

Vertical circulations and heat and moisture budgets in the time-mean July atmosphere over India and Bay of Bengal

KSHUDIRAM SAHA

27, B-Road, Maharani Bagh, New Delhi

and

SURANJANA SAHA

Dept. of Met., Univ. of Maryland, College Park, MD, USA

(Received 10 March 1988)

सार — क्षैतिज गति के घटकों के साथ उर्ध्वाधर गति के संयोजन से उर्ध्वाधर परिसंचरण प्राप्त किये गये हैं। इनसे भारत और निकटवर्ती बंगाल की खाड़ी में समय-माध्य में जुलाई वायुमंडल में मानसून द्रोणी क्षेत्र के पार निश्चित संकीर्ण देशांतर और अक्षांतर भागों में धाँकर, हेडले और मानसून कोशिकाओं की उपस्थिति का पता चलता है। व्युत्पन्न उर्ध्वाधर परिसंचरण कोशिका, ताप और नमी बजट से अभिकलित डायबेटिक ऊष्मन और शीतलन तथा नमी बजट समीकरण से अभिकलित वर्षा के वितरण के अनुकूल प्रतीत होते हैं। ताप बजट यह बताते हैं कि एक सन्निकट सादृश्य ($Q/c_p \simeq -\sigma\omega$) (जहाँ Q डायबेटिक ऊष्मन की दर है, c_p एक समान दाब पर हवा का विशेष ताप है, ω उर्ध्वाधर p वेग है, और σ स्थित स्थायित्व प्राचल है) इस क्षेत्र पर रहता है और मानसून पट्टी के कुछ अन्य भागों में पाया जाता है। उत्तरी भारत पर वर्षा के वितरण और मानसून द्रोणी के अनुरक्षण में पूर्वी हिमालय की पर्वतीय प्रणालियों द्वारा प्रणोदित उर्ध्वाधर परिसंचरण कोशिका की महत्ता का विवेचन किया गया है।

ABSTRACT. Vertical circulations obtained by combining vertical motion with the components of horizontal motion suggest the existence of Walker, Hadley and monsoon-type cells in certain narrow latitudinal and longitudinal sections across the monsoon trough zone in the time-mean July atmosphere over India and neighbouring Bay of Bengal. The deduced vertical circulation cells appear to be consistent with the distributions of diabatic heating and cooling computed from heat and moisture budgets and rainfall computed from the moisture budget equation. The heat budget suggests that to a close approximation, $Q/c_p \simeq -\sigma\omega$ (where Q is the rate of diabatic heating, c_p is the specific heat of air at constant pressure, ω is the vertical p -velocity and σ is the static stability parameter) over this region as well as found in some other parts of the monsoon belt. The importance of a vertical circulation cell forced by the mountain systems of eastern Himalayas in the maintenance of the monsoon trough and the distribution of rainfall over northern India is discussed.

1. Introduction

Although monsoon has been studied in India over many decades (for reviews of studies, see, e.g., Ramage 1971, Rao 1976, Krishnamurti 1985), there remain several areas in which our knowledge and understanding are far from complete. One of these relates to vertical motion and possible existence of vertical circulation cells (monsoon, Hadley and Walker-type) which are directly related to distributions of monsoon rainfall. As is well-known, vertical motion is not directly observed and has to be computed from other parameters involving wind, temperature or vorticity. Quite a few methods are available for such computations. Yet, to date there have been only a few computations of vertical motion in basic monsoon flows over the Indian region including the Bay of Bengal (e.g., Das 1962, Saha 1968, Luo and Yanai 1983). Most of the computations done relate to monsoon disturbance situations

(e.g., Rao and Rajamani 1970, Krishnamurti *et al.* 1975, Godbole 1977, Saha and Chang 1983, Sanders 1984). Possible existence of vertical circulation cells in monsoon has been examined by some workers (e.g., Koteswaram 1958, Rao 1962, Das 1962, Raman 1965, Krishnamurti 1971, Asnani 1973) but only a few of them based their conclusions on actual computation of vertical motion. Rao (1962) who studied mean meridional circulation on the basis of the vertical distribution of the meridional component of the wind at rawin stations in India concludes that an elevated Hadley cell (northerlies below, southerlies above) exists to the north of about 25°N with the monsoon cell (southerlies below, northerlies above) lying below the Hadley cell north of this latitude. Das (1962) who computed mean vertical motion over the Indian sub-continent finds evidence of an east-west anticlockwise vertical circulation cell with its rising branch over the eastern Himalayas and sinking branch over the desert

region of northwest India and Pakistan. Since monsoon circulation is primarily forced by diabatic heating and cooling of the atmosphere, these vertical circulation cells, if they exist, should be consistent with the distributions of heat sources and sinks and the requirements of heat balance over the region.

The objective of the present study is to compute mean vertical motion and deduce mean vertical circulation cells by combining the computed vertical motion with the horizontal components of the wind in zonal and meridional vertical cross-sections. Heat and moisture budgets are computed in an attempt to identify the dominant heat sources and sinks which provide the basic forcings for the observed circulations. An attempt is made to compute monsoon rainfall from the moisture budget equation.

2. Computational methods

Methods used for computation of the various parameters are briefly stated in the following sub-sections :

(a) Vertical motion

The vertical p -velocity (ω) is computed by integrating the continuity equation in the form :

$$\omega = - \int \nabla \cdot \mathbf{V} \delta p \quad (1)$$

where $\nabla \cdot \mathbf{V}$ is divergence of the horizontal wind vector \mathbf{V} , given by the expression :

$$\nabla \cdot \mathbf{V} = \partial u / \partial x + \partial v / \partial y - (v/a) \tan \phi \quad (2)$$

where u & v are the eastward and northward components of the horizontal wind, a is the mean radius of the earth and ϕ is the latitude.

The integration is carried out from the earth's surface upward, the lower boundary condition being $\omega_s = \mathbf{V}_s \cdot \nabla p_s$, where p_s is the surface pressure and \mathbf{V}_s is the wind at the station level (if available, otherwise the wind at the standard pressure surface immediately above the station). The space derivatives are calculated by using a centred finite-differencing scheme. The well-known O'Brien correction is applied to the computed vertical velocity at each pressure surface so as to reduce the vertical velocity at the top (100 hPa) to zero.

