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SOME NEW FEATURES OF THE VERTICAL DISTRIBUTION OF TEMPERATURE AND HUMIDITY OVER BOMBAY DURING THE SOUTH-WEST MONSOON SEASON *

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ABSTRACT

The aerological data of Bombay with the new American type of radiosonde have been examined for the monsoon seasons of 1968, 1969 and 1970. Even during the peak monsoon months of July and August large changes occur in the thermal and humidity structure of the atmosphere. It is found that except during spells of good rainfall over and around the station the depth of moist air over Bombay rarely exceeds 750 mb above which there is often an inversion or layer of stable lapse rate with dry air aloft. On some occasions there is again an increase of humidity towards the 500 mb level and an inversion or layer of stable lapse rate is also noticed near this level. These features are illustrated with tephigrams for the months of July and August 1968. Examination of upper wind flow patterns shows that the meridional component of the winds at and above 3 km tends to be northerly when the atmosphere is dry with little or no rainfall while it is southerly when the humidity content is high. Both the continental origin of the air as well as subsidence appear to be responsible for the low humidity and inversion. The study shows that it is not correct to assume that a deep moist column of air exists over peninsular India after the monsoon has established. Large space-time variations occur in the vertical distribution of humidity. Vertical transport of moisture beyond the first 2 or 3 kilometres is brought out only by low-level convergence associated with weather systems of various scales and there are compensating areas of descending motion outside the rainfall area.

INTRODUCTION

BEGINNING from 1967 the C and F type radiosondes which were in operation at Indian stations for over two decades are being progressively replaced by a new radiosonde of the American type with better performance characteristics. Not only are the temperature and humidity readings between successive soundings more consistent, but humidity values are now available upto heights of nearly 250 mb in the monsoon months whereas such data were seldom available even upto 500 mb with the older instruments. A study of the recent data reveals several new features of the vertical distribution of temperature and humidity over the monsoon field and their day-to-day variations which are being discussed in detail in a separate paper. The present paper reports some results of the study of the upper air changes over Bombay during July and August 1968. Features similar to those reported here have been noticed also in other years and at neighbouring stations.

DAILY TEPHIGRAMS

One of the striking results revealed by the daily tephigrams of Bombay for the monsoon months is that on several days the depth of moist air is only about 2.0 to

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2.5 km (800 to 750 mb). Above this there is a pronounced inversion with very dry air. This feature is illustrated by the series of tephigrams for July and August 1968 reproduced in Figs. 1 (a), (b), (c) and (d). Broadly speaking the tephigrams of Bombay during the southwest monsoon months fall into two categories : (i) the moist type ; and (ii) the dry type. Examples of the first type are the tephigrams of 7th, 19th and 24th July and 6th August. In these cases the atmosphere is highly humid upto the maximum height reached by the humidity record (9 to 10 km). The second type is characterised by a shallow depth of moist air of less than 3 km thickness, topped by an inversion with dry air aloft. A large number of such examples can be seen in Fig. 1A and 1B. There are considerable variations among these. In general, the dryness is a maximum at and immediately above the level of the inversion. There are many occasions when the dry bulb and dew-point temperature curves again get close to each other near about 500 mb. A second inversion or isothermal layer is noticed at this height on some days. The tephigrams for a number of days in August illustrate this feature.

Humidity and Rainfall

A diagrammatic representation of the day-to-day values of dry bulb temperature and dew-point at 950, 900, 850, 800, 750, 700, 600, 500 and 400 mb over Bombay for June to September 1968 is given in Fig. 2. The length of the vertical lines is a measure of the dew-point depression. The 24-hour rainfall values for all the days from 1st June to 30th September 1968 are shown at the bottom of Fig. 2. The normal daily rainfall curve for this period is also shown. It will be noticed that rainfall activity at Bombay was generally below normal in August 1968.

An examination of Fig. 2 reveals a number of interesting features. Before the onset of the monsoon over Bombay by about the middle of June, the depth of the moist layer is only about 1 km or less. Thereafter, the depth of the moist layer is never less than 2 km. At 750 mb level (2.5 km) we notice a tendency for the occurrence of dry and moist spells. These have their parallel in the higher layers also. It is found that the penetration of moisture to levels above 750 mb occurs in association with spells of good rainfall activity in and around Bombay. Among the synoptic situations favourable for such rainfall are the movement of depressions from the Bay of Bengal towards Gujarat and formation of mid-tropospheric low pressure systems over the Gulf of Kutch area. When the rainfall decreases with the weakening or movement of the synoptic systems, the depth of the moist layer is again reduced to about 2.5 km with re-establishment of the inversion and dry air aloft.

