

Interaction of the summer monsoon current with water surface over the Arabian Sea

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ABSTRACT. A critical examination has been made of the papers of Colon (1964) and Bunker (1965) on the subject. Bunker's data are for days when there were weak monsoon conditions as judged from subsequent rainfall on the west coast of the Peninsula; Colon's data are for active or strong monsoon conditions on the west coast. Convergence in lower levels in the eastern Arabian Sea within about 500 km of the coast due to falling jet velocities or decrease in speeds cannot alone explain the large amounts of rainfall over the area and the coast. Presence of (1) characteristic airmass stratification over the Arabian Sea and (2) the Western Ghats, is largely responsible for considerable precipitation over and off the coast and in making the moist current about 6.0 km deep over the Peninsula. The inversion is due to airmasses and *not* due to subsidence.

A model for vertical distribution of airmasses over the Arabian Sea when there is characteristic airmass stratification during active or strong monsoon conditions on the west coast, is suggested and data for variations of low level jet given by Bunker are discussed with reference to the same.

1. Introduction

The problem of the interaction between the monsoon air and the water surface over the Arabian Sea has been dealt with by Colon (1964) and Bunker (1965) from different points of view. Colon has considered the influence (1) of the monsoon circulation over the water body and (2) of the latter on the atmospheric current above it. He has stated that the aircraft observations during June–July 1963 indicated in general what one would expect on the basis of the regime of heat flux from ocean to atmosphere; the observations indicated similarity between the southwest monsoon and trade winds, *viz.*, large moisture content in the surface layer topped by a temperature inversion. Bunker has considered aircraft observations during August–September 1964 from the point of development of the Somali wind jet, its geographical distribution over the Arabian Sea and influences on weather due to variations of the jet; he has also given the energy budget of the monsoon airmass.

Colon has considered that the deflected trades are present upto 1.0 to 1.5 km, while Bunker would appear to consider as seen from his trajectories for the layers 1000–850 mb and 850–700 mb from two locations off Somalia (Figs. 5 and 6 and 7 and 8 respectively of his paper) to the west coast, presence even in the first 1.5 km of airmass of continental and *not* oceanic origin.

These papers are very interesting from the point of the Indian meteorologists for understanding mechanism of the monsoon rains on the west coast and it is proposed to examine them critically in this communication.

2. Discussion of Results of Bunker and Colon

(a) Bunker's paper (Bunker 1965) has postulated that strong winds over Somalia and off Somalia coast due to steep pressure gradient between the trough extending from Arabia down into Ethiopia and the ridge along the African coast transport large quantities of warm surface waters to the eastward. The water so transported can be replaced only by deep cold water coming up along the coast, giving rise to the well-known upwelling effect over the western coastal sections of the Arabian Sea, particularly near Somalia and Arabia. After this wind blows for a period of time, water with temperatures as low as 13°C replaces original water with temperatures 20 to 25°C. Air, presumably, from northeast Africa and Arabia blowing over this cold water cools quickly by turbulent transport, cross-wind flight data on 30 August 1964 between 12°N, 50°E and 4°N, 56°E showing great degree of cooling by the passage of air over about 300 km of water as judged from cross-section of potential temperatures (Fig. 1 of his paper); horizontal temperature gradients applied to the thermal wind equation showed that increase in velocity should be about 10 m/sec through the lowest 600 m of air. Temperature gradient was found to reverse above the layer of cool air, thereby indicating decrease in wind speed with height. A wind profile made in the jet region two days later (1 September 1964) at 11°N, 58°E (Fig. 2 of his paper) confirmed the expectation in that the wind increased to a maximum of 25 m/sec at 1000 m and decreased to a very low value (5 m/sec) thereafter as in the case of a thermal wind. Wind profiles at different locations (Fig. 3 of his paper) traced the jet across the central

