Some flow features of the Indian summer monsoon deduced from Nimbus-II radiation data

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ABSTRACT

Radiation data obtained from Nimbus-II MRIR (10–11μ) and HRIR (3.5–4.1μ) radiometer for 14–19 June 1966, over the Indian Ocean are used to study some features of the monsoon circulation during the six-day period. Low values of radiation which are associated with cloudiness show two distinct features from 15–17 June: (i) a very extensive band of approximately 1000 km in width at the equator between 50°–60° E extending towards both hemispheres, and (ii) a synoptic-scale cell covering the equatorial region approx. between 70°–90° E and 0°–10° S. The two cloud systems are separated from each other by a wide region of high radiation indicating clear conditions. Sub-synoptic scale features could be detected in the radiation field (which in turn are related to the cloud field). Northern and Western sections of the Arabian Sea were relatively cloud-free.

An attempt is made to relate the cloud fields with computed vertical motion fields. Areas of upward motion seem to coincide well with centers of low radiation (clouds) and those of subsidence with regions of high radiation. Horizontal flow features related to the computed vertical motion fields are discussed in the paper.

1. Introduction

During the International Indian Ocean Expedition period (1963–64) when intensive efforts were made for massive collection of data from the Indian Ocean area by all possible means, the daily satellite coverage of the area was unfortunately very inadequate. The introduction of the operational satellite systems of the ESSA series in 1966 provided for the first time the regular daily coverage of cloud systems over this region. Almost concurrently with the television pictures by the ESSA-I satellite, the Nimbus-II satellite provided the radiation data relating to the cloud systems over the region.

In the present paper, satellite data relating to period 14–19 June 1966, together with conventional synoptic data of the same period are used to study the distribution of cloud systems and related flow patterns over the Indian Ocean and adjoining land areas. The synoptic situation during the period 15–17 June included an intense cyclonic circulation over the Head of the Bay of Bengal and a clockwise eddy south of the Equator in the eastern part of the equatorial south Indian Ocean. Utilising the conventional synoptic data the vertical velocity is first computed in an attempt to show to what extent areas of updraft coincide with those of cloud systems. Fields of divergence and vorticity required to explain the observed cloud systems are then discussed and it is tentatively concluded that such fields may arise in connection with passage of velocity maxima in fresh monsoon surges.

2. Satellite data and cloud distribution

Digitized Nimbus-II MRIR (10–11 μ) data for 14–19 June 1966 are used to study the distribution of clouds over the Indian Ocean and adjoining land areas. Centers of low radiation values generally correspond to areas overcast with clouds and high radiation values correspond to relatively cloud-free areas. Nimbus-II HRIR (3.5–4.1 μ) data were also used for the same period. This data is presented in the form of grey scale display. The white areas correspond to areas of low radiation and hence regions of extensive cloudiness. Darker areas are relatively cloud-free. Even though the absolute values of temperatures are in doubt in these channels due to difficulties in calibration on board, they can be used for relative comparisons.

Cloud pictures from Nimbus-II AVCS and ESSA-I camera systems were also used in this study but they are not reproduced in order to keep the number of figures to a minimum.

All the data examined showed the following main cloud systems during the period under study:

1. An extensive cloud band, about 1000 km wide at the equator between 50° E and 60° E and extending into both the hemispheres. Many sub-synoptic or mesoscale clouds appear to be embedded in this band. The band formed on or about the 14th of June, was most intense on the 16th and weakened by the 17th.

2. An equatorial cloud system extending from 70°–90° E and covering a latitude band of about 10° mostly south of the Equator. This cloud system formed on 14 June, reached its maximum intensity on the 16th and dissipated by the 18th, indicating a life span of about 3 to 4 days.

3. A synoptic-scale intense cloud system over the Head Bay of Bengal associated with a deep depression.

4. A sub-synoptic scale isolated cloud mass off south Burma coast.

A remarkable feature of the above cloud distribution was that between the cloud systems that lay across south India and the Head Bay of Bengal and that of the Equatorial belt east of Gan Island, there was a wide region of the north Indian Ocean which was practically cloud-free. North and west Arabian Sea were also practically clear of clouds.