(b) Vertical circulation cells

These are explored by combining the computed vertical motion (ω) with the horizontal components (u , v) of the wind in zonal or meridional vertical cross-sections, as appropriate. Though the vertical velocity in the atmosphere is normally about two orders of magnitude smaller than the horizontal velocity (u or v), the combinations reveal the existence of rising and sinking currents and possibly, in some cases, vertical circulation cells, such as Hadley and monsoon in the meridional planes and Walker-type in zonal planes.

(c) Heat budget

Heat budget is studied by using the First Law of Thermodynamics in the form :

$$\frac{Q}{c_p} = \frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T - \sigma \omega \quad (3)$$

$$\begin{matrix} (1) & (2) & (3) & (4) \end{matrix}$$

where Q is the rate of diabatic heating, c_p is the specific heat of air at constant pressure, T is temperature and σ is static stability parameter given by the expression :

$$\sigma = (R/c_p) (T/p) - \partial T / \partial p \quad (4)$$

where R is the gas constant for dry air ($=287 \text{ J kg}^{-1} \text{ K}^{-1}$). For long-term mean data, $\partial T / \partial t$ may be neglected. Q/c_p is then evaluated from Eqn. (3) as a residual from values of the term (3) (thermal advection) and term (4) (adiabatic warming or cooling due to vertical motion).

Term (3) is computed by using a centred finite-differencing scheme. The static stability parameter (σ) at a pressure surface is computed from the values of temperature and pressure at the surface and the lapse rate of temperature between the pressure surfaces immediately above and below. For example, at 850 hPa,

$$\sigma_{850} = \frac{R}{c_p} \frac{T_{850}}{850} - \frac{T_{1000} - T_{700}}{1000 - 700}$$

Total tropospheric heating is calculated by integrating Q from 925 hPa to 150 hPa.

(d) Moisture budget and precipitation

The moisture budget is computed from the law of conservation of water vapour in the form :

$$(1/g) \int_0^{p_s} (\partial q / \partial t) \delta p = E - P - (1/g) \int_0^{p_s} \nabla \cdot q \mathbf{V} \delta p - q_s \omega_s / g \quad (5)$$

where, q : is the humidity-mixing-ratio of air,

E : rate of surface evaporation,

P : rate of precipitation,

ω_s : vertical p -velocity at the earth's surface,

p_s : surface pressure,

q_s : humidity-mixing ratio at surface and

g : acceleration due to gravity.

Term (4) in Eqn. (5) is a measure of the total vertically, integrated moisture convergence and term (5) gives an approximate measure of rainfall due to orography.

As in the case of the heat budget, $\partial q / \partial t$ is assumed to be zero for time-mean data. The approximate relation which is used to compute precipitation is then :

$$P = E - (1/g) \int_{150}^{925} \nabla \cdot q \mathbf{V} \delta p - q_s \omega_s / g \quad (6)$$

where the moisture convergence is integrated between 925 hPa and 150 hPa.

3. Data and analysis

Basic data used for the study are the four-year (1963-66) mean July wind, temperature and humidity-mixing-ratio (computed from dew-point) data at individual stations at m.s.l. and standard isobaric surfaces 850, 700, 500, 300, 200 and 100 hPa over the domain 0-30° N, 70-110° E. The main data sources are : (i) *Meteorological Atlas of the International Indian Ocean Expedition* (IIOE), Vols. 1 and 2 (Ramage *et al.* 1972a, Ramage and Raman 1972b) and (ii) the *WMO Monthly Climatic Data of the World*, for the years 1963-66.

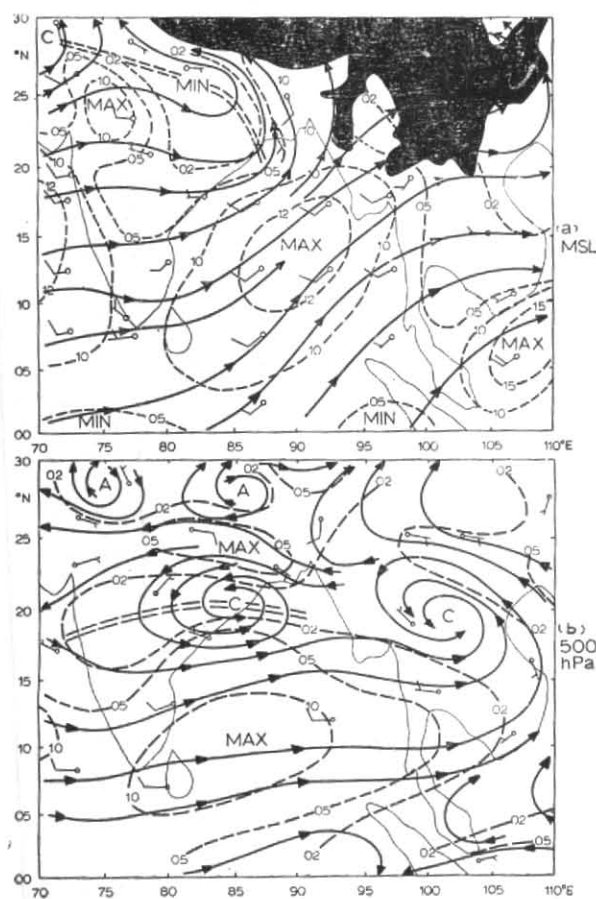


Fig. 1. Streamline-isotach analysis over India and neighbourhood : (a) m.s.l. and (b) 500 hPa. Double-dashed line denotes the monsoon trough. Single-dashed lines are isotachs (knots). Topography (shaded areas) shown at m.s.l. (Fig. 1a) is above 1 km a.s.l. A denotes anticyclonic, C: cyclonic

Rainfall data are obtained from the India Meteorological Department sources (monthly summaries) for stations in India and from the *WMO Monthly Climatic Data of the World* for stations in regions outside India. Evaporation data are obtained from a publication entitled "Evaporation data of observatories in India (India Met. Dep., 1980) for stations in India and from Ramage *et al.* (1972 a) for the sea areas.

