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Some aspects of break and active monsoon over southern Asia during summer

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ABSTRACT

North of 10° N, at least three synoptic phases of the summer monsoon can be identified. Two of these phases—the break and active monsoon—are extremes. Patterns of cloudiness and rainfall for these two phases differ substantially. These indicate differences in the geographic location and intensity of tropospheric energy sources.

Tropospheric circulations over the equatorial Indian Ocean during break and active monsoon also differ. A break is often accompanied by the development of a trough in the lower troposphere northeast of Gan; this appears to enhance rainfall over southeast India. Although cause and effect are difficult to separate using scanty aerological data, synoptic variation over the equatorial Indian Ocean east of 60°–65° E may influence rainfall over western and southern India.

1. Introduction

In most years the fully-developed Indian summer monsoon circulation exhibits at least three synoptic patterns, namely, "moderate", "active" and "break" phases. The relative duration of these three phases has a direct influence on Indian agriculture and economy because patterns of rainfall associated with these phases usually differ considerably. This study focuses on the active and break phases, which may be regarded as synoptic extremes.

Essentially, the active phase is a more energetic version of the prevailing moderate phase. The moderate phase is typified by a complex distribution of rainfall associated with weak, short-lived and slow-moving cyclones and ridges in the middle and lower tropospheres and an absence of monsoon depressions. During an active phase, at least one monsoon depression develops over north Bay of Bengal, at the eastern end of a low pressure (monsoon) trough and moves westnorthwestward for 4–10 days. Cyclogenesis may also occur in the middle troposphere over northeastern Arabian Sea. Rainfall is widespread over much of the subcontinent. When a break occurs, the axis of the monsoon trough over a wide longitudinal belt either shifts poleward to the Himalayan foothills or disappears below 500 mb as an anticyclonic ridge develops near 20° N. Although no monsoon depressions form during a break, weak cyclonic disturbances often form in the middle troposphere over India south of 15° N. Rainfall diminishes over India outside the northeast and southeast. Breaks usually persist for 3–7 days but may last 2–3 weeks in some years.

Horizontal and vertical flow patterns during active and break phases have been compared and contrasted before (see, for example, Dixit & Jones, 1965; Srinivasan & Sadasivan, 1975; Datta & Mukerji, 1975) and models developed (Asnani, 1973; Krishna Rao & Datta, 1975). Significant changes in circulation which occur as a break develops have received some attention (Raghavan, 1973). However, data from meteorological satellites have been used relatively little. These data, which are usually more spatially homogeneous and continuous than aerological data provide a useful additional tool for diagnostic studies of synoptic variation. The present study documents mean cloud cover during both phases and relates this to contrasts in equatorial circulations south of India.

2. Analysis of satellite data

Microfilms of scene-corrected mosaics of television and scanning radiometer visible data ob-

Table 1. *Active and Break Monsoon Phases 1967–1974*

Active	Break
July 26–August 2, 1967	July 6–15, 1967
July 26–August 6, 1968	August 5–8, 1967
July 28–August 1, 1969	August 25–31, 1968
August 13–16, 1969	August 17–20, 1969
September 2–11, 1970	August 25–27, 1969
August 5–19, 1972	July 12–15, 1970
July 5–9, 1973	September 24–28, 1970
August 26–September 6, 1973	August 1–6, 1971
August 13–20, 1974	July 17–August 3, 1972
	September 1–5, 1972
	July 25–31, 1973
	July 26–28, 1974
	September 1–6, 1974

tained daily between 0400 and 1000 GMT from ESSA, ITOS and NOAA satellites during 1967–1974 were used. Each day's mosaic was analysed visually to determine the presence or absence of cloud within a 1° latitude square centred on each intersection of a 2½° latitude-longitude grid covering the region 2½° N–37½° N, 65° E–125° E. Cloud was deemed present (absent) if cloud cover within a 1° square was greater (less) than 50%. An estimate of "mean" cloud cover for a period was computed for each grid intersection by calculating the ratio of the number of "cloud present" events to the number of days in the period.

