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Some Aspects of Tropical Meteorology with special reference to the Indian Weather--An examination of Malurkar's concepts regarding them

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ABSTRACT. In this article an examination has been made (with special reference to the Indian weather) of Malurkar's concepts regarding some aspects of Tropical Meteorology discussed in a series of notes published by him. Approximate normal positions of the ITF between Longs. 50°E and 100°E during different months have been given and it has been shown that it is not invariably necessary to have all the three air masses *Em*, *Tm* and *Tc* for the formation of tropical depressions or cyclones, and that they move sometimes northeastwards even when *Em* air is present in the field of the disturbances. *Tm* air cannot be present in the lower levels in the monsoon season over India to the north of about Lat. 18°N due to the presence of high mountains to the east. While there is no objection to the view that at times waves in the 'Trades' move westwards towards and close to the equator, there is difficulty in accepting the view that 'lows' move across the equator from one to the other hemisphere carrying *Em* with them. The factors responsible for the transport of *Em* air across the equator during the southwest monsoon season have been discussed. It is shown that the presence of cyclones in the southern hemisphere is not necessarily likely to affect the activity of the western disturbances. Heavy rain in connection with tropical depressions and cyclones in India is not ordinarily associated with the turning of *Tm* towards the north coupled with a fresh supply of *Tc*; it is caused as a result of the steep slope of the front at which moist air ascends and also actually turns southwards in the case of the disturbances moving west or northwestwards, in addition to the influence of orography, which is predominant in some cases.

During 1947 and 1948 S. L. Malurkar published a series of notes in the Current Science [1,2,3] about various points dealt with in his pamphlet on "Forecasting Weather in and near India"[4]. It is proposed to examine in this article the validity of some of the important conclusions of Malurkar on the basis of (i) the normal charts for the Indian area published by I. Met. D.[5], (ii) the charts prepared by Inst. Cdr. Pendal[6] and (iii) other published papers.

1. The Inter-Tropical Front during the year

In Fig. 1 are given the approximate normal positions of the Inter-Tropical Front (ITF) at the surface as determined from the normal winds. It may be mentioned that, except in the monsoon months June to September, there are trades (from the summer hemisphere) and recurved trades (from the winter hemisphere) on the two sides of the ITF. During the monsoon season the ITF consists of three sections. Over the Arabian Sea, winds to the south of ITF are from the winter hemisphere (recurved trades—*Em* air mass) and to its north are the westerlies of the middle latitudes which have travelled over southwest Asia and have been brought into the circulation around the monsoon low (*i.e.* *Tc*—continental air as modified in the lower levels due to travel over colder sea surface). Over the Bay of Bengal to the south of ITF there will be both *Em* entering directly into the south Bay and *NEm* *i.e.* *Em* from the Arabian Sea which has travelled across the Peninsula and got modified in some of its properties. Over the Indian subcontinent, there will be *NEm* (modified *Em* from the Arabian Sea side and *Em* which has entered directly into the south Bay but has also got modified in some of its properties during its travel overland after crossing coast) to the south of ITF, while to its north except towards the northwest, there will be mostly the old monsoon air, *i.e.*, the mixture of *NEm* and *TmS* which is Tropical Maritime air (Tm)* from the Far East which has subsided due to high mountains towards the

**Tm* air has its source in the "high" in the north Pacific Ocean. Malurkar[2] has designated tropical air from the Far East as *Tr*, but this has been designated as *Tm* in the present article, following the convention adopted by a majority of the Indian Meteorologists.

