On the instantaneous distribution of vertical velocity in the monsoon field and structure of the monsoon circulation[1]

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ABSTRACT

An approximate representation of the instantaneous three-dimensional circulation of the Asian summer monsoon has been obtained using data and analysis at a given map time in July 1963 during the International Indian Ocean Expedition (1963–65). For this purpose, vertical velocity was computed using the continuity equation and by stepwise integration of the divergence field, at the standard isobaric levels at every five-degree grid-point along seven meridional sections extending from 50° E to 140° E between latitudes 35° N and 25° S. In conjunction with the meridional and zonal components of the winds, the vertical velocities yielded the instantaneous vertical circulation patterns and these are presented along seven meridional and four zonal sections. The isobaric distribution of vertical velocity is presented along four standard pressure surfaces, viz. 850, 700, 500 and 100 mb.

The computed vertical velocities show three well-defined updraft areas over the landmass of Asia, one over Arabia, one over India, and the third over China. A few localized updraft cells of feeble intensity appear over the sea areas, e.g. one in the equatorial region between Gan Island (00°41′ S, 73°09′ E) and Indonesia and another in western central Pacific, east of the Philippines. Extensive downdraft areas are found over the land area between India and Arabia, over western Himalayas and Tibet, and over most of the sea areas lying to the south of the continental landmass. Practically the whole of the west Arabian Sea appears under intense downdraft.

Over many areas, however, the computed vertical velocities increase continually with height showing little or no vertical compensation. This is, of course, due to analysis Notwithstanding this basic problem, the computed vertical velocity patterns are found to be compatible with the observed distribution of temperature, humidity, vorticity, rainfall, and jet streams. The presence of a belt of equatorial westerlies (south of the Equator) in the Indian Ocean area would also seem to support computed updraft in this region.

The evidences furnished in the paper strongly suggest that it is only a three-dimensional thermal convective model that can describe the giant monsoon circulation over the north Indian Ocean and adjoining Asian continent adequately.

1. Introduction

The summer monsoon of Asia has been studied in India for many decades and an account of the state of knowledge during the first quarter of the present century may be found in a paper by Simpson (1921) which has recently been reviewed by Desai (1965). One of the important conclusions of the earlier studies was that the monsoon originated in the southern hemispheric subtropical anticyclone and travelled all the way over the Indian ocean before it reached the Asian continent. Recent studies (Pisharoty, 1965; Krishnamurti, 1966), however, have questioned this origin of the monsoon and expressed the view that the source-region of the monsoon current that enters India is to be found not in the southern hemisphere but over the Arabian Sea.

Lack of adequate aerological data over the Indian ocean has in the past stood in the way of an objective study of the three-dimensional structure of the summer monsoon circulation over Asia and the neighbouring ocean areas.

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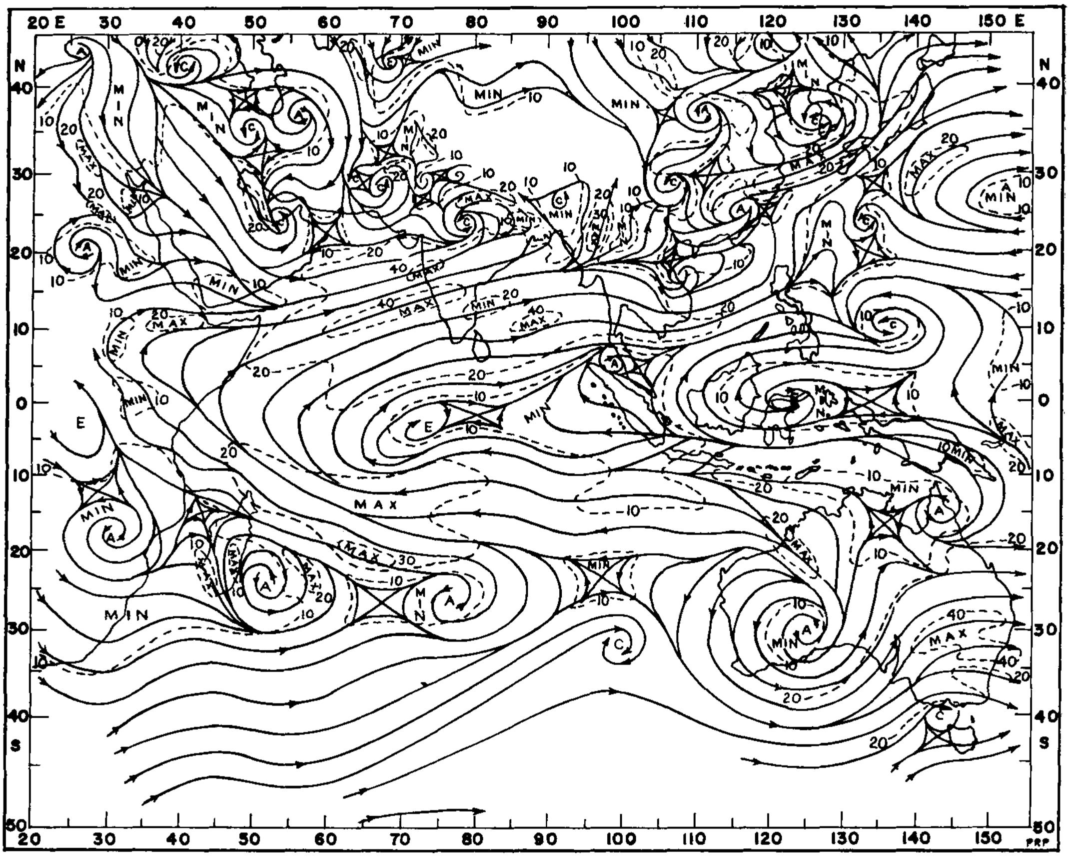

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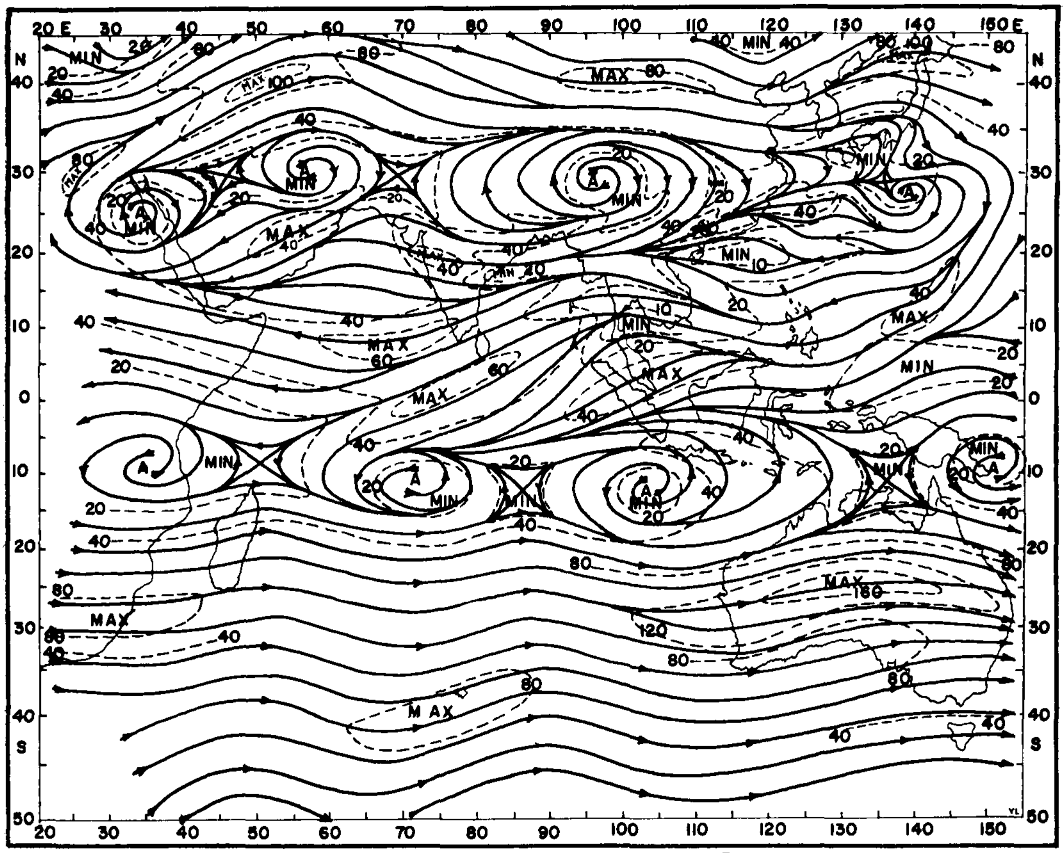
Fig. 1 (*a*)–(*b*). Streamline-isotach analysis, 1200 GMT, 7 July 1963. (*a*) 850 mb, (*b*) 200 mb level.

For a proper understanding of the circulation, we require to know not only the horizontal or isobaric flow patterns but also the distribution of the vertical velocity. Actual computations of vertical velocity in the monsoon atmosphere have been very few, indeed! Das (1962) computed mean vertical air motion over India and neighbourhood during the southwest monsoon season and was the first to show quantitatively that there is an area of ascending motion over northeast India and one of descending motion over northwest India and adjoining Pakistan and western Tibetan plateau.