Analyses were performed for 75 days each of active and break monsoon covering 8 monsoon seasons—defined as the period during which the monsoon covered all of India (Table 1). A break phase was selected only if it persisted for 3 days or more and both ends of the monsoon trough were close to the Himalayas. An active phase commenced on the day of initial development of a depression (with a lifetime exceeding 2 days) and ended with its passage across longitude 80° E. When another depression developed during this period the date of transit of this second depression was used.

3. Analysis of aerological and rainfall data

Because of its equatorial position and of its being a small island more than 800 km from the nearest land mass, Gan (0°41′S, 73°09′E) was chosen for detailed analysis. Aerological data from Gan are considered representative of the atmosphere over the equatorial Indian Ocean. Also, Gan is in the vicinity of the axes of two vertical circulation modes proposed by Ramage (1971). Hence, changes of circulation in the upper and lower tropospheres at Gan should relate to synoptic-scale changes over the Indian subcontinent. A successful attempt to seek consistent relationship(s) should encourage research into prognostic applications of aerological data from the equatorial region.

Temperature, dewpoint depression, wind speed and direction data were used to compute mean temperature and dewpoint profiles (not shown) and mean zonal and meridional wind components for the two 75-day samples for every standard level up to 100 mb from radiosonde soundings made daily at 1200 GMT. Mean anomalous wind components were derived from means of data for 10 monsoon seasons.

Anomalies of weekly rainfall for rainfall subdivisions of India published by India Meteorological Department were used to derive mean anomalies for those (10–11) weeks each dominated by break or active monsoon.

4. Mean cloudiness and rainfall

Only gross features of 75-day mean cloud cover are discussed. Many small features require further study.

The dominant feature during break is the strong cloudiness (over 70%), over southeastern Tibet and adjoining states (Fig. 1). Relatively clear skies dominate northwest India, Pakistan and much of the oceans. Stronger cloudiness over the Philippines and Indonesia results from frequent sub-synoptic scale (~5° latitude) convection aided by orography. Marked gradients of cloudiness along most of the Asiatic coast reflect a transition from synoptic scale ascent of moist air overland to subsidence over the oceans, probably through a cooperative interaction between sub-synoptic and synoptic vertical circulations. Over India between 80–85° E a meridional circulation regime similar to that proposed by Krishna Rao and Datta (1975) operates but with subcells of smaller latitudinal extent.

Few readily identifiable cloud masses track westward across south Bay of Bengal during break.

