551.513·2 : 551.553.21(54)

Meridional circulation associated with the monsoons of India

Y. P. RAO

Regional Meteorological Centre, Madras

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ABSTRACT. Meridional components in January and July at twelve Indian Rawin stations and Colombo, Nairobi, Aden, Bahrein and Tashkent based on three years' data are presented. The centres of direct and indirect cells are located at higher elevations, probably to overcome the obstruction to meridional exchange from high mountain ranges running east to west. At Bahrein and Aden the upper southerlies of the direct cell are absent in winter. The direct cell retreates northward to near 30°N in July and a 'monsoon cell' with lower southerlies and upper northerlies occupies the Indian area from 26 to 13°N. Northerlies at Colombo and Trivandrum in the lower troposphere in July suggest that the feed across the equator into the Arabian Sea branch of the monsoon may be extremely limited.

1. Introduction

The best estimate of the meridional circulation from 10 to 70°N has been made by Tucker (1959). He has considered the area between the longitudes 160°W and 40°E. In winter he finds a direct circulation with northerlies below 700 mb and southerlies aloft between 10 and 25°N. Weaker indirect circulation is present from 35 to 50°N with southerlies below and northerlies aloft, the transition being at 600 mb between 35 and 45°N. In summer the direct cell is centred near 25° and transition to upper southerlies is at 600 mb. The indirect cell is still weaker and is mainly located to the north of 40°. At 10° southerlies are present from about 950 to 600 mb and northerlies up to 200 mb. This circulation is probably an extension of the direct cell of the winter hemisphere across the equator.

The eastern limit of Tucker's study is at 40° E and, therefore, the monsoon area of India and neighbourhood has not been sampled. As sufficient rawin data are available from this monsoon area qualitative comparison of the associated meridional circulation is made in this study with the results of Tucker.

2. Data

For the twelve Indian stations the monthly mean vector winds for the three years 1957-59 for the afternoon rawin flights were used. Mean meridional components were computed upto the level for which at least thirty observations were available over the period. For similar computation for Colombo and Nairobi, on more than seventy days rawin flights reached 100 mb. Data of Aden and Bahrein were extracted from publications of Air Ministry, London. Aden and Bahrein winds are for 1949-50. Meridional components of Tashkent for January are for 1957, 1959 and 1960 and for July 1957, 1958 and 1959. 30 observations were available for January at 100 mb but only 21 for July.

A cross-section of the meridional flow in January and July representative of about 40° E prepared with the data of Nairobi, Aden and Bahrein is shown in Figs. 1 and 2. Wind component from south is taken as positive. Figs. 3 and 4 present the meridional components at Indian stations in January and July. Taking into account the broad similarities for January the data of Madras and Port Blair have been averaged to represent 12°N; Veraval, Bombay, Nagpur and Calcutta for 21°N and Jodhpur, Amritsar, Delhi, Allahabad and Gauhati for 28°N. These along with Trivandrum and Colombo are represented in Fig. 5 as a meridional cross-section for January for the Indian region. In Fig. 6 for July, the same procedure has been followed, except that Jodhpur, Bamrauli