Recently, Krishnamurti (1966), using a balanced model, computed vertical motions in the monsoon field between latitudes 6° N and 48° N and longitudes 30° E and 108° E at 900, 700, 500, and 300 mb surfaces for 2, 3 and 4 August 1961. He found general rising motion of air in the northeastern parts of the monsoon trough with a maximum intensity of around 1 cm/sec and sinking motion to the southwest. He, however, remarks that there were considerable variations in the distribution of vertical motion field during the three days he studied in the form of local intense centers of rising and sinking motions associated with smaller scale perturbations that moved from southwest to northeast, south of the major axis of the monsoon trough.

In the present paper, a study has been made of the instantaneous three-dimensional structure of the summer monsoon circulation at a selected map time during the International Indian Ocean Expedition (1963–65), by computing vertical velocity at all standard pressure



STREAMLINE ANALYSIS 200Mb 1200 GMT 7TH JULY 1963

b

surfaces from 1000 to 100 mb over the monsoon field bounded by latitudes 35° N and 25° S and longitudes 50° E and 140°E. The computed vertical velocities were combined with the zonal and meridional components of the horizontal wind to reveal the instantaneous three-dimensional structure of the air circulation. The circulation patterns derived were examined for consistency with distribution of temperature, humidity, absolute vorticity, rainfall, and jet streams. The extent to which a reversed-Hadley cell type of meridional circulation explains the observed circulation over Asia and the neighbouring ocean areas is discussed.

2. Computation of vertical velocity

(a) Method

The vertical velocity ω in pressure coordinates was computed by integrating the continuity equation in the form

$$\frac{\partial \omega}{\partial p} = -\nabla \cdot \mathbf{v}, \qquad (1)$$

where $\omega = dp/dt$, $\nabla \cdot \mathbf{v}$ is divergence of the horizontal velocity vector $\mathbf{v}$, and p is pressure. The velocity divergence was computed by using the relation

$$\nabla \cdot \mathbf{v} = \frac{1}{A} \oint_C \mathbf{n} \cdot \mathbf{v} \delta l, \qquad (2)$$

where δl denotes a line segment of the boundary of a region of area A, $\mathbf{n}$ is the horizontal unit vector normal to δl, and the integral is taken round the whole closed boundary C of the region. When integrated over a layer from p_0 to p_1, the vertical velocity ω_1 at the top of the layer is given by

$$\omega_1 = \omega_0 + \overline{(\nabla \cdot \mathbf{v})}(p_0 - p_1), \qquad (3)$$

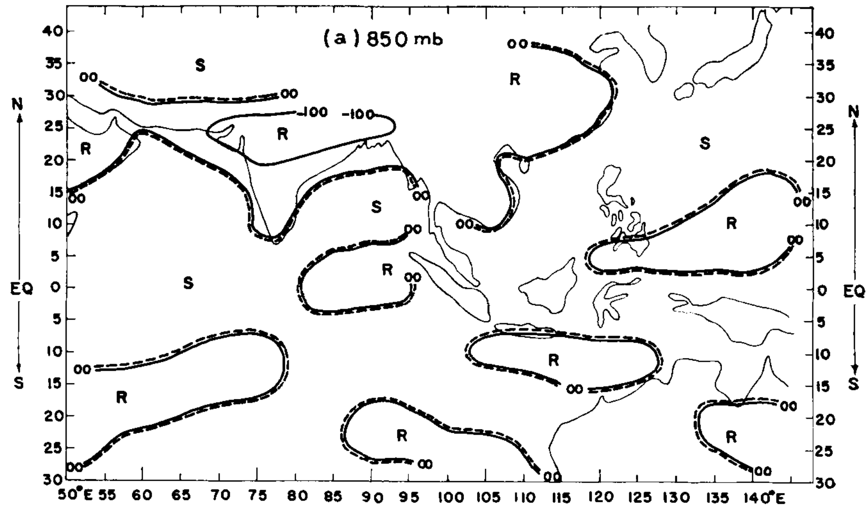


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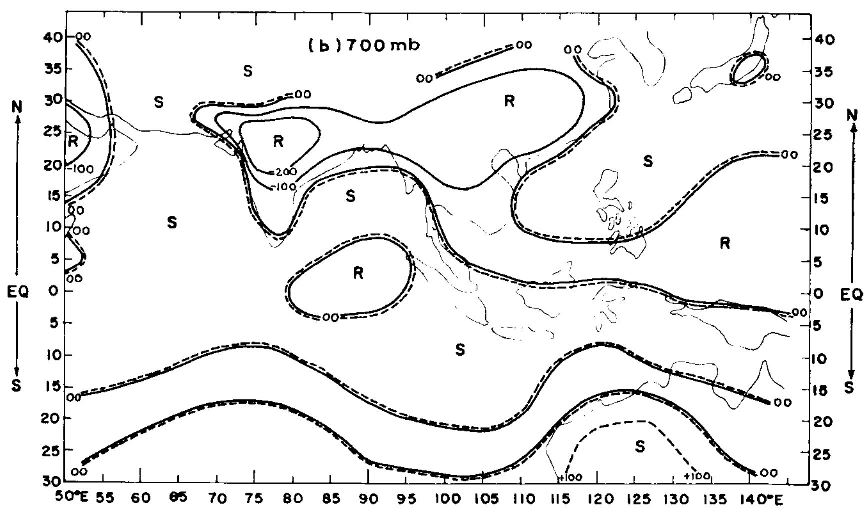
Fig. 2 (*a*)–(*d*). Distribution of vertical velocity in millibars per day at (*a*) 850 mb, (*b*) 700 mb, (*c*) 500 mb, and (*d*) 100 mb levels. Negative values (heavy continuous lines) indicate rising (*R*) and positive values (heavy dashed lines) sinking (*S*) air.

where ω_0 is the vertical velocity at the bottom of the layer, and the quantity within the bracket under the bar represents a mean value of the divergence of the layer. Equation (3) was used in stepwise integration to obtain the values of vertical velocity at all the standard pressure levels.

(*b*) *Analysis and data*

The above kinematic method was applied to situation at 1200 GMT, 7 July, 1963, for which streamline-isotach charts for all the standard pressure levels, analysed by the International Meteorological Center (Meteorological Wing of the International Indian Ocean Expedition), were available. Fig. 1 *a* and *b* show the analyses at 850 and 200 mb levels respectively. The density and distribution of data on these maps, particularly where they relate to ocean areas, were certainly not as good as might be considered satisfactory for kinematic computations but they were undoubtedly the best ever for



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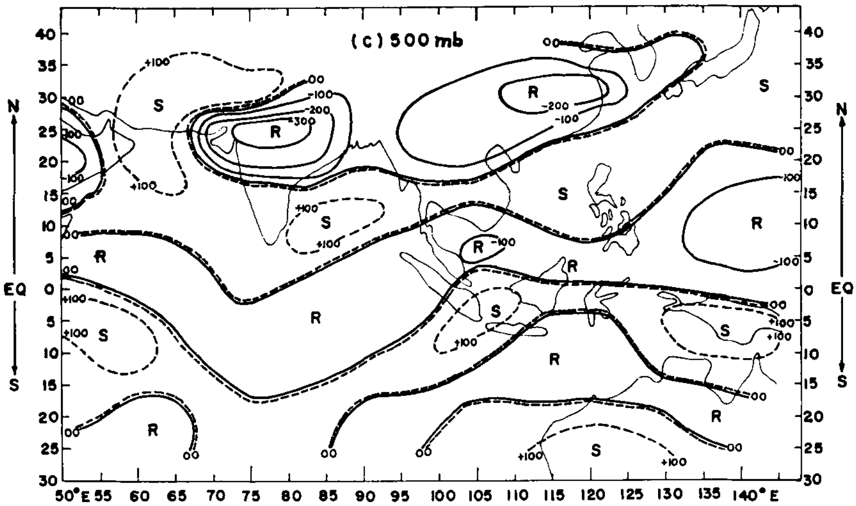

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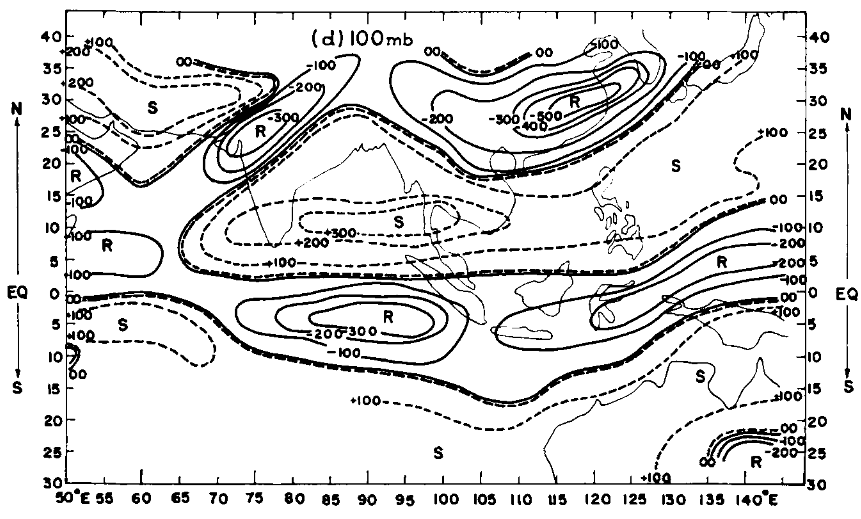
the region, considering the data network available before and during the IIOE period. During this period (1963–65) a dozen or so fairly well-distributed island stations in the Indian ocean area reported aerological data regularly and at the chosen map time reports from all these stations except one were available. In addition extensive aircraft-in-flight reports and ships' reports were available. The continental sections were generally well-covered except in regions of east Africa, Arabia, Iran, and Tibet where the aerological networks are generally poor. Regarding the quality or accuracy of the data, little definitely can be said, since varying degrees of instrumental errors and different types of sounding equipment and methods of measurement were involved.