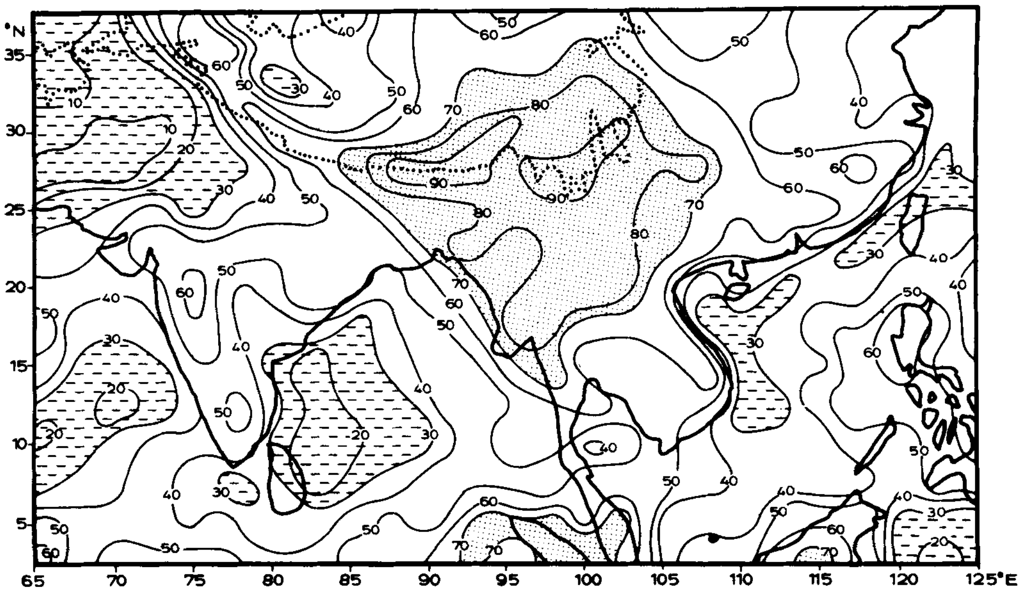

Fig. 1. Mean cloudiness (in percent) during break monsoon over India. Stippled shading: areas with over 70% cloud cover. Dashed shading: areas with under 30% cloud cover. Dotted line: 3000 m contour.

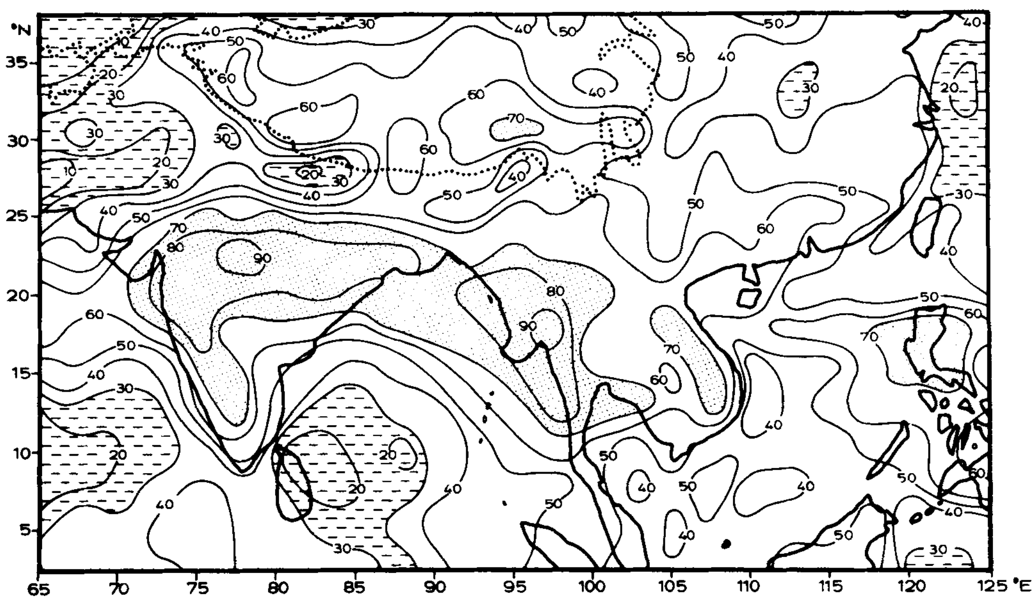

Fig. 2. Mean cloudiness (in percent) during active monsoon over India. Key as for Fig. 1.

Instead, cloud masses often remain stationary or move only slowly northeastward off the coast of southwest India. Westward moving disturbances below 500 mb only become evident from satellite pictures when west of 85° E.

During active monsoon, strong cloudiness associated with the monsoon trough and depressions over India, Bay of Bengal and Western Burma is flanked by clearer skies associated with subsidence to the north and south (Fig. 2). Further