3. Relationship between clouds and vertical motion

It is generally believed that updraft is a necessary pre-requisite for development of clouds in a moist atmosphere. But the question that is of interest here is the reverse: Given a distribution of clouds, how far is it justified to assume that updraft is present in the area of the clouds? Perhaps the matter can only be settled by actual computation. Shenk (1963) and Hansen & Thompson (1965) found high correlation between computed vertical motion at 700 mb level and cloud distribution as obtained from satellite data over the United States. Alperson & Zangwill (1966) examined this question by comparing vertical velocity field at the 500 mb surface with the distribution of large scale cloud systems as observed by TIROS satellite over the Mediterranean Sea and North Africa and found that there was a high correlation between the two. Sanders (1966) computed vertical motion in the field of a pronounced cloud vortex over the United States and southern Canada and found that, in general, areas of cloud mass were positively correlated with those of ascent, with only a few exceptions.

In the present study, the authors examined the question by computing vertical motion using the kinematic method, over an area bounded by longitudes 47.5° E and 107.5° E and latitudes 7.5° S and 32.5° N, at six standard pressure levels 850, 700, 500, 300, 200 and 100 mb using 2.5 degree grid points, on the days selected for the study. Fig. 1 shows the streamline-isotach analysis at 500 mb level at 00Z on 16 June 1966, (for economy of space only one level is presented) and Fig. 2 gives the distribution of vertical velocity at 500 mb level along with that of the principal cloud systems on 16 June 1966 as derived from Nimbus-II radiation data. It may be seen that there is high correlation of updrafts with well developed synoptic scale convective cloud systems in many regions. However, in some regions especially in data-sparse areas and in areas of sub-synoptic scale cloud systems, the correlation is poor or even negative.

4. Vertical velocity in relation to vorticity and divergence of horizontal motion

The mechanism by which vertical motion and clouds and precipitation form is determined by the distribution of vorticity and divergence of the horizontal flow.

The vorticity equation and the continuity equation governing air motion on an isobaric surface may be written as:

$$(d\eta/dt) = -\eta\nabla\cdot\mathbf{V} - \mathbf{k}\cdot\nabla\omega\times(\partial\mathbf{V}/\partial p) + \mathbf{k}\cdot\nabla x\mathbf{F} \quad (1)$$