(*c*) *Actual computations*

Divergence was computed over $10° \times 10°$ grids using equation (2) at every five-degree latitude point from 35° N to 25° S, along seven selected meridians viz. 50°, 60°, 75°, 90°, 105°, 120° and 140° E at all the standard pressure



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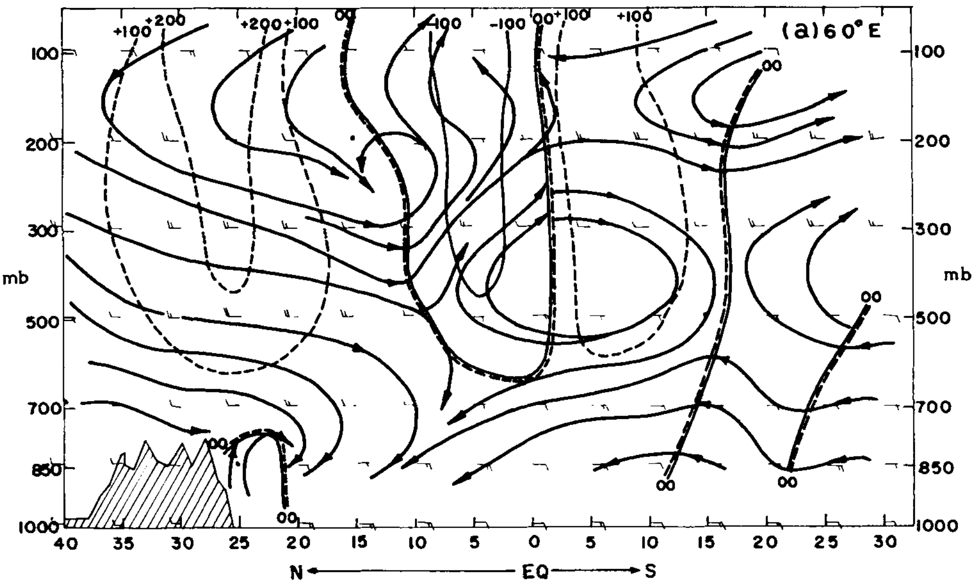

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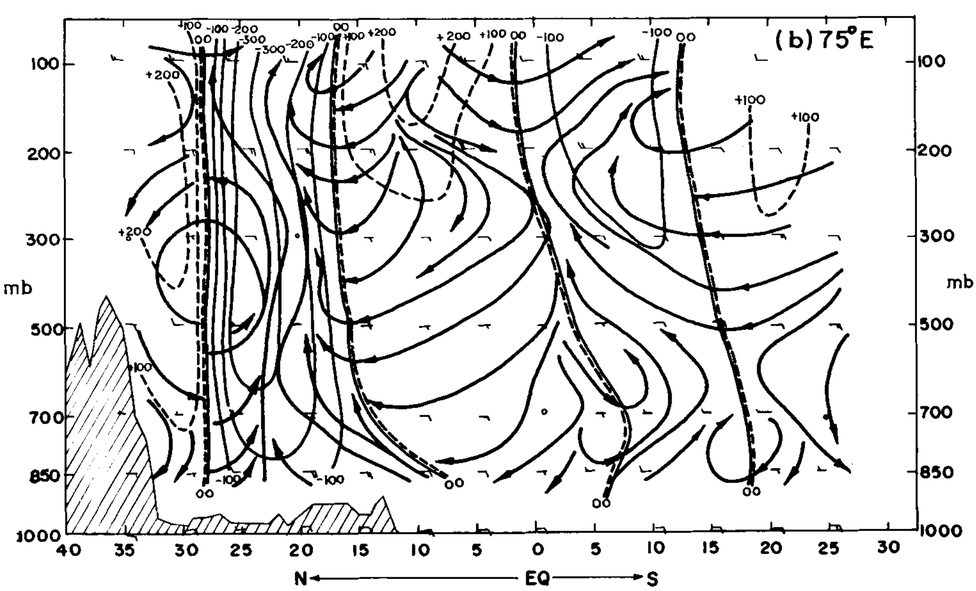
Fig. 3 (*a*)–(*d*). Approximate resultant streamlines between vertical velocity and the meridional wind in vertical planes along meridians (*a*) 60°E, (*b*) 75° E, (*c*) 90° E, and (*d*) 120° E. Meridional winds (deg/knots) are shown by conventional symbols, vertical velocities (mb/day) are shown by contours. Hatched areas indicate ground contours.

levels from 1000 to 100 mb. For this purpose, wind direction was read to within 10° and speed to the nearest knot. The vertical velocities were then computed using equation (3) and the results were expressed in units of millibars per day. The vertical velocity at the 1000 mb level was assumed to be zero over all computation areas as a first approximation.



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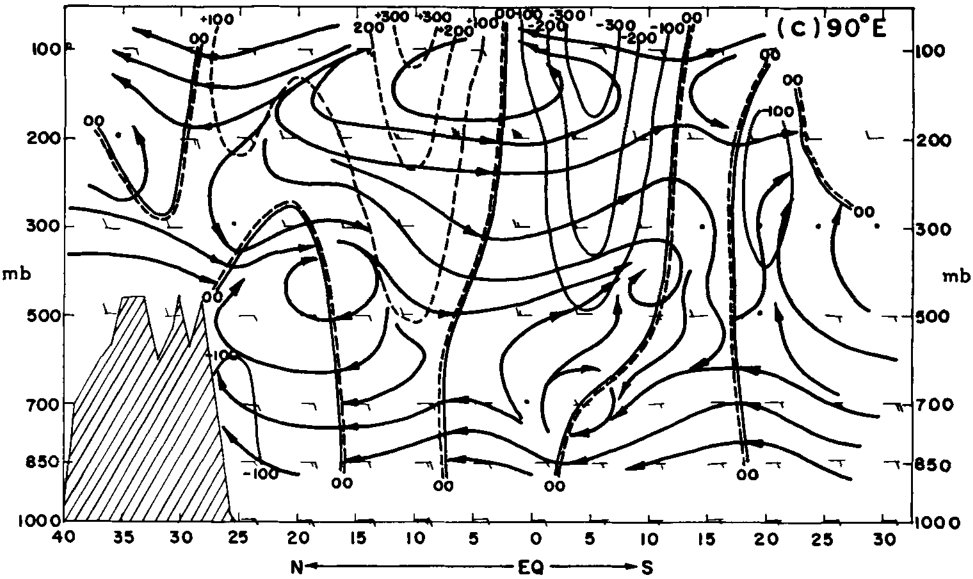

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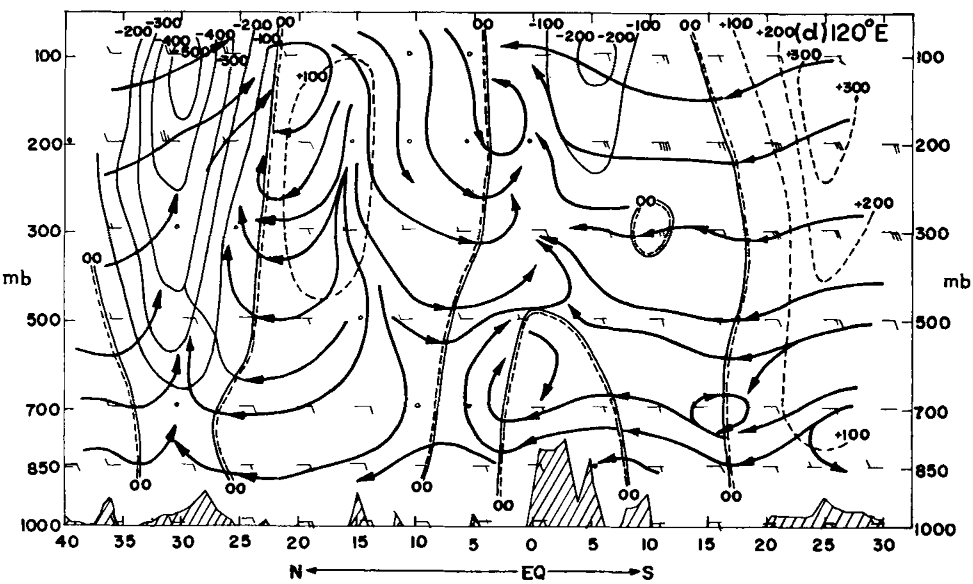
3. Distribution of vertical velocity along isobaric surfaces and with height

Fig. 2*a–d* show the distribution of vertical velocity at the given map time along four standard isobaric surfaces viz. 850, 700, 500 and 100 mb. For economy of space, four levels only are presented although computations were carried out for all the standard isobaric levels. The diagrams would appear to reveal the following features: Three areas of updraft appear over the landmass of Asia, one over Arabia, one over India, and a third over China. A few localised feeble updraft areas appear over the ocean, e.g. one over the north Indian