U and V Components of Wind

The time series of the U and V components of the wind over Bombay from the surface to 6 km for the period 1st June to 30th September 1968 is shown in Fig. 3. Till the establishment of the monsoon the v-component of the wind is from the north above 1 km. When the monsoon establishes the meridional component of the wind becomes southerly in the lower troposphere. However, fluctuations in the depth of the southerlies are noticed throughout the monsoon months. Above 2.5 km spells of northerlies lasting for a number of days alternate with southerly spells till the end of August. There are similar fluctuations in the zonal component. In general, spells of good rainfall activity with high humidity extending to the upper troposphere

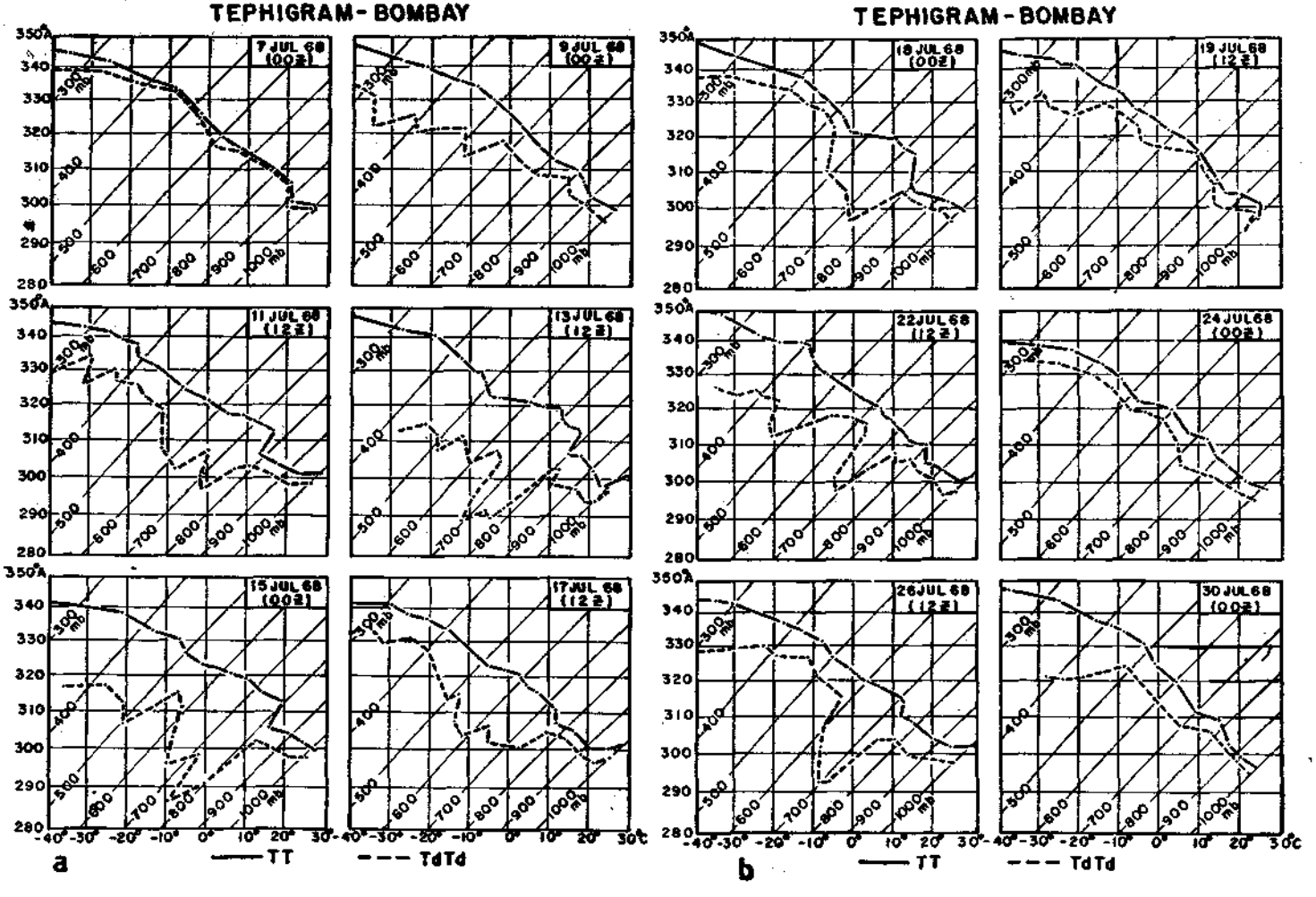
TEPHIGRAM - BOMBAY
7 JUL 68 (00Z)
9 JUL 68 (00Z)
11 JUL 68 (12Z)
13 JUL 68 (12Z)
15 JUL 68 (00Z)
17 JUL 68 (12Z)
a
TT
TdTd
TEPHIGRAM - BOMBAY
18 JUL 68 (00Z)
19 JUL 68 (12Z)
22 JUL 68 (12Z)
24 JUL 68 (00Z)
26 JUL 68 (12Z)
30 JUL 68 (00Z)
b
TT
TdTd