$$\nabla\cdot\mathbf{V} = -\partial\omega/\partial p \quad (2)$$

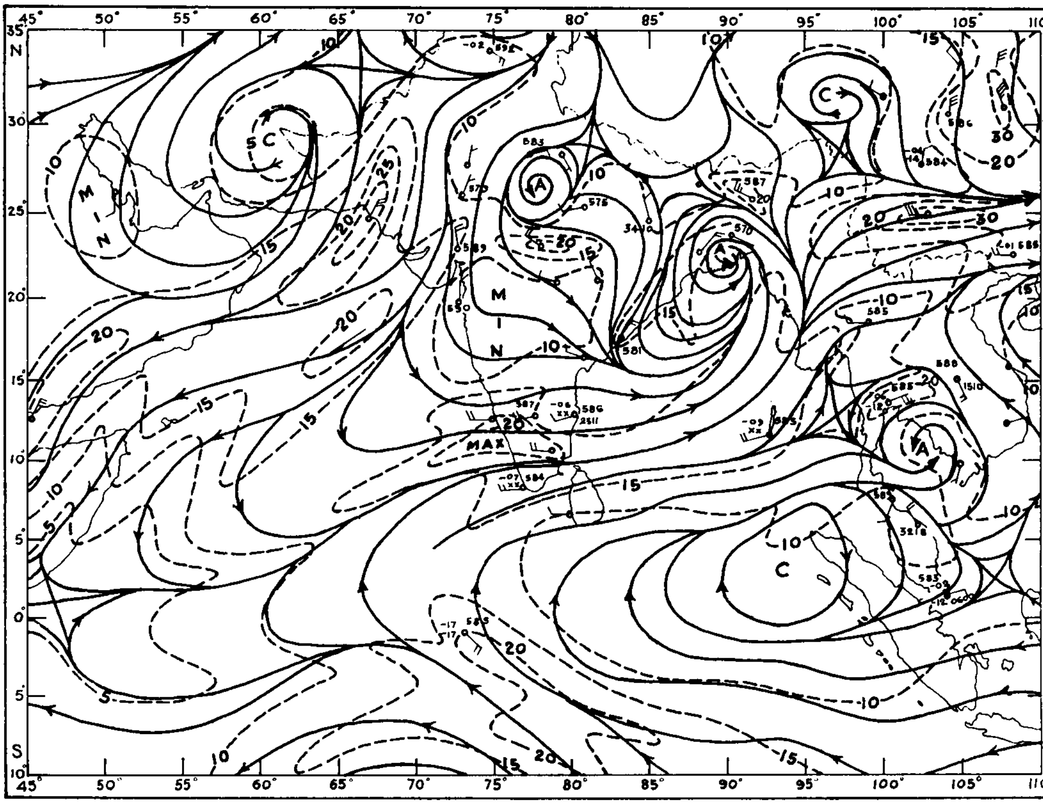

Fig. 1. Streamline isotach analysis at 500 mb level, 00Z 16 June, 1966. *C*, Clockwise; *A*, anticlockwise.

where the symbols used have the following meanings:

η is absolute vorticity
$\mathbf{V}$ is horizontal wind vector
ω is vertical p-velocity
F is frictional force
∇ is horizontal Nabla operator
$\mathbf{k}$ is the vertical unit vector
p is pressure

and d/dt is time differentiation following motion.

Equation (1) states that the rate of change of absolute vorticity of a moving parcel of air depends on three terms: divergence, tilting and friction. Of these, the magnitude of the tilting term is generally small in the Tropics. The frictional term is difficult to evaluate but is believed to be small except in the boundary layer. Hence, to a first approximation, equation (1) may be written in the simplified form

$$d\eta/dt = -\eta\nabla\cdot\mathbf{V} \tag{3}$$

Equation (3) states that if the absolute vorticity of a moving air parcel increases/decreases in the northern hemisphere, it must be accompanied by convergence/divergence. The reverse is the case in the southern hemisphere.

The distribution of absolute vorticity along a streamline which represents the trajectory of an air parcel under steady state is given by the sum of the relative vorticity $(Vk_s - \partial V/\partial n)$ and the coriolis parameter f. Here K_s is the curvature of the streamline, reckoned positive when anticlockwise and negative when clockwise irrespective of the hemisphere and $\partial V/\partial n$ is the wind velocity shear (n reckoned positive to the left of the streamline looking downstream). A change of absolute vorticity may therefore occur through change in any one or more of the constituent terms, viz. curvature, shear, and coriolis parameter.

Fig. 3 shows schematically and in a qualitative manner the signs of the three terms that enter into consideration of absolute vorticity

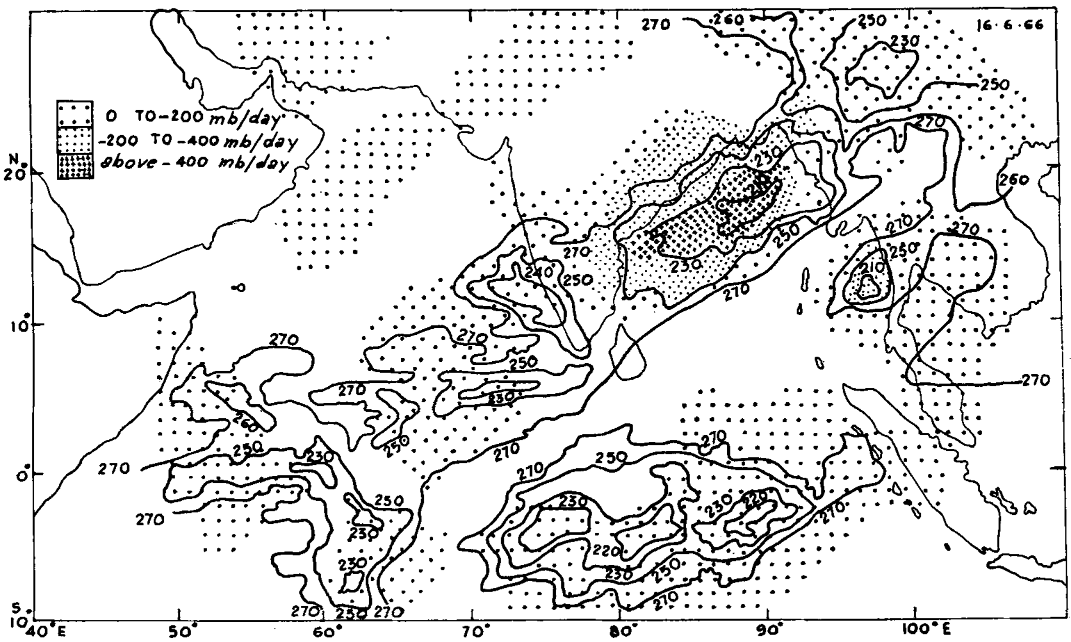

Fig. 2. Distribution of vertical velocity at 500 mb level in units of mb/day at 00Z 16 June, 1966 and Nimbus-II channel-2 low radiation values in terms of equivalent black body temperature ≤270°A composited from orbits 425 and 426 with mean time 0647Z on 16 June 1966. Isopleths in degrees Absolute are shown by solid lines.