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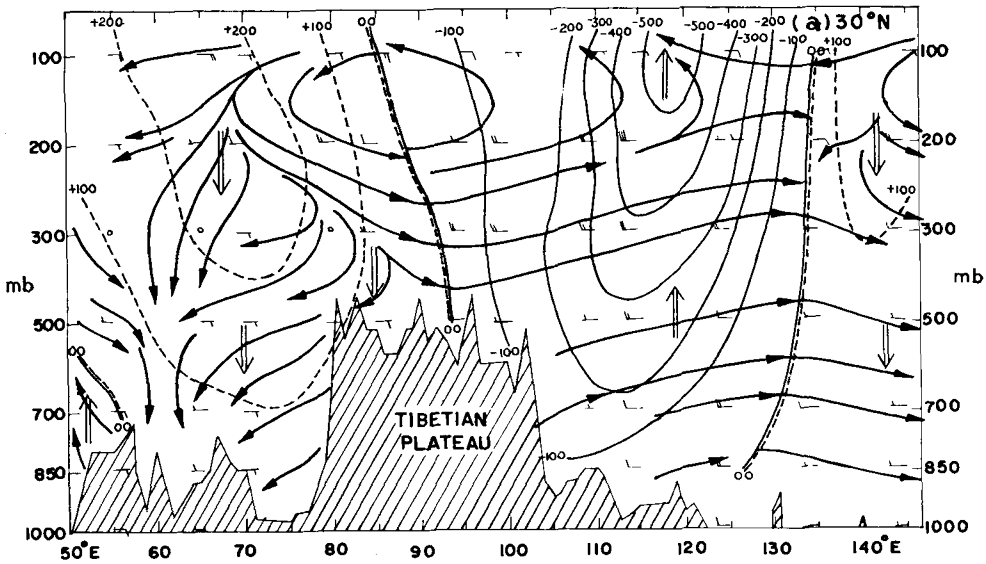

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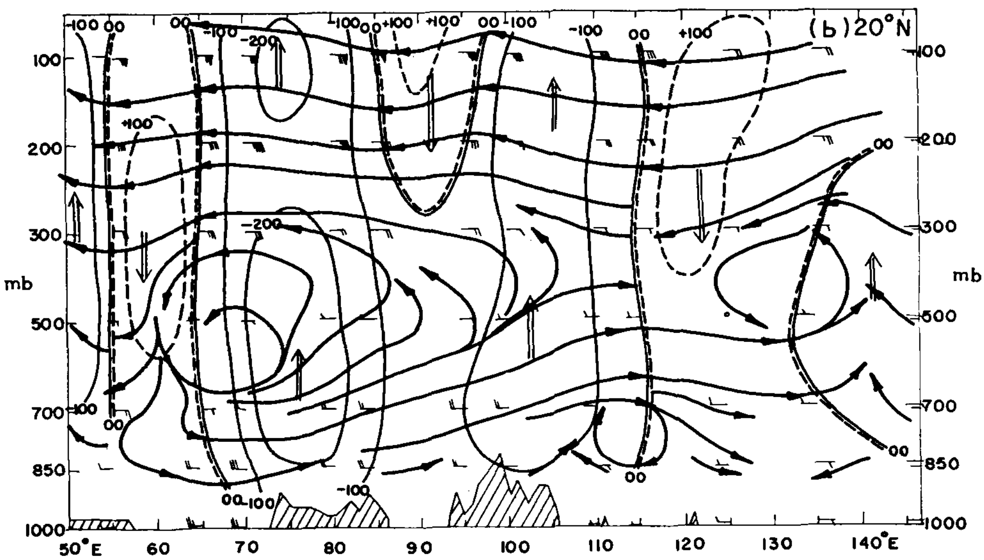
Fig. 4 (*a*)–(*d*). Approximate resultant streamlines between vertical velocity and zonal wind in vertical planes along latitudes (*a*) 30° N, (*b*) 20° N, (*c*) 10° N, and (*d*) the equator. Zonal winds (deg/knots) are shown by conventional symbols, vertical velocities (mb/day) are shown by contours. Doubled-lined vertical arrows show regions of updraft and downdraft.

ocean in the region between Gan Island and Sumatra, and another over the central Western Pacific just east of the Philippines. Over most of the remaining sea areas general sinking air motion appears. An extensive region of down draft appears over the west Arabian sea and the adjoining land areas between India and Arabia.

It may, however, be seen that the computed vertical velocities increase monotonously with height over many areas, indicating little or no



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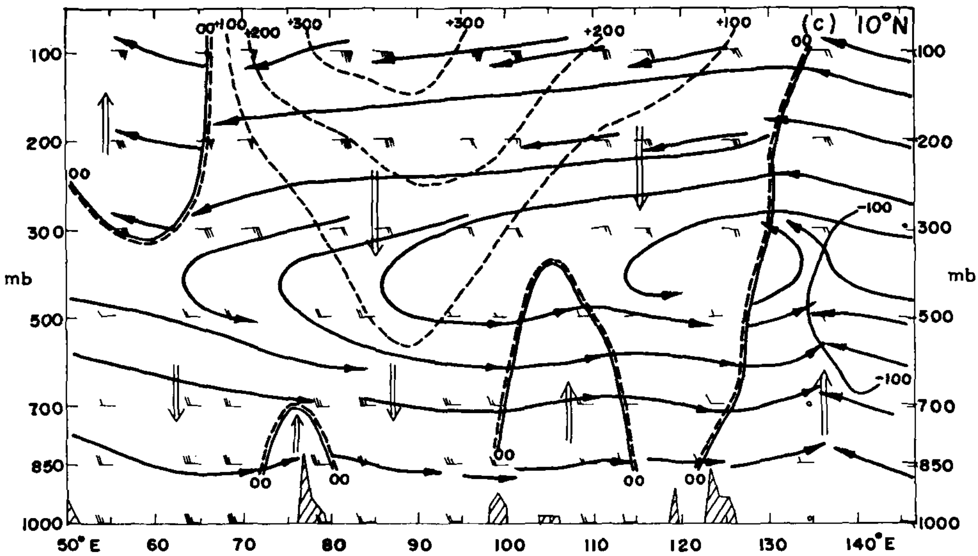

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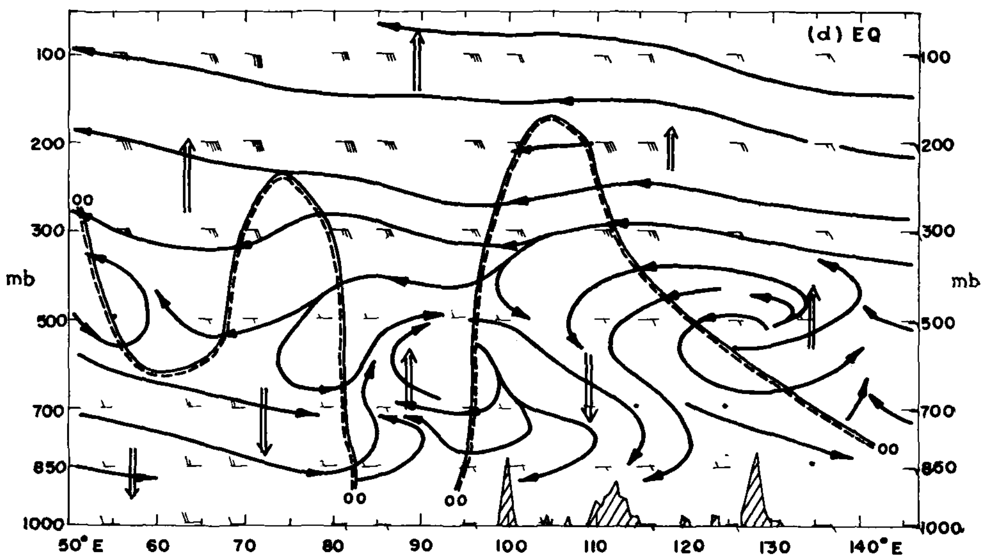
vertical compensation within the troposphere Similar results were also obtained by Miller (1958) in a study of the three-dimensional wind structure around a tropical cyclone and by Rex (1958) in a study of vertical motion in the equatorial central Pacific. It is well known that computations of vertical velocity by the kinematic method are highly sensitive to errors in basic data and analysis, but the exact manner in which the errors accumulate is difficult to determine. The fact that the computed vertical velocities continually increase with height, however, would seem to indicate that there are some systematic errors in the computations or the data used. Nevertheless, it is plausible that the vertical velocities in the lower troposphere are subject to smaller errors and may yet show a realistic and meaningful pattern.



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Amongst others who used the kinematic method to compute vertical velocity in the tropics are Palmen (1958), Flohn (1960*a*), and Riehl (1965).

4. Vertical cross-sections through the monsoon circulation

To obtain an instantaneous three-dimensional representation of the monsoon circulation, values of computed vertical velocity were plotted along with meridional components of the horizontal wind (positive for southerly component) in meridional sections and zonal components of the horizontal wind (positive for westerly component) in zonal sections. Meridional sections were prepared for longitudes 50°, 60°, 75°, 90°, 120° and 140° E, and zonal sections for every five-degree latitude from 35° N to 25° S. The data were plotted from surface to 100 mb level at all the standard pressure levels. At every point in the vertical sections the meridional or the zonal component of the wind as the case may be was combined with the vertical velocity and a resultant direction shown (not to scale). Streamlines were then drawn through these rough resultant directions to show the instantaneous air motion at the selected map time in vertical sections. For lack of space, the results of four meridional sections and four zonal sections only are presented in Fig. 3*a–d* and Fig. 4*a–d* respectively. The diagrams are self-explanatory but the sectional patterns when viewed in an integrated manner would seem to bring out the following essential three-dimensional circulation features:

(*a*) Three prominent synoptic or sub-planetary-scale convection cells appear to dominate the Asian summer monsoon scene, one located over the Arabian region, one over India, and a third over China. The cell over Arabia is weak as compared to those over India and China.

