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Influence of frontal systems moving across southern Africa and southwest Indian Ocean on the onset of southwest monsoon over west coast of India*

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सार — मई जून के महीनों में दक्षिणी अफ्रीका और निकटस्थ दक्षिणी-पश्चिमी हिन्दमहासागर के आर पार निचले क्षोभमण्डल में शीत-वाताग्रों और सम्बद्ध पश्चिमी तरंगों के संचलन की भारत के पश्चिमी तट पर दक्षिण-पश्चिमी मानसून की शुरुआत के सन्दर्भ में जांच की गई है। वर्ष 1971 तथा 1972 में उपग्रह से लिए गए चित्रों और वर्ष 1979 में मॉनेक्स से प्राप्त विस्तृत आंकड़ों के आधार पर यह अध्ययन किया गया है। पता चला है कि दक्षिणी अफ्रीका और निकटस्थ महासागरीय क्षेत्रों के आर-पार गहन शीत वाताग्रों का मार्ग भूमध्यरेखा के ऊपर के प्रवाह की शक्ति पर गहरा प्रभाव डालता है। इसके फलस्वरूप अन्त: क्षोभमंडलीय अपसरण जोन (आई० टी० सी० जेड०) के तीव्र गठन को बढ़ावा मिलता है और उसके उत्तर दिशा में गमन से दक्षिण-पश्चिमी मानसून की शुरुआत होती है। भारत के पश्चिमी तट पर दक्षिण-पश्चिमी मानसून की शुरुआत का 4 से 7 दिन पहले पूर्वानुमान करने के लिए इस सम्बन्ध की सहायता ली जा सकती है।

ABSTRACT. The movement of cold fronts with associated westerly waves in the lower troposphere across southern Africa and adjoining southwest Indian Ocean during the months of May and June has been examined in relation to the onset of southwest monsoon over the west coast of India. The study is based on satellite pictures for the years 1971 and 1972 and on extensive MONEX data for the year 1979. It has been found that the passage of deep cold fronts across southern Africa and adjoining oceanic areas exercise marked influence on the strength of the cross equatorial flow which in turn leads to the organisation and intensification of ITCZ and its northward advancement causing the onset of the southwest monsoon. This association can be used as an aid in forecasting the onset of southwest monsoon along the west coast of India 4 to 7 days in advance.

1. Introduction

The onset of southwest monsoon over India is a most significant seasonal change, as it marks the commencement of the rainy season, vital to the agricultural economy of the country. Ramdas *et al.* (1954) made an extensive statistical study of the dates of onset of the monsoon along the west coast of India during the 60-year period 1891-1950 and related the onset to a variety of parameters. They found that the standard deviation of the dates of establishment of monsoon along the west coast south of 20 N is 6 to 7 days. The earliest date was 17-22 days before, while the most delayed onset was 10-13 days after the normal date of 1 June. Studies relating to the onset of monsoon have been made by Yin (1949), Sutcliffe and Bannon (1954), Ananthakrishnan and Ramakrishnan (1965), Wright (1967), Ramaswamy (1971) and Rao (1976). Despite the extensive literature on the subject, prediction of the date of onset of monsoon still poses a difficult problem.

Malurkar (1958) postulated that shallow westward moving low pressure areas south of equator which he called "pulses" were responsible for the air stream crossing the equator from south to north which according to him, strengthen the monsoon current. Kumar (1980) has shown that in the southern hemisphere summer season frontal systems have considerable influence on the daily fluctuations in intensity and position of Inter-Tropical Convergence Zone (ITCZ) over Africa and adjoining oceanic areas. A northward displacement of ITCZ is noticed when the frontal systems move across southern Africa in quick succession.

The mean pressure distribution in the southern hemisphere in the month of July is shown in Fig. 1. This may be taken as representative for the months of May and June also.

During these months over southern Africa, there is a pressure trough with its axis running north-south over central parts and a pressure ridge also north-south oriented along the east coast. Though the basic flow is easterly, the trough-ridge system which generally extends upto equator, introduces a meridional component to the basic flow.