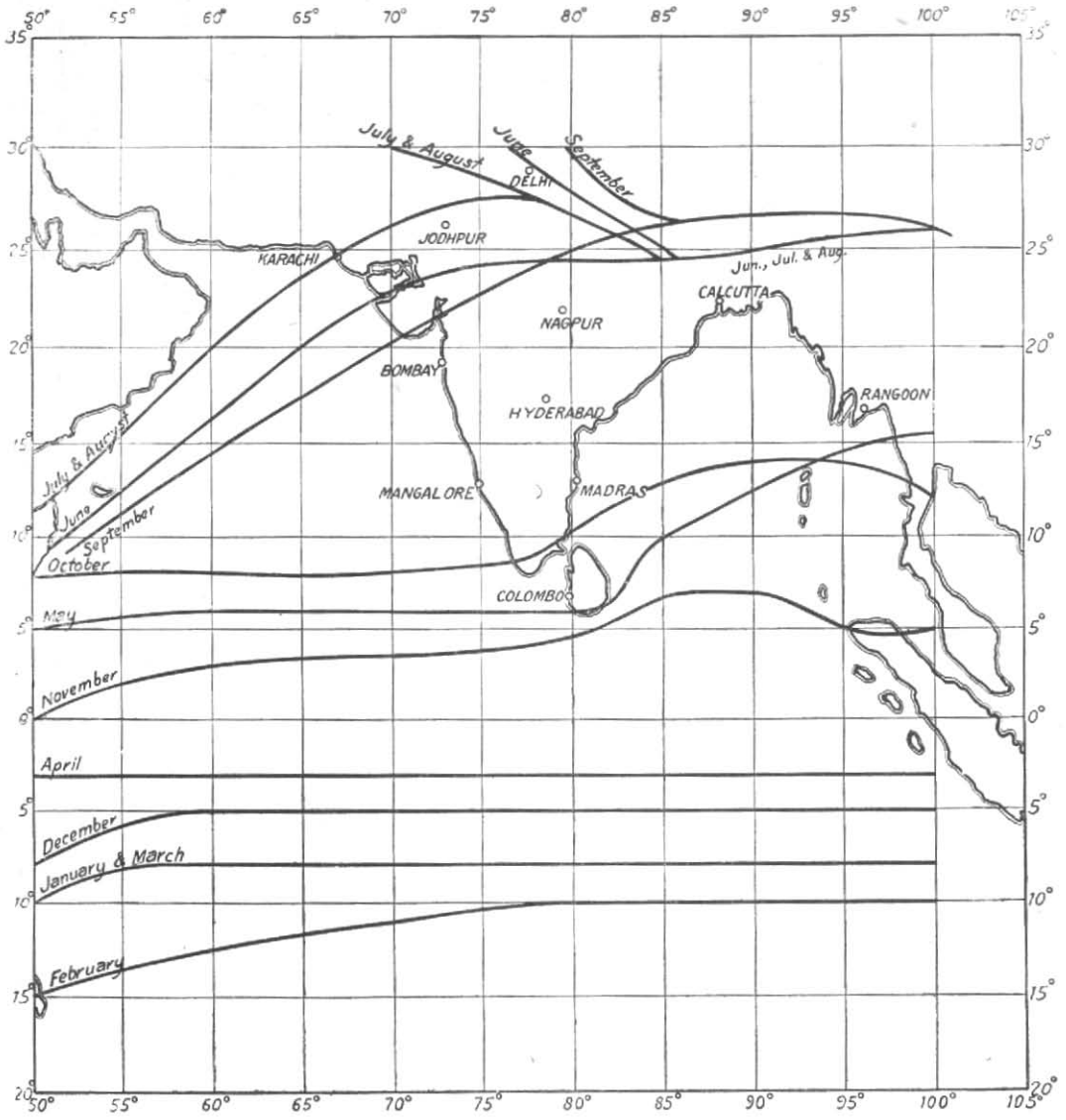

Fig 1. Chart showing the Inter-Tropical Front over India and its neighbourhood and Indian Ocean

east and north. Over northwest India and neighbourhood there is between the *NEm* air to the south of ITF and the old monsoon air (mixture of *NEm* and *TmS*) to its north, hot and dry *Tc* air from west or northwest. Pure *Tc* air mass is normally absent over the north Bay of Bengal and northeast India during the monsoon season except during "breaks" in monsoon or when the setting in of the monsoon is delayed or when there is an early withdrawal of the same. The position of ITF at the surface during the southern summer and the northern summer as given here corresponds roughly with the

position of the same given by Bjerknes and Berjeron and by Petterssen[7] except for the position east of about Long. 67° E for which they have not shown ITF over India during the northern summer.