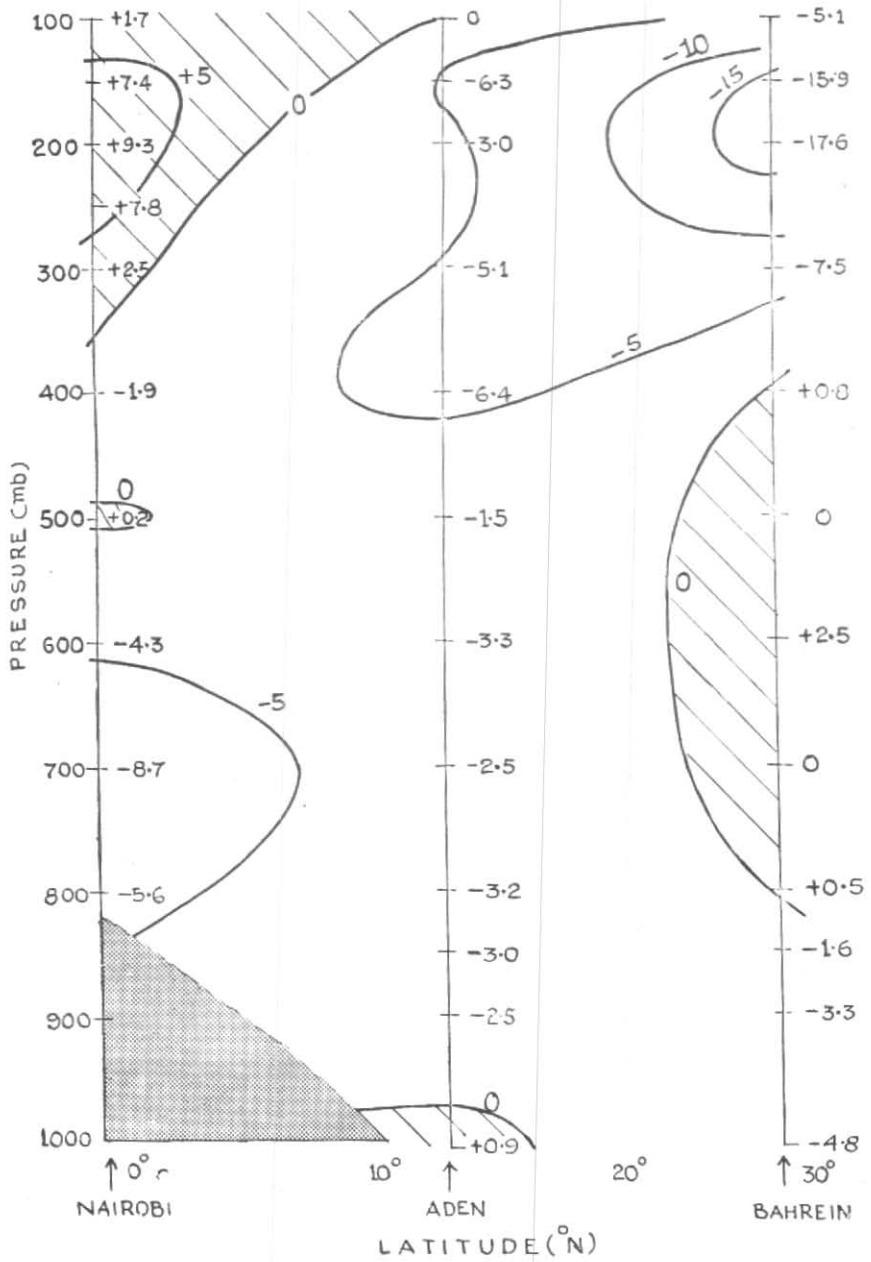

Fig. 1. Mean meridional components (kt) for January (40° E)
Component from south is positive and hatched