Fig. 1-A

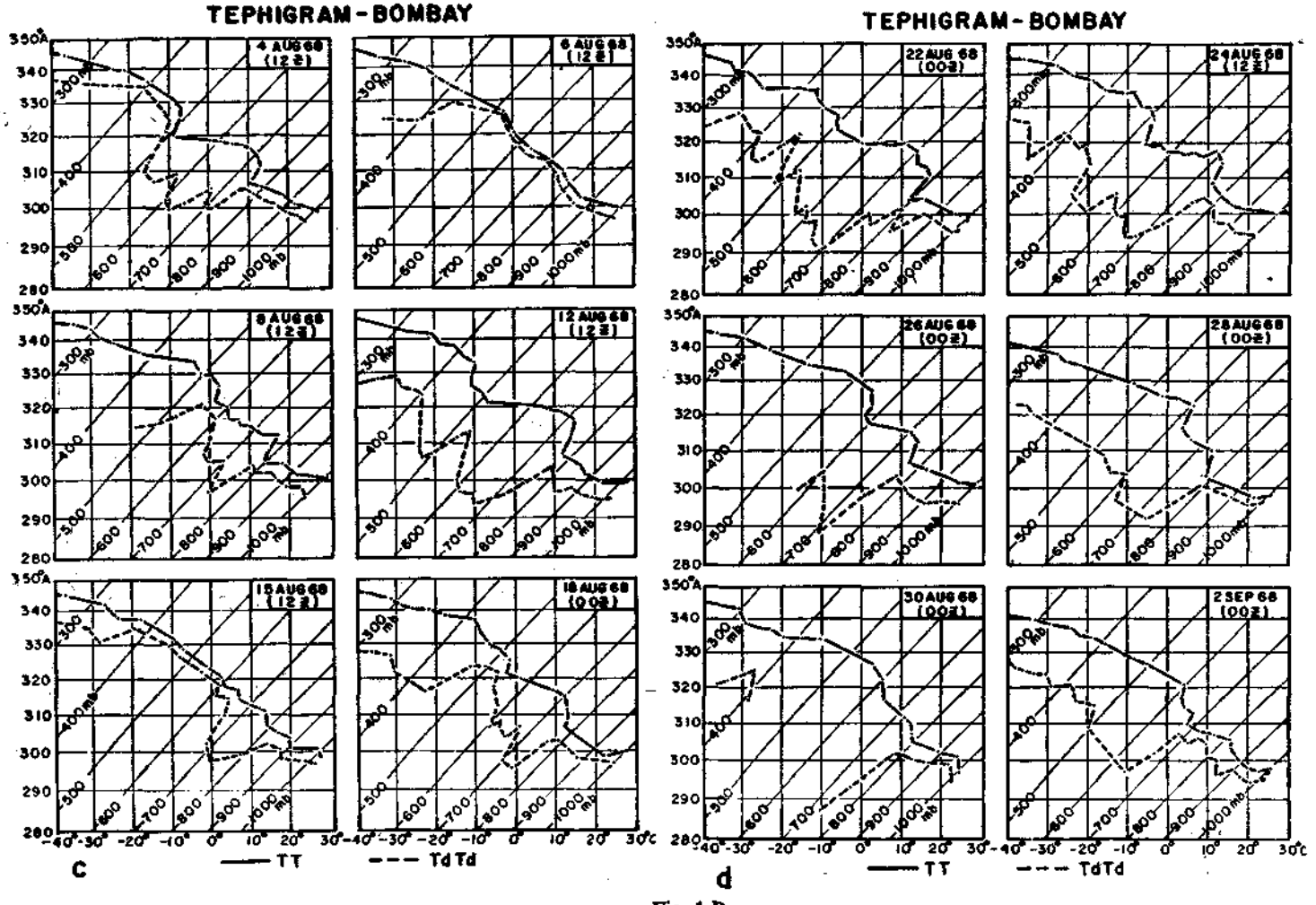
TEPHIGRAM - BOMBAY
4 AUG 68 (12 Z)
6 AUG 68 (12 Z)
8 AUG 68 (12 Z)
12 AUG 68 (12 Z)
15 AUG 68 (12 Z)
18 AUG 68 (00 Z)
c
TT
Td Td
TEPHIGRAM - BOMBAY
22 AUG 68 (00 Z)
24 AUG 68 (12 Z)
26 AUG 68 (00 Z)
28 AUG 68 (00 Z)
30 AUG 68 (00 Z)
2 SEP 68 (00 Z)
d
TT
Td Td

