On summer atmospheric processes over south-west Asia

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ABSTRACT

This paper considers subsidence in the upper and middle troposphere and convection in the lower troposphere over south-west Asia in relation to atmospheric circulations associated with the monsoon of southern Asia.

Introduction

The theory that the aridity of south-west Asia is maintained during summer by widespread and persistent subsidence of air in the middle and upper troposphere on the poleward side of the deceleration region of the easterly jet stream which overlies southern Asia and North Africa during summer, first proposed by Koteswaram (1958), has been upheld by several observational and quantitative studies, notably those by Das (1962), Flohn (1964), Ramage (1966), Saha (1967), Sajnani (1968), Ruprecht (1970) and Murakami (1974). Nevertheless, Desai (1967, 1968) has remained unconvinced, preferring an explanation in terms of air-mass dynamics. However, current opinion apparently favours Koteswaram's interpretation of rainfall patterns, but with a few reservations. For example, Walker (1972*a*) has pointed out that, although there is a general tendency for subsidence to occur in the middle and upper troposphere between Pakistan and the western Sahara, the assumption that the easterly flow decelerates *gradually* downwind from India is not supported by observations; the precise distribution of associated convergences and divergences from day to day is complex.

According to Ramage (1966), the extensive summer heat-low system of south-west Asia "develops in the normal way over desert regions" and is "maintained and intensified through the summer by subsidence of air originally lifted and warmed by the release of latent heat in monsoon rain systems to the east and south". He believes further that there is a symbiotic relationship between the heat-low over the north-west of the Indian subcontinent and the mid-tropospheric cyclones which are largely responsible for the monsoon rains on the Indian Konkan Coast. Ramamurthi (1972) is somewhat sceptical, for he has been unable to find an inverse relationship between surface pressures in the heat-low and intensity of monsoon rains on the Konkan Coast, but since Ramage related the heat-low surface pressures to rainfall in a band between 18° N and 27° N stretching *across* India, whereas Ramamurthi considered only the west coast of India, Ramage's hypothesis has certainly not been disproved.

Clearly, understanding of atmospheric behaviour over southwest Asia is, as yet, far from satisfactory. The lack of data over large tracts, particularly over Arabia and the Arabian Sea, is an obvious hindrance in studies of this region, but a further factor is the tendency among meteorologists to focus attention upon areas of inclement weather while neglecting areas where skies are largely cloudfree. The importance of descending branches of atmospheric circulations has been stressed by Green et al. (1966), and Walker (1972*a*) has discussed their ideas in relation to monsoon circulations of North Africa.

Descent aloft

The present author's analyses, based upon climatic data and upon daily surface and aerological observations, employing, in particular,

