The south Asian summer monsoon

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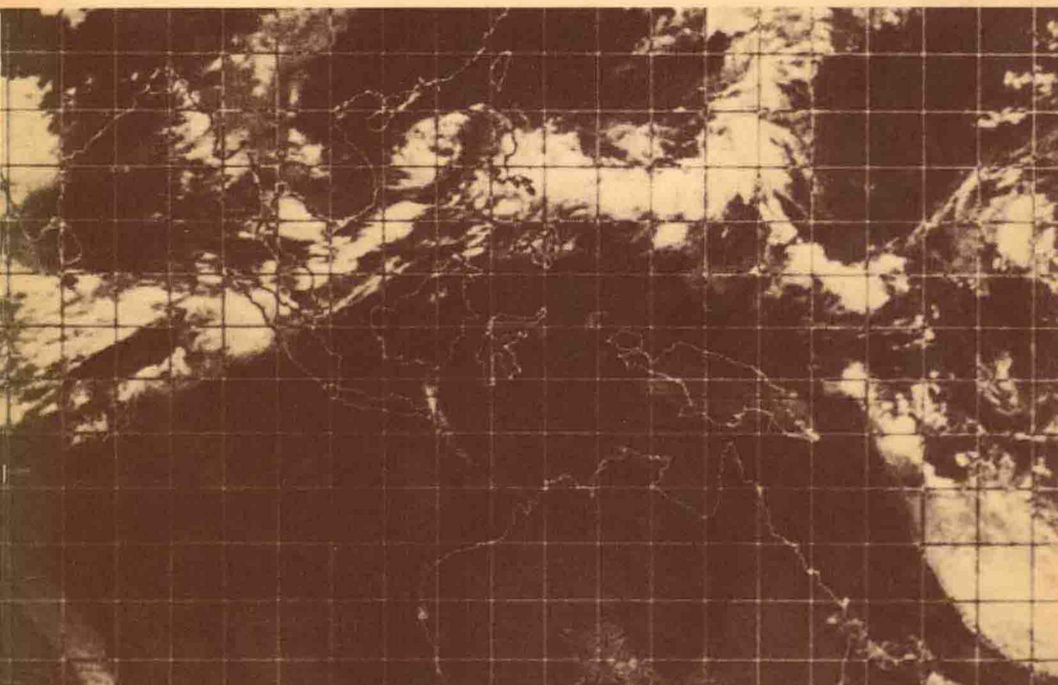

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Preface

The summer monsoon of southern Asia has been studied for more than three centuries. Early work dealt mainly with surface features of the monsoon over India, where meteorological observations were commenced in the eighteenth century. Today, observations from India remain the primary source of information on monsoon activity west of 100°E.

In the last twenty-five years the advent of radiosonde and radiowind measurements have provided knowledge of the four-dimensional structure of the monsoon and revealed its important role in the maintenance of the global circulation of the atmosphere. Knowledge of planetary-scale and synoptic features of the monsoon is reviewed in the present book because variations in sequences, frequency, intensity and geographical location of these features are essential parts of the monsoon variability on many space and time scales. Major scientific problems are discussed because dynamical and physical processes which drive the monsoon are poorly understood.

Much of the material for this booklet has been derived from an article written by the author and published in *Progress in Geography 9* in 1976. Soon after its publication, it became clear that the article would serve as an introduction to the monsoon for college and university students studying the atmosphere. Therefore, it was decided to issue the article as a small paperback. In doing this, the material has been brought up to date and extended.

The author expresses his thanks to all who have helped with the preparation of this booklet. In particular, the author gratefully acknowledges assistance from the National Meteorological Library at Bracknell and the technical staff at the Department of Geography, University of Birmingham. Last, but not least, my wife has contributed much by her unfailing encouragement.

Birmingham, M. G. Hamilton
February 1978

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I Introduction

The most impressive atmospheric phenomenon within the tropics is the seasonal variation of monsoon circulations over southern Asia. This has long fascinated and occupied natural philosophers, more especially since the livelihoods of at least one quarter of all humanity, living in predominantly agrarian conditions, are influenced directly.