TABLE 1

| Pressure (mb) | 12°N, 50°E | | 11°N, 52°E | | 9°N, 53°E | | 6°N, 55°E | | 4°N, 56°E | |
|------------------|---------------|---------------------------|---------------|---------------------------|---------------|---------------------------|---------------|---------------------------|---------------|---------------------------|
| | Temp. (°C) | Mixing ratio (g/km) | Temp. (°C) | Mixing ratio (g/km) | Temp. (°C) | Mixing ratio (g/km) | Temp. (°C) | Mixing ratio (g/km) | Temp. (°C) | Mixing ratio (g/km) |
| 1000 | 31.8 | 15.3 | 19.5 | 10.6 | 23.8 | 17.0 | 24.2 | 17.5 | 25.0 | 18.8 |
| 850 | 24.5 | 11.5 | 24.0 | 9.3 | 16.8 | 9.8 | 16.2 | 10.2 | 16.2 | 12.4 |
| 700 | 12.8 | 6.0 | 11.2 | 6.6 | 10.2 | 1.7 | 9.0 | 2.1 | 8.0 | 6.8 |

portion of the Arabian Sea to the coastline of India, maximum values of the velocity decreasing progressively to east, dropping to less than 15 m/sec near India. To the north no jet was found to exist at all and maximum values occurred near the surface. At 4°N both in the western and eastern Arabian Sea no sign of a low level jet could be found.

Potential temperature cross-section referred to above showed that air was hydrostatically very stable and no clouds and rainfall could occur during its flow across the Arabian Sea. To explain convective clouds and showers which occur in the east Arabian Sea, Bunker constructed equivalent potential temperature cross-section across the Arabian Sea from readings of aircrafts on 30 August and 1 September 1964 (Fig. 4 of his paper) which showed that the airmass was conditionally unstable. He then postulated mechanism which can lift lower air and help growth of *Cu* clouds reaching about 3.0 km, a height which can produce rain from such clouds. The mechanism was a decrease in jet magnitude eastwards giving about 200 m lifting in 3 hours—most probably a small mean convergence. This, according to him would produce showers and moisten the airmass in the eastern Arabian Sea in the region within 500 km of the west coast. In the western half of the Arabian Sea as the jet winds are accelerating there would appear a widespread subsidence—about 200 m in 3 hours, the inference being supported by absence of convective clouds and shower activity there. He has supported his thesis on the basis of dropsonde and cloud observations made from the aircraft during crossings of the Arabian Sea.

While discussing the jet variation over the Arabian Sea Bunker has stated "Either the maximum is at 53°E and the winds at 1000 metres are higher than 25 m/sec or the jet has a maximum value on a surface sloping upwards from 560 metres

at 53°E to 1000 metres at 58°E." According to Bunker one additional type of data available indicated that the aircraft was flying underneath the maximum level of the jet *en route* from 53°E to 58°E.

It is well-known that during July, the typical monsoon month, the winds over the Peninsula are strong and practically westerly in the first 3.0 km or so, the speed decreasing above. During September, however, the winds are not so strong and get northerly component. As such, even the surface charts which show a number of isobars running across the Peninsula during July when the monsoon is active, do not show the same trend in September—the isobars running more north-south and only a few running across the Peninsula. Further, in line with this, the west coast gets more rain ordinarily in July than in September. Bunker has used data for August and September 1964 in his discussion. The mechanism of interaction between the cold water surface and the air flowing above it would hold better during July-August than in June or September because as stated by Bunker himself, water with low temperatures replaces original relatively warmer water only after the winds have been blowing for a period of time, the lowest water surface temperatures occurring in August. In view of the fact of weather and climatology mentioned above for July and September, it is considered that one will have to be very cautious in applying Bunker's conclusions for August-September to active monsoon conditions in July or any other period when winds over the Peninsula are strong and mainly westerly in about 3.0 km above the surface and there is plenty of precipitation over the west coast.

In Table 1 are given temperature and mixing ratio values from the dropsondes data on 30 August 1964 (date in Bunker's paper) at different levels for the five locations at 1000, 850 and 700 mb.