Fig. 1-B

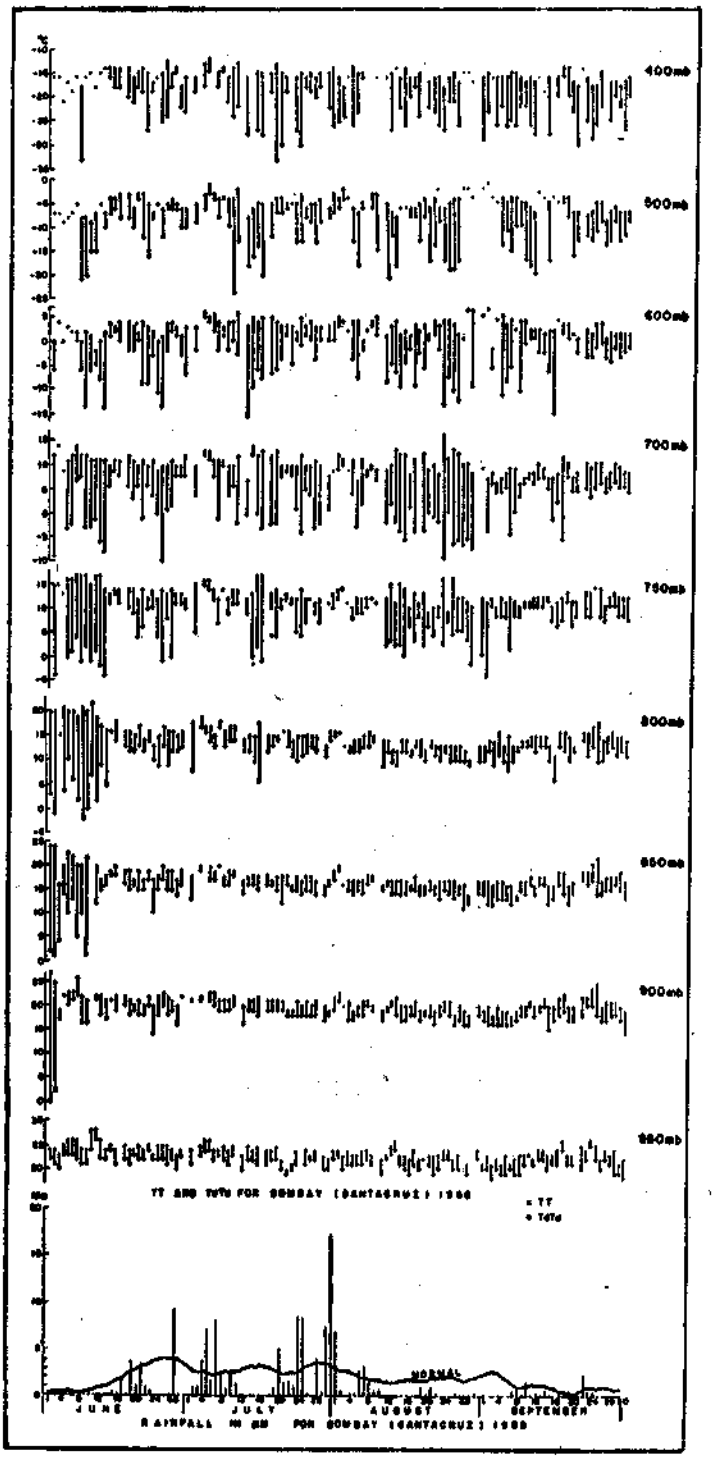
400mb
500mb
600mb
700mb
750mb
800mb
850mb
900mb
950mb
TT AND TdTd FOR BOMBAY (SANTACRUZ) 1966
TT
TdTd
NORMAL
JUNE
JULY
AUGUST
SEPTEMBER
RAINFALL IN MM FOR BOMBAY (SANTACRUZ) 1966

Fig. 2

are associated with deep southerly and westerly components of the wind during June, July and August. Periods of shallow southerly components of the wind are generally those when the moist air is less than 3 km deep with inversion and dry air above it.