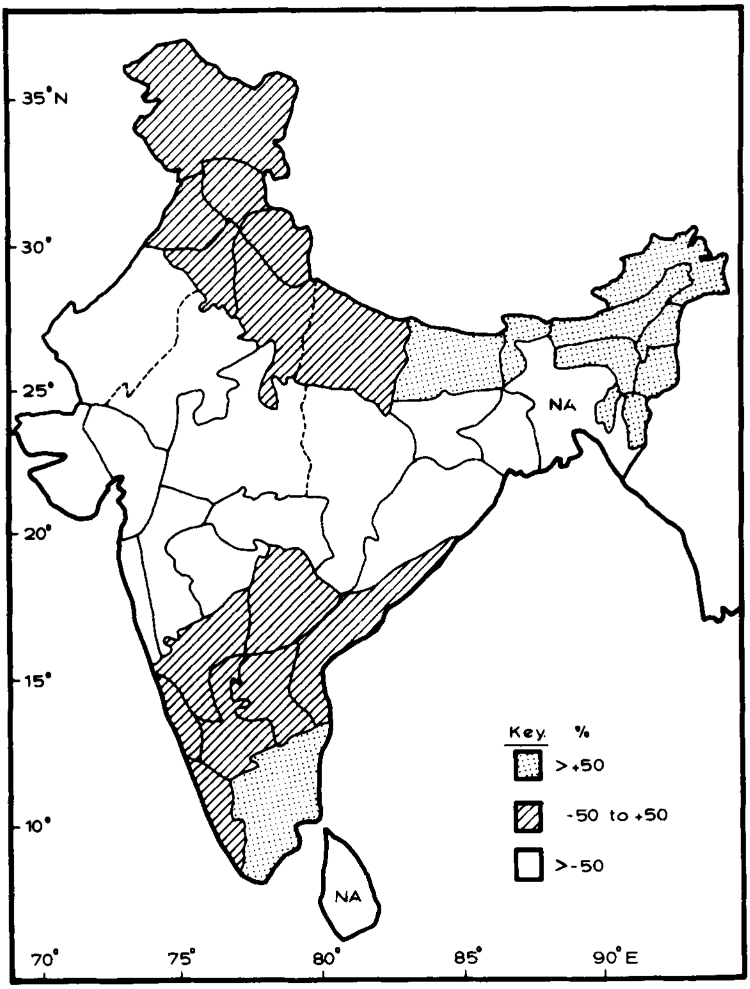

Fig. 3. Mean difference (break minus active) between rainfall anomalies associated with break and active monsoon over India.

east, numerous tropical cyclones moving northwestward across the Philippines towards Indo-China often accelerate the lower tropospheric westerlies, thereby aiding convection over southeast Asia.

Figs. 1 and 2 indicate substantial differences of cloud cover (and thus mean vertical motion). Most notable are weaker cloudiness over southwest Tibet, India south of 25° N, north of Bay of Bengal and Gulf of Tonkin and stronger cloudiness over northeast India, southwest China, Borneo and equatorial Indian Ocean during break. At the same time, broken cumuliform cloudiness usually replaces well-developed cloud clusters over north-eastern Arabian Sea, India, Indo-China and the Philippines because upward motion is weaker.

The differences in cloudiness are reflected by broadly similar differences in rainfall, at least over India (Fig. 3). A notable exception is the increase of rainfall over Tamil Nadu during break. This results from an enhancement of upward motion near a transient trough southwest of India (cf. Thiruvengadathan and Jambunathan, 1971).

5. Upper winds and temperature at Gan

Figs. 4–7 show that the zonal flow during break is more westerly at all levels except 500 mb because

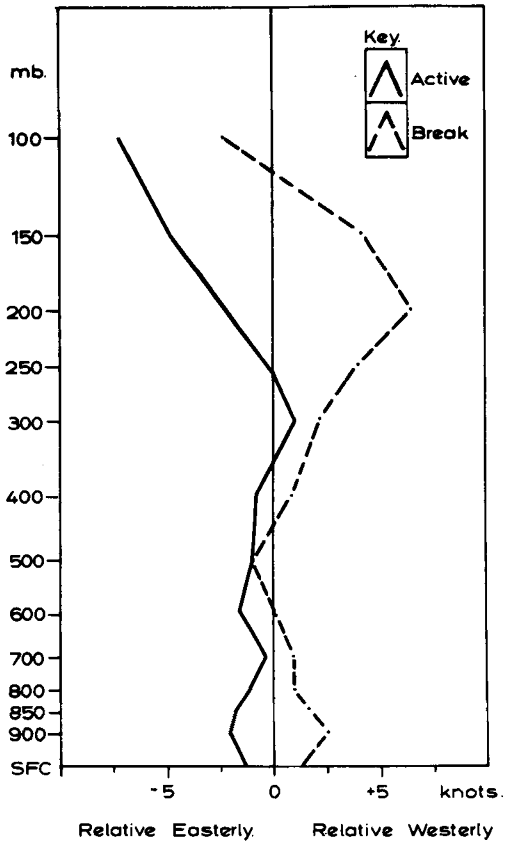

Fig. 4. Mean zonal wind anomaly at Gan during active and break monsoon over India.