Data plotted on maps are analyzed manually for fields of wind, temperature and humidity-mixing-ratio at the standard pressure surfaces and evaporation and precipitation at the earth's surface. A horizontal grid of 2° Lat./ 2.5° Long. is used.

The salient points of the data analysis are as follows :

(a) The wind field

The isobaric wind analysis reveals the well-known broad-scale features of the mean summer monsoon circulation over the region, *viz.*, a cyclonic circulation in the lower troposphere (below about 500 hPa) and an anticyclonic circulation above. As part of the lower-tropospheric wind-field over India, there appears a trough which extends from the centre of the 'heat low' over Pakistan to the northern part of the Bay of Bengal at m.s.l. (Fig. 1a) and slopes equatorward with height to be located in an approximately west-east orientation across central India, along about

20° N at 500 hPa (Fig. 1b). This is the well-known lower-tropospheric monsoon trough over India which generally disappears above about 500 hPa.

(b) Temperature

Figs. 2(a, b) present the vertical distribution of zonal anomaly of temperature (deviation from zonal mean temperature) along latitudes 26° N and 20° N respectively. They show warm anomaly through the whole troposphere over the monsoon trough zone and cold anomaly in the lower troposphere to its east. Fig. 2(c) presents the vertical distribution of meridional temperature anomaly (deviation from meridional mean temperature) along 85° E. It shows strong warm anomaly over the whole land section and cold anomaly to the south of about 16° N. Strongest warm anomaly appears to be located at 200 hPa over the Tibetan region and adjoining northern India.

(c) Humidity-mixing-ratio

The distribution of humidity-mixing-ratio (g/kg) at two pressure surfaces, 850 hPa (full lines) and 500 hPa (dashed lines), is shown in Fig. 3. At both the surfaces, humidity maxima appear to be located over the north-eastern parts of India and eastern Himalayas. Humidity generally decreases westward and equatorward.

4. Results

The results of the computations are presented in the following sub-sections :

(a) Divergence

Computed divergence field (not shown for lack of space) appears to meet largely the requirements of Dines' compensation in the vertical, *i.e.*, between the lower and the upper tropospheres over most areas. In a vertical section along 20° N, strong divergence appears in the upper troposphere above about 500 hPa with convergence below in the monsoon trough zone. Mainly divergence appears to prevail in the lower troposphere over the Bay of Bengal with convergence aloft. Convergence occurs through most of the troposphere over the Burmese and Indo-China peninsula mountains.

(b) Vertical motion

Orographically-forced vertical motion (ω_s), presented in Fig. 4(a), shows upward (U) motion on the windward slopes of the Western Ghats mountains along the west coast of India, the Arakan Yoma on the Burmese coast and the mountain ranges of eastern Himalayas and downward (D) motion on their leesides. Fig. 4(b) which presents the distribution of vertical motion at 500 hPa shows strong upward motion to the southwest of the m.s.l. location of the monsoon trough and downward motion to the east over the northern part of the Bay of Bengal and adjoining Bangladesh. Strong upward motion appears over the mountain ranges of northeastern India, Burma and Indo-China peninsula. Weak downward motion appears over the southern parts of the Indian Peninsula on the leeside of the Western Ghats mountains and over the whole of northwestern India. Zonal vertical cross-sections showing the distributions of vertical motion along latitudes 26° N, 20° N and 14° N are presented in Fig. 4(c).

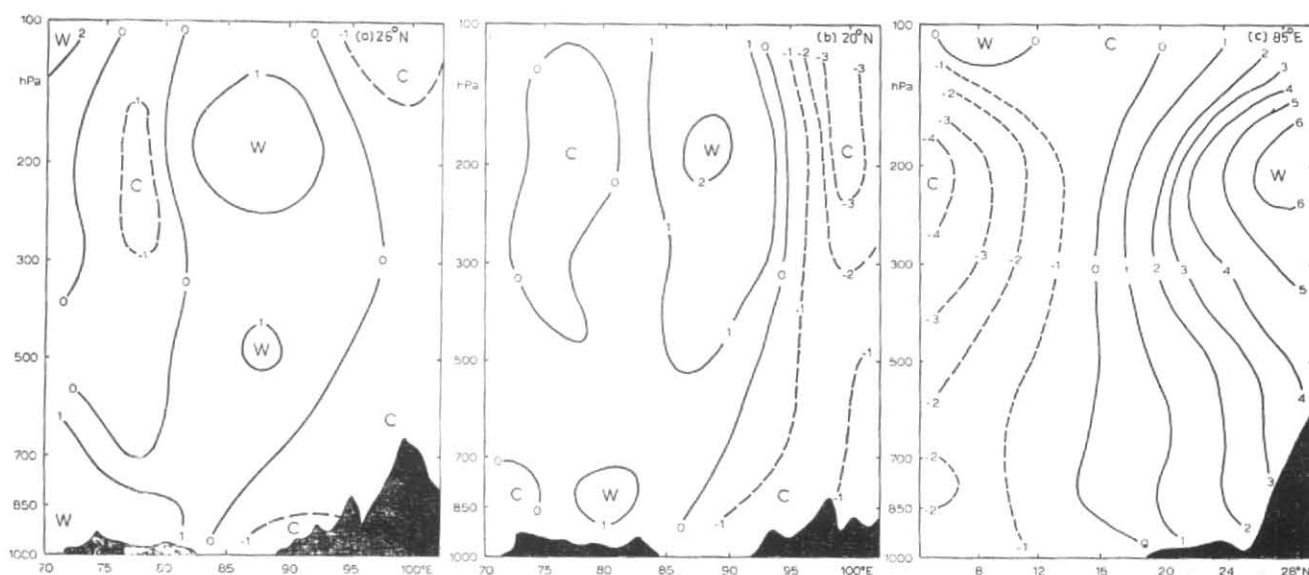


Fig. 2. Temperature anomaly ($^{\circ}\text{C}$) in zonal and meridional vertical sections : (a) 26°N , (b) 20°N and (c) 85°E . W denotes warm, C : cold, Orography is shaded.