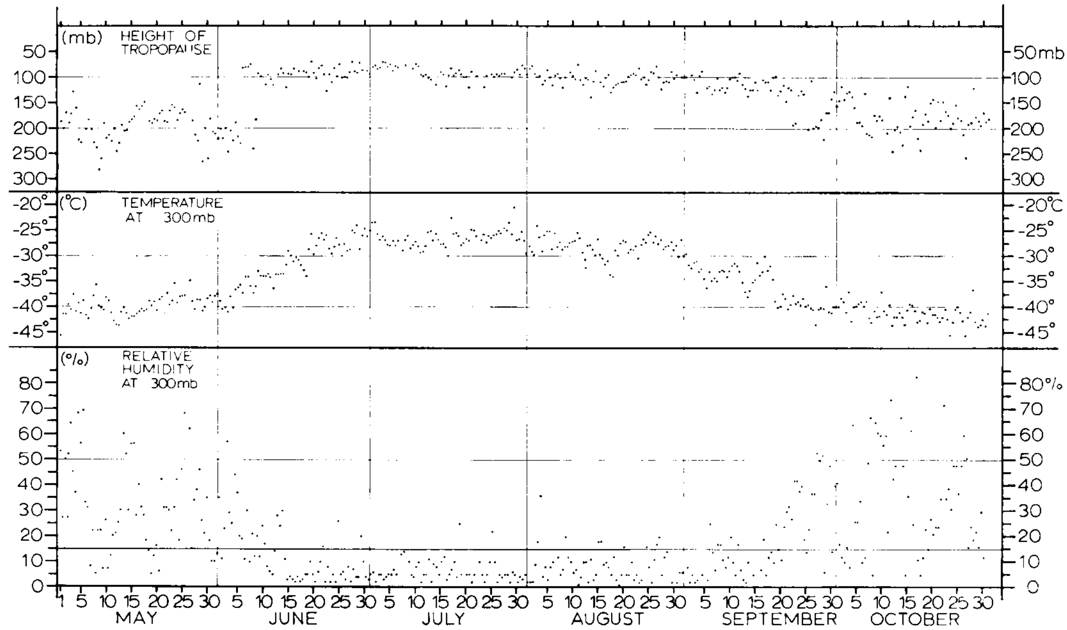

Fig. 1. Height of Tropopause I, temperature at 300 mb and relative humidity at 300 mb over Tehran at 00 and 12 GMT each day from May 1 to October 31, 1966.

winds, potential temperatures and mixing-ratios, suggest that air which ascends nearly vertically, and rather rapidly, to the upper troposphere in the cumulonimbus clouds of mid-tropospheric cyclones over the Indian west coast flows away westward, decelerating, subsiding slowly and turning anticyclonically as it goes.

Typically the air emerges from the cyclones near 18° N at a height of about 170 mb, with a speed in excess of 30 m sec^{-1}, a potential temperature (θ) of about 83°C, a wet-bulb potential temperature (θ_w) of about 25°C and a mixing-ratio of less than 10^{-1} g kg^{-1}. Over northern Iran the air is at about 300 mb, or a little below, and heading approximately eastward, with θ and θ_w reduced due to radiative heat loss to 70–75°C and 22–23°C respectively (see Fig. 1). Over south-eastern Iran the air is between 400 and 500 mb and heading roughly southward, with θ and θ_w now of the order of 60–65°C and 21°C respectively.

The temperature inversion at the base of this subsiding air limits the vertical development of convection from the surface of the elevated Plateau of Iran.

Small-scale convection

Over land, small-scale, nearly upright, convection is most commonly created by insolation. In particular, over arid ground in sunshine, deep dry-adiabatic layers and high daytime surface temperatures are observed. There is little surface moisture to be evaporated for the provision of latent heat and so the majority of the energy is introduced as sensible heat. Consequently, such regions are notable for the creation of layers of cloudless air of high θ, instead of cloudy convection, which occurs over moister terrain. High values of θ are, as Carlson & Ludlam (1968) have explained, associated with dry, elevated ground, and are created by the exaggeration of high initial values of θ by the effect of daytime insolation on the arid surface.

During summer such thermal conditions prevail over much of south-west Asia. Mid-afternoon values of θ exceed 50°C over most of the Plateau of Iran and reach about 48°C over a large part of the less elevated Arabia (Fig. 2). Deep dry-adiabatic layers form near the ground (Fig. 3), and, apart from a few cumulus clouds over mountain tops, cloudfree conditions are the norm, even though over Iran convection is capable of extending to about 500 mb (Fig. 4). In the convective layer winds are generally north to north-westerly.

Green et al. (1966), considering processes associated with extra-tropical circulations, have shown that subsiding air is moistened in regions of small-scale convection and thereby provided with potential energy. The moistened air ascends on the eastern flanks of middle-latitude troughs, and the potential energy is converted into the kinetic energy of jet streams near 300 mb. Furthermore, Carlson & Ludlam (1968) have demonstrated that plumes of warm air, layers of high θ, are commonly advected from the adiabatic layers found over hot and arid plateaux.

In like manner it is reasonable to infer that over the Plateau of Iran subsiding air is moistened by passage through a region of small-scale convection, thus becoming prepared for ascent, and also that plumes of warm air, possessing values of θ characteristic of the lower-tropospheric adiabatic layer over Iran, are present downwind of the plateau, i.e. over northern parts of the Arabian Sea and over eastern Arabia. It is not possible to detect the moistening, because the available upper-air information is inadequate for the purpose, but