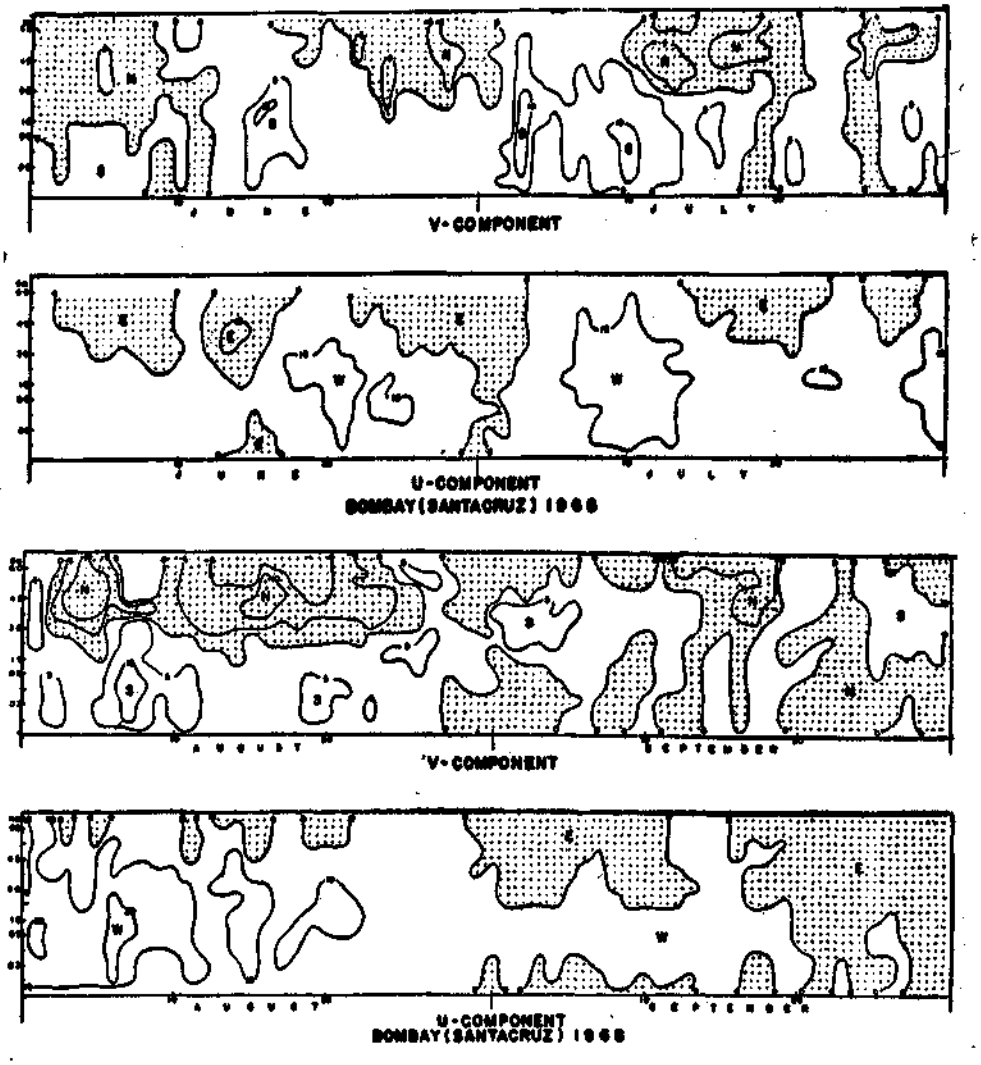

Fig. 3

Fig. 4 shows the time series of the shear in the zonal wind between Bombay and Ahmedabad at 700 mb for the same period. It is seen that the shear is small or negative in the early part of June as well as during September. During July and August the shear is generally positive.

Power Spectra

The power spectra of the time series of the following elements have been studied for the period 1st June to 30th September 1970 :

(i) v-component of the wind at 700 mb

(ii) dew-point temperature at 700 mb level

(iii) dry bulb temperature at 700 mb level

(iv) zonal shear at 700 mb level between Bombay and Ahmedabad

(v) daily 24-hour rainfall of Bombay.

The results are shown in Fig. 5. The v-component at 700 mb shows two dominant peaks with periods of about one month and 8 days. Nearly similar behaviour is also shown by the dew-point temperature at 700 mb. The rainfall shows a number of peaks one of which corresponds to a period of about a week.