To most south Asian peoples the term 'monsoon' refers to the rain which falls during June–September every year. This is not surprising since over

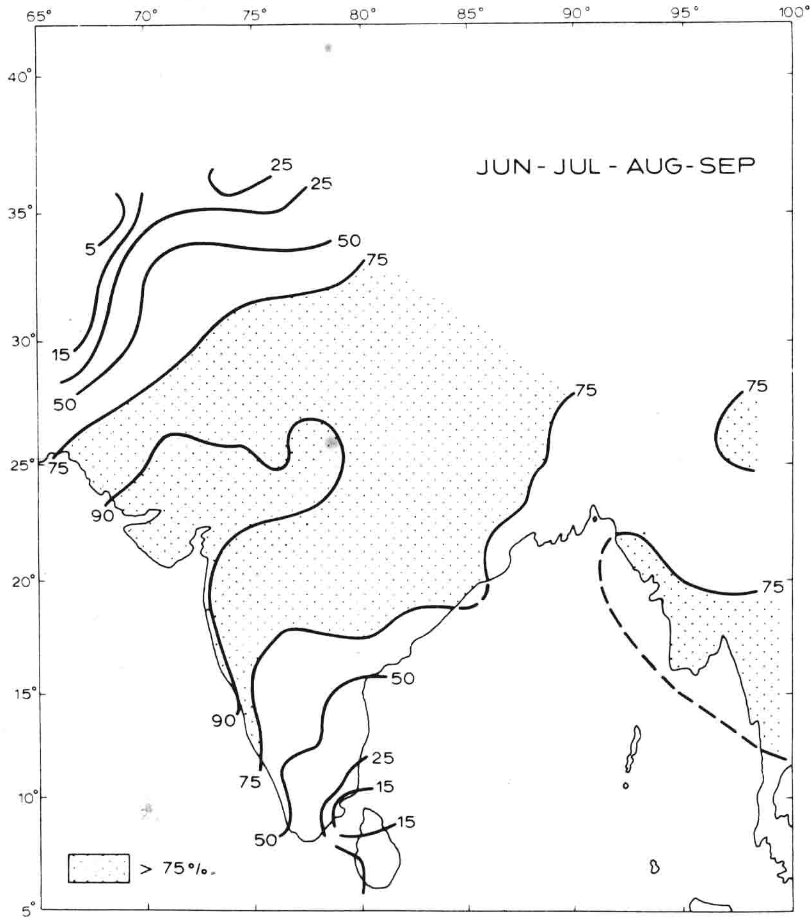

Figure 1 Seasonal distribution of rainfall as a percentage of annual. *After Ananthakrishnan and Rajagopalachari (1964)*

80 per cent of the annual precipitation received by the Indian sub-continent as a whole falls in the summer monsoon season (Parthasarathy, 1960). In some areas, western India for example, the summer contribution approaches 90 per cent (Figure 1). However, the areal extent and intensity of the monsoon rains can vary considerably within a season and from year to year. In some parts of southern India and Pakistan the variability of annual rainfall is about 50 per cent with respect to the long-term mean (Figure 2). Moreover, these areas receive very little rain. By contrast, the

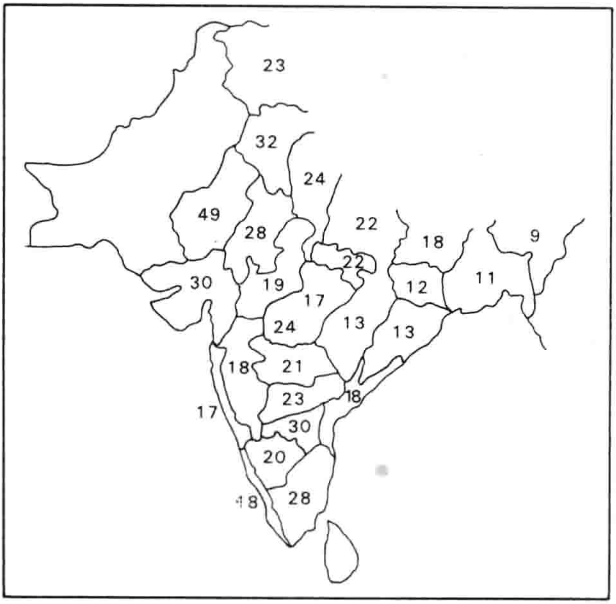

Figure 2 Seasonal variability of rainfall over India for the monsoon months June–September (Standard deviation/mean) × 100. *After Rao and Ramamoorthy (1960)*

variability of rainfall over much wetter northeastern India is less than ten per cent.