at different points along a southwest monsoon current associated with a velocity maximum and on either side of it. It is plausible that development of excessive negative relative vorticity to the right of such a velocity maximum may lead to the formation of clockwise eddies even before it crosses the Equator. The convergence pattern resulting from the formation of such an eddy should be associated with clouds. Elsewhere along the path of the velocity maximum, the occurrence of clouds would depend upon the convergence resulting from the net effect of the three terms involved in the vorticity changes.

Fig. 4 shows the results of an actual computation of absolute vorticity over the region of interest at 00Z on 16 June 1966 at 850 mb level. This would seem to support the scheme presented above at least qualitatively. Incidentally, it may be seen that the isopleth of zero absolute vorticity is located in the northern hemisphere well away from the Equator in most areas.

5. Discussion

In the present study an attempt has been made to relate cloud patterns as revealed by satellite data to horizontal flow features through vertical motion in a specific monsoon situation. A remarkable feature of the synoptic situation appears to be the co-existence and contemporaneous character of the two main cloud systems, viz. the inter-hemispheric cloud band in the Arabian Sea sector extending into both the hemispheres and the equatorial cloud system in the eastern part of the south Indian Ocean. In Fig. 5 is presented the life cycle of the equatorial cloud system as revealed by low radiation data and it may be seen that the life span of this cloud is about 3–4 days. The inter-hemispheric cloud band also maintained its form and structure for about the same period. From the results of a single case study, it is difficult to state whether any physical or dynamic connection exists between the two but it would seem that along with other factors, velocity maxima in the monsoon airstream may play an important role in shaping the pattern of clouds, as shown schematically in Fig. 3. No statistics of the frequency and location of velocity maxima in the Indian Ocean area have been collected but meteorologists in this part of the Tropics are familiar with the fairly frequent fluctuations or

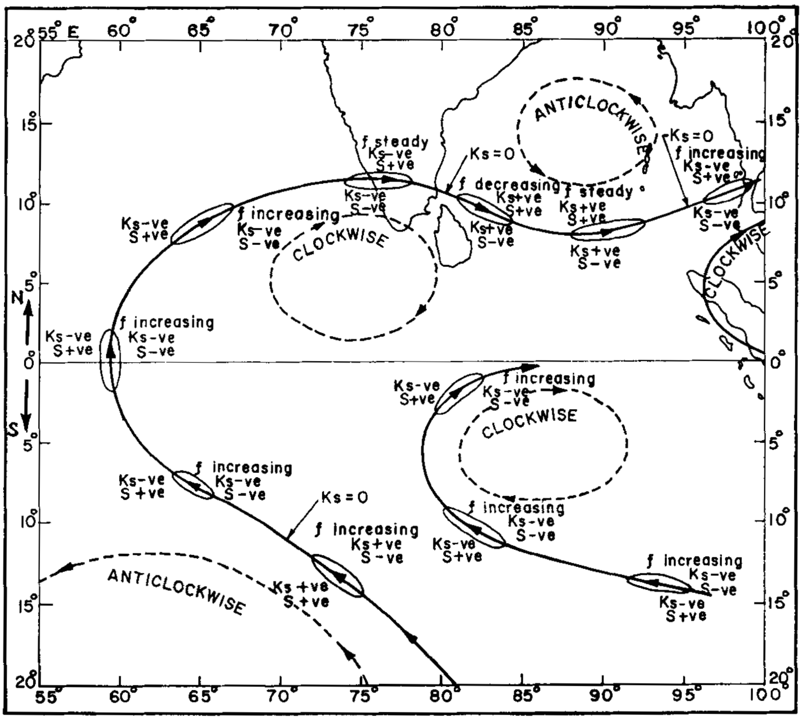

Fig. 3. Schematic representation of the signs of the various terms involved in consideration of absolute vorticity along monsoon streamlines with associated velocity maxima. Preferred locations of clockwise and anticlockwise eddies are shown. K_s is curvature and S is the wind shear term $(-\partial v/\partial n)$.