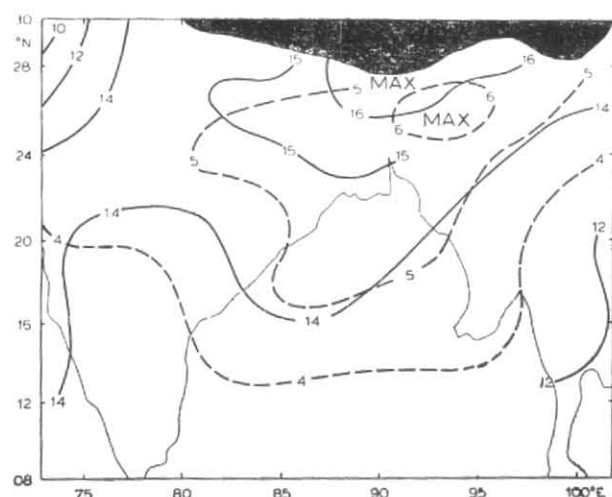
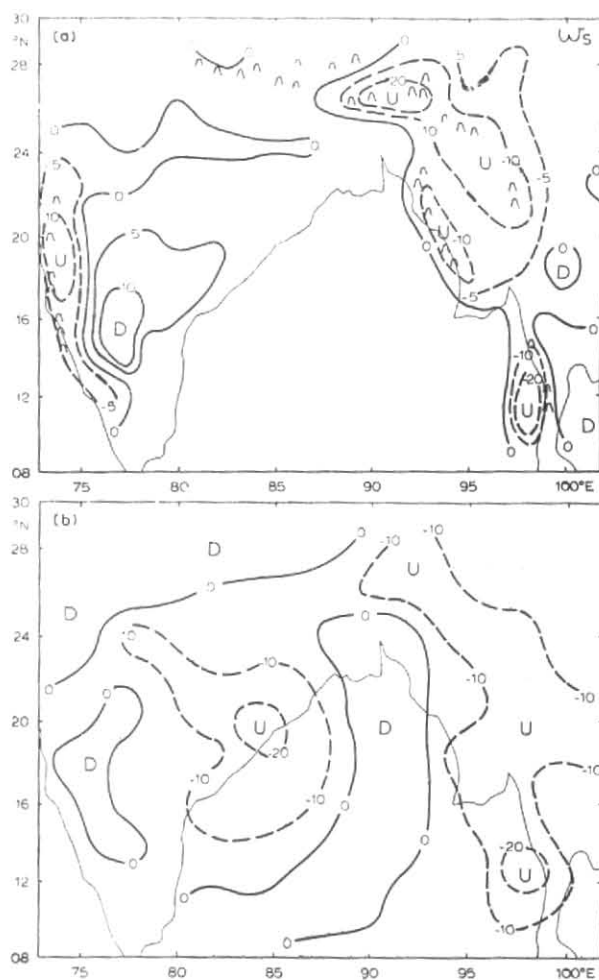


Fig. 3. Humidity-mixing-ratio (g/kg) at 850 hPa (full lines) and 500 hPa (dashed lines). Shaded area shows orography above 3.0 km a.s.l.

(c) Vertical circulation cells

Resultant streamlines based on (u, ω) values in zonal-vertical sections along latitudes 28°N , 26°N , 24°N , and 20°N are presented in Figs. 5 (a-d) respectively. They appear to reveal the following :

Along 28°N (Fig. 5a), the whole tropospheric flow over and to the west of the Himalayan massif appears to be descending strongly, except over the Assam valley where there is upward motion below about 500 hPa . Along 26°N (Fig. 5b), an anticlockwise vertical circulation cell appears to be centred at about 78°E at 800 hPa with strong upward motion to the east, easterlies above, downward motion to the west and westerlies below the centre. To some extent, this cell which is forced by the mountains (MTN) appears to



Figs. 4 (a&b). Vertical motion (unit : $10^{-4}\text{ hPa s}^{-1}$) : (a) due to orography (ω_y) and (b) at 500 hPa . U-upward, D-downward. In (a), hats denote prominent hills and mountains

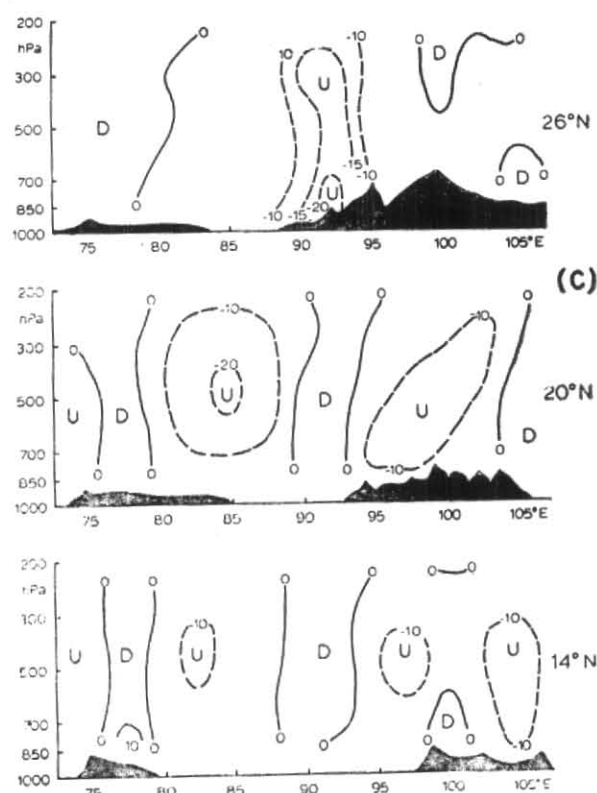


Fig. 4 (c). Vertical motion (unit : $10^{-4} \text{hPa s}^{-1}$) in vertical-zonal sections along 26°N , 20°N and 14°N . U-upward, D-downward

resemble the east-west vertical circulation cell suggested by Das (1962). Two anticlockwise Walker-type vertical circulation cells, one centred at about 77°E at 700 hPa and the other centred at about 93°E at 600 hPa appear in the vertical section along 24°N (Fig. 5c). Circulation cells along 20°N (Fig. 5d) show features which are very similar to those along 24°N . The sections along both 24°N and 20°N bring out the existence of strong upward motion in both the lower-tropospheric westerlies and the upper-tropospheric easterlies to the west of the monsoon trough zone near the Head Bay of Bengal and strong downward motion to the east. They also show strong orographic lifting of air at the mountain ranges of northeastern India and Burma.