the lower tropospheric westerlies are stronger and the seasonal easterly flow above 400 mb is weaker. An anomalous northerly flow below 500 mb and anomalous southerlies above 300 mb indicate a weaker (but not a reversed) seasonal meridional circulation (with northerlies aloft and a southerly flow below 500 mb) during break. Note that during both phases the net *anomalous* meridional transport, integrated through the troposphere, is approximately zero.

The stronger westerlies below 700 mb during break possess a mean northerly component because the frequency of northwesterly winds is over 50% higher whilst the frequency of southeasterly winds is halved (Figs. 8 and 9). Although the proportion of southwesterly winds below 500 mb is similar during both phases, winds are usually lighter during break. Above 500 mb, wind frequencies in the four compass quadrants are about the same during both phases except at 200 mb where the flow is often weaker and from a southeasterly quarter during break.

These differences suggest changes in trough-ridge patterns in the lower troposphere near Gan. During a break, anticyclonic ridges probably occur northwest and southeast of Gan with troughs to the southwest and northeast. Satellite evidence supports this notion (Ramaswamy, 1971). Ridges replace troughs and vice versa during active monsoon. Most of these developments seem to occur in situ.

To determine whether or not the differences in wind direction are due to sampling variations, a chi-squared test on one degree of freedom using Yate's correction was applied, assuming the data to be representative samples of break and active phase. This test indicated a significant difference (at at least the 5% level) between the frequencies of meridional and zonal components below 800 mb and the zonal and meridional components at 800 mb and 700 mb, respectively. Similar results were obtained when the quintile of lowest wind speeds was removed.

Wind profiles during the pentad immediately preceding each active and break phase studied show no regular variation at any level. However, at 900 mb northwesterly winds tend to occur twice as often before a break whilst the frequency of southeasterly flow is halved. At 200 mb, winds often weaken and become more variable before a break.

Mean vertical profiles of temperature (to 100 mb) and humidity (to 300 mb) indicate a slightly cooler atmosphere (by 1 °C) below 700 mb during break. Warming (~2 °C) appears above 300 mb (Table 2). However, these differences may arise from sampling variations. During a break, air is moist (relative humidity over 60%) up to 600 mb (compared with 850 mb during active phase) and more moist in the 500–800 mb layer. This increase of moisture is statistically significant at all but the 700 mb level. Similar differences are found over India (Srinivasan and Sadasivan, 1975).

Above 850 mb, pseudo-equivalent potential temperatures are less than 3 °K higher during break whilst below this level temperatures are, on average 5 °K lower. This indicates a reduction of convective instability below 850 mb.