Johnson and Morth (1960) have shown that the pressure distribution with low pressure area to the north of the equator and high pressure area to the south is favourable for causing cross equatorial flow

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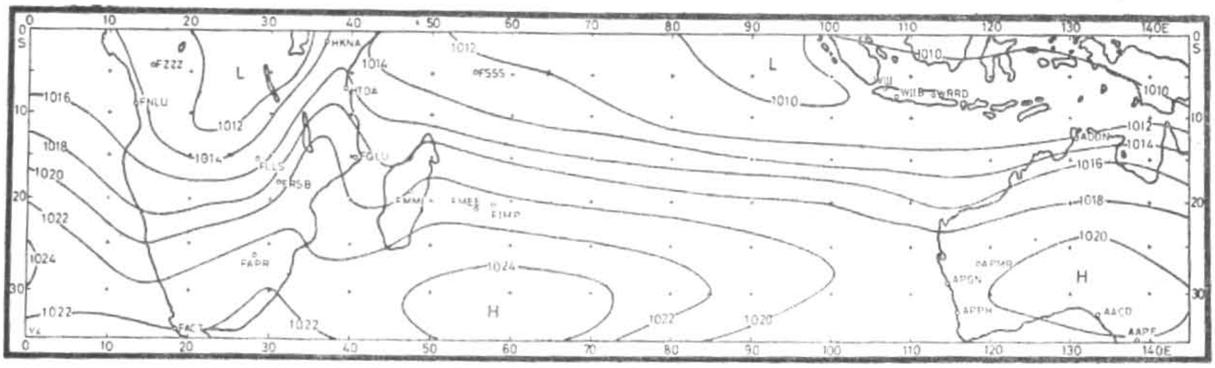


Fig. 1. Mean pressure at sea level in southern hemisphere in July (*after* Taljaard 1969)

TABLE 1 (a) — 1971

Cold fronts			ITCZ	
Cold front S.No.	Dates on which noticed	Northernmost latitude of penetration	Date	Position of ITCZ over Arabian Sea and west coast of India
I	17-20 May	10°S	1-18 May	Weak and disorganised
			19 May	5°S
II	21-22 May	5°S	20 May	ITCZ not discernible
			21 May	Do.
			22 May	Do.
III	23-25 May	10°S	23 May	Do.
			24 May	8°N
			25 May	11°N
			26 May	15°N
			27 May	16°N
			28 May	17°N
			29 May	18°N
V	30 May-1 Jun	18°S	30 May	19°N
			31 May	20°N
			01 June	21°N
V	2 Jun-6 Jun	15°S	02 June	22°N

TABLE 1 (b) — 1972

Cold fronts			ITCZ	
Cold front S. No.	Dates on which noticed	Northernmost latitude of penetration	Date	Position of ITCZ over Arabian Sea and west coast of India
I No cold front	06 May	5°S	Till 07 June	No clear ITCZ
II	08-10 June	7°S	08 June	2°N
			09 June	4°N
			10 June	5°N
			11 June	4°N
			12 June	4°N
			13 June	5°N
			14 June	6°N
			15 June	8°N
III	16-18 June	7°S	16 June	9°N
			17 June	10°N
			18 June	12°N
			19 June	15°N
			20 June	17°N
			21 June	19°N
			22 June	21°N
			23 June	22°N

and termed this as "Equatorial drift" (Fig. 2). On occasions when the pressure gradient becomes large, it leads to the cross isobaric explosive drift (jet) of air from south to north across the equator.

The most noteworthy surface synoptic feature of the region under study is the rythmic eastward movement of troughs and ridges across the south and east coasts of Africa. The associated pressure changes lead to weakening/intensification of the pressure ridge over southeast Africa and consequent decrease/increase in the cross equatorial flow from the southern hemisphere. The normal variation of pressure at 25 S along the southeast coast over periods of 4 to 7 days is from 1010 to 1025 mb, but extreme variation from about 1005 to 1035 mb occur once in a month or two (Taljaard 1972). Generally the sequence of changes in the pressure pattern in association with the eastward movement of frontal system across southern Africa lasts for about one week.

In the present study, an attempt has been made to investigate the influence of the frontal systems moving across southern Africa and adjoining southwest Indian Ocean on the cross equatorial flow and northward progression of ITCZ leading to the onset of southwest monsoon over the west coast of India. The ITCZ and its structure is a subject of some controversy. For the present study, the ITCZ has been taken as the zone of convergence between the northeast and the southeast trades of the two hemispheres and located in the trough of the *summer* hemisphere. This has been delineated on the surface charts by kinematic analysis of the windfield along the marked confluence line of the surface winds over Arabian Sea. There is also a trough in the *winter* hemisphere where the air from the same hemisphere flows around it.