2. ITF and its Structure

Mulurkar [1] has stated that three air masses —(i) Equatorial Maritime air *Em* from the other hemisphere, (ii) Far Eastern Transitional or mixed air *Tr* (*i.e. Tm*) and (iii) Continental air *Tc* and occasionally Polar continental air *Pc*—are required for the formation of depressions and cyclones in the Indian area. According to him no tropical depressions usually form and only low pressure areas result, in the absence of one of the three air masses. If *Em* is withdrawn due to a cyclone in the southern hemisphere, the disturbance will die or weaken and move northeastwards like an extra-tropical cyclone. As long as supply of *Em* is maintained, the disturbance moves in a westerly direction.

According to Malurkar[1], with the three air masses which go to determine tropical weather, it is hardly possible to represent the semi-stationary conditions by a single front as ITF. He has shown two partitions between *Tm* and *Tc* or *Tcm*, one running north from about Lat. 21° N along about Long. 71° E and the other also running north from about Lat. 21° N along about Long. 90° E; from these points partitions between *Em* and *Tm* have been drawn extending southeastwards to places about Lat. 14°N, Long. 75°E and about Lat. 10°N, Long. 100°E respectively. Partitions between *Em* and *Tc* or *Tcm* are shown to run southwestwards from the points.

The following noteworthy features of the normal conditions and facts may be mentioned in this connection—

(*i*) Tropical depressions and cyclones are not frequent in the south Indian Ocean during the months May to October; they however do form in the Indian seas, their frequency being relatively much less in the Arabian sea when compared with the Bay of Bengal. The position of ITF as given in Fig. 1 is to the north of the equator during all these months. One can, therefore, assume that the recurved trades air mass *Em* from the southern hemisphere and *Tc* can be present in the tropical depressions and cyclones. *Tm* from the east can also be present in the cyclone field except for the fact that during the months June to September there will be mixture of *NEm* and *TmS* air masses in the lower 2 to 3 km due to mountains to the east [8,9] as mentioned earlier; during the monsoon season *Tm* can thus ordinarily be present only above about 2 to 3 km in the cyclone field.

(*ii*) During November when ITF is within about Lat. 5°N of the equator over most of the Indian sea area and in April when it is within about Lat. 3°S of the equator, tropical depressions or cyclones form both in the Indian seas and the south Indian Ocean. Conditions are favourable for transport across the equator of the trades (*Em*) from one hemisphere to the other, and as such, *Em* can be present in the tropical depressions and cyclones which form both to the south and north of the equator in the Indian Ocean. *Tc* and *Tm* can also be present in the cyclone field.

(*iii*) During the months December to March when ITF is about 5° or more to the south of the equator, tropical depressions and cyclones form in the south Indian Ocean. In the Indian seas practically no tropical depressions and cyclones form during February, although they do form in the other winter months between about Long. 80° and 93° *E* and between Lat. 5° and 12° N, the number in December being the largest. ITF being about 5° or more to the south of the equator, there are ordinarily relatively less chances for the trades (*Em*) of the southern hemisphere to enter the cyclonic circulation in the Indian seas. There will be, however, *Tc* or *TcTm* air masses and relatively warmer and more moist *Tm* air mass from the east over the Indian seas.

(*iv*) During the monsoon months, particularly, during July and August, there are occasions when there is one depression over Madhya Bharat, southeast Rajasthan or north Gujarat and another depression forms at the head of the Bay of Bengal. In such cases there is no possibility of *Tc* in the cyclonic circulation over the head of the Bay of Bengal as the same is confined near and to the west of the earlier depression. The monsoon depressions can, therefore, have at the surface either *Em*, *NEm*, *NEm*+*TmS* (old monsoon air) and *Tc* or only *Em*, *NEm* and *NEm*+*TmS* or *NEm* and *NEm*+*TmS*.[8,9]

(*v*) There is evidence in the Indian charts that not only depressions but even cyclones developed with only two air masses and that as long as they moved west or northwestwards in the low latitudes, the feed was by *Tm* air right from the surface to 4 to 6 km, there being no trace of *Em* from the other hemisphere[10-13].