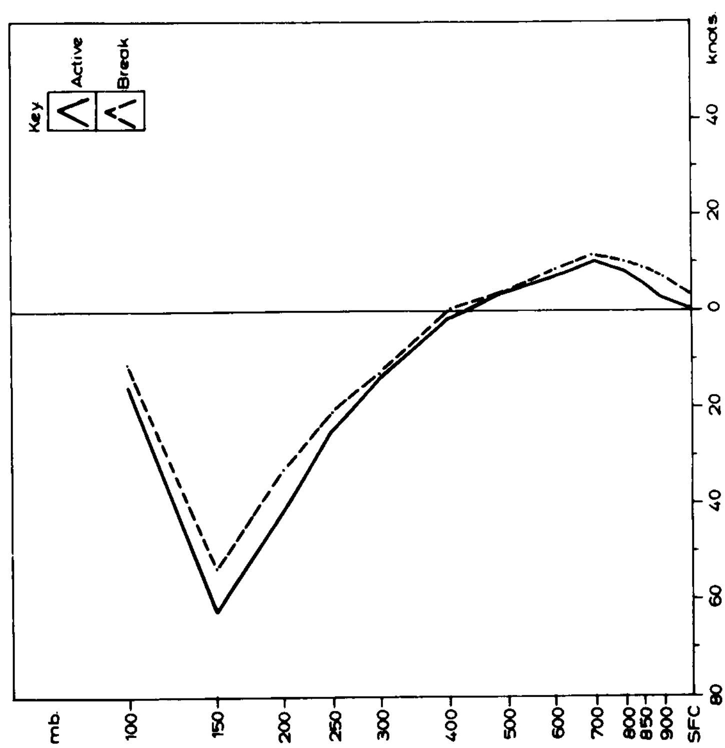

Fig. 5. Mean zonal wind component at Gan during active and break monsoon over India.

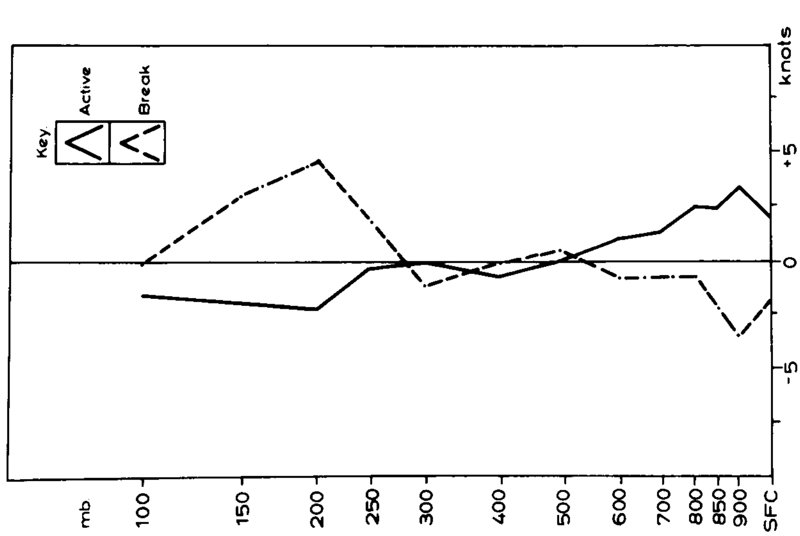

Fig. 6. Mean meridional wind anomaly at Gan during break and active monsoon over India.

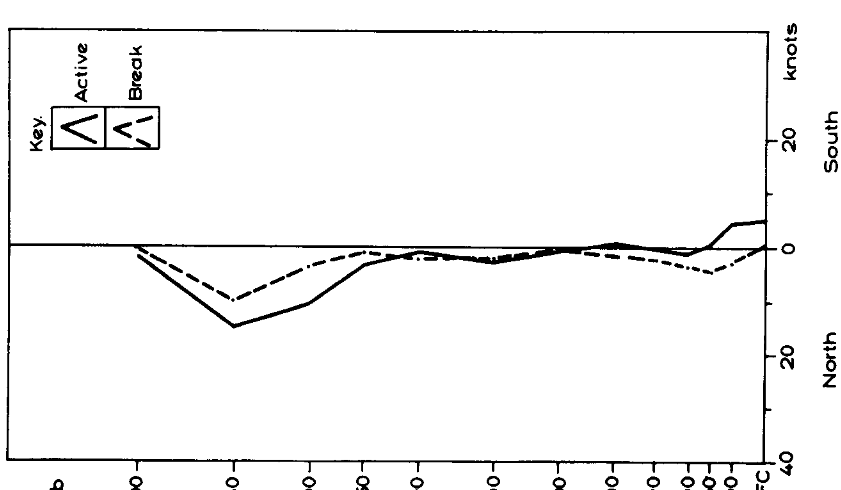

Fig. 7. Mean meridional wind component at Gan during break and active monsoon over India.