2. Preliminary work

For the purpose of preliminary study, two contrasting years 1971 and 1972 were selected. The onset of

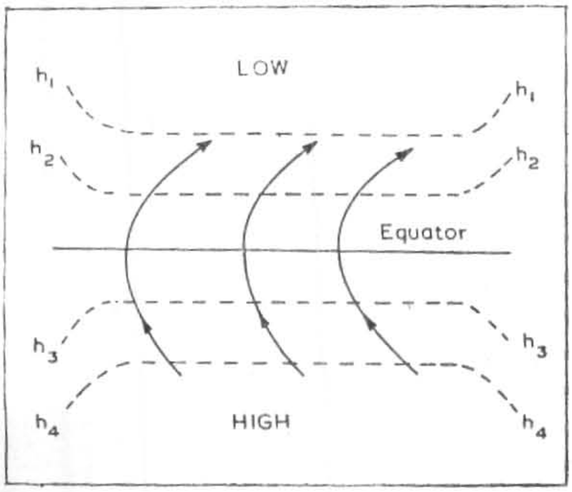


Fig. 2. Schematic representation of pressure distribution and flow associated with cross-equatorial 'drift' (Johnson and Morth 1960)

southwest monsoon over the west coast of India in the year 1971 was early by 7-10 days while it was late by 15 to 20 days in 1972.

From an examination of the satellite pictures for the month of May and June for these two years, the details of cold fronts and the position of ITCZ were noted and are presented in the Tables 1 (a) & (b).

From the table, it may be seen that in 1971, there were a number of cold fronts which passed across the area under consideration in the second fortnight of May and the monsoon set in earlier by 7-10 days along the west coast. In the year 1972, however, there was a conspicuous absence of cold fronts in May and upto 7 June and the monsoon was delayed by 15-20 days. This association was further examined for the year 1979 based on MONEX data.

3. Onset of monsoon in 1979

The monsoon set in over Kerala on 11-12 June and steadily advanced northwards and covered the entire west coast (upto Gujarat) by 21 June. The onset of monsoon during this year was delayed by 12 days.

3.1. *Data and analysis*

During the Arabian Sea phase of Monex 1979 in May and June, extensive data were available over Arabian Sea and southwest Indian Ocean. The synoptic surface and upper air charts for 1200 GMT were constructed utilising the data from all observational platforms. Though most of the research flights were carried out between 0500 and 1100 GMT, yet to increase the data coverage, the non-uniformity in time of 1 to 7 hours was neglected. The surface charts were extended upto 45 S by incorporating the data supplied by the Zambia Meteorological Department.

3.2. *Pressure index*

The maximum pressure at 1200 GMT between 25 S and 30 S along southeast coast of southern Africa was taken as an index to measure the intensity of the south to north pressure ridge along the east coast of southern Africa. The daily values of the above index were worked out for the months of May and June 1979.

3.3. *Air and water transport*

The computations of fluxes of air and water vapour were made before the onset of the monsoon (7 June 1979) and during its advance over the west coast of India (12, 15 & 17 June 1979) utilising the following formulae :

$$\text{Air transport} = 1/g \int_p \int_s V(P,S)\, dp\, ds$$

and watar vapour transport

$$= 1/g \int_p \int_s V(P,S)\, q\,(P,S)\, dp\, ds.$$

where S is the length along the boundary (meridional/latitudinal), q = Specific humidity and V= Wind speed normal to the boundary. The two parameters for each 100 mb layer from 1000 mb to 500 mb in the vertical for every 2 degrees of latitude in the horizontal were computed. The zonal and meridional transports of air and water vapour have been worked out across each meridian, 5 degrees apart, between 55 E and 75 E.

4. Synoptic features of the region in May & June 1979

(i) *May* 1979 — Six cold fronts traversed across southern Africa, the Mozambique channel and adjoining south Indian Ocean. Their details are enumerated below :

S.No. of cold front	*Period of its passage*	*Northern-most Lat. (°S) of penetration*	*Intensity*	*Intensity at rear anticyclone*
1	1-3 May 79	24	Feeble	No rear high
2	3-8 May 79	19	Deep	1034 mb
3	11-13 May 79	22	Feeble	1027 mb
4	17-20 May 79	24	Do.	1026 mb
5	21-27 May 79	22	Moderate	1028 mb
6	28 May-1 Jun 79	20	Feeble	1025 mb

It will be seen from the above that except for one cold front from 3 to 8 May '79, all other fronts were either feeble or of moderate intensity and did not penetrate in sustained strength north of 20 deg. S. The associated rear anti-cyclones were also not intense, the central pressure being less than 1030 mb.

During this month, the ITCZ was also weak and disorganised. Its position fluctuated between 2° N and 4° N during the first fortnight and between 3° N and 6° N during the second fortnight.