(*b*) Air rising in these convection cells appears to diverge in the upper troposphere and sink in most cases over the lower tropospheric currents, forming a kind of vertical circulation cells.

(*c*) A vast area of intense downdraft appears over the land to the west of India.

(*d*) No downdraft appears to reach the ground between the cells over India and China.

(*e*) There is generally sinking air motion over the sea areas immediately to the south of the continental landmass. A very wide area of intense downdraft appears over the Arabian sea.

(*f*) Air motion north of latitude 30° N is generally one of subsidence. Over China this boundary appears to shift somewhat poleward.

(*g*) Over the Indian ocean, an updraft cell appears in the equatorial region between Gan Island and Sumatra. A fairly well-defined convection cell appears in the Western Central Pacific, somewhat east of the Philippines.

(*h*) Considerable asymmetry is seen in circulation patterns in both zonal and meridional sections.

5. Distribution of temperature and humidity

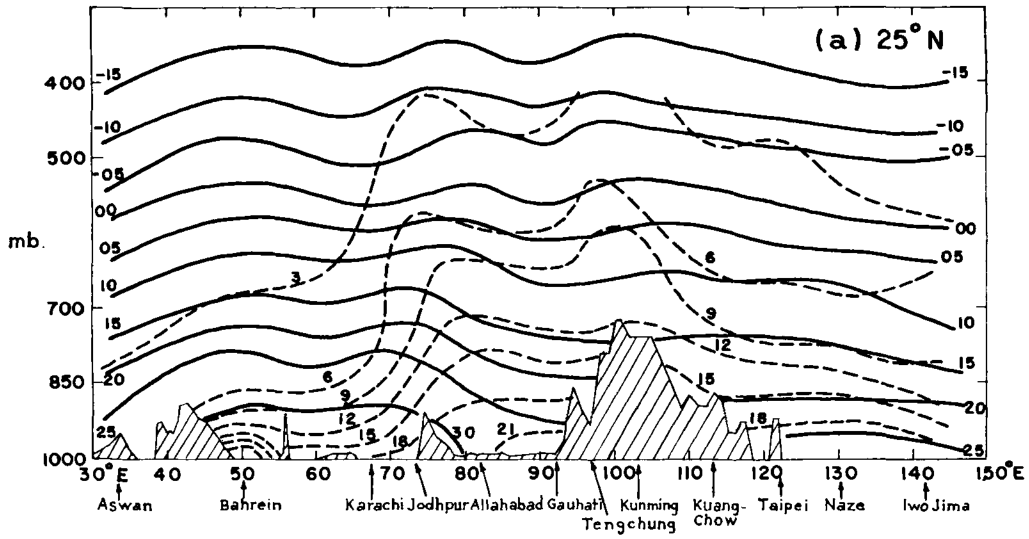
It may be of interest to inquire to what extent the computed vertical velocities and the resulting air motion are compatible with the spatial distribution of temperature and humidity on this occasion. For lack of space zonal and meridional distribution of temperature and humidity-mixing-ratio along latitude 25° and longitudes 75° and 100° E only are presented in Fig. 5*a* and Fig. 6*a* and *b* respectively. The zonal distribution along the Equator presented in Fig. 5*b* relates to 20 June 1963, since adequate data at the selected map time were not available. On 20 June 1963, when conditions along the Equator were more or less similar to those at the selected map time, special drop-sonde observations were available for the sector between Gan Island and Singapore. Many interesting features are revealed by these sections but the essential points may be summarized as follows:

(*a*) High temperature is concentrated over land, with a pronounced ridge in the latitude band 25°–30° N, extending from surface to at least 200 mb level. The position of the axis of the thermal ridge shifts poleward from west to east and appears to be related to the elevated Plateau over China.

(*b*) Temperature decreases both equatorward and poleward from the ridge but the poleward decrease appears to be the steeper of the two.

(*c*) The highest temperature at the surface occurs in the land area between India and Arabia.

(*d*) Humidity variations are more marked than temperature variations in both zonal and meridional sections.



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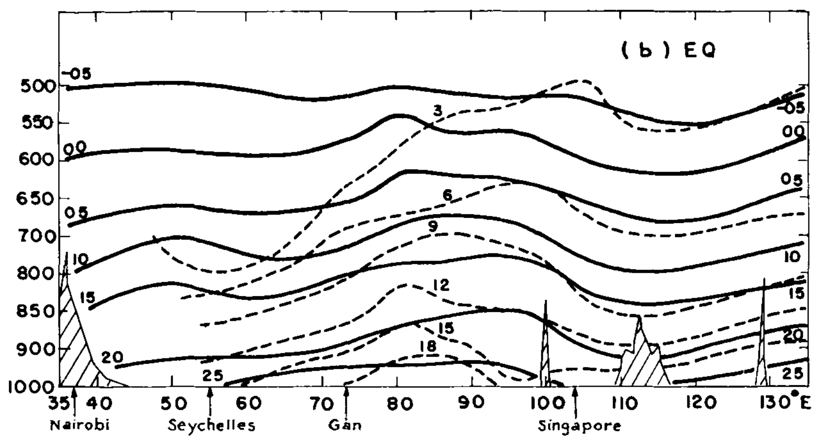

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Fig. 5 (*a*)–(*b*). Vertical distribution of temperature (°C) and humidity-mixing-ratio (g/kg) in zonal sections along (*a*) 25° N and (*b*) equator. Full lines are isotherms and dashed lines isohygrics. The section along the equator relates to 20 June 1963.

(*e*) The whole land area to the west of India is extremely dry. Even over the north and west Arabian sea, the atmosphere is extremely dry except for a very shallow layer, hardly a kilometer deep, close to the sea surface. A steep low-level temperature inversion and marked humidity drop with height characterize the lower troposphere in this part of the Arabian sea (Bunker, 1963; 1965; Colon, 1964).

(*f*) A paradoxical feature of the humidity distribution is that although the source of moisture is the ocean area, the humidity ridge appears over the land.

(*g*) In general the humidity ridge appears to lie equatorward of the temperature ridge to the extent of about 10 to 15 degrees of latitude in the Arabian region, 5°–10° in the Indian section, and less than 5° in the Chinese section.

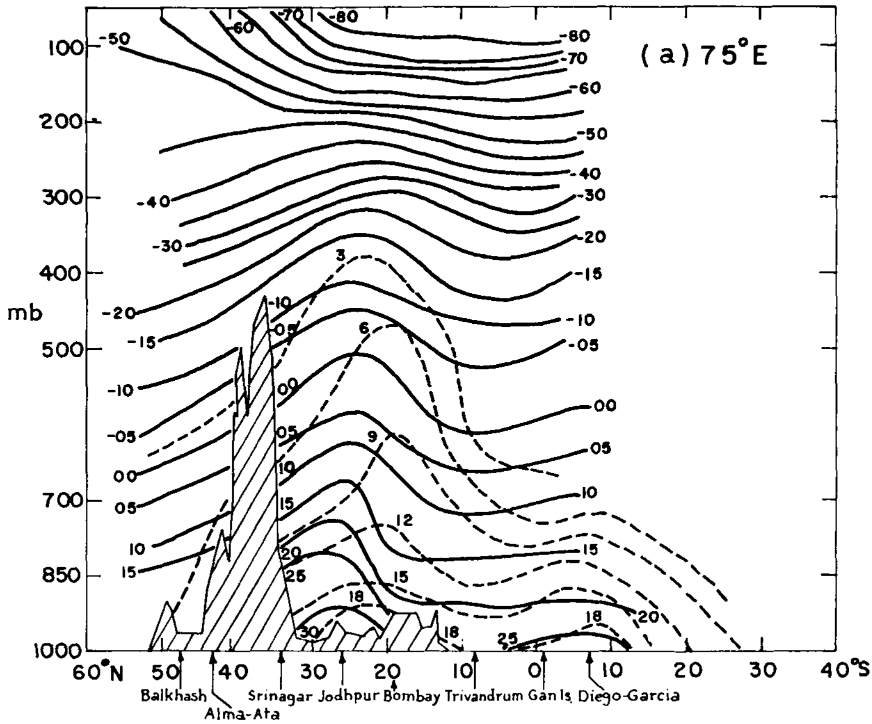

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Fig. 6 (*a*)–(*b*). Vertical distributions of temperature (°C) and humidity-mixinr-ratio (g/kg) in meridional sections along (*a*) 75° E, and (*b*) 100° E. Full lines are isotherms and dashed lines isohygrics.

(*h*) The thickness of moist air in the monsoon current appears to increase generally from sea to land (Asia) and from west to east in the northern Indian ocean.