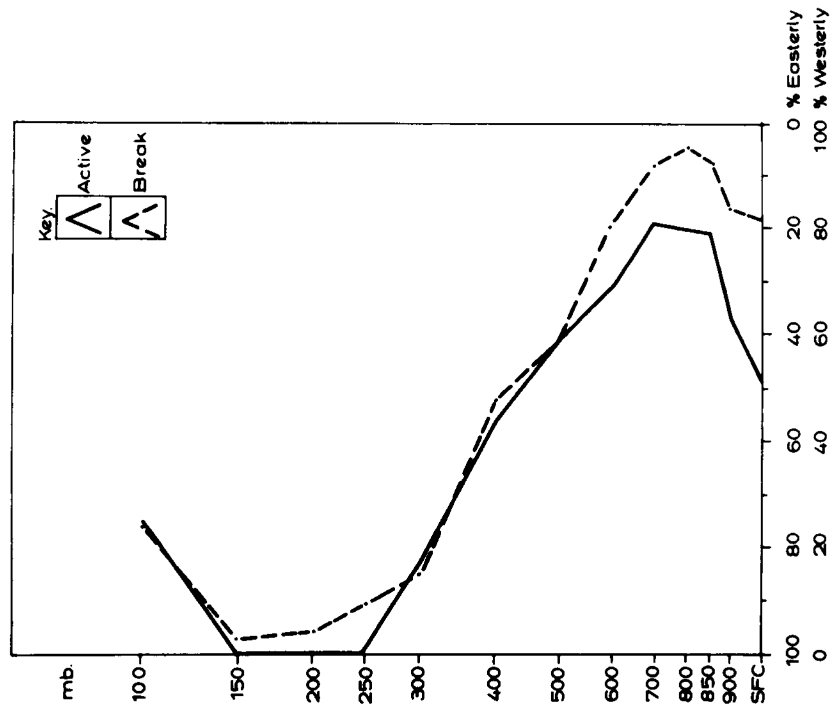

Fig. 8. Frequency (in percent) of zonal wind directions at Gan during active and break monsoon over India.

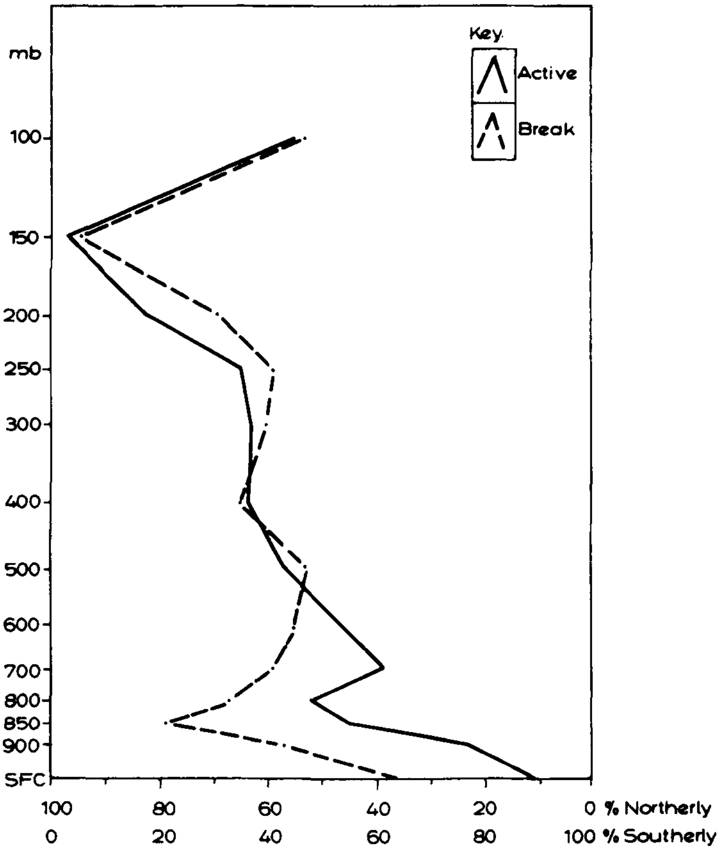

Fig. 9. Frequency (in percent) of meridional wind directions at Gan during active and break monsoon over India.