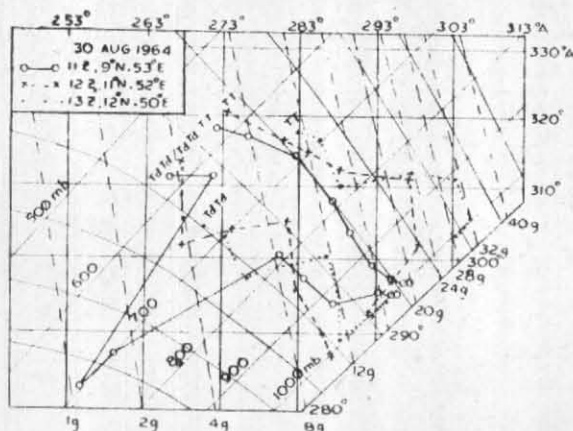


Fig. 1(a)

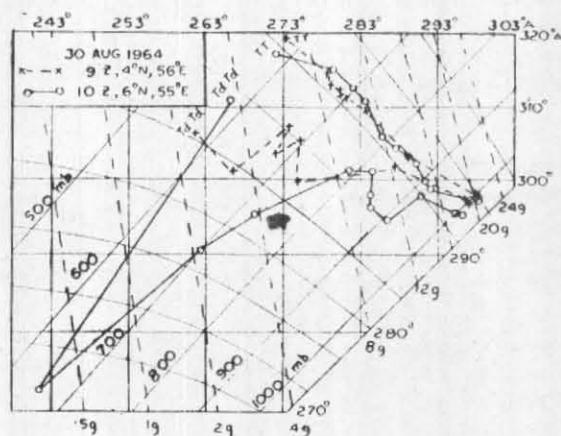


Fig. 1(b)

As seen from the table the lowest temperature at 1000-mb level during flight between 12°N, 50°E and 4°N, 56°E was 19.5°C at 11°N, 52°E, within about 100 km of the coast, temperature rising rapidly southeastwards to 23.8°C at 9°N, 53°E and slowly thereafter to 24.2°C at 6°N, 55°E and 25°C at 4°N, 56°E. In view of this, it is felt that Bunker's conclusions from Fig. 1 of his paper about maximum cooling of air by its passage above about 300 km of water, is not fully justified; further in that case the air from 12°N, 50°E should be considered to move to 4°N, 56°E, *i.e.*, from NW to SE; the trajectory in Fig. 5 of his paper, however, shows SW to NE movement of air.

On an examination of the tephigrams (Figs. 1a and 1b) for the five locations given in the above table, it is seen that there was no monsoon air (deflected trades) at the first two locations, there being in all the levels continental air from Arabia and neigh-

bourhood, inversion having developed right from the surface (Fig. 1a) as the warm air moved over colder sea surface; the second ascent off Somalia showed lower temperatures than in the first in the low levels because of appreciably low water temperatures off Somalia than over the Gulf of Aden and the interchange of heat in those levels between water surface and air above. Inversion right from the surface would prevent significant convective transfer of moisture upwards. The data for 4°N, 56°E (Fig. 1b) showed absence of inversion or isothermal region except close to the surface and near moist adiabatic lapse in all levels; this presumably was air from west which had given precipitation over the high-lands during its travel. At locations 6°N, 55°E (Fig. 1b) and 9°N, 53°E (Fig. 1a) there was probably deflected trades air-mass in the first 30 to 80 mb, the lapse being near dry adiabatic and moisture concentrated in that layer; there was air from west Africa above, lapse being near moist adiabatic.