Considerable longitudinal variation is observed in the resultant streamline, (v, ω) patterns along meridional-vertical sections along 77.5°E , 85°E and 90°E presented in Figs. 6 (a-c) respectively. The section along 77.5°E (Fig. 6a) shows an elevated Hadley (H) cell centred at about 25°N at about 400 hPa but no monsoon cell below, as visualized by Rao (1962). Northerlies below the centre of the cell appear to rise to the south of the m.s.l. location of the monsoon trough between 24°N and 21°N but sink further south. An entirely different pattern is presented along 85°E (Fig. 6b) where a well-defined Hadley (H) cell appears to be centred at about 26°N at

500 hPa and a Monsoon (M) cell to the south, as suggested by Rao (1962). The section along 90°E (Fig. 6c) shows no Hadley or monsoon cell but an anticlockwise circulation cell centred at about 25°N at 500 hPa with strong upward motion to the north, northerlies above, downward motion to the south and southerlies below the centre. Clearly, this cell is forced by the mountains and may be called a Mountain (MTN) cell. Downward motion appears in the whole troposphere over the Bay of Bengal.

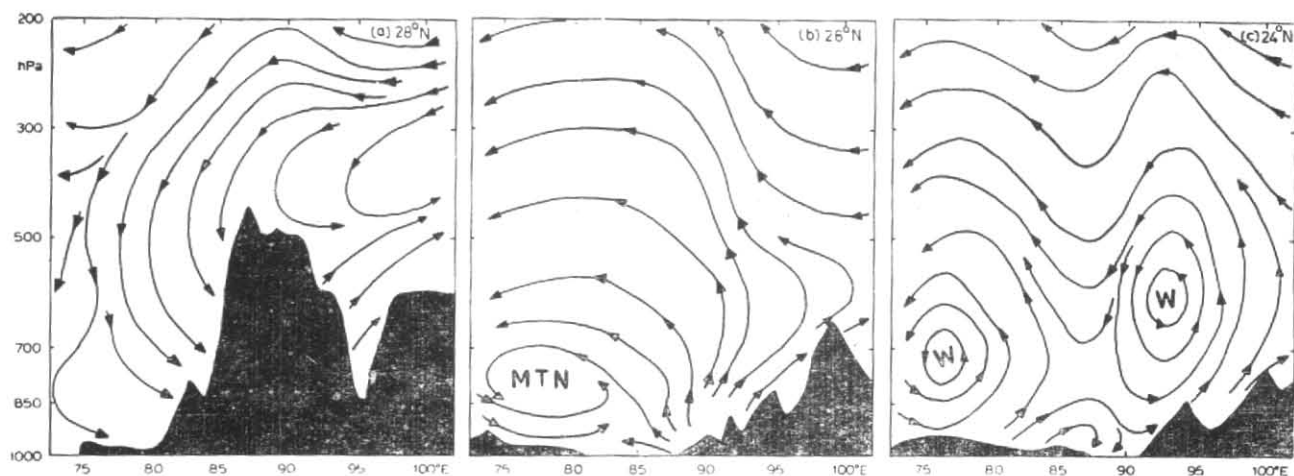
(d) Heat budget.

Fig. 7(a) which presents the computed values of the terms of the heat budget equation along meridian 85°E at 500 hPa appears to reveal the following :

(i) Diabatic heating (Q/c_p) is strongly positive to the south of the m.s.l. location of the monsoon trough with a maximum value of about $12 \times 10^{-5} \text{K s}^{-1}$ at 20°N ;

(ii) The effect of diabatic heating is almost totally compensated by adiabatic cooling due to upward motion ($-\sigma\omega$), i.e., $Q/c_p \approx -\sigma\omega$ and

(iii) Thermal advection ($V \cdot \nabla T$) is relatively very small at 500 hPa, with slight warm advection to the north of about 21°N and cold advection to the south



Figs. 5 (a-c). Resultant streamlines (u , ω) in zonal-vertical sections along : (a) 28°N , (b) 26°N and (c) 24°N

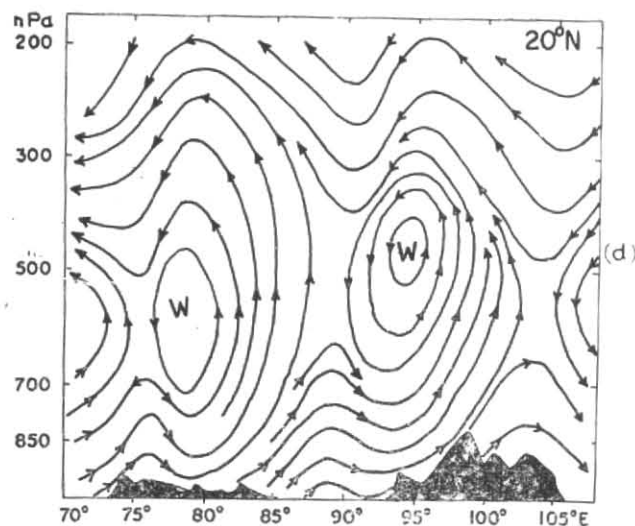


Fig. 5 (d). Resultant streamlines (u , ω) in zonal-vertical section along 20°N

The distribution of total diabatic heating Q (vertically integrated between 925 hPa and 150 hPa) is presented in Fig. 7 (b). It shows strong diabatic heating to the southwest of the m.s.l. location of the mean monsoon trough and over the mountainous regions of north-eastern India, Burma and Indo-China peninsula and diabatic cooling over the trough location itself and over Bangladesh and most parts of the Bay of Bengal.