(*vi*) There are a number of cases where it can be traced that the recurvature or change in the direction of depressions and cyclones took place as a result of the feeding current *Tm* from the east having weakened and/or been replaced by *Em* or *TcTm* from west or southwest [10,12] (this is *Tc* in most cases which has travelled over the Arabian Sea, also over the Bay in the case of Bay cyclones and depressions) or by their coming under the influence of the prevailing westerlies, besides under the influence of the Western Disturbances.

(*vii*) Distribution of mountains and land and water in a peculiar manner also helps in the formation of cyclonic vortex as well as subsequent movement[8,9].

(*viii*) From Fig. 1 which has been prepared on the basis of the normal charts[5] as stated above, it will be seen that the partitions between the various air masses during June which have been shown by Malurkar to meet at the two points near about Lat. 21°N, Long. 71°E and Lat. 21°N, Long. 90° E cannot be accepted. It is not clear how he has stated that the partitions have been drawn by him on the available climatic information.

3. Movement of low pressure areas across Equator

Malurkar[1,2,4] has stated that a series of low pressure areas (also called pulses) moving west or northwestwards just south of the equator cross into the northern hemisphere and give rise to *Em* there. The low pressure areas could, according to him, be traced to the northern side of the " high " over the south Atlantic in the southern winter; in the northern winter the southern side of the " high " in the northern Pacific Ocean acts as a source of the westward moving low pressure areas. The time interval for the low pressure areas to reach the Indian area during the southwest monsoon season after crossing the equator is supposed to be about 30 to 45 days. If there is a tropical depression in the south Indian Ocean, the low pressure area will not cross the equator but move away westwards and there will be a " break " in the monsoon of the other hemisphere; the same result will also follow if extra-tropical cyclones of the winter hemisphere are fed by its trades.

The following points may be mentioned regarding the above conclusions of Malurkar—

(*i*) It has been recognised by the majority of Indian Meteorologists since long that the southwest monsoon is caused by the transport of air across the equator from the southern hemisphere [14].

(*ii*) There cannot be any objection to the acceptance of the idea about the movement at times west or northwards of the low pressure waves in the southeast trades to the south of the equator in the southern winter. Presence of such waves fairly close to the equator in the southern hemisphere and their position and intensity will determine which part of the Indian seas is to have bulk of the *Em* current on such occasions. One also finds occasionally low pressure waves from the east moving towards west across the south of Bay and the southeast Arabian Sea to the north of the equator in the northern winter. But one cannot accept the view that the low pressure waves (or areas) cross the equator from one hemisphere to the other and carry *Em* air with them. From the charts of the Indian Ocean published by the London M.O.[6] in which are also available a number of ships observations south of the equator, one cannot find low pressure waves crossing the equator and carrying *Em* air to the other hemisphere along with them.

(*iii*) There is considerable evidence in the Indian Ocean charts[6] referred to above that the tansport of air across the equator into the Indian seas from the south is stimulated by the intensification of the permanent " highs " in the south Indian Ocean and a change in their orientation and position as a result of the migratory anticyclones of the middle latitudes in the rear of the extra-tropical cyclones in that hemisphere and of the influence of the associated cold fronts which induce surges or waves in the southeast trades accompanied with pressure, wind and weather changes.

(*iv*) From the normal winds and isobaric charts of the Indian Ocean area [5] it is seen that the pressure gradient over the east

coast of Africa upto British Somaliland and in the adjoining sea area to the east is well-marked when compared with that between about Long. 60° and 100° E, particularly between about Lat. 5°S and 5°N; in the south Indian Ocean isobars run southeast to northwest to the east coast of Africa. This probably facilitates transport of air across the equator in the summer hemisphere under the influence of (*iii*) above and of the position and intensity of the Indian monsoon low, and of the "high" in the north Pacific Ocean. If the isobars run east to west in the south Indian Ocean to the south of the equator instead of southeast to northwest, conditions become adverse for the transport of air across the equator and consequently for the activity of the southwest monsoon in the Indian seas.