Table 2. *Mean dry bulb temperature and relative humidity at Gan during break minus mean values for active phase*

Level (mb)	Sfce.	900	850	800	700	600	500	400	300	250	200	150	100
Temp. (°C)	−1.2	−1.1	−1.0	−1.1	−0.1	−1.3	−0.5	+0.4	+0.4	+1.7	+1.2	+1.6	+3.6
Rel. Hum. (%)	+2.6	−1.2	+1.2	+19.7	+7.0	+16.5	+15.5	+2.7	+2.6	—	—	—	—

6. Summary and remarks

The dynamics and origin of sequences of synoptic events which precede and often determine each development of active or break monsoon sometimes differ substantially. But gross features of cloudiness associated with each occurrence of a phase are usually similar to one another and to mean patterns for that phase although smaller scale circulations and interannual variations complicate these features. Evidently, mean subsidence along southern foothills of the Tibetan plateau during active phase is replaced by ascent east of 80° E during break. Also, ascent over central and western India and western Tibet is weaker during break. Although cloudiness along the Himalayan mountains west of 90° E differs little between phases, greater variations occur over western Tibet because troughs above 600 mb often form over or progress slowly across Tibet east of about 80° E during break.

Both satellite and aerological data for a number of stations (not discussed here) suggest qualitatively that the genesis and persistence of both phases depend mainly on a transport and transformation of energy between components of the monsoon circulation, aided by oceanic storage. Daily satellite evidence suggests that, additionally, interactions occur between the monsoon and circulations primarily to the east and west although cause and effect are difficult to ascertain. These interactions are, in turn, influenced from time to time by variations in the zonal flow of both hemispheres. Hence the monsoon is primarily a dynamic phenomenon.

Although substantial interannual and intraseasonal variations of circulation can occur over the equatorial Indian Ocean, large fluctuations (from a seasonal mean) which occur during contrasting monsoon phases are usually at least as great, particularly near 200 mb and below 700 mb. Frequently, a weak flux of moisture below 850 mb from the southern hemisphere at Gan seems either to disappear or diminish before and during a break. If this also occurs far to the west in the presence of subsidence in the middle troposphere (Ramage, 1966), as seems likely from Pisharoty and Asnani's (1960) work, then rainfall over western India, which derives partly from this transequatorial flux, will diminish. Evaporation from the Arabian Sea is likely to diminish also, if warmer air moving southeast from Arabia is present.

An understanding of the thermodynamic and kinematic processes operating during the monsoon is incomplete without studies of comprehensive information on sea-surface temperatures and aerological details over remote parts of the oceans south of Asia. Cloud pictures from satellites provide only a limited plan view of synoptic events whilst satellite radiance measurements require reliable radiosonde data to produce accurate aerological measurements. Therefore, complementary satellite and ground-based observations must be used in future studies.

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НЕКОТОРЫЕ АСПЕКТЫ ЗАРОЖДЕНИЯ И АКТИВНОЙ ФАЗЫ МУССОНА НАД ЮЖНОЙ АЗИЕЙ ЛЕТОМ

К северу от 10° с.ш. можно идентифицироваться, по крайней мере, три синоптических фазы летнего муссона. Две из этих фаз — зарождение и активный муссон — являются предельными. Поля облачностей и осадков существенно различаются для этих двух фаз. Это указывает на различия в

географическом положении и интенсивности тропосферных источников энергии. Циркуляции тропосферы над экваториальной частью Индийского океана также отличаются для периодов зарождениями активного муссона. Зарождение часто сопровождается развитием ложбины в нижней тропосфере к северо-востоку от Гана. Представляется, что это усиливает выпадение осадков над юго-восточной Индией. Хотя явления и их причины трудно разделить, используя редкие аэрологические данные, синоптические изменения над экваториальной частью Индийского океана к востоку от 60–65° в.д. влияют на осадки над западной и южной частями Индии.