This variability is important since excess or deficit precipitation, allied with insufficient soil moisture storage (Rao *et al.*, 1976), may have equally dire consequences for a high proportion of a population which has an economy wedded largely to the success or failure of crops. Extreme weather events such as undue delay in the onset of the monsoon, extensive flooding, prolonged drought and cyclones have dramatic effects on agricultural potential even though average weather conditions account for only 50 per cent of the variability of crop yields (Raman, 1971). Agronomic practices, seed varieties and fertilizers account for the rest.

Even on a global scale the importance of the monsoon rains to human life and economy cannot be underestimated since even with the best harvests stocks of food today amount to less than three months' supplies. This seems likely to encourage closer links between political developments and the production and distribution of food, not only on the Indian sub-continent.

In spite of the importance of the summer monsoon in the human economy satisfactory explanations of seasonal weather and climate characteristics of southern Asia remain elusive. This lack of understanding arises because the monsoon is a highly complex and varied phenomenon. Moreover, many weather-significant developments have their birthplace over a vast data-remote oceanic area which borders southern Asia. Many explanations of monsoon phenomena are therefore based largely upon aerological and surface data, obtained by land-based (conventional) observatories. There are very few conventional observatories in the Indian Ocean. Furthermore, few regular commercial aircraft routes cross this area. Consequently, most studies using conventional data have investigated circulations mainly within the region east of 60°E and north of 10°S. Attention has focused largely on circulations over the Indian sub-continent and its coastal waters.

Since the mid-1960s Earth-orbiting meteorological satellites which provide photographs of global cloud cover at least once each day have permitted studies of atmospheric energy, moisture and circulation over southern Asia and the whole of the Indian Ocean. Such studies aid the location and description of weather disturbances and the chief sources and sinks of various forms of energy and can indicate modes of energy transport. Although few satellite-based studies have so far considered the weather and climate of southern Asia, satellite data have improved knowledge of the space–time organization of clouds and their structure and at the same time have both confirmed previously formulated theories concerning the monsoon and raised new questions.

Before discussing aspects of present knowledge of the monsoon, a scheme which classifies the continuous spectrum of temporal and spatial scales of atmospheric motion is required. Such a scheme should facilitate identification of major weather-producing organizations. Table 1 shows a scheme based largely on conventional data (Barry, 1970). A scheme based upon analyses of meteorological satellite data has also been devised (GARP, 1970) (Table 2). Although a hybrid scheme designed specifically for use over southern Asia is desirable, Barry's scheme is adopted since much of this discussion will draw upon analyses of conventional data.

Over southern Asia macroscale features seem to contribute most directly to weather and climate. But occasionally mesoscale disturbances are most

Table 1 The scales of meteorological motion systems (*from Barry, 1970*)

Motion system	Approximate characteristic dimensions		
	Horizontal scale (km)	Vertical scale (km)	time scale (h)
Macroscale: Planetary waves	5,000	10	200 to 400
Macroscale: Synoptic perturbations	500 to 2,000	10	100
Mesoscale phenomena	1 to 100	1 to 10	1 to 10
Microscale phenomena	$<10^{-1}$	$<10^{-2}$	10^{-2} to 10^{-1}

weather-significant, sometimes with combined effects exceeding those of macroscale features. However, the three-dimensional structure of most of these disturbances is poorly known because of a lack of data. Hence, this account will focus largely on macroscale features.

Observations of surface weather have been made in southern Asia for many years. However, aerological observations at levels above 500 mb have been made only since the 1939–45 war. Even then, only since the mid-1950s has the network of upper air stations been dense enough for delineation of macroscale features of the circulation in the middle and upper tropospheres. Observations of stratospheric circulations are still sparse. However, it is known that large seasonal changes in circulation do occur over Asia as a part of a system of global changes (see Palmén and Newton, 1969). Also, there is some evidence to suggest that fluctuations in lower stratospheric circulations are related in some way to lower tropospheric circulations (Raghavan, 1973). This discussion will confine attention exclusively to present knowledge of tropospheric phenomena.