It has been shown by Koteswaram [15] that when the monsoon is feeble or there is a " break " in it, low pressure waves in the upper air move from east to west across the south Bay and south Arabian Sea. On such occasions upper winds over northern and eastern India and upper Burma are westerly, the easterly winds being absent sometimes even above 6 km. Some of the factors presumably responsible for these abnormalities are (i) more southerly position than usual of the " high " in the north Pacific Ocean, causing shifting to more southerly latitudes of the easterly air (*Tm*) originating from it; (ii) more northerly tracks than usual of the Western Disturbances, pushing the monsoon trough into the hills; and (iii) lows over China in the neighbourhood of Indian and Burmese frontier. These factors will be responsible for the westerly winds over northern and central India and upper Burma during the periods of " breaks "in monsoon.

(*v*) From the climatological charts it is difficult to see how low pressure areas or their secondaries will travel all the way from near south America to the Indian longitudes, a distance of about 15,000 miles, without being modified or filling up. On the contrary from the charts of Pendal[6] as well as the Indian climatological charts[5], it is seen that the origin of the monsoon air which enters the Indian area across the equator might not be in longitudes further east of Australia. This view also finds support in a paper by Hogan [16].

4. Depressions to the south of Equator and Western Disturbances of India

It has been stated by Malurkar[1] that, if there is a tropical cyclone or depression moving from east to west south of the equator but not too far south in the south Indian Ocean, lower secondaries of the Western Disturbances either will not be formed or will be ill-defined over northwest India and produce scanty rain. He[2] has also inferred that two tropical cyclones or depressions cannot continue to move westwards and co-exist on either side of the equator when the longitudinal separation is small (about 10°).

The following observations may be made regarding the above —

(*i*) From the charts issued from the London M.O.[6], it is seen that during February 1937 cyclones formed in the south Indian Ocean, one near about Lat. 13°S, Long. 65°E on 7 February 1937 and the other near about Lat. 14°S, Long. 67°E on 25 February 1937 but the secondaries of the Western Disturbances did develop within about 10° of Long. 65°E in and near India at about the same time and there was abundant precipitation over India in that month. One can also find a number of similar instances in the winter months in other years.

(*ii*) There is a zone of conditional frontogenesis extending from the Persian Gulf to the north Bay where secondaries can develop [17]. If the passage of the Western Disturbances coincides with the stimulation of the northeast monsoon in the south Bay, the south of the Peninsula and the southeast Arabian Sea due to the passage of waves in the easterlies from east to west, the secondary of the Western Disturbances formed at the time generally gives considerable precipitation.

(*iii*) The main reason for the failure of winter rains is to be traced in the intensity and the tracks taken by the primary Western Disturbances[17,18]. If the temperature contrast between the air (*Pc* or *NPc* or *PcTc*) brought in the rear of the primary disturbances and the *TcTm* or *Tm* air is not appreciable and the primary is weak or the track of the primary is too far north and the *TcTm* or *Tm* air cannot come in contact with the cold air in its rear, the secondaries will not form or will be weak even if formed and there will be very little rain over the Indian area.

(*iv*) The mere coincidence of a cyclone in the southern hemisphere weakening or dying when there is a cyclone in the northern hemisphere or *vice versa* cannot be taken as an evidence of the impossibility of the co-existence of the two cyclones unless the progress of the air masses, taking part in the cyclone field on both the sides of the equator, is followed from day to day by locating fronts associated with them and one takes into consideration all other relevant detailed information in both the hemispheres. This has not been done by Malurkar.

5. Heavy rain during depressions and cyclones

Bending back of *Tm* towards the north coupled with a fresh supply of *Tc* gives rise, according to Malurkar[1], to heavy or abnormally heavy rain when monsoon depressions do not travel much further west and are almost filling up; abnormally heavy rain in east Gujarat, southeast Rajputana etc. in connection with monsoon depressions has been sought to be explained by him on this basis. It is also stated that heavy rain which usually develops along a sort of front extending from SW to NE at the stage of recurvature of tropical depressions or cyclones is determined by the degree of abruptness with which *Tm* is bent back to a poleward direction.