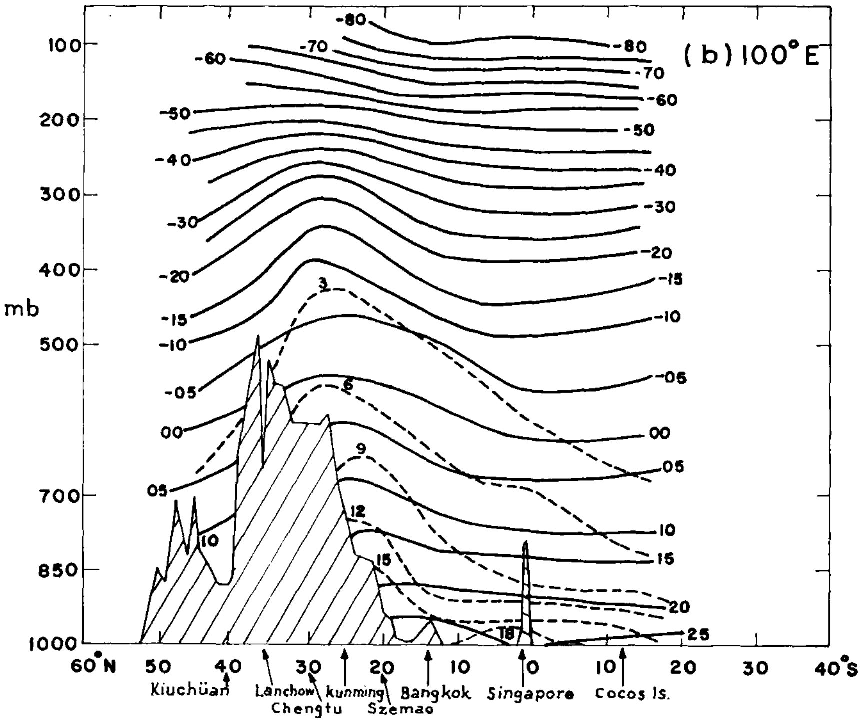
(*i*) A warm, humid atmosphere appears to exist between Gan Island and Sumatra.

The distributions described above would seem to be consistent with the general principle that the existence of the principal updraft cells over the hot Asian landmass in summer would cause increased influx of moisture from the ocean areas into these cells and eventual appearance of a humidity ridge over the land at the expense of the sea. The occurrence of a humidity ridge a few degrees to the south of the temperature ridge which marks the axis of the heat "low" in the lower troposphere would seem to be in line with findings of Soliman (1960) for Africa, Flohn (1960*a*) for equatorial Atlantic, and Sadler (1964) for eastern Central Pacific for distribution of rainfall in relation to axis of the equatorial trough.

Sawyer (1947) proposed an airmass frontal model for southwest monsoon over northwest India, in which cool monsoon air was assumed to lie below warm continental air below about 3 km level but overlie continental air above this level in view of steeper lapse rate of temperature in the dry continental air. It may be seen from the present investigation that such a frontal slope with warm monsoon air overlying cooler continental air above 3 km is most unlikely to occur in view of a temperature ridge over the area. This has also been pointed out by Koteswaram (1958).

6. Absolute vorticity and rainfall

We may now consider the distributions of absolute vorticity and rainfall in the monsoon region and see to what extent they are consistent with the computed vertical velocities, the general principle being that rainy areas should roughly coincide with areas of large updraft and positive vorticity (negative vorticity in the southern hemisphere), provided that



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the atmosphere is sufficiently humid. Fig. 7 shows the distribution of absolute vorticity at 700 mb level over the Indian ocean and the adjoining continental area (India-Arabia section). Fig. 8 shows distribution of 24 hours rainfall as measured at 03 GMT on 8 July 1963 along with that of absolute vorticity and vertical velocity at 850 level along meridian 77½° E. As usual, there were few reports of rainfall from the oceanic section but those from the neighbouring island stations showed that Gan Island had no rainfall and that the rainfall at Diego Garcia (07°14′ S, 72°26′ E) was 0.6 mm. For comparison, the distribution of normal July rainfall was also plotted on the same diagram. It may be seen that two maxima occur in the rainfall curve, one over India between latitudes 20° and 25° N and the other the Indian ocean between the equator and about 10°S. The two areas of peak in rainfall would thus appear to correlate very well with fields

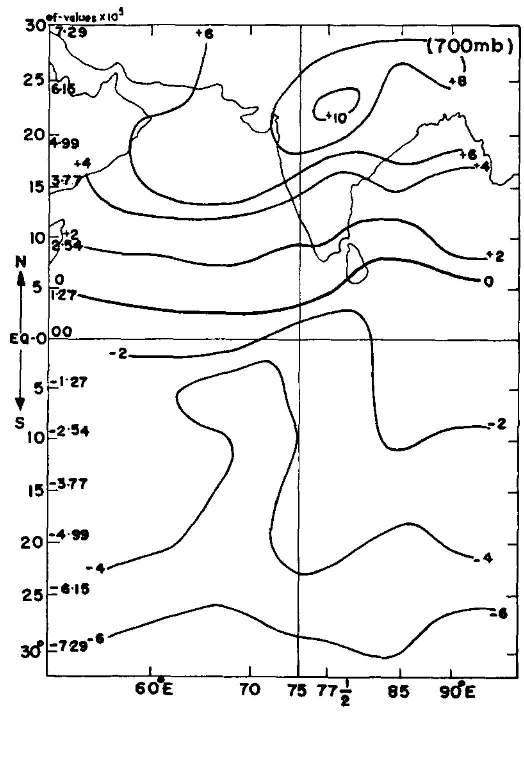

Fig. 7. Distribution of absolute vorticity at 700 mb level over the Indian Ocean and neighbouring continental area at 12Z, 7 July 1963. Unit 10^{-5} sec^{-1}.

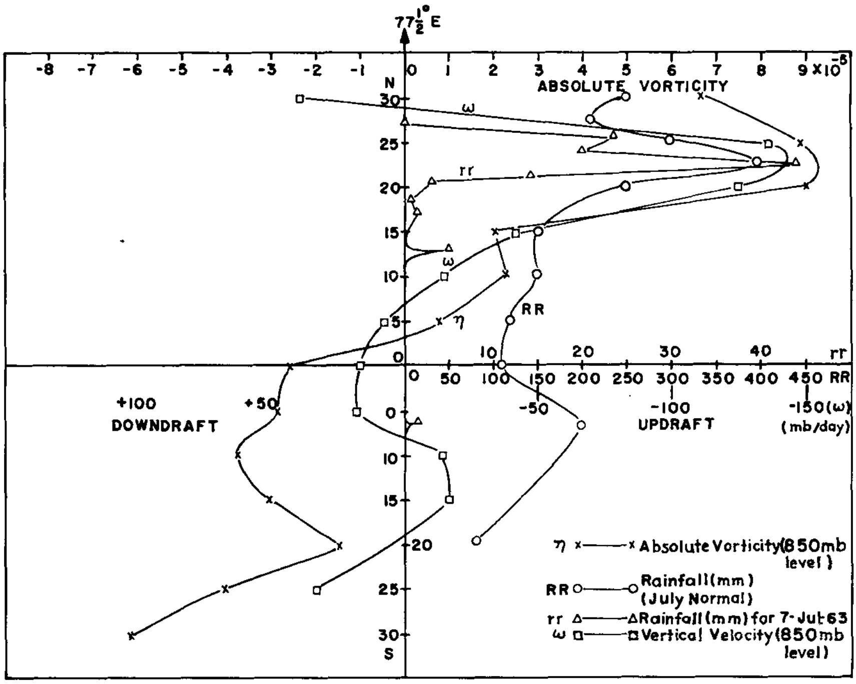

Fig. 8. Distribution of absolute vorticity (η) and vertical velocity (ω) at 850 mb level, 24 hours rainfall (rr) as measured at 0300 GMT on 8 July 1963, and July normal rainfall (RR) along 77½° E. (Unit of rainfall mm.)

of vorticity and updraft. In Fig. 9 is presented the normal July distribution of rain over the Indian ocean and the adjoining continental Asia. It is most interesting to find two markedly contrasting areas in the same monsoon field, one over India and China with enormous amounts of rainfall and the other west of about longitude 70° E consisting of the Arabian sea and the whole land area lying to the west of India, which are practically dry. East of 70° E,

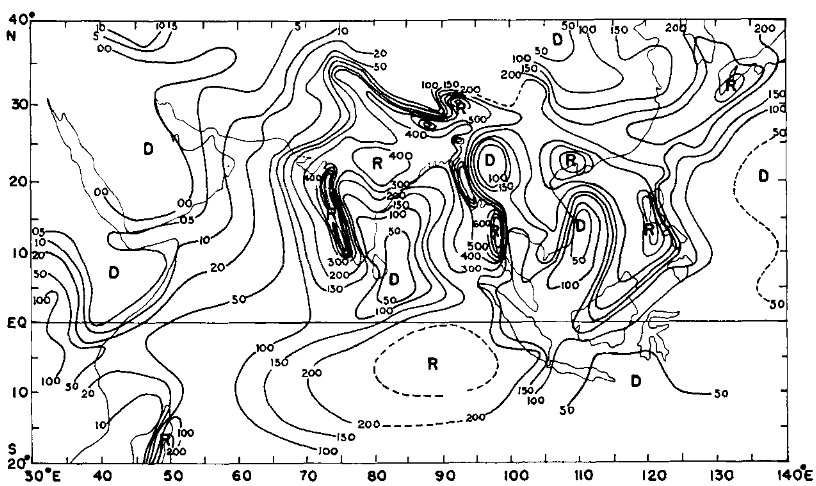

Fig. 9. July normal rainfall over the Indian Ocean and the neighbouring continental areas (in mm). *R* denotes areas of moderate to heavy rain, and *D* dry or rain-shadow areas.

there is generally more rain over land than over sea areas. The association with orographic features appears most dominantly. These distributions of rainfall would seem to fit in well with those of computed vertical velocities in the present investigation although the latter relate to a single map time. Over Arabia, the updraft area is non-effective in producing any appreciable cloud and rain because of extreme dryness of air. The monsoon circulation imports very little moisture into this region. Over most of the western Arabian sea, subsidence of air produces a steep temperature inversion between about 900 mb and 800 mb levels and this serves as a powerful inhibiting factor for development of cloud and rain. The presence of updraft in the equatorial region between Gan Island and Sumatra and in the southwestern Pacific (east of the Philippines) appears to fit in with rainfall maxima over these areas. The heavy rainfall over southeast China and Japan would also seem to be explained by the presence of pronounced updraft over these areas.