(e) Moisture budget and precipitation

Fig. 8(a) presents the distribution of computed orographic rainfall (term 5 of the moisture budget Eqn. 5). Positive values of rainfall (R) occur on the windward slopes of mountain ranges where the vertical motion is upward and negative values on the leesides and where the vertical motion is downward and which are relatively dry (RD) areas. A negative value for orographic rainfall has no other significance except that it occurs due to downward motion on the leeside. Fig. 8(b) shows strong moisture convergence (MC) to the southwest of the m.s.l. location of the monsoon trough and strong moisture divergence (MD) to east and northeast. Strong moisture convergence occurs over the eastern Himalayas, Burma and Indo-China peninsula. There appears to be moisture divergence over the western half of the Indian Peninsula and moisture convergence over the eastern half of the Peninsula and adjoining western part of the Bay of Bengal.

The distribution of total precipitation, computed from Eqn. (6) is presented in Fig. 9(a). Here, areas of positive values are indicated as rainy (R), while those of negative values are designated as relatively dry (RD). A negative value may arise from strong moisture divergence or downward motion or both. The distribution of the 4-year (1963-66) mean July observed rainfall is presented in Fig. 9(b). Fig. 9(a) when compared with Fig. 9(b) suggests that despite differences in magnitude the computed rainfall pattern corresponds reasonably well to the observed rainfall pattern in some areas, such as the Western Ghats mountains, the monsoon

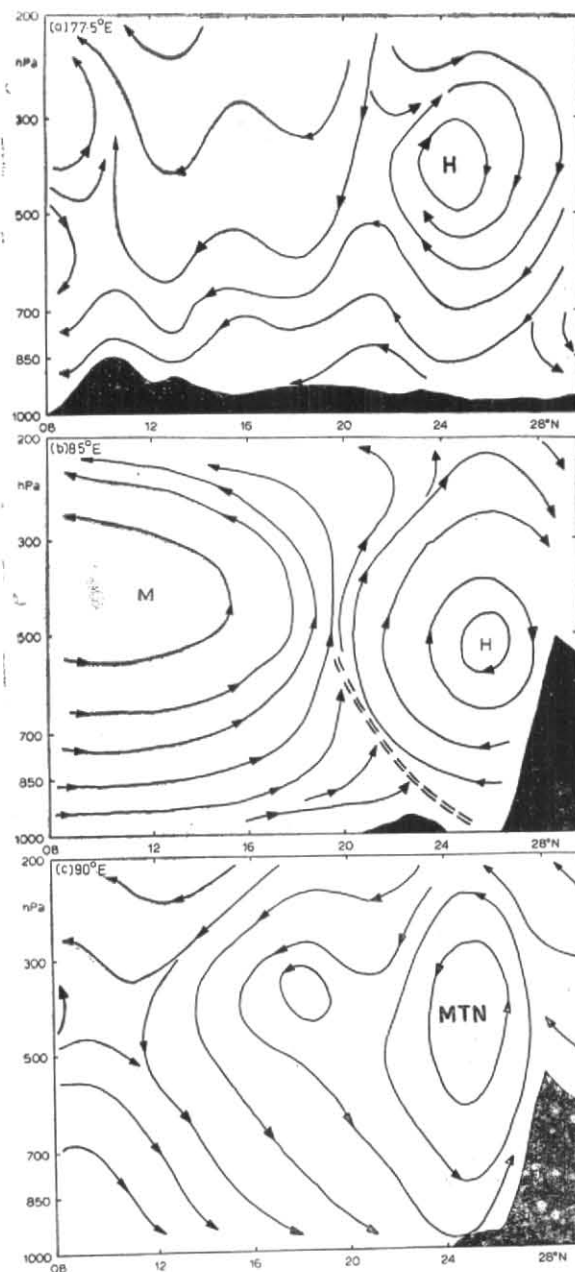


Fig. 6. Resultant streamlines (v , ω) in meridional-vertical sections along (a) 77.5° E, (b) 85° E and (c) 90° E

trough zone and the mountain ranges of eastern Himalayas, Burma and Indo-China peninsula. However, some dissimilarities are noticeable over the southern part of the Indian Peninsula, Bay islands, parts of West Bengal and over Bangladesh. Lack of rainfall data over the Bay of Bengal hampers comparison of the computed rainfall with the observed over the sea area.

The distribution of observed rainfall (Fig. 9b) shows a relative rainfall minimum at the m.s.l. location of the monsoon trough with the main rainfall areas lying to its southwest and northeast. Fig. 9 (a) suggests that the computed rainfall also is similarly distributed relative to the monsoon trough.