Against the above, it may be mentioned that it is observed from the available charts that the heaviest falls of rain in southwest quadrant of the monsoon depressions moving west or northwestwards occur generally as a result of steep slope of the partition at which the warm moist air (*NEm*+*TmS* in the lower levels and *Tm* in the higher levels as stated earlier) is rising over the cold moist air (*Em* or *NEm*) [8,9,19,20]; there will also be considerable convergence in the southwest sector near the centre. In such cases there is no abrupt bending back of *Tm* towards the north; there is actually abrupt bending of *Tm* towards the south. The same thing can be said about heavy rain associated with depressions or cyclones in the non-monsoon months when they are moving west or northwestwards[10-13]. Heavy rain associated with depressions or cyclones during the stage of their curving to northeast [14,21] is due to steep slope of the partition at which the warm moist air is rising as well as due to considerable convergence near the centre. The upper winds and data from sounding balloons and aeroplane or radio-sonde ascents which have been discussed in some of the papers referred to above also support the above view and are against the inferences of Malurkar. The hills in the path of the disturbances will also play an important part in the production of very heavy rains.

6. General remarks

The following additional points may also be mentioned regarding some of the conclusions of Malurkar—

(*i*) Conclusions regarding conditions south of the equator upto Lat. 20° S between Long. 55° and 105° E are based on observations of the following stations—

Name of Station	Latitude	Longitude
Cocos Island ..	.. 12°05′ S	96°42′ E
Diego Garcia ..	.. 7°14′ S	72°26′ E
Addu Atoll ..	.. 0°41′ S	73°10′ E
Seychelles ..	.. 4°37′ S	55°27′ E
Agalega Island .. (available in 1945-46)	.. 10°30′ S	56°40′ E
Rodriguez ..	.. 19°41′ S	63°27′ E
Mauritius ..	.. 20°18′ S	57°30′ E
Reunion ..	.. 20°52′ S	55°27′ E

It will be seen that distance between Addu Atoll and Diego Garcia on the one hand and Cocos Island on the other is more than 1500 miles; similarly the same pair of stations and either Seychelles or Rodriguez or Mauritius are more than 800 miles apart. Any inference drawn from such distant observations cannot be accepted as reliable as it will not be possible to follow movements of air mass partitions or of low pressure waves/depressions and cyclones with any degree of certainty. Further, Addu Atoll being almost on the equator, its winds can get westerly component at times under the influence of the circulation round the Indian "monsoon low", while to its south there will be southeasterly winds circulating round the "high" in the south Indian Ocean. Under such circumstances, it will not be correct to infer that there is a "low" moving near about the station across the equator from the southern to the northern hemisphere. Similar arguments also apply to wind changes at other stations near the equator in both the hemispheres.

(*ii*) In connection with the tracing of the Far Eastern air *Tr* (or *Tm* as designated in this article), Malurkar and Pisharoty[3] have used the radio-sonde data of

Kweilin Lat. 25° 15′N Long. 110° 10′E
558 ft. a.s.l.

Chengtu Lat. 35° 15′N Long. 104° 02′E
1574 ft. a.s.l.

Yunnanyi Lat. 25° 25′N Long. 100° 44′E
6452 ft. a.s.l.

besides those of Lalmanirhat and Calcutta. It is stated by them " There is unmistakable incursion of fresh air mass from Kweilin on 28 June 1944 to Chengtu on 29th, to Yunnanyi on 2 July and to Assam and Bengal on 4 July 1944 " and " the thickness of the layer is about the same and occurs at the same height intervals ". It is difficult to understand their conclusion as they have not considered the effects of mountains (Yunnanyi is at a height of 6452 feet a.s.l.) across the path of the *Tm* air mass and of the Western Disturbances moving across north China and the actual speed of the air masses at different levels. Both Lalmanirhat and Calcutta are to the west of the hills and the effect of the hills near Yunnanyi are sure to be felt at least upto 10,000 feet a.s.l., and as such, it is incorrect to say that there will be *Tm* air over Calcutta and Lalmanirhat below about 10,000 feet, having about the same properties as when to the east of the said hills in the same layer, except for an increase in its temperature and moisture content due to travel near the thermal equator and over swamps and forests. The same arguments also hold good for the second case considered by them ; they have stated " the fresh air mass that was over Chengtu about the 6th October 1944 passed over Calcutta on the 12th to feed the Bay depression .....".