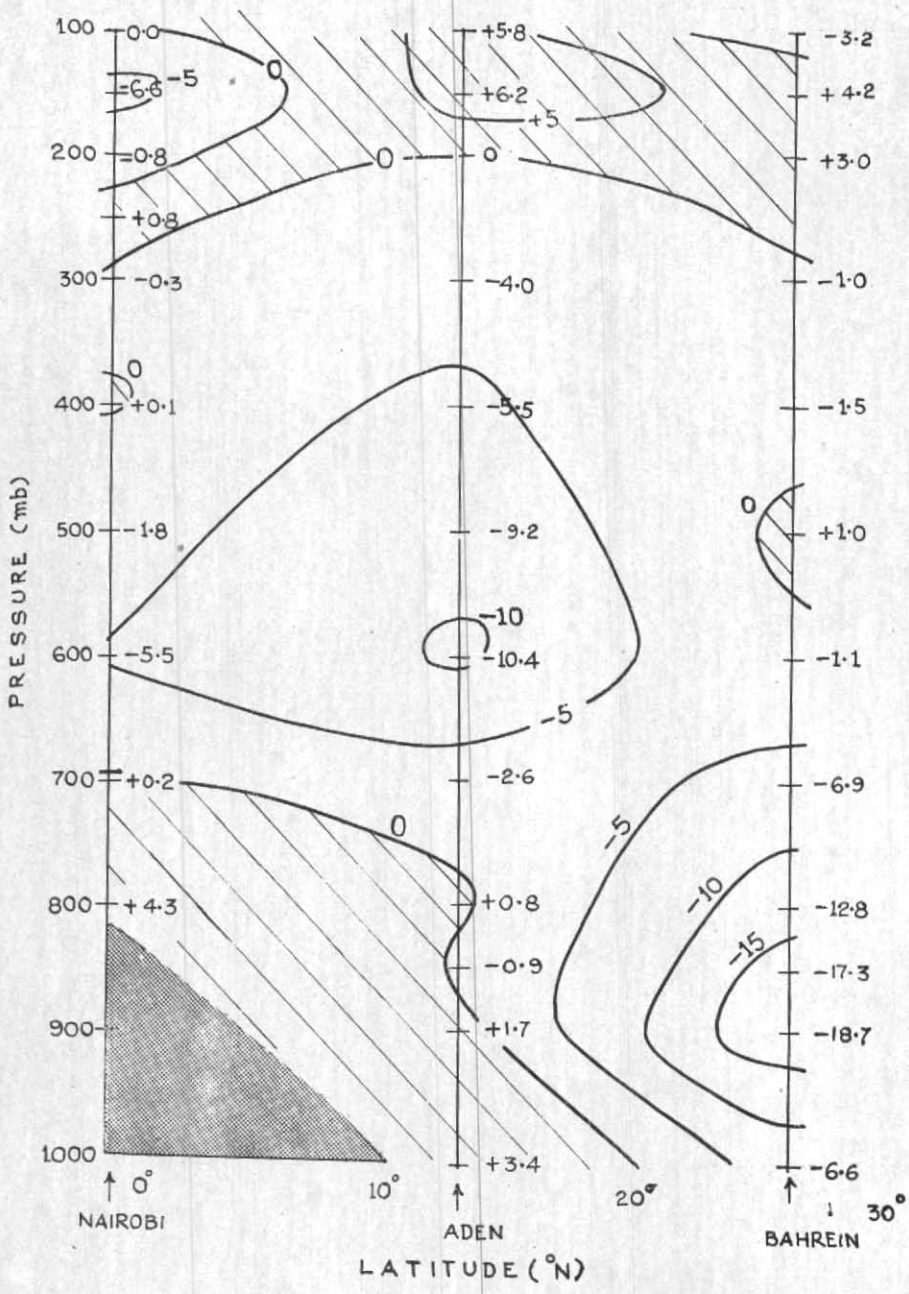

Fig. 2. Mean meridional components (kt) for July (40 °E)
Component from south is poitive and hatched