(ii) *June 1979* — During this month, 5 cold fronts were noticed over southern Africa and south Indian Ocean and their details are given below :

S.No. of cold front	*Period of its passage (Dates Jun 79)*	*Northern-most Lat. (°S) penetration*	*Intensity*	*Intensity(mb) of rear anti-cyclone*
1	4-7	26	Feeble	1024
2	8-17	20	Very deep	1040
3	18-22	22	Moderate	1030
4	21-23	23	Do.	1030
5	23-29	20	Do.	1030

From the above table it may be seen that the very deep cold front on 8 June '79 was prolonged and sustained and was followed by 3 other moderate cold fronts in succession. The movements of this deep cold front and associated displacements of Indian Ocean

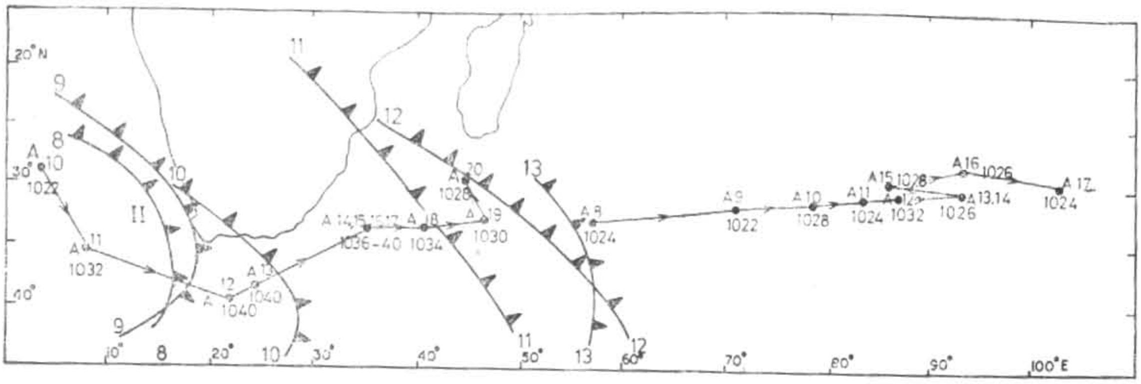
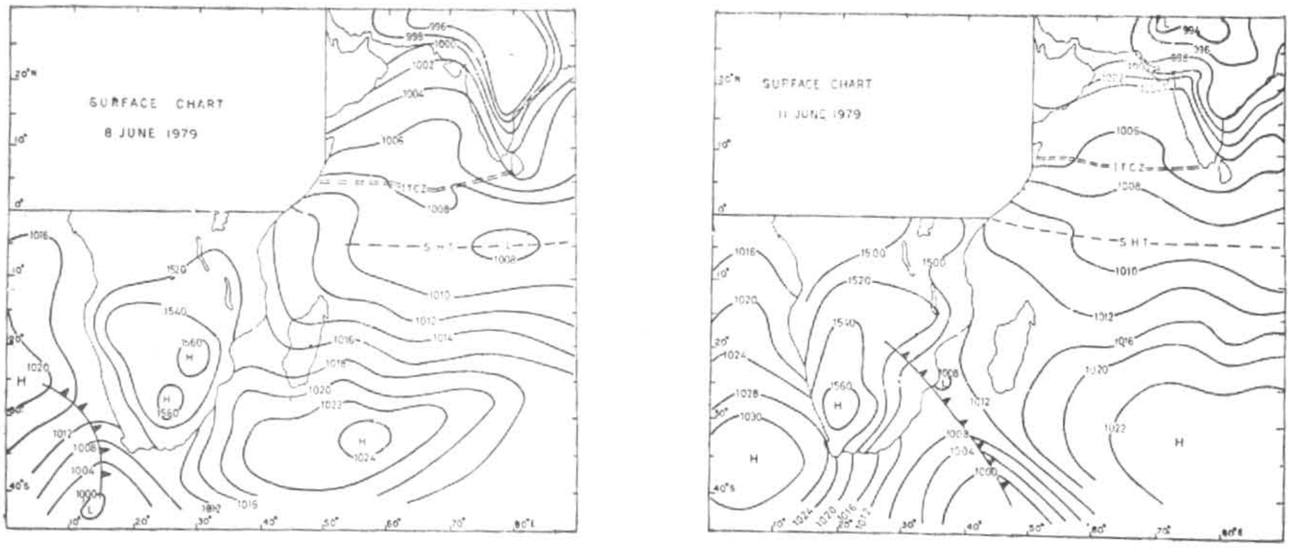


Fig. 3. The position of the cold fronts and centre of the anticyclones with central pressure from 8 June to 17 June 1979



(a) 8 June 1979

(b) 11 June 1979

Figs. 4 (a&b). Surface synoptic chart for 1200 GMT

Fig. 4 (c). Surface synoptic chart — 14 June 1979

Anticyclone (IOA) and Atlantic Ocean Anticyclone (AOA) are shown in Fig. 3.