Studies made before the mid-1950s have related mainly to the lower troposphere. These have been reviewed adequately elsewhere (see, for instance, India Meteorological Department, 1960; Pédelaborde, 1963).

Table 2 Scales of satellite-viewed tropical cloudiness (*from GARP, 1970*)

Scale A (the large wave scale): wavelengths range from 2,000 to 10,000 km; lifetimes are very long.

Scale B (cloud cluster scale): these cloud masses have characteristic sizes of 100 to 1,000 km; lifetimes range from one to five days.

Scale C (mesoconvective scale): the sizes of these 'cumulonimbus clusters' or 'mesoconvective elements' range from 10 to 100 km; lifetimes vary according to type of organization.

Scale D (convective cells): characteristic sizes range from 1 to 10 km; lifetimes are typically of the order of a few hours.

Studies undertaken mainly since the mid-1950s have distinguished macroscale circulation features which are likely to determine space–time distributions of wet and dry conditions on both the meteorological and climatological scales.

Most investigations based on aerological data have used information obtained from relatively few aerological stations. For instance, in 1977, there were only 80 regular rawinsonde and upper air stations within the region bounded by meridians 30°E, 100°E and parallels 30°N, 30°S, comprising an area of approximately 49×10^6 km². Furthermore, most of these stations were situated poleward of latitudes 15°S and 15°N. This number of stations is rather inadequate for investigations of macroscale phenomena since it is generally accepted that such studies ideally require data spacings of about 500 km. However, the recent arrival of satellites capable of making vertical soundings of atmospheric thermal structure have mitigated this deficiency to some extent.

Despite the shortcomings of a small number of aerological stations, it has been possible to delineate salient features of the monsoon circulation, especially since the mounting of the International Indian Ocean Expedition in 1963–4. Some interesting and unexpected results have been obtained.

These features may be regarded as components of a time-averaged circulation which determines seasonal weather over southern Asia. Some of these components, notably cyclonic vortices in the lower and middle troposphere, have a direct and profound effect upon the well-being of the indigenous population.

These components will be described largely in terms of their 'conventional appearance' and their contribution to surface weather. Then, their contribution to the climatology of the summer monsoon will be exemplified by a brief chronology of the sequence of major changes in macroscale distributions of energy, moisture and circulation that occur every year. A discussion of attempts to predict the short- or long-term behaviour of monsoon circulations using statistical and/or dynamic models is beyond the scope of this account. It is sufficient to note that there is an increasing need to improve our understanding of the origin of fluctuations in monsoon weather and climate through judicious use of more extensive data coverages and analytical methods. More realistic prognostic models coupled with better descriptions of the initial state of the atmosphere might then permit more consistently accurate forecasts. Particular attention should be paid to seasonal and subseasonal incidence of drought and floods.

The south Asian summer monsoon is the best developed among the monsoon systems of the world. It has long been regarded as a gigantic sea breeze with a low-level source in the winter hemisphere and sink in the summer hemisphere. However, there is evidence that suggests shortcomings in this model. For example, Simpson (1921) noted that temperatures over the

Indian sub-continent are higher in May, before the onset of the monsoon, than in July, when the monsoon is fully established over the sub-continent, and that the hottest part of the sub-continent remains mainly dry and cloud-free throughout the summer. This suggests that heating and cooling gradients are not merely surface phenomena.

More recent evidence obtained from aerological soundings has revealed the important contribution of upper tropospheric circulations (through patterns of vertical motion) to these and other features of weather over southern Asia (see, for example, Newell *et al.*, 1972 and 1974; Flohn, 1971; WMO, 1972). Circulations predominantly within the middle troposphere have also been identified from aerological data and their contribution to atmospheric energetics and surface weather discussed (see, for example, Pisharoty and Asnani, 1957; Chang, 1972; Flohn *et al.*, 1970; Rao, 1976; Miller and Keshavamurthy, 1968). These disturbances cause monsoon winds and rainfall to vary in both time and space. Moreover, it has been found that although surface disturbances are rare, middle or upper tropospheric disturbances are not, especially north of about 15°N, where they are the main agents of precipitation.