7. Equatorial westerlies

The presence of a region of updraft and a peak in rainfall just south of the Equator in the Indian ocean area is also testified by the blowing of a belt of westerlies in this region. As early as 1686, Halley drew the boundary between the southesast trades and the deflected southwesterly monsoon current a few degrees south of the equator. Meinardus (1893) pointed out the occurrence of equatorial westerlies south of the equator from extensive observations in northeastern Indian ocean. Flohn (1955) and Koteswaram (1960) have discussed the origin of these winds and Flohn (1960*b*), Raman & Dixit (1964), Frost & Stephenson (1964) and others have recently brought convincing evidence of their occurrence south of the equator normally from surface to about 700 mb level but sometimes up to 500 mb level. But what is the cause of these equatorial westerlies south of the equator? Various explanations have been offered for the observed turning of the southeast trades before they reach the equator. Flohn (1960*b*) following a treatment given by Hollmann (1955) "considers an ageostrophic zonal component produced by the latitudinal adaptation of wind to the meridional variation of the coriolis parameter to be responsible for deflecting the meridional flow into a westerly one". There is conflicting evidence about the persistency or steadiness of the equatorial westerlies. Flohn (1960*b*) states that they are rather variable in time and space, whereas Raman & Dixit (1964) and Frost & Stephenson (1964) maintain that they exist at all seasons between Gan Island and Sumatra from the surface to 700 mb (in July up to 500 mb). Frost and Stephenson seek to explain them on the basis of a zonal circulation cell with its rising branch over Indonesia and descending branch near Gan Island. It may, however, be seen from the zonal circulation patterns presented in the present paper that in the situation chosen there is rising air in the sea area near Gan Island and sinking air over the Indonesian region. The large negative values of relative vorticity acquired by the southeast trades approaching the equator as shown in Fig. 7 may well explain the formation of equatorial westerlies in this region.

8. Warm anticyclones

It is evident from Fig. 6 that a warm ridge extends all along the continental belt in the latitude band 25°–30° N from Arabia to China. The work of Rangarajan (1963) and Ananthakrishnan & Rangarajan (1964) would appear to confirm this distribution of temperature. In the middle and upper troposphere, the position of the thermal ridge appears to coincide with the axes of three anticyclones, one over Arabia above about 850 mb level, one over India above about 500 mb level, and a third over China above about 700 mb level. The intensity of all the three anticyclonic circulations increases with height and becomes maximum in the upper troposphere between 200 and 100 mb level. In general, warm anticyclones appear over areas of surface "low" but in the India-Tibet sector the axis of the upper anticyclone appears to lie slightly poleward of the position of the equatorial trough near the surface in July. Using mean monthly data, Raman & Dixit (1964) have shown that the axis of the upper tropospheric warm anticyclone over India lies as much as five to seven degrees of latitude north of the 850 mb level position of the equatorial trough during the height of the monsoon. This is shown in Fig. 10 for meridian 77° E. The question that interests

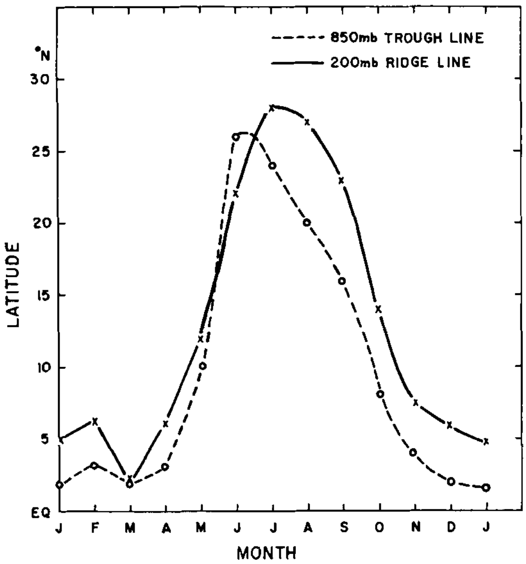

Fig. 10. Latitudinal positions of the 850 mb level trough line and 200 mb level ridge line along 77° E meridian in different months (after Raman & Dixit).

us here is how the separation occurs between the axes of the lower-tropospheric trough and the upper-tropospheric High in the India-Tibet region. Flohn (1960*c*), Koteswaram (1958) and Staff Members of Academia Sinica (1958) are of the view that the upper-tropospheric High over the India-Tibet region arises directly from the solar heating of the elevated Tibetan plateau. Koteswaram (1958) makes a distinction between the anticyclones over Arabia and India stating that the former is a dynamic anticyclone whereas the latter (over India) is a thermal anticyclone.

There would seem to be some definite indication from the thermal structures of the monsoon atmosphere presented in Fig. 6 that the middle and upper troposphere over the vast Tibetan plateau is, indeed, warmer than its environment and that, perhaps, due to this warmth alone an upper-tropospheric High pressure and anticyclonic circulation would develop over the region. This anticyclone would plausibly become more dominant in the upper troposphere than the anticyclone associated with the heat low over the northern Indian plains with the result that above a certain height, say about 500 mb level, the two anticyclones, one associated with the surface heating over Northwest India and the other with the heating of the elevated Tibetan plateau, would merge and form a single upper-tropospheric anticyclone with its axis somewhat north of that of the lower tropospheric thermal trough over India. Perhaps, it is this combination of forces which also makes the Indo-Tibetan anticyclone the most intense of the three upper-tropospheric anticyclones over monsoon Asia.

9. The jet streams

The warm anticyclones discussed in the preceding section would appear to guide the two dominant upper tropospheric air currents over monsoon Asia, Westerlies north of the axis of the anticyclone which runs roughly along 30° N and easterlies south of it. Fig. 6 shows the thermal ridge and the temperature gradients that exist to north and south of it. If the wind at any pressure level is assumed to be geostrophic, its vertical variation due to horizontal temperature gradient is given by the relation

$$\frac{\partial \mathbf{v}}{\partial p} = -\frac{R}{pf}\mathbf{k} \times \nabla_p T, \tag{4}$$

where R is the gas constant for air, f the coriolis parameter, $\mathbf{k}$ the vertical unit vector, and $\Delta_p T$ is the isobaric temperature gradient.

If we integrate equation (4) between the pressure levels 0 and 1 and assume mean values $\bar{p}$, $\bar{T}$, $\bar{f}$ for the layer, we get

$$\mathbf{v}_1 = \mathbf{v}_0 - \frac{R}{\bar{p}\bar{f}}(\mathbf{k} \times \nabla_p T)(p_1 - p_0). \tag{5}$$

The zonal and meridional components of the wind are then given by

$$\left.\begin{aligned} u_1 &= u_0 + \frac{R}{\bar{p}\bar{f}}\frac{\partial \bar{T}}{\partial y}(p_1 - p_0), \\ v_1 &= v_0 - \frac{R}{\bar{p}\bar{f}}\frac{\partial \bar{T}}{\partial x}(p_1 - p_0). \end{aligned}\right\} \tag{6}$$

In equation (6), the x-coordinate points to east and the y-coordinate to the north.

We may use the equation (6) for the zonal wind component to compute the winds at isobaric levels, starting from the observed wind at 850 mb level and utilising the observed gradients of temperature. For the computations R was taken as 2.87×10^6 ergs per gram per degree absolute.