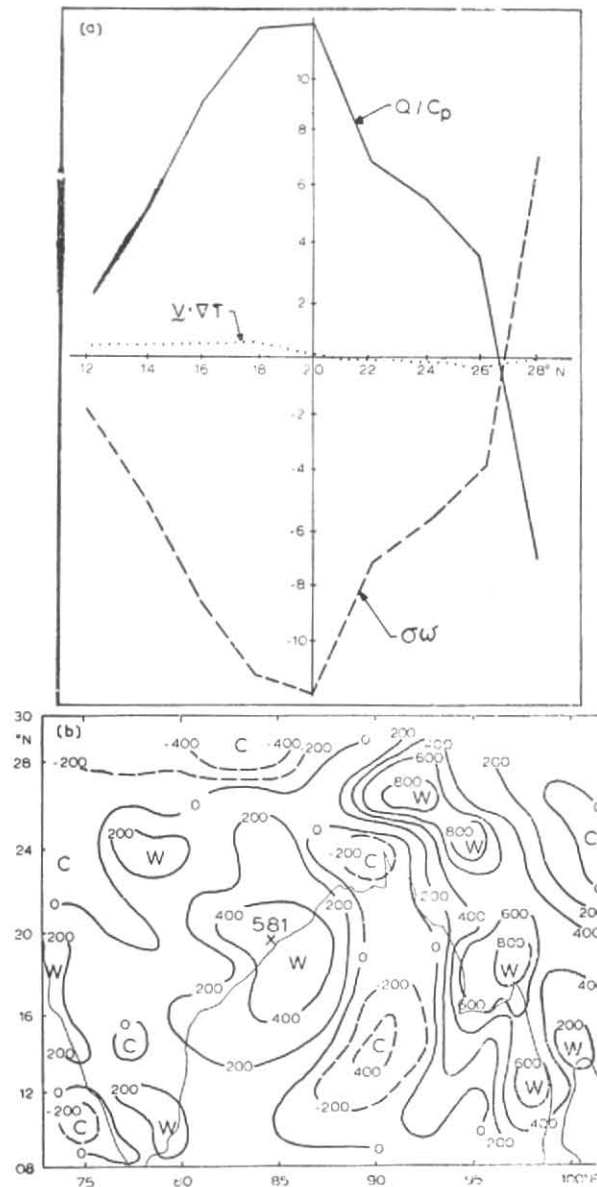


Fig. 7. Computed values of the terms of the heat budget : (a) Meridional profiles at 500 hPa along 85° E (unit : 10^{-5} K s^{-1}) and (b) Horizontal distribution of vertically-integrated total diabatic warming (W) and cooling (C) (unit : W m^{-2})

5. Concluding remarks

Through simple analysis of the time-mean horizontal and vertical motion field and computation of heat and moisture budgets, the study has identified the principal rising and sinking air currents and the meridional and zonal vertical circulation cells that exist in the time-mean July atmosphere over India and the adjoining Bay of Bengal. Mean meridional circulations associated with the monsoon trough over India consist of a monsoon cell which lies equatorward of the m.s.l, location of the trough with rising motion along the equatorward-sloping surface of air mass discontinuity

between the predominantly continental air to the north of the trough and the moist southwest monsoon air to the south and an elevated Hadley cell with its sinking branch over the areas to the north of the trough and rising branch in the south coinciding with the rising branch of the monsoon cell. An important vertical circulation cell which is evident in both the zonal (Figs. 5 b, c, d) and the meridional (Fig. 6c) cross-sections is that forced by the mountains of eastern Himalayas and northeastern India and which may be more appropriately called a Mountain cell. It arises as follows : The S/SE winds from the Bay of Bengal which enter the plains of northern India at m.s.l. veer with height and strike the

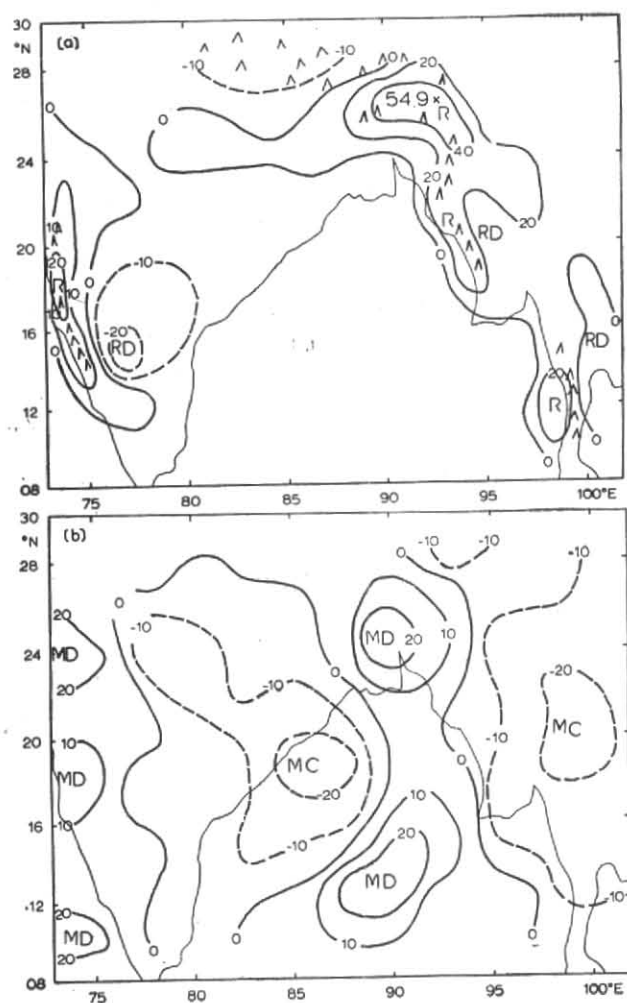


Fig. 8. Computed values of the terms of the moisture budget equation 5 (unit: $10^{-5} \text{ kg s}^{-1} \text{ m}^{-2}$): (a) Orographic rainfall (R-rainy, RD-relatively dry) and (b) Vertically-integrated total moisture divergence (MD) and moisture convergence (MC)

high mountain barrier head-on and rise in deep convection and diverge in the middle and upper troposphere to sink over the plains of northeastern India. Heavy precipitation that occurs in the rising branch of the mountain cell creates a strong diabatic heat source there, while a relative rainfall minimum which occurs in the sinking branch becomes a diabatic heat sink (Fig. 7b). Thus the monsoon trough at m.s.l. is located in a region which is characterized by diabatic cooling, tropospheric subsidence and a relative rainfall minimum. A hypothetical question which has often been asked: What will happen to the monsoon over India if the Himalayan mountain complex was removed or did not exist at all? Hahn and Manabe (1975) who addressed this very question in their General Circulation experiment on the South Asian Monsoon circulation with and without mountains find that in the absence of the Himalaya mountains and the Tibetan Plateau, the rain-belt associated with the summer monsoon advances northward only up to the southern part of India and no farther north. In western