Conventional and satellite observations also suggest that the south Asian monsoon is by no means a self-sealed circulation little influenced by other tropical and extratropical circulations. Interdependence was suggested as early as 1923 when a significant correlation between pressure changes in the southern hemisphere and oscillations and rainfall of the Indian summer monsoon was found by Walker (1923).

Hence, vertical motion associated with a giant sea breeze circulation probably cannot alone explain the observed temporal and spatial variation of precipitation over southern Asia. Recent research suggests, in fact, that latent heat and kinetic and potential energy transports in convective clouds, as well as radiation balances, must be considered also since they play a primary role in driving the monsoon circulation. Quantitative assessments (aided by appraisals of both video and infrared satellite data) of vertical energy exchanges, transformations, sources and sinks, should, therefore, be pursued further since the monsoon rapidly transmutes internal, latent, potential and kinetic energy forms on a scale probably far exceeding that of the remainder of the tropical atmosphere.

Research has shown, however, that land–sea breeze effects and orography do act powerfully, especially diurnally, to change patterns of vertical motion and hence patterns of precipitation. For example, Ramage (1971) noted that the circulation over the Indian sub-continent varies diurnally and out of phase with the sea breeze–land breeze cycle. Interaction between the two is therefore complex. So, since patterns of precipitation are related to the three-dimensional fields of energy, moisture, and circulation on both the macro- and meso-scales, synoptic changes, as well as orographic and land–sea effects, must be invoked in order to forecast local weather (India Meteorological Department, 1970).

It seems therefore that the south Asian summer monsoon is not as simple a phenomenon as once thought. Its great complexity will become more evident in the following sections in which synoptic systems common over southern Asia are discussed. Many of these systems are discussed more extensively by Ramage (1971) and Rao (1976).

II Components of the monsoon circulation

1 Circulatory systems

a Heat lows: Heat lows are usually found in an area extending from Somalia across southern Arabia to Pakistan and northwest India between May and September and are most intense in July. They are predominantly quasi-stationary desert phenomena and for that reason have been poorly observed. However, it is generally agreed that these heat lows develop in response to the changing elevation of the sun.

Surface southwesterly winds prevailing over the Arabian Sea from May to September are thought to be associated with the heat low over Pakistan. This heat low has an extraordinary intensity and persistence. Its maintenance is therefore of interest to meteorologists. Furthermore, despite considerable low-level convergence into the low there is very little rain over northwestern parts of the Indian sub-continent. In fact, skies usually remain cloudless throughout the summer because of extremely low humidities and/or well-marked inversions. At least one of these operates, otherwise cloud and rain, by depleting insolation, would significantly weaken the heat low (Ramage, 1971).

Analyses of aerological data for northeast Africa, Arabia and the Indian sub-continent have revealed a tendency for middle tropospheric subsidence to occur beneath a convergent upper tropospheric easterly flow (again, see Koteswaram, 1958; Flohn, 1964; Ramage, 1966). However, the precise distribution of upper tropospheric convergence and divergence from day to day is complex (Walker, 1972; Rao 1976).

Probably, this subsidence affects the Indo–Pakistan heat low by:

1 Limiting the height to which surface air from the Arabian Sea can

ascend, restricting cloud development and thus favouring strong isolational heating; and

2 Raising the temperature of middle and upper tropospheric air, reducing surface pressure below what is observed in heat lows elsewhere.

Both of these effects help to maintain the heat low and consequently the strength of the low-level flow over the Arabian Sea. Similar, but less marked, effects probably operate over Arabia and Somalia.

It appears, therefore, that the heat low system of Indo–Pakistan and Arabia is maintained and intensified primarily by subsidence of air which has been warmed by release of latent heat in monsoon rain systems to the east and then transported westward by the upper tropospheric easterlies (Ramage, 1966). This mechanism is in turn aided by the protection from cold air advection afforded by the chain of mountains extending from Turkey to western China (Ramage, 1970).