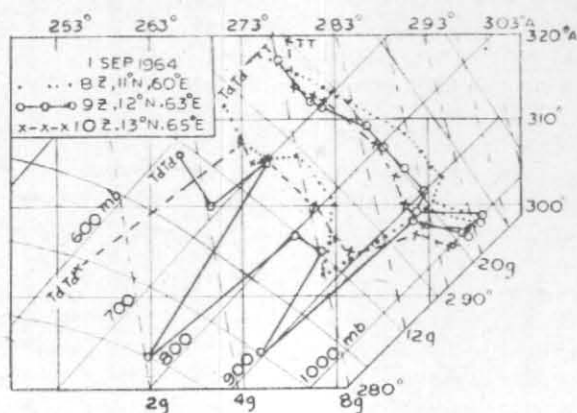


Fig. 2 (a)

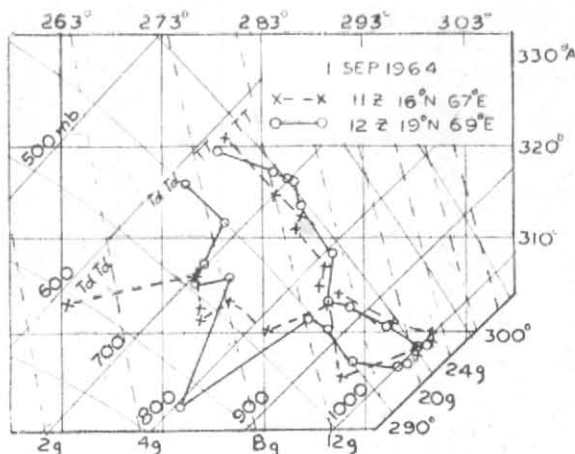


Fig. 2(b)

For 1 September there were dropsonde data for five locations from 11°N , 60°E to 19°N , 69°E (Figs. 2a and 2b). The data show that there were deflected trades in the lower levels in all the cases with an inversion above except for the location 13°N , 65°E (Fig. 2a). Even where inversions occurred there was no systematic variation in the heights of their bases from 11°N , 60°E to 19°N , 69°E . In all the cases the lapse rate in the air above the deflected trades was near moist adiabatic. The trajectories for different levels at different locations were presumably different.

All the above data are for weak monsoon conditions as judged from subsequent rainfall on the west coast.

As there are possibilities of varying conditions at different locations on the same date or at the same place on different days, it is not advisable to draw conclusions for any particular set of pro-

cesses in the atmosphere from averages as done by Bunker.

(b) Colon's paper (Colon 1964) has stated that the combination of the moist southwest current in the surface layer (about 1.5 km deep) and a dry unstable airmass above that flowing eastwards from northeast Africa and Arabia, produces a characteristic thermal inversion that in some respects resembles the famous trade wind inversion. There is a large concentration of moisture below the inversion. The surface layer showed frequently a nearly dry-adiabatic lapse rate. The inversion was located around 900 to 800 mb. Above, a dry and quite unstable layer with lapse rate close to dry-adiabatic prevailed. The distribution of clouds observed by the aircraft showed a stratocumulus layer with base around 0.5 km and tops mostly around 1.0 km prevailing to the west of about 65°E . There were very little amounts of middle and