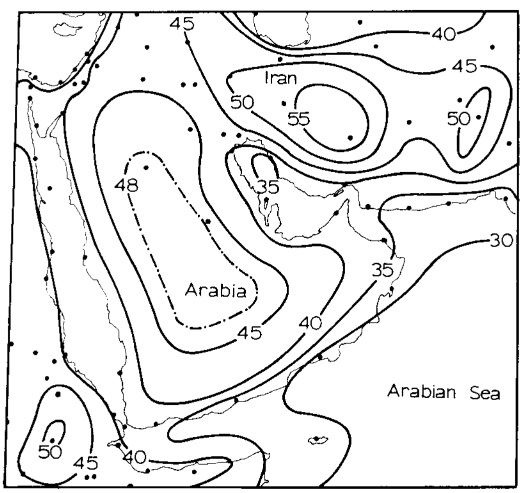

Fig. 2. Distribution of mean daily maximum screen-level potential temperature (in °C) over south-west Asia in July. Dots show the location of reporting stations.

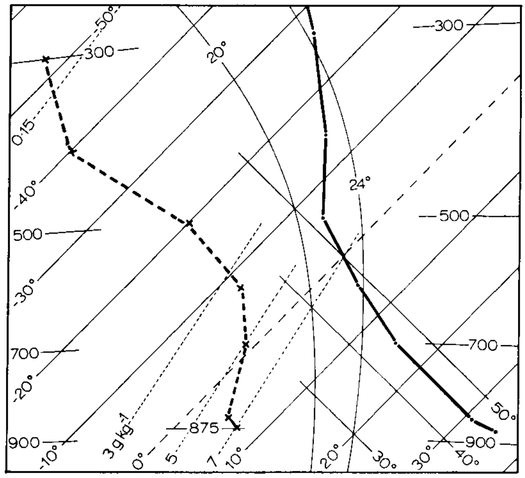

Fig. 3. Monthly-mean aerological sounding, Tehran, 12 GMT, July 1966.

aerological soundings from the station on Masirah Island show that deep dry-adiabatic layers within the height-range 800 to 550 mb, together with winds from a northerly point, occur frequently in summer (Figs. 5 and 6). In these layers $\theta \simeq 45$–$48°C$ and $\theta_w \simeq 19°C$, values typical of the lower troposphere over the Plateau of Iran immediately above the surface super-adiabatic region (Figs. 3 and 4). Sawyer (1947) has noted the presence over the Pakistan coast of lapse-rates approaching the dry-adiabatic from above a lower-tropospheric inversion to a height of 12 000 to 15 000 feet.

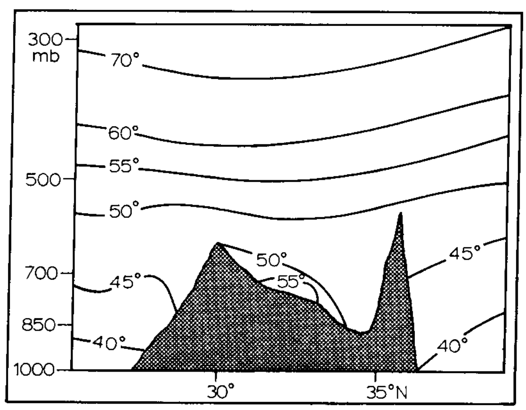

Fig. 4. Vertical section along approximately 52° E showing mean mid-afternoon potential temperatures (in °C) in July. The Plateau of Iran is shown schematically in stippling.

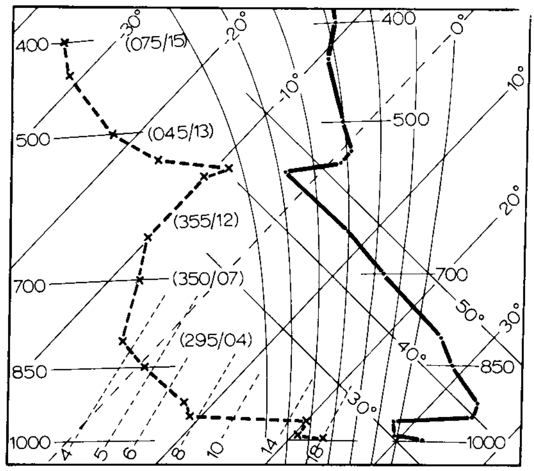

Fig. 5. Aerological sounding for Masirah Island (20°40′ N, 58°54′ E), 12 GMT, 12 July 1970. Wind directions in degrees and speeds in knots are shown in brackets; below 800 mb winds backed and increased in speed to become south-westerly, about 17 kt, near the surface.