Mid-tropospheric subsidence over the deserts of southern Asia is also thought to develop partly in response to radiation divergence by a deep dust layer over Indo–Pakistan (Bryson *et al.*, 1964; Lal, 1973). This dust (often visible on photographs taken by meteorological satellites) is blown up from the desert by a strong surface flow, particularly during the premonsoon months. Bryson and his co-workers have argued that, in the absence of dust, the rate of mid-tropospheric subsidence would be halved and the monsoon rains would extend further into Indo-Pakistan. Is the desert a permanent feature then? If not, is it man-made or is it the result of purely climatic changes? Bryson and Baerreis (1967), in an examination of archaeological evidence, concluded that man has played an important part in the making of the Indo-Pakistan desert and suggest that man might be able to reclaim it perhaps by stabilizing the soil (thus reducing the amount of airborne dust) through the use of grass. If reclamation could be effected, partial relief to the economic and human problems of the sub-continent could be obtained.

Although heat lows themselves are clearly not major producers of rain, it is possible that the Indo-Pakistan low may export energy in the middle and upper tropospheres which in turn 'causes' subtropical cyclogenesis, leading to copious rain along the west coast of India [although because of its nature the heat low is more likely to exert a thermodynamic rather than a mechanical effect on its environment (Ramage, 1971)].

This suggestion seems to be substantiated by a comparison between a copious rains situation and lull conditions along the west coast of India (Dixit and Jones, 1965). This study located by far the largest middle and upper tropospheric temperature differences in the region above the heat low, with the rains situation 2°–6°C warmer than the lull situation. Ramage (1966) also noted that surface pressure near the centre of this low may be inversely related to the intensity of monsoon rainfall over Gujarat and Maharashtra. Ramamurthi (1972) found no such relationship but instead suggested that subtropical cyclogenesis may be closely associated with events further east.

The final overall impression of the vertical circulation of a heat low is one of convergence in the troposphere above about 400 mb and below about 850 mb, separated by a region of divergence. Weather is mainly hot, dry and cloudless.

b Subtropical cyclones: Subtropical cyclones were first noted and named by Simpson (1952) in an examination of weather over the eastern Pacific Ocean. They have also been identified over the North Atlantic Ocean using satellite and ship observations (Herbert, 1973).

Usually, subtropical cyclones occur in the Indian Ocean region mainly over the northeastern Arabian Sea between mid-June and mid-September and occasionally over the southern Bay of Bengal and Burma in April and May. They are usually quasi-stationary and are a major source of precipitation along the west coast of India north of about 15°N. On rare occasions, they move westward towards Muscat and Oman (Pedgley, 1970). Subtropical cyclones usually develop, intensify and decay over a period of one to three weeks (Ramage, 1966).

Over western coastal India north of about 15°N, year-to-year variations in annual rainfall amplify rapidly with increasing latitude. Here, the balance between crop yield and the temporal distribution of rainfall is so delicate that even with a normal annual total, maldistribution in time may be disastrous (Spate and Learmonth, 1967). Hence the formation or otherwise of subtropical cyclones has an important bearing on the economy of these parts of the sub-continent.

(*i*) *Structure:* Subtropical cyclones over the Arabian Sea were first investigated in 1963 during the International Indian Ocean Expedition by Ramage (1964) and Miller and Keshavamurthy (1968). Using an extensive data coverage of a subtropical cyclone obtained by research aircraft in July 1963, Miller and Keshavamurthy derived a model of a steady state subtropical cyclone which showed it to be most intense at 600 mb and to have a cold core below that level and a warm core above, and to have an axis of lowest pressure sloping southward with height. Lapse rates were less within the circulation than on the periphery although the reverse situation occurred in the case of relative humidities, reflecting transport of moisture westward from a depression over the Bay of Bengal and also from the south where moisture was being evaporated from the Arabian Sea.

Divergence predominated within this cyclone at levels above 300 mb and was as large as convergence in the middle troposphere. In the lower troposphere, divergence or convergence may predominate, depending on the intensity of the circulation. Vertical motion was therefore mainly upward between the surface and 200 mb although some downward motion seems common between 800 mb and 600 mb within relatively weak cyclones. This was evidenced by divergence in the mean resultant circulation in the layer 0–900 m.

Precipitation was confined mainly to the region within a radius of 300 km from the cyclone's centre and mainly to the south and west of its 700 mb location. Beyond the periphery of the circulation, maximum downward motion occurred between 500 mb and 200 mb to the west of 65°E where air which had moved out of the top of the cyclone had subsided. The resulting marked subsidence inversions and very hazy conditions have been observed by aircraft and satellites (Bunker and Chaffee, 1970; Saha, 1971).