high clouds, and definitely no clouds of convective nature. As the air approached the Indian coast there was a tendency for lifting and weakening of the inversion and for development of considerable cloudiness and precipitation. There was probably dry adiabatic upward motion in the lower moist current that flowed northeastwards towards India and a more vigorous convergence aloft. The establishment of the monsoon current by itself is not enough to guarantee the release of rainfall. There is a vast reservoir of moisture near the surface (lower moist layer about 1.5 km deep), but a suitable mechanism must exist to overcome the thermal inversion and release of moisture upwards for condensation and precipitation to occur. The instability in the lower moist air can lead to vertical mixing across the inversion base resulting in mixing and diffusion of moisture upwards, and in the lifting of the inversion. Picking up moisture and sensible heat from the sea surface will enhance convective processes in the moist air moving northeastwards towards the coast. These processes mentioned by Colon will not, however, cause considerable rainfall on the west coast. The most important points according to the author of this paper (Desai 1966a, 1966b, 1966c, 1967) are—(1) the orographic effect caused by the Western Ghats—a mountain range which runs north-south along the west coast of India and whose influence will also extend some distance off the coast producing a trough due to configuration of the isobars and the stream flow (Banerji 1930, 1931), and (2) the presence of the upper unstable layer above the inversion which is of great importance to rain-producing potential of the lower monsoon current—the deflected trades (Colon 1964). Once the inversion is destroyed due to the influence of the Ghats in the manner contemplated by Desai (1966, 1967), the stratification is very favourable for rapid release upwards of the moisture leading to considerable condensation and rainfall. This process gives about 6.0 km deep moist current over the Peninsula. The tendency to form perturbations in the low level flow in the vicinity of the coast (George 1956) due to the presence of the Ghats which can give cyclonic convergence if the moist westerly to southwesterly winds strike the Ghats at an angle larger than 90° , will also have to be taken into account for increase in precipitation. It has been shown by Desai (1967) that mid-tropospheric perturbations of the type contemplated by Ramage (1966) and referred to by Colon are due to facts of weather, climatology and topography of the sub-continent and that there is no development of the cyclones of the sub-tropical type over the northeast Arabian Sea in the vicinity of Bombay.

During the period of data given by Colon the monsoon was active or strong over the west coast.

The flight was between Bombay and Nairobi *via* Aden. The temperature data discussed were for 1 and 2 July on the return flight. Colon has also presented in his paper (Colon 1964) wind data for 0.5 km (1500 ft) for the period 26 June to 2 July. They showed southwesterly winds—speed 25–35 kt from about 4.7°N , 48.7°E near Somalia coast to 13.7°N , 56.9°E east of the Arabian coast, the winds being lighter and south to southwesterly further south to the equator from 4°N and veering to west and progressively decreasing in strength to 10 kt off Bombay further east from 13.7°N , 56.9°E . The soundings at 13.7°N and 18.6°N showed marked inversion and higher temperatures above presumably because the air above the deflected trades was of continental origin from Arabia and neighbourhood. Due to topographical features to the west of the Red Sea and south of the Gulf of Aden, the hot continental air from Arabia and neighbourhood will be at the surface only to north of about 10°N , to the south of that latitude the air being from west (southwesterly to westerly monsoon air from the Atlantic—there might be also air from the Indian Ocean—southeast trades which have crossed the east coast of Africa south of the equator and after travelling over land, veered to southwest to west) which has moved eastwards after causing considerable orographic precipitation over Ethiopia and neighbourhood (windward side) and has been flowing over the deflected trades; the air flowing eastwards south of 10°N will not be as hot as that to its north.

Colon has considered that cooling of the waters over the Arabian Sea may be brought about either due to the deep cold waters being forced to ascend and mix with the surface water or through the heat flux to the atmosphere by evaporation and heat conduction. According to Fig. 2 of his paper, while water temperature lowers from June to August at location near 17°N , 66°E , the net heat flux from ocean to atmosphere which is almost entirely due to evaporation—about 600 cal per day, occurs between May and June after which it decreases slowly upto August but increases rapidly during September. The radiation varies from a maximum of 600 cal per day in April to a minimum of 250 cal per day in August. As the water temperature changes only slowly, the lowest being reached in August, while the flux due to evaporation is maximum from May to June and actually decreases thereafter upto August, it is considered that cooling of waters is largely due to deep cold water being forced to ascend and mix with the surface water; relatively colder surface waters from off Somalia-Arabia coast might also be transported northeast to eastwards by strong southwesterly to westerly winds.

Evaporation cooling will be there, but it will be relatively small.