To investigate the inter-relation between the different elements the cospectra of the v-component at 700 mb with the other elements were calculated. The cospectra in the dominant periods of 1 month and 8.6 days are shown in Table 1.

Table 1

Element	Period	
	1 month	8.6 days
^{v}700—Td 700	+ 3.80	+ 1.94 kt deg day^{-1}
^{v}700—Rainfall	+ 12.85	+ 7.42 kt mm day^{-1}
^{v}700—T 700	— 1.95	—0.12 kt deg day^{-1}

The cospectrum between the meridional component at 700 mb and the dew-point at this level is positive indicating that southerlies are associated with greater humidity and vice versa. The positive association between the southerlies at 700 mb and rainfall shows that southerly component of the wind over Bombay at 700 mb is associated with upward motion at this level which transports moisture from the lower to the higher levels. Southerlies at 700 mb with cyclonic vorticity of the zonal wind at this level shows that rainfall occurs in the eastern sector of the disturbances. Under these circumstances, northward moving air would gain cyclonic vorticity leading to convergence.

The association between the meridional component of the wind at 700 mb and the dry bulb temperature at this level is negative which shows that higher temperatures at this level are associated with northerly component of the wind, that is sensible heat is transported down the temperature gradient. Thus conditions at 700 mb appear to be such that air at this level which is ascending in the southerly current over Bombay and neighbourhood during spells of rainy weather is colder than the air in the northerly current to the west. This would imply that the midtropospheric system is an energy consuming indirect system.

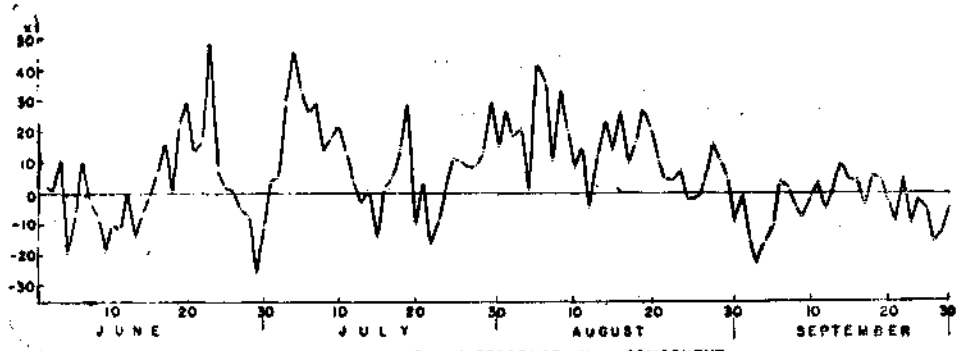
JUNE
JULY
AUGUST
SEPTEMBER
BOMBAY - AHMEDABAD DIFFERENCE IN U-COMPONENT
700 mb, 1968