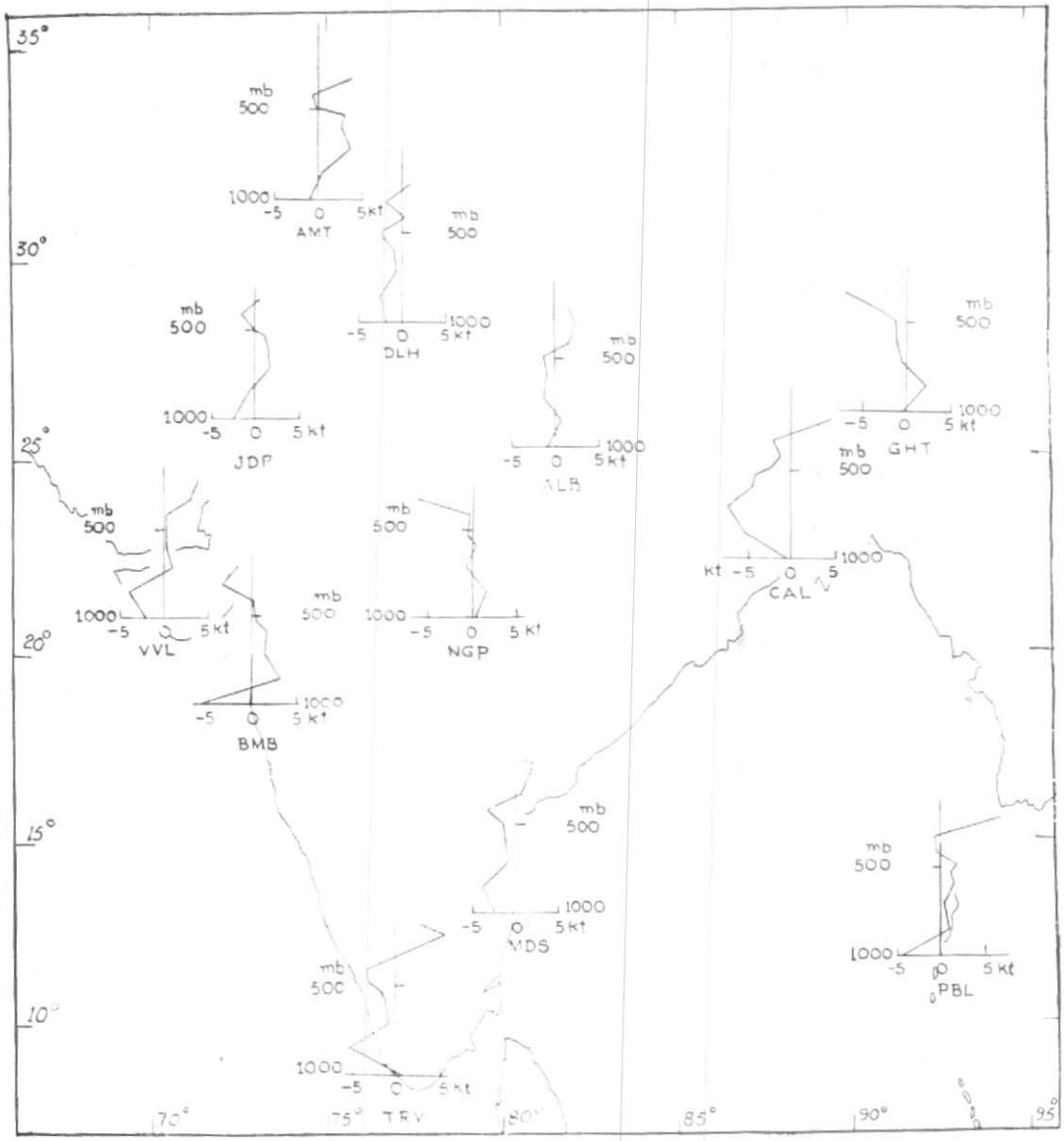

Fig. 3. Mean meridional components for January
Component from south is positive

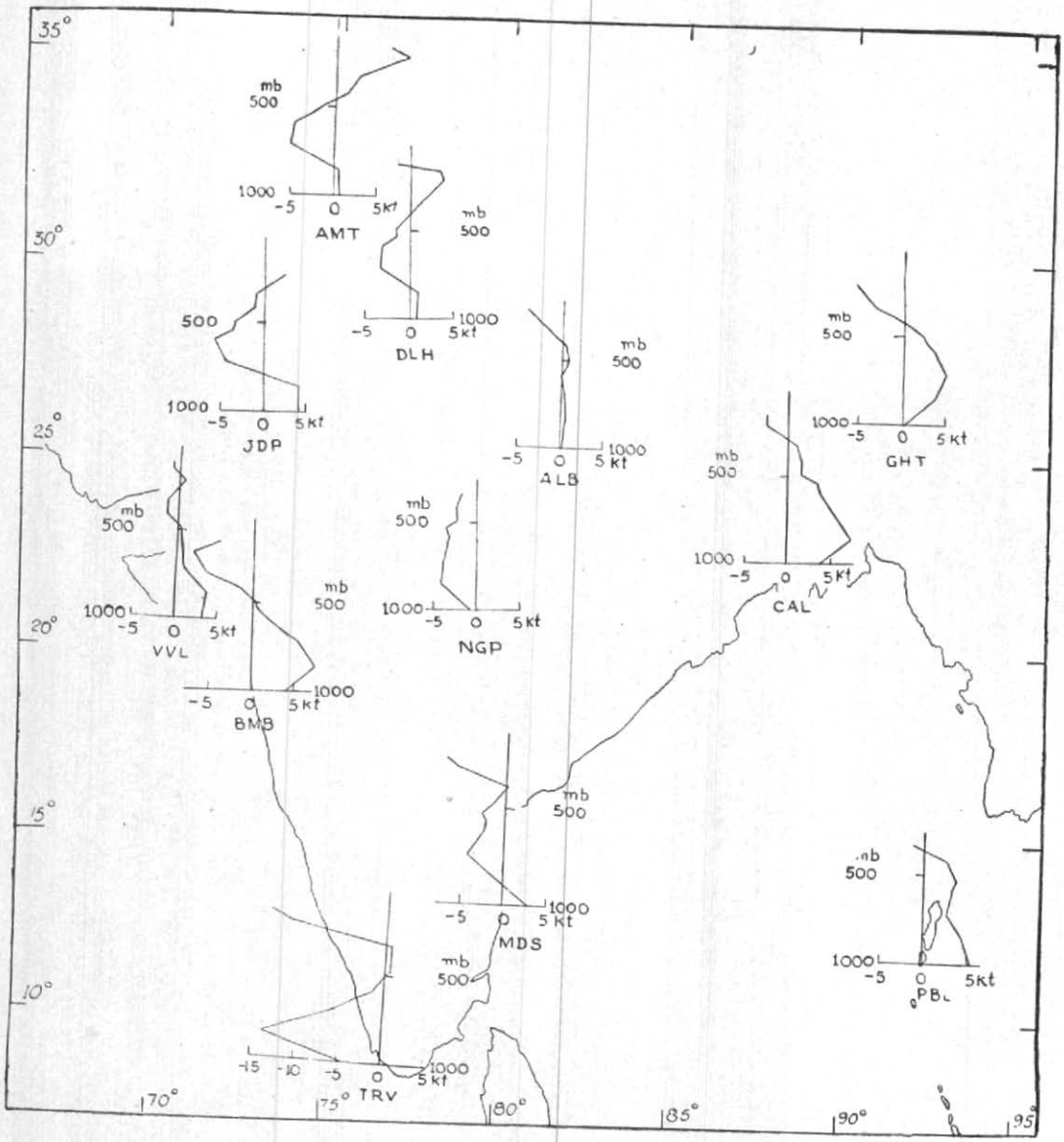