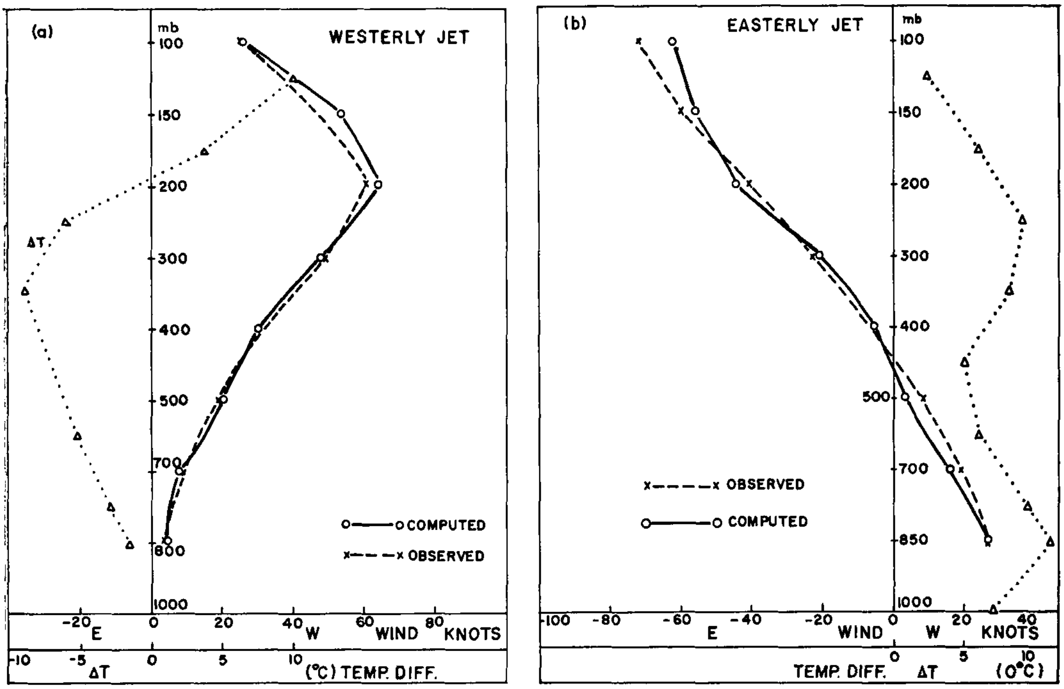

Fig. 11 (*a*)–(*b*). Computed and observed zonal wind components in the case of (*a*) westerly wind maximum along 120° E meridian and (*b*) easterly wind maximum along 75° E meridian. ΔT gives the temperature difference between the latitude 40° N and the thermal ridge at 30° N in the case of the westerly wind maximum and the thermal ridge at 26°N and latitude 8½° N in the case of the easterly wind maximum.

The results of computation for the westerly and easterly jet streams are presented in Fig. 11*a* and *b* respectively. The observed difference in temperature at different pressure levels between latitude 40° N and the thermal ridge at 30° N along 120° E in the case of the westerly jet and between the thermal ridge at 26° N and latitude 8.5° N (Trivandrum) along about 75° E in the case of the easterly jet is given by ΔT. The mean coriolis term $\bar{f}$ was taken for latitude 35° N and 17° N in the respective cases. The observed winds plotted in Fig. 11*b* were mean of those at 15° and 20° N. It may be seen that the agreement between the computed and observed winds is very close.

A feature of the easterly jet stream which is frequently observed during the summer monsoon is the fluctuation in its direction and speed downstream from east coast of China to Africa. These fluctuations appear to occur as the airstream passes down from one anticyclone to another. Initially, as the air diverges from the Chinese anticyclone its speed is low (20–30 knots) and it has a pronounced equatorward component. As it leaves the Chinese anticyclone its direction turns poleward but soon changes equatorward on entering the domain of the Indian anticyclone. Here there is considerable confluence of air over central and south India between the air that has arrived from the Chinese anticyclone and the air that diverges and flows equatorward from the Indian anticyclone. The result is rapid strengthening of the easterly wind to a jet stream in the neighbourhood of about 15° N. In passing from the Indian anticyclone to the Arabian anticyclone, a very similar sequence of change is followed in direction but the speed of the easterlies is reduced on account of lower intensity of the Arabian anticyclone. The same sequence of change is followed further downstream to Africa where the easterly jet is again revived at the southern periphery of the upper-tropospheric anticyclone over Sahara. As found by Koteswaram, the axis of the easterly jet stream over western Africa lies along about 10° N.

Changes similar to the above are also found in westerly jet streams north of the axis of the warm anticyclones. The close agreement found between the computed geostrophic winds and the observed winds in the present case appears to be a confirmation of the view that the monsoon winds are primarily thermally-driven and geostrophically controlled over the landmass of Asia.

10. A three-dimensional integrated model

An attempt at modelling of the monsoon on the basis of a single case study can hardly be justified but considering the fact that the monsoon is a seasonal phenomenon and that the day-to-day variations are not ordinarily large, even a single day's data should reflect the broad features of the circulation. There is little doubt that the basic pattern of the Asian summer monsoon circulation as revealed by the present study, is that of multiple subplanetary-scale thermal convection cells on a rotating earth, superimposed as perturbations in the general circulation of the atmosphere. Such a pattern in gross features should reveal Hadley-type meridional circulations with rising air over southern Asia and sinking air over the Indian ocean. There is evidence of Hadley-type circulation in some of the meridional sections, while it is hardly noticeable in others. For example, in the vast Arabian sea region, it is difficult to visualise a circulation cell which will resemble a Hadley cell even remotely. Further, air rising over the continents in large-scale convection cells descends not only over the sea areas in the south but also over the land areas around the cells. Thus, an adequate representation of the monsoon circulation can only be given by a three-dimensional thermal convective model with rising air in the middle of the cell and descending air all round. Over the north Indian ocean, equatorward-moving upper-tropospheric air gradually sinks over the sea areas and in some sections crosses the equator to descend in the region of the southern-hemispheric subtropical anticyclone. In the lower troposphere, the southeast trades from the southern hemisphere cross the equator in appreciable depth in the Arabian Sea—Bay of Bengal sectors except in localised regions where due to marked negative relative vorticity equatorial westerlies and vortices form causing an interruption of the crossing. The depth of the southeast trades in the region of heavy crossing in the west Arabian sea exceeds 3 km in the present case.

11. Conclusions

The present study although based on data and analysis at a single map time would seem to reveal the following characteristics of the Asian summer monsoon circulation:

(*a*) The monsoon winds are basically thermally-driven, i.e., they are guided by three well-defined synoptic-scale convection cells with heat sources over the continent of Asia, one over Arabia, one over India, and a third over China.

(*b*) There is general sinking air motion in the middle and upper troposphere over the land area to the west and north of India. General sinking motion is also observed over most of the Arabian Sea and the sea areas lying to the south of the continental landmass.

(*c*) The presence of a thermal ridge over northwestern India would seem to preclude a frontal slope between the monsoon air and the dry continental air in the middle and upper troposphere, as visualised by Sawyer (1947). This has also been pointed out by Koteswaram (1958).

(*d*) The equatorial westerlies south of the equator in the Indian ocean area would appear to originate when the equatorward-moving southeast trades of the southern hemisphere develop large negative relative vorticity.

(*e*) The upper-tropospheric warm anticyclone over India-Tibet region appears to be a combined effect of the heat source over the plains of northwest India and that over the elevated Tibetan plateau.

(*f*) A thermal-convection cell model with strong temperature gradients north and south of the thermal ridge would appear to explain the summer jet streams over Asia.

(*g*) There is considerable asymmetry in the meridional circulation in the monsoon field. Air converging to land in the lower troposphere would seem to originate over the north Indian Ocean in some areas while in others its origin may be traced directly to the southern hemisphere. Maximum cross-equatorial flow appears to take place in the Arabian Sea—Bay of Bengal region.

(*h*) The distribution of rainfall and other observed properties of the summer monsoon would seem to be explained by a three-dimensional convective model as proposed in the present paper.

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О МГНОВЕННОМ РАСПРЕДЕЛЕНИИ ВЕРТИКАЛЬНОЙ СКОРОСТИ В МУССОННОМ ПОЛЕ И СТРУКТУРЕ МУССОННОЙ ЦИРКУЛЯЦИИ

Получено приближенное представление мгновенной картины трехмерной циркуляции азиатского летнего муссона путем использования данных и анализа для определенного момента времени в июле 1963 г. во время международной экспедиции в Индийском океане (1963–65). Для этой цели была вычислена вертикальная скорость путем использования уравнения неразрывности и интегрирования шагами поля дивергенции на стандартных изобарических уровнях через каждые пять градусов вдоль семи меридиональных разрезов, простирающихся от 50° до 140° в. д. между широтами 35° и 25° ю. ш. Совместно с меридиональной и зональной компонентами ветра вертикальные скорости давали мгновенную картину вертикальной циркуляции, которая представлена вдоль семи меридиональных и четырех зональных разрезов. Изобарическое распределение вертикальной скорости представлено вдоль четырех стандартных поверхностей давления: 850, 700, 500 и 100 мб.

Вычисленные вертикальные скорости образуют три хорошо выраженные области восходящего движения над Азией, одна из которых над Аравией, другая над Индией и третья над Китаем. Несколько локализованных слабых ячеек имеют место над морем, т. е. в экваториальной области между островом Ган (00°41′ ю. ш. 3°09′ в. д.) и Индонезией, и другая в западной части Тихого океана, к востоку от Филиппин. Обширные области нисходящего движения имеют место над сушей между Индией и Аравией, над западными Гималаями и Тибетом и над большей частью моря к югу от континента. Практически весь запад Аравийского моря является областью нисходящего движения.

Однако над большинством областей вычисленные вертикальные скорости непрерывно возрастают с высотой, обнаруживая лишь малую вертикальную компенсацию или совсем никакой. Это, конечно, является следствием анализа. Несмотря на это, вычисленная вертикальная скорость совместима с наблюдаемым распределением температуры, влажности, вихря, осадков и струйного течения .Наличие полосы экваториальных западных ветров (к югу от экватора) в Индийском океане, по-видимому, также подтверждает вычисленное восходящее движение в этом районе.

Доказательства, представленные в настоящей статье, свидетельствуют о том, что только модель трехмерной термической конвекции может адэкватно описать гигантскую муссонную циркуляцию над северной частью Индийского океана и прилегающим азиатским континентом.