(*ii*) *Lifetime:* Observations have revealed that the Indo-Pakistan heat low always develops before any subtropical cyclones although this does not mean that a subtropical cyclone will necessarily form. In fact, it appears that cyclonic activity over eastern India, above-normal anticyclonic vorticity above the heat low, and above-normal cyclonic vorticity over the Arabian Sea usually precede subtropical cyclogenesis (Miller and Keshavamurthy, 1968). However, the problem of why subtropical cyclones develop, intensify, and fill *in situ*, apparently under the influence of orography, has still not been resolved.

As a subtropical cyclone intensifies, anticyclonic vorticity above the heat low increases markedly, reflecting subsident heating and intensification of the low-level monsoon circulation (Miller and Keshavamurthy, 1968). Once developed, a subtropical cyclone (a) further intensifies the heat low through the agency of subsidence in the westward-flowing air from its top which then exports additional cyclonic vorticity to the middle and upper tropospheres over the northern Arabian Sea; and (b) produces a subsidence inversion and persistent fine weather over the central and western Arabian Sea (Colon, 1964).

Later, a subtropical cyclone modifies its environment so as finally to reduce the supply of moist air to the circulation to a level below that required to sustain it. Probably, this usually arises from ventilation of the cyclone by drier air from the northwest either by the northeastward movement of a monsoon depression over Punjab (Miller and Keshavamurthy, 1968), or by large amplitude troughs in the polar westerlies (which might advect cold air south of the Himalayas (Ramaswamy, 1962)) or by very slight shifts in the direction of middle tropospheric inflow (Ramage, 1971).

When a subtropical cyclone fills, rainfall decreases rapidly over western India and a lull ensues. Then, when a new supply of moisture becomes