Fig. 4. Mean meridional components for July
Component from south is positive

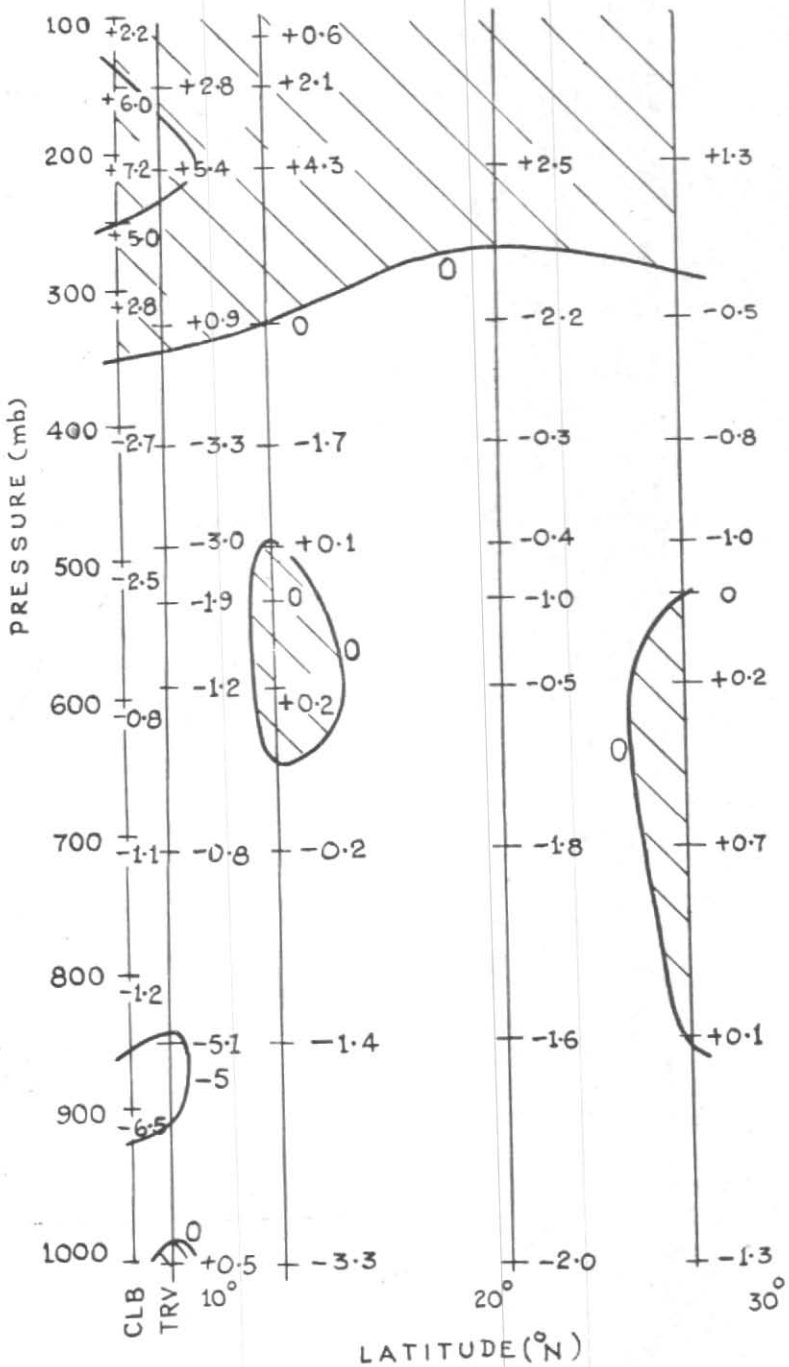

Fig. 5. Mean meridional components (kt) for January (Indian longitude)