Fig. 4

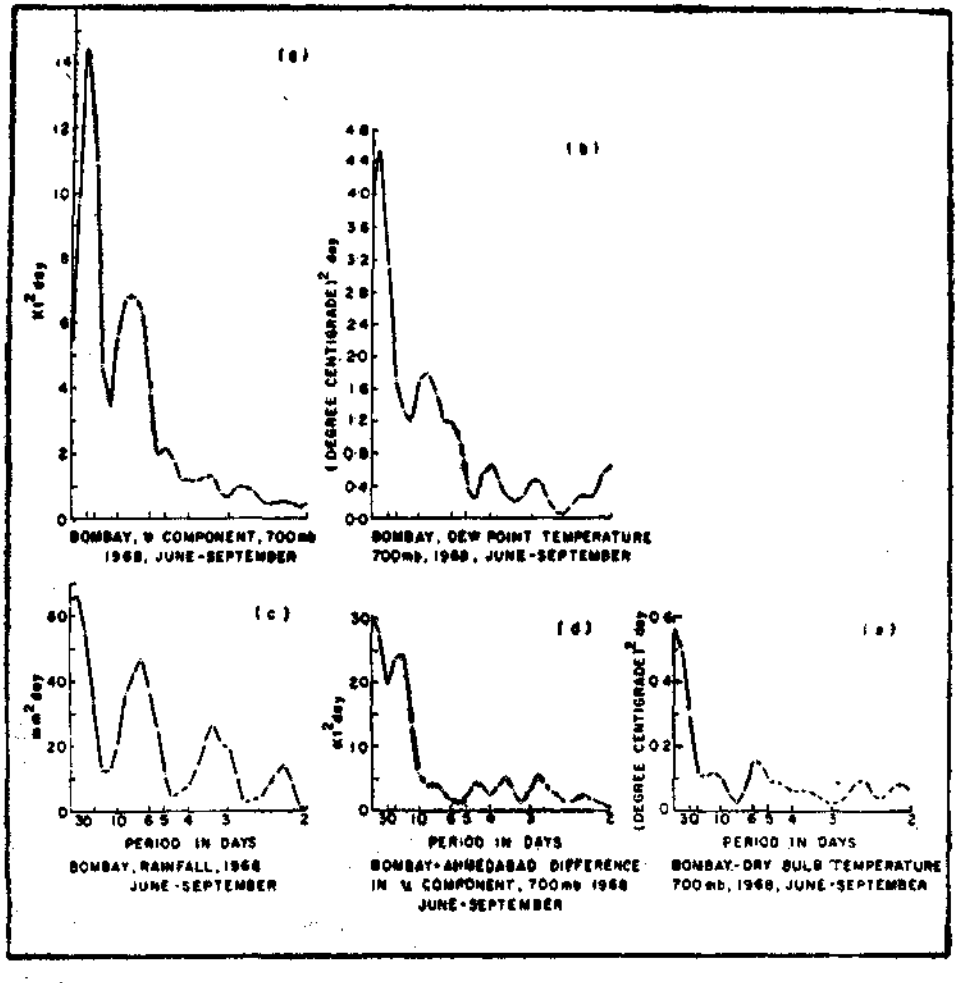
(a)
BOMBAY, U COMPONENT, 700mb
1968, JUNE-SEPTEMBER
(b)
BOMBAY, DEW POINT TEMPERATURE
700mb, 1968, JUNE-SEPTEMBER
(c)
PERIOD IN DAYS
BOMBAY, RAINFALL, 1968
JUNE-SEPTEMBER
(d)
PERIOD IN DAYS
BOMBAY-AHMEDABAD DIFFERENCE
IN U COMPONENT, 700mb 1968
JUNE-SEPTEMBER
(e)
PERIOD IN DAYS
BOMBAY-DRY BULB TEMPERATURE
700mb, 1968, JUNE-SEPTEMBER

Fig.

DISCUSSION

The classical idea that the southwest monsoon is a deep moist current originating in the southern hemisphere and moving towards India had to be revised when reconnaissance flights and dropsonde ascents over the Arabian sea by research aircraft of the US Weather Bureau during the southwest monsoon months of 1963 and 1964 (IIOE period) showed for the first time that the depth of the moist air beyond two to three hundred kilometers away from the west coast of India is only of the order of about 1 to 2 kms. Above this there is a pronounced inversion similar to the trade wind inversion. Dry air with nearly dry adiabatic lapse rate upto about 500 mb prevails above the inversion.

The causes of the inversion and the circumstances leading to its disappearance and increase in depth of the moist layer as the westerly monsoon current gets close to the west coast of India have been discussed by Colon (1963), Pisharoty (1965) and Desai (1966). The southerwesterly flow at the surface of the Arabian sea in July and August rapidly changes to a westerly flow even at 1 km which suggests that the dry air above the surface moist layer has its origin probably over the continental masses of Africa and Arabia. Several causes appear to help the vertical transport of moisture across the inversion and its eventual disappearance as the air approaches the coast. Among these are the orographic effects caused by the Western Ghats, sea-air interaction and vertical mixing processes in the lower layers (Riehl, 1954) and meso-scale and synoptic scale disturbances giving rise to low level convergence.

There is a general impression that once the monsoon is well established there is a deep layer of moist air over the whole of peninsular India. Our study shows that this is not the case. The vertical transport of moisture beyond the first two or three kilometers appears to be intimately connected with meso-scale and synoptic scale systems giving rise to appreciable rainfall. The inversions over Bombay between 800 and 750 mb in July and August are generally associated with air flow having a northerly component above this level. Apart from the fact that the source of this air is continental, there is strong suggestion that subsidence also plays an important part in producing and maintaining this inversion in the Bombay-Ahmedabad region. There are a large number of days during the southwest monsoon months when this inversion is conspicuous over Bombay. On such days clouds can form only in the lower moist layer and their tops cannot go above the base of the inversion. Rain from such clouds is of the warm type since the freezing level is at a height of about 500 mb. The rainfall is generally of short duration and is a common feature at Bombay during the southwest monsoon months. Heavy rainfall of sustained duration can occur only in association with situations that give rise to pronounced low level convergence leading to the disappearance of the inversion and increase in depth of the moist layer to the middle and upper tropospheric levels. Rao, Srinivasan, Raman and Ramakrishnan (1970) have drawn attention to the distinctly different nature of the tephigrams of Ahmedabad in association with active and weak monsoon over Gujarat State. The features are similar to those noticed over Bombay.