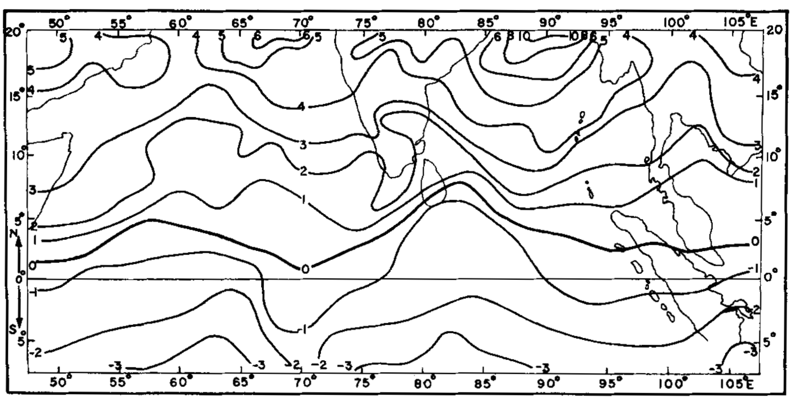

Fig. 4. Distribution of computed absolute vorticity, 00Z16 June 1966 at 850 mb level. Unit: 10^{-5} sec^{-1}.

pulsations of the monsoon current as evidenced by alternations of strong and weak monsoon conditions. Malurkar (1950) who studied the summer monsoon flow over the Indian Ocean area during the Second World War noted several intermittent surges of the equatorial maritime air crossing the Equator as feeble low pressure waves, which he called "pulses", each pulse lasting about 3 to 4 days.

The frequent passage of velocity maxima in the lower-tropospheric south-east trades may explain the formation of a low pressure trough

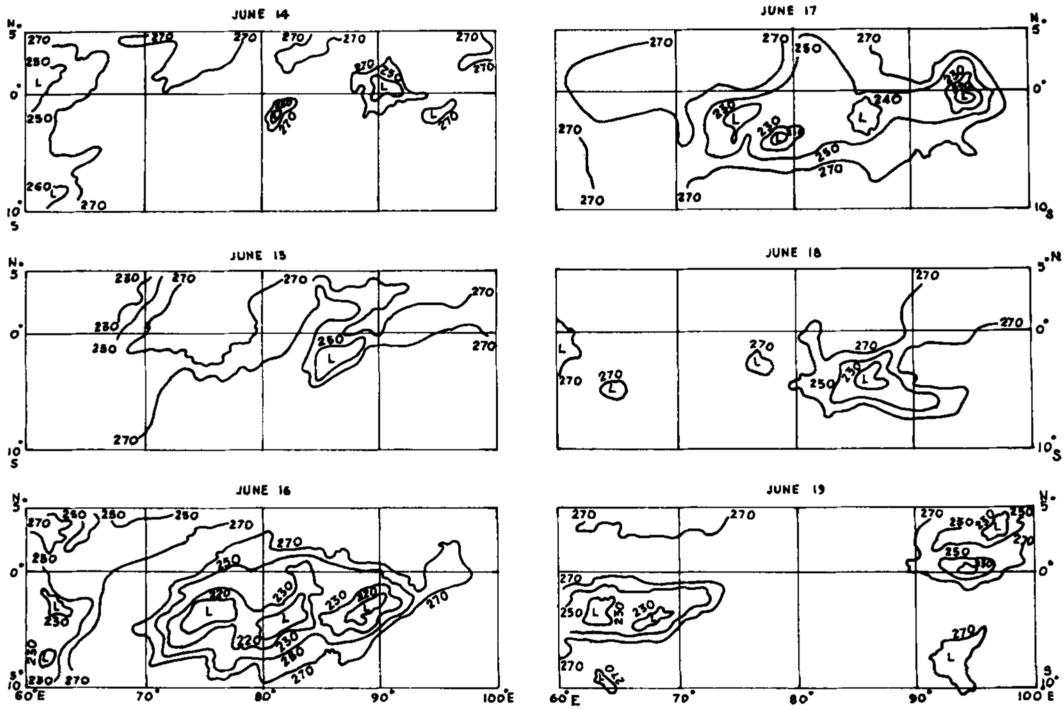

Fig. 5. Areas of Nimbus-II MRIR channel-2 low radiation values in terms of equivalent black-body temperature <270°A during the period 14–19 June 1966, in the equatorial region. Times of orbits composited lie between 0432 and 0647Z. Centers of low radiation cells are marked as *L*.