Flow over the arabian sea

According to Walker (1972*a*), the subsided outflows from the monsoons of eastern and western North Africa turn steadily (anticyclonically), over the Sahara Desert and the Atlantic Ocean respectively, to arrive in the lower troposphere as broad currents from an approximately north-easterly direction. The outflow from the

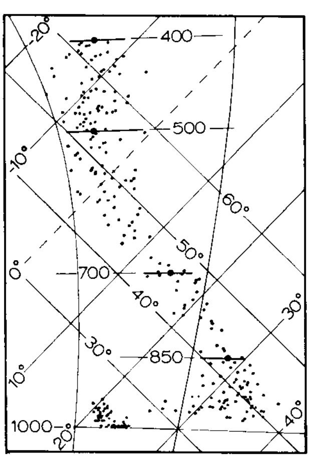

Fig. 6. All temperatures up to a height of 400 mb recorded over Masirah Island at 00 GMT during July 1971. At the standard levels mean temperatures and extreme ranges are shown.

monsoon circulations over western India, as was mentioned earlier, behaves similarly in the upper and middle troposphere, curving anticyclonically to arrive over southeastern Iran as a northerly current. In contrast, however, it does not thereafter continue curving anticyclonically to become a north-easterly current in the lower troposphere over southern Arabia and the Gulf of Aden. Instead, observations and analyses show (Findlater, 1971; Ramage & Raman, 1972) that over these areas winds blow persistently from a westerly direction.

The subsided air from the Indian monsoon apparently develops cyclonic curvature after travelling over Iran, presumably as a consequence of interacting with the convective lower troposphere over the plateau and thereby acquiring an element of cyclonic vorticity. This is consistent with the view of Ramage (1966) that the heat-low system of south-west Asia "exports cyclonic vorticity in the middle and upper troposphere to the northern Arabian Sea". Ramage, however, believed Pakistan to be the centre of action, rather than the Plateau of Iran farther west.

The lack of upper-air soundings precludes a systematic investigation of the composition and thermodynamic properties of the middle troposphere over the Arabian Sea. Consequently, in drawing conclusions reliance has been placed upon observations made during the International Indian Ocean Expedition (IIOE), in the course of which atmospheric processes over the Arabian Sea in association with the development, mature and dissipation stages of mid-tropospheric cyclones over the west coast of India were thoroughly studied (Miller & Keshavamurthy, 1967). These observations show that over northern parts of the Arabian Sea the moist surface layer is bounded by a pronounced temperature inversion at about 900–800 mb, above which is dry air possessing a lapse-rate close to the dry-adiabatic (Colon, 1964).

The IIOE wind and drop-sonde data lend support to the view that dry-adiabatic layers are advected from over easternmost Arabia across the central Arabian Sea towards the Indian Konkan Coast. Further support is provided by the observations of thick haze extending to a height of about 4–5 km over much of the Arabian Sea, but particularly over northern parts. Bunker & Chaffee (1969) have pointed out that the haze cannot be produced by the condensation of water vapour on hygroscopic nuclei because in the hazy air relative humidity is typically less than 50%. Like Colon (1964) they were of the opinion that dust and sand from desert areas are the chief source of the haze. Colon thought Africa and Arabia likely source-regions; Bunker & Chaffee mentioned specifically Somalia, Arabia and Iran. Possibly, there are immediately above the inversion warm plumes derived from the convective layer over Arabia, with plumes from Iran above (Fig. 7).

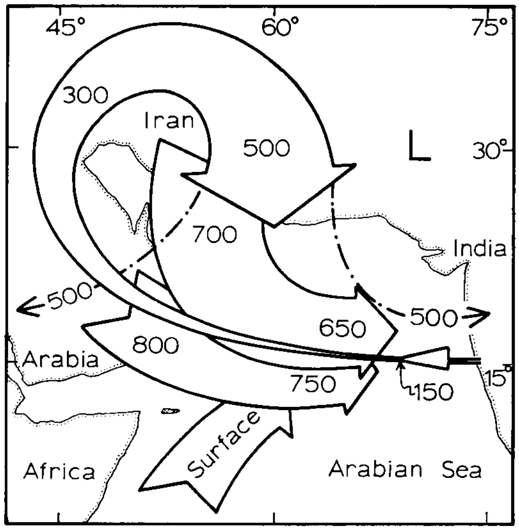

Fig. 7. Schematic representation of major airflows over southwest Asia and the Arabian Sea during summer. The figures indicate heights in mb. The location of the centre of the surface heat-low is shown by *L*.

