime westerly jet stream, known to circle the southern periphery of the Himalayas, moves far enough north so that the major portion of the mass flow in this current is detoured to the north of the high mountain ranges. He noted that the monsoon advances first over Burma and later over India, and attributed this to a westward shift of the through in the westerlies located over the Bay of Bengal during the cool season. This shift occurs together with the northward displacement of the westerlies aloft. The author and PARTHASARATHY (1954) have also observed a progressive northward shift of the mean westerly wind maximum during the pre-monsoon season.

Fig. 9 shows a time-space section of 200-mb wind speeds for the whole monsoon period from May to October 1955. The northward shift of the westerlies at the time of the burst of the monsoon on the west coast of the Indian peninsula is spectacular. However, strong westerly winds are still reported intermittently by stations north of 30° N even after the onset of the monsoon. Peshawar (34°), for instance, reported a westerly wind of 64 knots and Lahore (31.5° N) 42 knots on June 6, 1954, when the monsoon had advanced halfway up the peninsula. One June 12 Lahore reported 280°, 67 knots, at 30,000 feet and Peshawar 270°, 55 knots. By that time the monsoon had extended to 20° N. It thus appears that the westerlies make incursions into western Pakistan even after the onset of the monsoon and that not untill the subtropical anticyclone is established over the Himalayas will westerly winds disappear completely from the region south of the mountains.

It is of interest to investigate the location of the easterly jet stream at the time of onset of the monsoon. Fig. 10 shows the upper winds at Madras for the period May 23—30, 1955. Unfortunately most balloons stopped at or below 200 mb. One can see however that the easterlies are still light on May 25 but reach values over 60 knots on May 27. A trough formed off the Malabar coast on the 26th and the monsoon advanced into Malabar by the 28th, when Trivandrum had 4 inches of rain. On may 29th the India daily weather report announced that the monsoon had revived over Malabar.[3] At that time upper winds at Aden were still weak; 27 knots from 100° was observed at 100 mb on May 27. Easterlies exceeding 50 knots set in at Aden after June 6. Thus it is probable that the easterly current which had advanced to southern India on May 27 was in the decelerating stage and that the core was so placed that the ascending motion occurred to the left of the axis looking downstream.

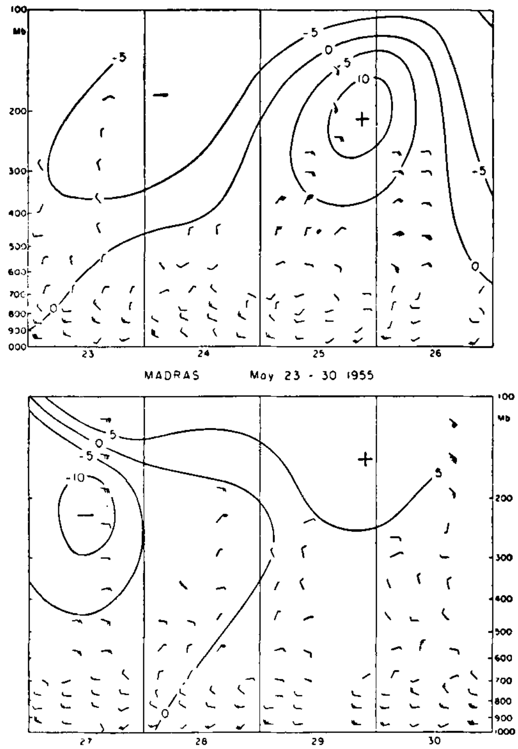

Fig. 10. Vertical time section of upper winds at Madras May 23—30, 1955.

The coincident arrival of monsoon and upper easterlies is probably not fortuitous but indicates a general pattern. As is well known, the monsoon at first develops at more easterly longitudes in the middles of May and successively advances over the Bay of Bengal and the Arabian Sea. The upper easterly current likewise appears to form initially east of India and then extend itself downstream across India to Arabia.

Surges and breaks of monsoon: The northward shift of the monsoon rain belt along the western coast of India and the periodic pulsations of the intensity of the monsoon are connected with similar shifts and pulsations in the upper easterlies.

During "breaks" in the monsoon, the monsoon trough shifts to the Himalayas and westerlies dominate the whole of southern Asia below 500 mb. In the upper troposphere however easterlies continue to prevail. The

[3] There was a temporary advance of the monsoon on May 20 in association with a Bay of Bengal depression.

high-level easterly jet is well marked and occupies a more northerly position than average. When the current reverts to lower latitudes and begins to decelerate over the Arabian Sea, a revival of the monsoon takes place along the Indian west coast, as happened on July 25, 1955.

Fig. 10 illustrates the shift in the position of the easterly core in 1955; it also gives a general picture of its latitudinal oscillations. A gradual northward advance, followed by sudden retreat to low latitudes, are the main features during July. At the beginning of August, the current again moves northward to about 18° N, then gradually drops off toward south until the current becomes unimportant coincident with the time of withdrawal of the southwest monsoon.

Conclusion

This paper has shown that an easterly jet stream overlies tropical Asia and Africa in the summer monsoon season and that this current forms an important part of the general circulation in those regions. Over the Atlantic and Pacific oceans no such jet stream exists; instead the high tropospheric circulation consists of a train of vortices (RIEHL 1948). We must conclude from this marked difference that the land-sea distribution plays a major part of shaping the flow pattern of the southern periphery of Asia. The equatorial region is covered entirely by ocean, the region north of 20° N by land. This arrangement prescribes maximum surface heating far to the north of the equator in the northern summer. In addition, the surface on which the insolation is absorbed and reradiated is greatly elevated in the region of the vast Tibetan plateau which extends to 700 mb over a wide area and to 500 mb and above in the high ranges. The large extent and high elevation serve to heat directly the middle troposphere and to produce a strong solenoid field in the upper troposphere for driving a clockwise circulation.

Thus the high-level anticyclone over northern India and Tibet appears to be thermally driven whereas the cells overlying Arabia and Africa are "dynamic" highs associated with descent and production of deserts. Along the northern margin of India the high-level circulation does not act to suppress, rather to assist large-scale ascent in the equatorial trough. The outflow from the trough is maintained by the combined solenoid field resulting from the high surface heat source plus condensation heating. At least the equatorward branch of the outflow moves at nearly constant absolute angular momentum where the constant is the earth's momentum at latitude 25° N, close to the region of high heat source and strong condensation heating as shown earlier (Figs. 6 a, b). In this way the upper jet stream is produced and it is not without interest to observe that this current in the mean reaches its greatest intensity approximately south of the western margin of the high plateau.

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