(c) Model for airmasses over the Arabian Sea during active or strong monsoon conditions on the west coast when there is characteristic air-mass stratification—from the average surface water temperatures during the monsoon months, it is seen that temperatures over the Arabian Sea north of Lat. 5°N are generally lowest in August; the lowest temperatures occur over the west Arabian Sea off the Somalia and north Arabian coast. The maximum gradient of temperature is within about 400 km of the coast, the gradient is much less thereafter upto about 65°E and there is practically a flat area further east to the west coast of the Peninsula. Mechanism postulated by Bunker can, therefore, apply only within about 500 km from the Somali-Arabia coast and for the air moving eastwards from Arabia and neighbourhood. But transport of moisture upwards will be prevented by the strong inversion which develops right from the surface as the hot continental air moves over colder sea, a fact shown by dropsondes data over the Gulf of Aden and off Somalia on 30 August 1964 (Fig. 1a) which have been referred to earlier. Further, Bunker has taken NW-SE direction cross-wind flight on 30 August 1964 and not in the SW-NE direction of the winds. On 1 September 1964 the aircraft followed SW-NE course (data in Figs. 2a and 2b). As such, his arguments would not appear justified. If Bunker's arguments are to be valid, a uniform airmass from surface upwards is necessary as seen from his trajectories (Figs. 5 and 7 of his paper) but it was not so. Again cases of 30 August 1964 and 1 September 1964 represent weak monsoon and *not* active or strong monsoon conditions as judged from subsequent rainfall on the west coast of the Peninsula.

In Fig. 3 are given the positions of partitions at different levels between the different airmasses over the Arabian Sea for active and strong monsoon conditions on the west coast on the basis of heights of base of inversion there during the HIOE period (Ramage 1966). It would appear from the figure that there is a surface sloping upwards towards east between about 10° and 20°N as contemplated by Bunker in the second possibility while discussing the geographical distribution of the jet. The continental air will flow eastwards over the sloping surface which can be considered as a barrier. The slope is large near Somali-Arabia coast, but decreases rapidly eastwards till about 68°E by which time the thickness of moist air becomes about 2.0 km, due to interchange of

heat and moisture between the sea surface and the deflected trades in the lower levels. Near about 70°E there is an increase in the thickness of the moist level from about 2.0 to 3.0 km in a distance of 100 to 150 km; further east there is no distinct continental airmass and there is more or less uniform moist airmass about 6.0 km deep over the Peninsula. This increase in depth of moist current to the east of about 68°E and north of 10°N is, it is considered, wholly due to the barrier of the Western Ghats referred to earlier (Desai 1966a, 1966b, 1966c, 1967). The rainfall of 1059 mm at Amini Devi island ($11^{\circ}07'\text{N}$, $72^{\circ}44'\text{E}$) when compared with 2302 mm at Calicut ($11^{\circ}15'\text{N}$, 76°E) at a distance of about 350 km to the east of the coast during June to September is mostly due to the Ghats' effect. This means that Amini Devi gets about 9 mm rain per day during the monsoon season; the mechanism contemplated by Bunker (convection of the order of 200 m in 3 hours) would give much less rainfall within about 500 km of the coast. Thus the mechanism contemplated by Desai (Desai 1966a, 1966b, 1966c, 1967) would appear justified.

As the slope of partition decreases eastwards and the partition actually disappears, there would be a falling of wind eastwards. As such, Bunker's conclusion that the velocity decreases progressively eastwards because the wind is thermal, is not justified. In view of the positions of the partitions at different heights (Fig. 3) for north of about 20°N and south of about 8°N , there would not be any jet over the sea over those areas.

Absence of convective clouds and rain over the west Arabian Sea is due to presence of inversion or isothermal layer between the two airmasses, lower moist deflected trades and upper drier continental air, which prevents development of sufficiently thick convective clouds as discussed by Colon (1964) and Desai (1966a, 1966b, 1966c, 1967) and not due to subsidence; subsidence of the scale of 200 m in 3 hours in the region where jet is accelerating as contemplated by Bunker (1965), is not the cause of absence of convective clouds over large areas over the west Arabian Sea between about 7° and 20°N and west of about 68°E . The inversion is due to airmasses and *not* due to subsidence.