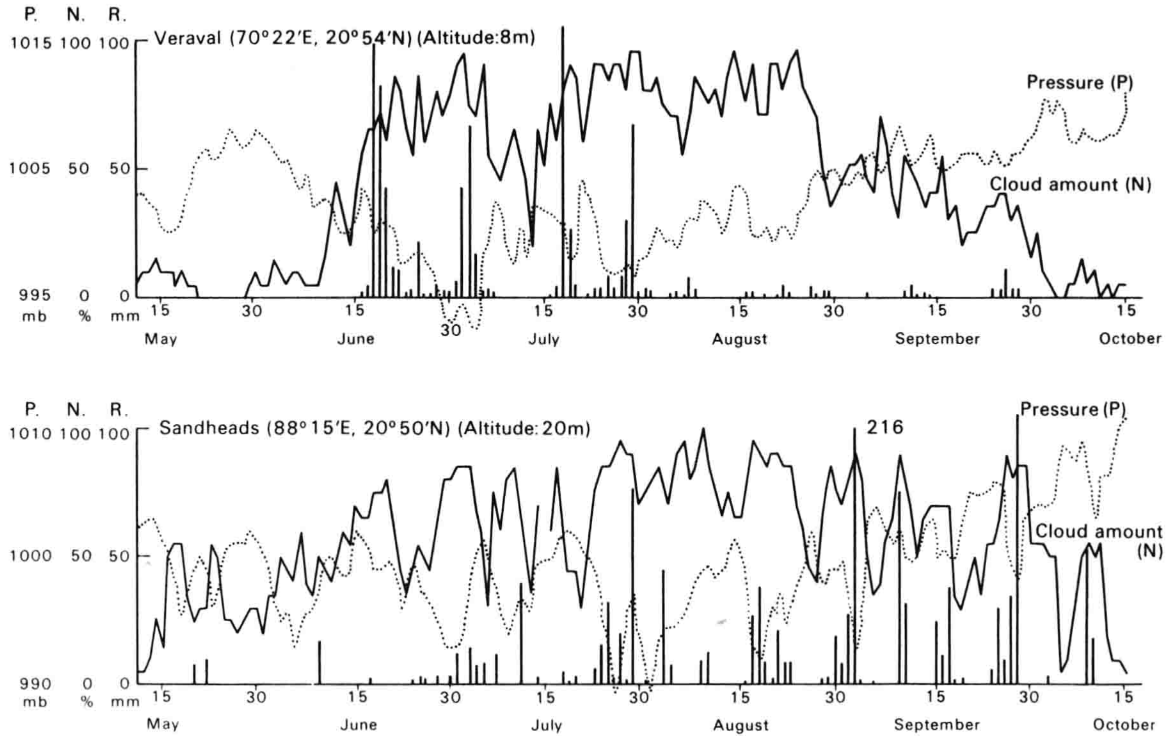

Figure 3 Daily percentage cloud cover (assessed to the nearest five per cent from ESSA photographic mosaics) at approximately 0900 GMT within 10° latitude squares centred at 70°E, 20°N (top) and 90°E, 20°N (bottom) versus 1200 GMT surface pressure and daily rainfall (0300 GMT of date to 0300 GMT next day) at a coastal station near the centre of each square. Data for 1967. After Hamilton (1974)

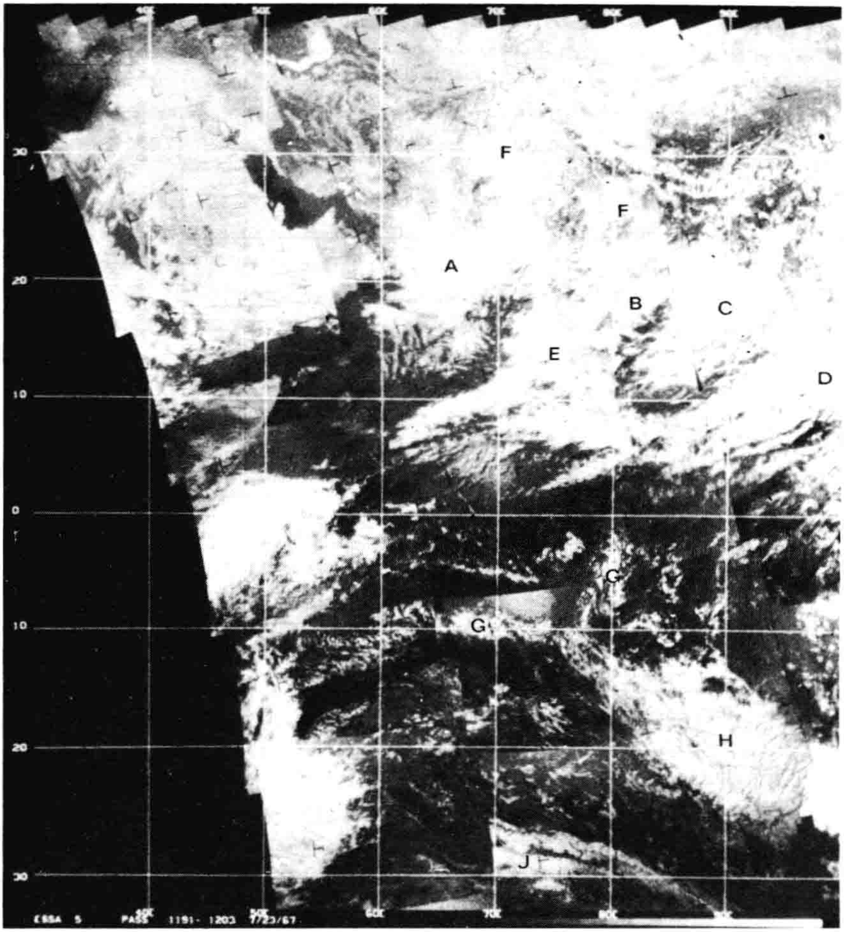

Figure 4 ESSA 5 digital product: 23 July 1967. The section east of about 60°E relates to the period 0800 GMT–1000 GMT (approx.) 24 July 1967. The western portion, relating to 1200 GMT (approx.) 23 July, is not discussed. Noteworthy features are identified by letters (see discussion on page 162). *ESSA photograph*

available (for example, through the agency of a monsoon depression moving from the east) subtropical cyclogenesis may once more occur.

Subtropical cyclones develop, intensify and decay close enough to react on the heat low, although they rarely produce a surface circulation (Anjaneyulu, 1969). In fact, from a consideration of vorticity transports over Pakistan, Ramage (1966) concluded that there may be a symbiotic relationship between the heat low and a subtropical cyclone. Also, the