Component from south is positive and hatched

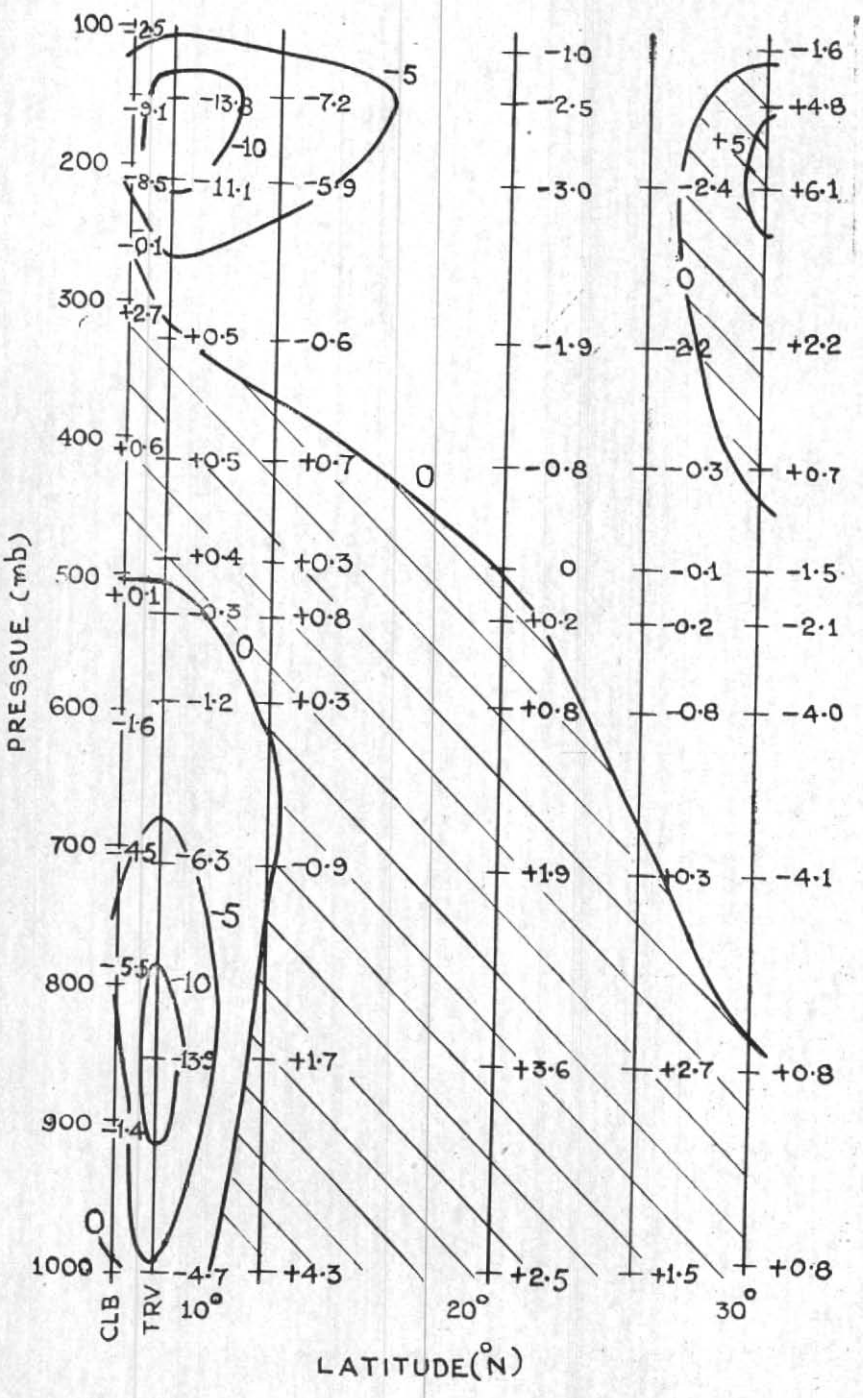

Fig. 6. Mean meridional components (kt) for July (Indian longitude)
Component from south is positive and hatched