Mid-tropospheric cyclones

Carlson & Ludlam (1968), discussing conditions for the occurrence of severe local storms, have written: "Extreme instability arises where small-scale convection is confined to a lowermost 1 or 2 km (leading to an abnormally high wet-bulb potential temperature) beneath a plume of very warm air lying downwind of an extensive arid plateau. The instability is released where the (backed) low-level flow eventually reaches the edge of the restraining plume aloft". Walker (1972*b*) has drawn attention to striking similarities between the severe-storm model of Ludlam and his collaborators (see Browning & Ludlam, 1962) and the air motions in mid-tropospheric cyclones over western India.

It has been recognized for many years that active monsoon periods on the Konkan Coast are generally preceded by the movement of cyclonic disturbances into western India, and it is clear from the investigations of Miller & Keshavamurthy (1967) that these disturbances provide the additional vorticity and moisture essential to the initial development of a mid-tropospheric cyclone over western India.

According to Carlson & Ludlam (1968), the development of severe local storms "requires the presence of a wind shear which permits the attainment of a large potential buoyancy represented by a difference between θ_w at low levels and θ_s aloft" (θ_s being the wet-bulb potential temperature for saturated air). They recognized that their ideas are relevant to the monsoon system of southern Asia, for they wrote: "the storms of the Indian monsoon develop in air in which θ_w rises significantly during flow over the Arabian Sea beneath an inversion produced by the advection aloft of a very warm adiabatic layer from Arabia". The present study supports this statement in principle but not in detail since the moist air (of high θ_w) required to produce the necessary buoyancy forces and initiate mid-tropospheric cyclogenesis is most probably advected across northern India from the Bay of Bengal (Ramage, 1966; Miller & Keshavamurthy, 1967), rather than across the Arabian Sea. At low levels over north-east India values of θ_w in excess of 29°C are normal (Fig. 8). The dependence of mid-tropospheric cyclones on favourable wind-shear has been discussed by Walker (1972*b*).

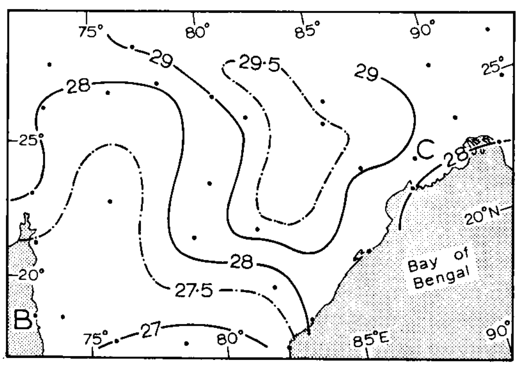

Fig. 8. Distribution of mean mid-afternoon wet-bulb potential temperature (in °C) at screen-level over northern India in July. Dots show the location of reporting stations; *B* and *C* are Bombay and Calcutta respectively.

Conclusion

It appears that the monsoon rain systems of western India can exist only by interaction with the fundamentally convective troposphere far beyond the cloud and precipitation fields of the systems. Indeed, collaboration between the various scales of atmospheric convection, a subject examined thoroughly by Ludlam (1966), is an essential part of the global tropospheric circulation. South-west Asia possesses geographical features which are apparently of considerable significance in the monsoon system of southern Asia. Until there is adequate observational coverage of tracts west of India, however, explanations of atmospheric behaviour there are bound to remain conjectural.

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О ЛЕТНИХ АТМОСФЕРНЫХ ПРОЦЕССАХ НАД ЮГО-ВОСТОЧНОЙ АЗИЕЙ

В статье рассматривается опускание воздушных масс в верхней и средней тропосфере и конвекция в нижней тропосфере над юго-восточной Азией в связи с атмосферными циркуляциями, образующими муссон над южной Азией.