In view of the foregoing it is possible to explain the wind velocities mentioned by Bunker as well as absence of convective clouds in the west Arabian Sea and presence of convective clouds and showers in the east Arabian Sea within 500 km of the coast on the basis of the airmasses ideas developed by the author (Desai 1966a, 1966b, 1966c, 1967).

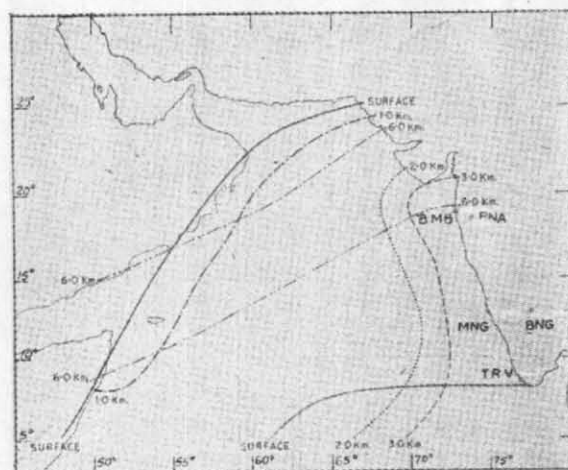


Fig. 3

Approximate positions of boundaries between different airmasses at the surface, 1.0, 2.0, 3.0 and 6.0 km over the Arabian Sea for active or strong monsoon conditions on the west coast; to the west of the partitions except at 6.0 km, there is drier continental air and to their east moist air; at 6.0 km there is moist air to the south of the southern partition and drier continental air to the north of the northern partition; between the two partitions there is tropical easterly air. To the west of the line from about 5°N, 61°E the deflected trades move to the west coast of the Indo-Pakistan subcontinent across the Arabian Sea and to its east they enter directly into the Bay of Bengal

It may be stated that on the coast and to the east of the Ghats the winds are again strong (Joseph and Raman 1966; also private communication by Joseph) and jet occurs over the Peninsula at about 1.5-km level during July, persists for a few days at a time, and moves northwards and southwards; it occurs either with or without a depression, being 7° to 10° south of the depression when there is one. At times there might be a secondary jet in the upper levels. The jet is associated with good rainfall around it. From an examination of July and August charts of 1964 by the author, it appears that winds of 50 kt or more occur at 1.5 km occasionally over more than one region at the same time; thus on 5 July 1964 jet winds occurred at Mangalore and about 300 km to its north at Gadag, on 7 August 1964 at Gadag, on the next day at Cochin and Poona, on the 9th at Anantpur and Trivandrum and on 10 August 1964 at Cochin and Gadag. There is no airmass distribution with temperature contrasts over the Peninsula of the type over the west Arabian Sea and off Somalia coast. It has to be recognised that jet winds occur on both the sides of the Ghats at the same time and are associated with heavy rain on the coast. The occurrence of this jet at 1.5 km over the Peninsula would not appear to be due to thermal causes and might be due to the Western Ghats (Banerji 1930, 1931).

The model in Fig. 3 would be valid only where there is drier continental air from Arabia and northeast Africa side above the deflected trades and *not* where there is moist air in all the levels. According to the data received from the U.S.A. research vessel *Oceanographer* there was air with humidity more than 70 per cent from the sea surface upto about 450 mb with near isothermal conditions between 732 mb (Temp. 8.9°C, humidity 92 per cent) and 677 mb (Temp. 7.7°C, humidity 83 per cent) at location 18.47°N, 65.20°E at 12 GMT of 18 June 1967; widespread and locally heavy rain occurred on the west coast between 10° and 20°N from 17 to 21 June. The *Oceanographer* data for 14 to 21 June 1967 do not show the characteristic airmass stratification reported by Colon (1964) for the HIOE period. Detailed discussions of the *Oceanographer* data from the point of airmasses present over the area will be given in a separate paper.

3. Acknowledgements

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