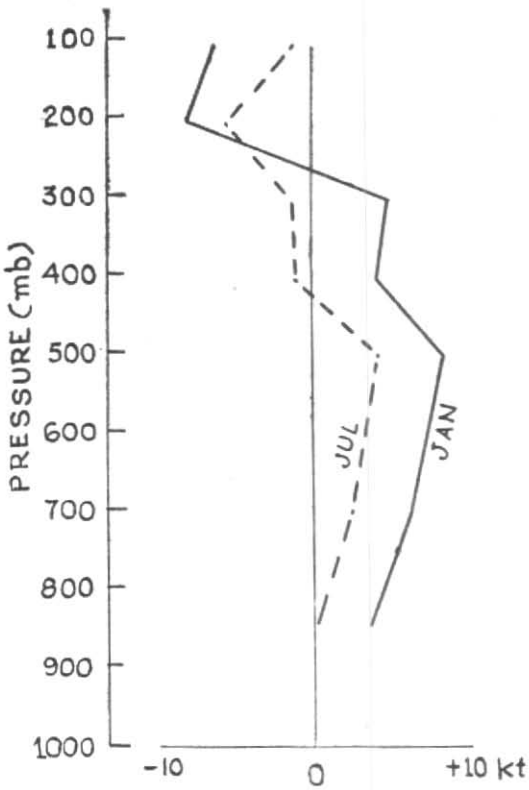

Fig. 7. Mean meridional components (kt) for Tashkent
Component from south is positive

and Gauhati have been averaged for 26°N and Amritsar and Delhi for 30°N. Meridional flow at Tashkent is shown in Fig. 7, for which data were available only from 850 mb upwards.

3. Meridional circulation

(*a*) *January*—As seen from Fig. 5, in the Indian area northerlies of the direct cell prevail from the surface up to 300 mb and southerlies aloft. Towards equator both the southerlies and northerlies are stronger. The northerlies either weaken or become light southerlies in the mid-troposphere but again strengthen higher up before giving place to the upper tropospheric counter-current. In Fig. 1 representing 40°E, the features are similar, except that upper tropospheric southerlies are absent at Aden and Bahrein. The northerlies reach upto the tropopause at these stations (except for weak mid-tropospheric southerlies as noticed in Indian longitudes) and are very strong in the upper troposphere at Bahrein. The indirect circulation is noticed at Tashkent which is at 42° N but the transition from lower southerlies to northerlies is near 250 mb.

There are a few differences between the area under study and the mean circulation obtained by Tucker (1959). The upper southerlies of the direct cell commence only at 300 mb in the Indian area while in Tucker's model it is as low as 700 mb. Also, the southerlies are stronger (4–7 kt) near 10 degree latitude compared with 2 kt found by Tucker. Along the meridian of 40°E, upper southerlies of the direct cell are not present in the tropical belt. The upper northerlies of the indirect circulation only commence at 250 mb at Tashkent while at that latitude in the mean circulation they commence at 600 mb. These differences may partly arise from the data discussed here being for January while the mean circulation computed by Tucker (1959) is for December, January and February.

(*b*) *July*—Along 40°E, the direct cell is well-marked at both Bahrein and Aden. Northerlies below and southerlies above are taken as direct cell, even if northerlies do not commence right from the ground. In contrast with winter conditions the upper southerlies of this cell are noticed at both the stations. The lower level northerlies are very strong at Bahrein. At Aden the direct cell circulation commences only at about 750 mb, below which southerlies of the southwest monsoon are present. These southerlies are also present at Nairobi. However, the circulation at Nairobi is not simple as in winter. While opposite to the surface southerlies, northerlies are present between 220 and 100 mb, there are in between layers of southerlies and northerlies. These northerlies are present from 700 to 300 mb and a thin layer of southerlies from 290 to 220 mb.