In the Table below are given wind directions and speeds at Calcutta on 3, 4 and 5 July 1944 and on 11, 12 and 13 October 1944, one day before and after the day *Tm* air is supposed to have come over Calcutta according to them on the above two occasions—

It will be seen from the table that upper winds over Calcutta on both 4 July 1944 and 12 October 1944 when air from Chengtu side is supposed to have come there, are from a direction other than east ; the synoptic charts also clearly show that the air which was over Calcutta and neighbourhood on both these days had come from west and not east of Calcutta. Under the circumstances, the inferences drawn by Malurkar and Pisharoty from the particular radiosonde ascents regarding arrival of *Tm* air mass from the east over Calcutta on 4 July 1944 and 12 October 1944 would appear incorrect.

7. Conclusions

1. It is not invariably necessary to have all the three air masses—*Em*, *Tm* and *Tc*—for the formation of tropical depressions or cyclones as they form even when there are less than three air masses. Orography

TABLE 1

Heights in Thousands of Feet A.S.L.

Date	Hours (IST)	1		3		5		7		10		15		20	
		*dd	vv	dd	vv	dd	vv	dd	vv	dd	vv	dd	vv	dd	vv
3. 7.44	0130	20	19												
	0830	22	10	25	08										
	1430	—		—											
4. 7.44	0130	—		--											
	0830	23	13	24	13	24	14								
	1430	36	03	24	12	26	12	26	15	29	08	29	05		
5. 7.44	0130	19	19	20	15	21	12	23	09	25	12				
	0830	22	14	22	15	25	10	26	12	25	10				
	1430	—		—		—		—		—					
11.10.44	0230	35	03	34	08	33	23	29	17						
	0830	—		—		—		—							
	1430	30	10	30	13	29	15	31	10	18	06	23	26	32	08
12.10.44	0130	35	07	30	02	18	11	22	06	15	04				
	0830	33	04	36	08	27	07	22	05	20	04				
	1530	31	06	28	02	22	03	24	14	21	12	20	11	23	12
13.10.44	0230	27	04	32	09	26	06	23	19						
	0830	—		—		—		—							
	1530	07	03	32	02	25	12	22	09	20	06				

*dd is the direction in degrees from north, thus 35 is 350°, 05 is 50° and vv is speed in knots per hour.

and distribution of land and water also play an important part in the setting up of cyclonic circulation and its subsequent movement in some cases. Tropical depressions and cyclones move northeastwards even when *Em* air mass is present in the field of the disturbances.

The positions of the partitions between the various air masses for June as given by Malurkar are not supported by the available climatic data.

In the monsoon months it is ordinarily not possible to have *Tm* air from the Far East in the lower levels to the north of about Lat. 18°N due to the presence of high mountains over China, Burma, Assam, and east Bengal although it will be there in higher levels ; in the lower levels over eastern India there will be old monsoon air *i.e.*, the mixture of *NEm* and *TmS*.

2. While there is no objection to accept the view that at times low pressure waves in the southeast trades move west or northwestwards to the south of and close to the equator, the passage of low presssure areas across the equator from one to the other hemisphere is not supported by available observations. The southwest monsoon is caused by the transport of air from the southern into the northern hemisphere under the influence of the normal pressure distribution, the transport of *Em* across the equator being stimulated by the intensification of the " highs " over the south Indian Ocean and south Africa and a change in their orientation and position as a result of the movement of the extra-tropical cyclones of the southern hemisphere. One has also to consider the influence of the " high " in the north Pacific Ocean, the Western Disturbances and the conditions over China besides other factors affecting activity of the southwest monsoon.

3. The presence of cyclones in the southern hemisphere is not necessarily likely to affect the activity of the Western Disturbances. The amount of rainfall over the northern India in the winter months depends ordinarily upon the intensity and the track of the Western Disturbances and the supply of the *TcTm* or *Tm* air which generally constitutes the warm sector.

4. Heavy or abnormally heavy rain in connection with tropical depressions and cyclones is not ordinarily associated with the turning of *Tm* towards the north coupled with a fresh supply of *Tc*. Heavy rain can occur not only when depressions or cyclones stop moving further west or are filling up but from the very moment the disturbances have formed, as a result of considerable convergence near the centre and the steep slope of the front at which warmer and more moist air is ascending besides the influence of orography.

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