in the equatorial region of the southern Indian ocean, which we prefer to call a dynamic trough as against the thermal trough situated well north of the Equator over India. Their passage over the Arabian Sea may explain the observed higher frequency of clouding and rain in eastern Arabian Sea as compared to the west. From data of 130 aerological soundings made over the Arabian Sea during the summers of IIOE period, Ramage (1966) has shown that the base of the inversion level is much higher over the south-eastern part of the Arabian Sea as compared to the western or northern Arabian Sea and Rama (1968) using a radio-active tracer technique has produced evidence of the presence of south-east trades moist air over the eastern Arabian Sea as against the predominantly desert air over the western Arabian Sea. In Fig. 6 which is a photoprint of Nimbus-II night time HRIR data on 16 June 1966 the presence of the cloud band extending into the two hemispheres appears to be clearly suggestive of the crossing of the south-east trades into the northern Indian ocean.

6. Conclusion

Nimbus-II radiation data and television cloud photographs have been used to deduce information regarding vertical motion and associated features of horizontal flow relating to a specific monsoon situation. Vertical motion has been qualitatively related to vorticity changes arising from movement of velocity maxima. It is believed that the concept of the movement of velocity maxima in the monsoon current is an important one and its role in the context of the distribution of clouds and precipitation should be further explored.

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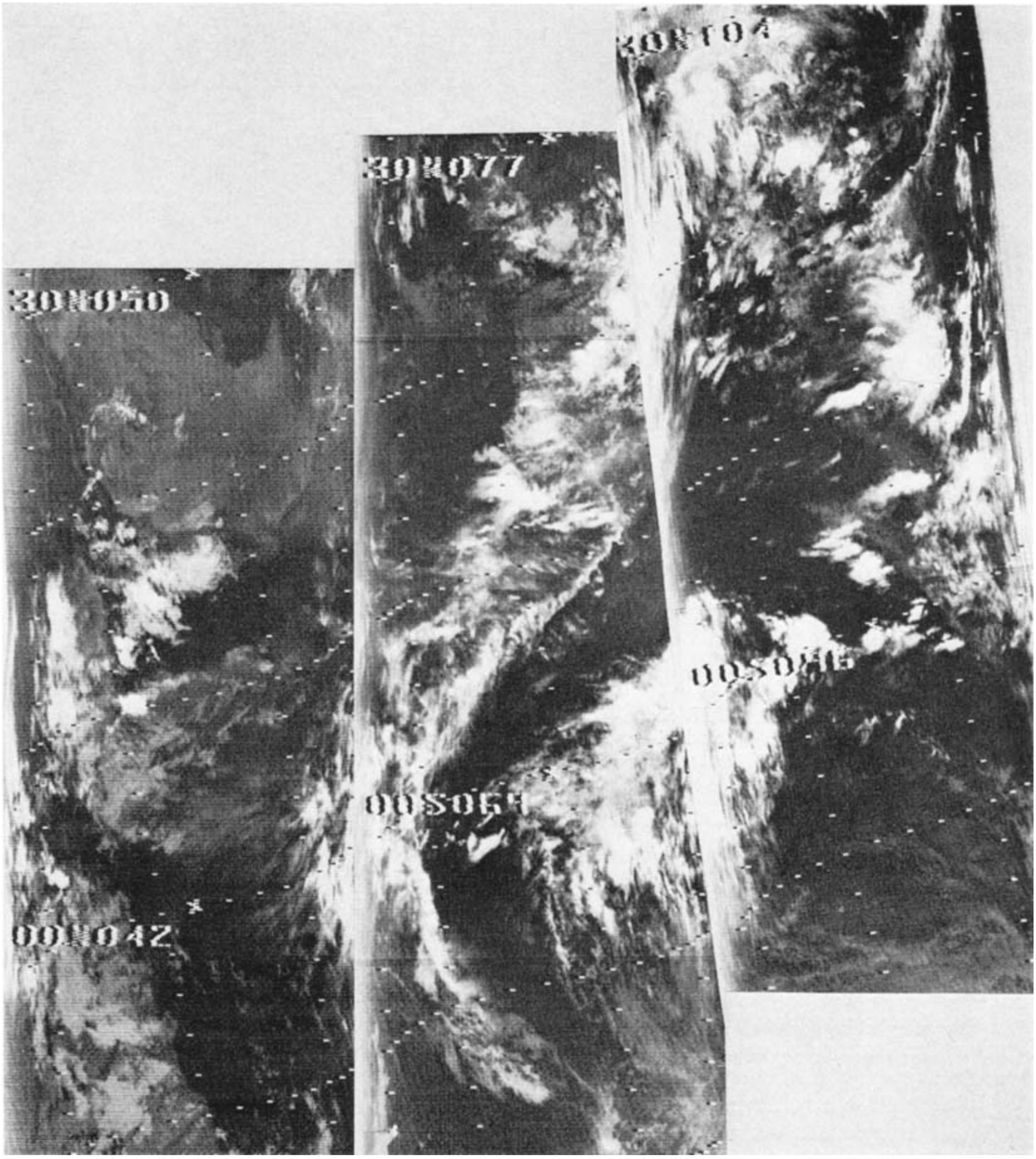