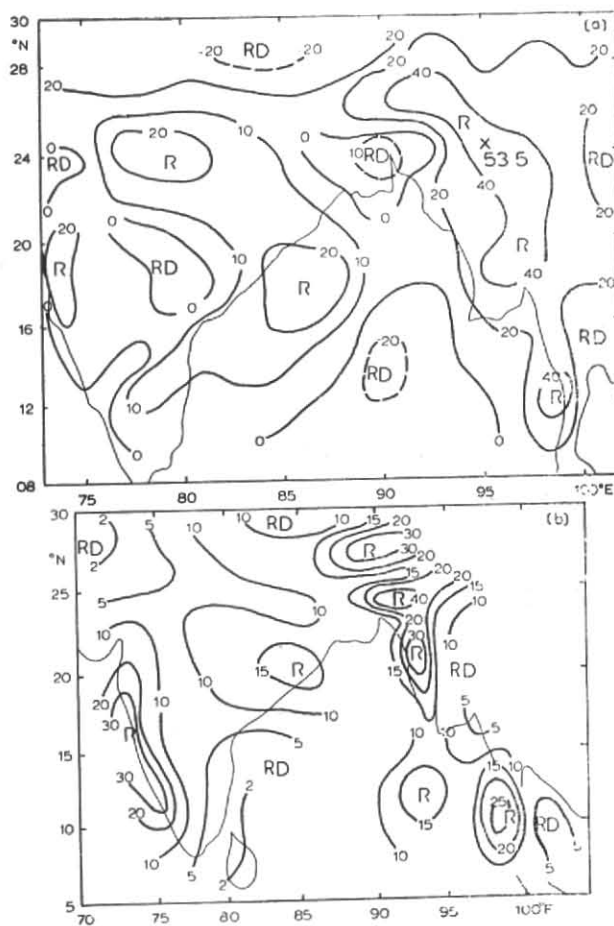


Fig. 9. Distribution of rainfall (R-rainy, RD-relatively dry): (a) Rainfall computed from the moisture budget and (b) Observed 4-year mean July rainfall (unit: $10^{-3} \text{ kg s}^{-1} \text{ m}^{-2}$)

Africa, except the coastal mountain ranges, there are no high mountains comparable to the Himalayas to act as a barrier to the low-level monsoon inflow from the Gulf of Guinea and it is well-known that little or no rain falls to the north of the monsoon trough there. One may conclude that similar would have been the fate of India in the absence of the Himalayas and the elevated Tibetan Plateau. The granary belts of northern India would turn into a Sahara-type desert without the Himalayas.

Acknowledgements

Facilities for this research were made available by the Director General of Meteorology, India Meteorological Department, New Delhi to whom the authors express their sincere thanks. They are also grateful to Huug Van Den Dool, University of Maryland, USA, who reviewed the first draft of the paper and Arun K. Attri, Jawaharlal Nehru University, New Delhi, who helped with the data processing and computations.

References

- Asnani, G.C., 1973, Meridional circulation in summer monsoon of southeast Asia, *Indian J. Met. Geophys.*, **24**, pp. 388-389.
- Das, P.K., 1962, Mean vertical motion and non-adiabatic heat sources over India during the monsoon, *Tellus*, **14**, pp. 212-220.
- Godbole, R.V., 1977, The composite structure of the monsoon depression, *Tellus*, **29**, pp. 25-40.
- Hahn, D.G. and Manabe, S., 1975, The role of mountains in the South Asian Monsoon Circulation, *J. Atmos. Sci.*, **32**, pp. 1515-1541.
- Koteswaram, P., 1958, The Asian summer monsoon and the general circulation over the tropics, *Monsoon of the World*, India Met. Dep., pp. 105-110.
- Krishnamurti, T.N., 1971, Observational study of the tropical upper-tropospheric motion field during the northern hemisphere summer, *J. appl. Met.*, **10**, pp. 1066-1096.
- Krishnamurti, T.N., Kanamitsu, M., Godbole, R., Chang, C.B., Carr, F. and Chow, J.H., 1975, Study of a Monsoon Depression : (1) Synoptic Structure, *J. met. Soc. Japan*, **53**, pp. 227-240.
- Krishnamurti, T.N., 1985, Summer Monsoon Experiment—A review, *Mon. Weath. Rev.*, **113**, pp. 1590-1626.
- Luo, H. and Yanai, M., 1983, The large-scale circulation and heat sources over the Tibetan plateau and surrounding areas during the early summer of 1979-Part I : Precipitation and kinematic analyses, *Mon. Weath. Rev.*, **111**, pp. 922-944.
- Ramage, C.S., 1971, *Monsoon Meteorology*, Academic Press, New York and London, 296 pp.
- Ramage, C.S., Miller, F.R. and Jefferies, C., 1972 (a), *Meteorological Atlas of the International Indian Ocean Expedition*, Vol. 1: *The Surface Climate*, National Science Foundation, Washington, D.C.
- Ramage, C.S. and Raman, C.R.V., 1972(b), *Meteorological Atlas of the International Indian Ocean Expedition*, Vol. 2: *Upper air*, National Science Foundation, Washington, D.C.
- Raman, C.R.V., 1965, Some aspects of the meridional circulation over the Indian monsoon area. Met. Results of the Int. Ind. Ocean Expedition, India Met. Dep., Bombay, pp. 401-412.
- Rao, K.V. and Rajamani, S., 1970, Diagnostic study of a monsoon depression by geostrophic baroclinic model, *Indian J. Met. Geophys.*, **21**, pp. 187-194.
- Rao, Y.P., 1962, Meridional circulations associated with the monsoons of India, *Indian J. Met. Geophys.*, **13**, pp. 157-166.
- Rao, Y.P., 1976, *Southwest Monsoon*, Met. Monogr.—Synoptic Met. 1/1976. India. Met. Dep., 367 pp.
- Saha, K.R., 1968, On the instantaneous distribution of vertical velocity in the monsoon field and structure of the monsoon circulation, *Tellus*, **20**, pp. 601-620.
- Saha, K.R. and Chang, C.P., 1983, The baroclinic processes of monsoon depressions, *Mon. Weath. Rev.*, **111**, 1506-1514.
- Sanders, F., 1984, Quasi-geostrophic diagnosis of the monsoon depression of 5-8 July 1979, *J. Atmos. Sci.*, **41**, pp. 538-552.