In the Indian longitudes direct cell circulation is noticed in the middle and upper layers at 30° but does not extend farther south. The indirect cell is still affecting Tashkent, though the surface northerlies of the direct cell appear to be encroaching there as the extrapolation of the curve in Fig. 7 would suggest northerlies below 850 mb. The southerlies of the southwest monsoon extend at 30° up to 850 mb. Between 12 and 26°N a simple circulation of southerlies below and northerlies aloft emerges. But closer to the equator, there is a deep layer of northerlies commencing almost from the surface, southerlies above and marked layer of northerlies aloft. In the sequence of layers there is certain resemblance between the Indian area south 10°N and Nairobi, the surface southerlies having become very shallow in the former. (The surface northerlies at Trivandrum are due to the monsoon air flowing around the edge of the western range of hills).

Compared with the mean circulation for July of Tucker, the differences are as follows. The equatorial southerlies do not lie above the surface northerlies of the direct cell but below in the area under study. The equatorial southerlies are stronger in the Indian area and the direct cell is farther to the north and smaller in meridional extent.

4. Discussion

The winter circulation over the seas around India has come to be known as the northeast monsoon. It is however no way different from the northeast trades, except that the northeasterlies are weaker in the Indian area. Hence any modification of the meridional circulation cannot be due to any monsoonal influence. Though the role of the various meridional cells has not been completely understood, their purpose is to link up the various latitudinal belts and through vertical motions associated with the cells, the lower and top layers of the atmosphere. However, the Indian area is bounded to the north by high mountains between 30 and 40°N which are unbroken up to about 4 km. In order to obtain the necessary interlinking between the lower and higher latitudes, the centre of the meridional circulations has to be lifted sufficiently above this barrier to such exchange. Possibly for this reason the level of transition in the meridional flow has been raised to about 300 mb in both the direct and indirect circulations in the Indian area, from 700 to 600 mb in the mean results of Tucker. The upper flow being thereby confined to a thinner layer is also stronger. This does not account for the absence of upper southerlies of the direct cell at Bahrein and Aden. The upper tropospheric northerlies at these places may be providing meridional mass compensation for the lack of flow at lower levels across the northern barrier.

The southwest monsoon of the Indian area represents the most developed monsoon latitudinally and vertically on the earth. Owing to the extent of monsoon circulation the direct cell retreats northward near 30°N in the Indian area but is more near the usual position along 40°E. Associated upper southerlies are now present in this region unlike as in winter. As the lower level northerly flow in Indian area is practically absent, there is probably no need for feed from higher elevations. As in winter the level of transition in meridional flow of the direct cell is higher than in Tucker's mean picture.

From considerations of heat balance, Riehl and Malkus (1958) derived a meridional circulation through a boundary located at 10 latitude degrees on the winter side of the equatorial trough. This is borne out between 12 and 26° latitudes over the Indian area and may be called the monsoon cell. Even over Aden at 13°N it can be visualised that there is monsoon cell below and direct cell aloft.

Tucker sampling both oceanic and continental areas obtains the equatorial southerlies as over-running the surface northerlies of the direct cell in summer. In the region under study which is largely continental

the lower northerlies of the direct cell are of continental origin and warmer and hence over-run the colder equatorial southerlies of maritime origin.

Data of Colombo and Trivandrum in Fig. 6 show deep northerlies in the lower troposphere and net southward mass tansport in the whole of the troposphere. The latter feature is also confirmed by Nairobi data. The net mass flow in the troposphere southwards across the equator between longitudes 40° and 80° and northwards further east was pointed out by Rao (1960) as two branches of the monsoon. The predominant northerlies in the lower troposphere at Colombo and Trivandrum would suggest that the feed across the equator into the Arabian Sea branch of the monsoon is extremely limited.

Flohn (1954) has recognised two types of direct circulations. The type characteristic of predominant easterly trades has a layer of southerlies at the middle level of the northerlies. The main layer of southerlies are much higher. This feature is confirmed by the present study for January. The meridional components (Fig. 3) at most of the stations in India show that at the middle of the layer of northerlies, there are weak southerlies and even at the other stations the northerlies weaken at about that level. The middle layer southerlies stand out also in the mean picture for January at 12°N and 28°N. Bahrein shows the same feature in January and slightly even in July. Meridonal flow for 15°N derived by Palmen, Riehl and Vuorela (1958) also shows very weak southerlies in winter at 600 mb. Thus it appears that the direct cell of winter may consist of three components, with weak southerlies prevailing at the middle level of the northerlies.

5. Acknowledgement

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