Fig. 6. A photo-print of Nimbus-II night time HRIR data composited from orbits 431, 432, 433, at times 1612, 1801, 1940Z respectively on 16 June 1966 over the Indian Ocean region showing *inter alia* a broad inter-hemispheric band of cloud across the Equator between longitudes about 50° E and 60°E.

REFERENCES

Alperson, Z. & Zangwill, A. 1966. Comparison between the 500 mb surface and the large scale cloud distribution as observed by TIROS Satellites, *Meteor. Sat. Data.* A Report of Studies. Report of work performed under contract cwb-11055 March 1965–February 1966.

Hansen J. & Thompson, A, H. 1965. Vertical motion calculations and satellite cloud observations over the Western and Central United States. *J. of App. Meteorology, 4,* 1, 18–30.

Malurkar, S. L. 1950. Notes on analysis of weather of India and neighbourhood. *Memoirs of the India*

Meteorological Department, *vol. XXVIII*, pt. IV, 139–215.

Rama, 1968. An attempt to trace the monsoon flow using natural radon. *Ind. J. Met. & Geophysics. 19*, 2, 167–170.

Ramage, C. S. 1966. The summer atmospheric circulation over the Arabian sea. *J. Atmos. Sci. 23*, 114–150.

Sanders, F. 1966. Large scale cloud systems. Satellite Data in Meteorological Research, *NCAR-TN-11*, 103–120.

Shenk, W. E. 1963. TIROS II. Window radiation and large scale vertical motion. *J. of App. Met. 2*, 6, 770–775.

НЕКОТОРЫЕ ОСОБЕННОСТИ В ПОТОКЕ ИНДИЙСКОГО ЛЕТНЕГО МУССОНА, ПОЛУЧАЕМЫЕ ИЗ РАДИАЦИОННЫХ ДАННЫХ НИМБУСА-II

Для изучения некоторых особенностей муссонной циркуляции используются данные, полученные в течение шестидневного периода (14–19 июня 1966 г.) над Индийским океаном с помощью инфракрасных радиометров среднего (10–11 μ) и высококо (3,5–4,1 μ) разрешения, установленных на спутнике Нимбус-II. Низкие величины радиации, связываемые с облачностью, показывают две отчетливые особенности в период с 15 по 17 июня: 1) очень протяженную полосу шириной приблизительно 1000 *км* на экваторе между 50–60° в.д., простирающуюся в оба полушария и 2) ячейку синоптического масштаба, расположенную в экваториальной области приблизительно между 70–90° в.д. и 0–10° ю.ш. Эти две облачные системы разделены одна от другой широкой областью сильной радиации, указывающей на ясные условия. В радиационном поле могут быть обнаружены особенности субсиноптического масштаба (которые в свою очередь связаны с полем облачности). Северная и западная части Аравского моря были относительно свободны от облаков. Делается попытка связать поля облачности с рассчитанными вертикальными движениями. Области восходящего движения представляются хорошо совпадающими с центрами низких величин радиации (облака), а (области нисходящих движений — с областями сильной радиации. Обсуждаются также особенности горизонтальных потоков, связанные с вычисленными полями вертикальных скоростей.