An examination of the tephigrams of the south Indian stations also lends support to the view that the depth of the moist layer is generally shallow except on occasions of good rainfall at stations such as Minicoy, Trivandrum and Ernakulam. Such rainfall does not appear to be purely orographic since there are instances of little or no rainfall at the southern stations with strong westerly winds.

Mathur (1965) has drawn attention to the fact that tephigrams of Minicoy for the months of May and July 1963 at times showed two inversions one near 850 mb and the other near 500 mb, the lower inversion being more marked. Inversions at these levels were also found in the tephigram of a dropsonde ascent taken south of the equator off the east African coast on 19th July 1963. It is interesting to note that besides the inversion near 750 mb level, an inversion or layer of stable lapse is also noticed in the tephigrams of the soundings over Bombay. The mid-tropospheric inversion appears to originate from divergence and subsidence at the upper tropospheric levels.

In discussing the thermal and humidity structure of the lower levels over the Arabian sea, Sikka and Mathur (1965) have concluded on the basis of the IIOE data that spectacular changes occur east of 70°E where the low level inversion disappears completely and the entire column from the surface to 500 mb becomes nearly saturated. This is an over simplification of facts and would appear to be true only for situations of good rainfall and convective activity. There are periods when such activity is weak either along the whole of the west coast or over certain parts of the coast. On such occasions the depth of moist layer may not exceed 2 or 3 km and inversions similar to those observed at Bombay can be expected to be present along the west coast.

REFERENCES

COLON, J. A. 1964. On Interactions between the Southwest Monsoon Current and the Sea Surface over the Arabian Sea. *Ind. J. Met. and Geophys.*, **15** : 183-198.

——— 1964. On Interactions between the Southwest Monsoon Current and the Sea Surface over the Arabian Sea. *Proc. Symp. Trop. Met.*, Rotorua, New Zealand, 5-13 Nov., 1963.

DESAI, B. N. 1966. Why little rain over west and north Arabian Sea and over and around West Pakistan heat low during the Southwest Monsoon Season. *Ind. J. Met. and Geophys.*, **17** : 399-400.

——— 1970. Synoptic Climatology of the Indian sub-continent. *Met. and Geophys. Rev.*, No. 2 (*Ind. Met. Dept.*).

Note.—References to several papers published by Dr. Desai can be found in this Review.

MATHUR, M. B. 1965. Some Remarks on the Distribution of Wind, Temperature and Humidity over the Southwest Arabian Sea. *Proc. Symp. Met. Results of IIOE*, pp. 118-124.

PISHAROTY, P. R. 1965. Evaporation from the Arabian Sea and the Indian Southwest Monsoon. *Ibid.*, pp. 43-54.

RAO, Y. P., SRINIVASAN, V., RAMAN, S., and RAMAKRISHNAN, A. R. 1970. Southwest Monsoon—Active and Weak Monsoon over Gujarat State. *FMU Rep. No. III-3.1*.

RIEHL, H. 1954. *Tropical Meteorology*, pp. 376-378.

SIKKA, D. R. and MATHUR, M. B. 1965. Transport of Water Vapour over Arabian Sea and adjoining Indian Region during an active monsoon situation. *Proc. Symp. Met. Results of IIOE*, pp. 55-67.

DISCUSSION

DR. JAYAMAHA : Over Colombo, too, we have a dry layer over the first 2 km or so during ordinary monsoon conditions. During such periods the rainfall consists of 'passing showers' from shallow clouds. When this dry layer is penetrated during disturbed weather, we have heavier and more widespread rainfall over the affected area.

DR. ANANTHAKRISHNAN : This is indeed very interesting and is in conformity with what we find at Bombay and other Indian stations.

DR. SAHA : Did you consider correlation of actual rainfall with the different types of vertical profiles of temperature and humidity shown by you ?

DR. ANANTHAKRISHNAN : As already mentioned by me, good rainfall occurs always in association with situations when the atmosphere is nearly saturated up to high levels and the low level inversion is absent. Small amounts of rainfall which Bombay gets almost daily during July and August are associated with situations in which the depth of the moist column does not exceed 3 km with inversion and dry air immediately above the moist layer.