In association with the deep cold front of 8 June 1979, the ITCZ organised, intensified and advanced northwards, ushering in the onset of monsoon along the west coast of India.

The passage of this deep frontal system across southwest Indian Ocean and the relevant sequence of events that occurred in association with this front are detailed below.

5. The movement of deep frontal system and advance of ITCZ

After the passage of the first cold front between 4 & 7 June 1979 which was feeble, the second cold front was seen approaching the west coast of southern Africa at 1200 GMT on 8 June. Under the influence of the frontal system the pressures started rapidly falling over south Africa and the pressure ridge over southeast Africa weakened, considerably. The Indian Ocean Anticyclone (IOA) was located near Lat. 33 S and Long. 55 E with central pressure of 1024 mb.

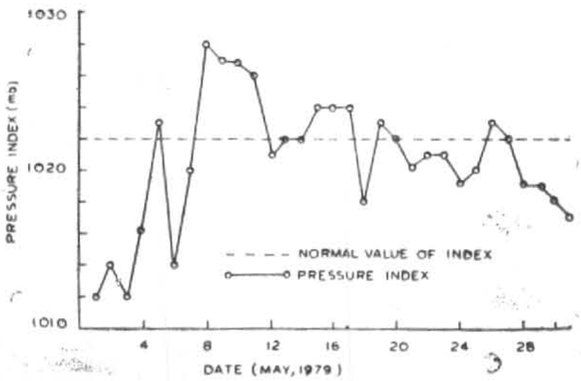


Fig. 5. Index for the intensity of pressure ridge for May 1979

The ITCZ was seen near Lat. 6 N and it was not well organised (Fig. 4a). The cross equatorial flow was also weak.

During the next 24 hours, the cold front was still slowly approaching the west coast of southern Africa but had deepened *in situ*. The pressure ridge over southeast Africa had disappeared. The IOA had weakened (1022 mb) and moved further eastwards to (65 E and 70 E). The ITCZ was still weak around Lat. 6 N.

On 10 June the cold front was seen over the Cape province of South Africa. Rapid pressure falls were noticed over southern Africa south of Lat. 15 S. The IOA had further moved eastwards by about 5 deg. of longitude. The ITCZ continued to be weak and along 6 N. During the next 24 hours, the cold front moved rapidly eastwards and at 1200 GMT on 11 June 1979 it was trailing over south Mozambique (Fig. 4b). A high (1030 mb) in the rear of the front had now started ridging over southwest coast of southern Africa, causing rapid pressure rises there. The pressure ridge over southeast Africa was seen reforming and the ITCZ was also getting itself organised around 7 N-8 N.

At 1200 GMT on 12 June, the front was moving across the Mozambique channel and large pressure rises were occurring over south Africa. The rear high had intensified (1040 mb) and located at Lat. 38 S, Long. 22 E. The pressure ridge over southeast Africa was rapidly strengthening. An increase in cross equatorial flow was also noticed. The ITCZ had become organised and moved to 9 N. The strength of the surface westerlies over south Arabian Sea between Lats. 4 N and 7 N was 40 kt and the depth was upto 500 mb.

On 13 June the rear high was still intense (1040 mb). It was situated over south of the Cape with a strong ridge over southeast Africa. Surface cross equatorial flow of the order of 20/25 kt was seen. The ITCZ had further organised and lay between 9 N & 10 N. A trough of low was seen forming over Laksha Dweep and adjoining southeast Arabian Sea embedded in the organised ITCZ which is a normal feature.

By 14 June, the cold front had slipped away southeastwards and the rear high (1036 mb) moved into southwest Indian Ocean, southeast of south Africa. The pressure ridge over southeast Africa had further strengthened (1035 mb). The cross equatorial flow more than 20 kt was maintained. The ITCZ appeared to have further intensified and moved to 11 N. The strength of surface westerlies over south Arabian Sea further increased to 50 kt and depth was now upto 400 mb. The trough of low had concentrated into low pressure area off the Kerala-Karnataka coast (Fig. 4c).

During the next three days, the high pressure area over southwest Indian Ocean continued to be intense (central pressure between 1036 and 1040 mb) and practically stationary. Thus, the strong pressure ridge over southeast Africa was maintained. The cross equatorial flow was seen steadily increasing during this period resulting in the increase in surface strength of the westerlies (75 kt) and their depth upto 300 mb over south Arabian Sea, on 17 June. The ITCZ also maintained its steady advance northwards from 11 N to 16 N. The low pressure area became well marked by 15 June, concentrated into depression on the morning of 16 June and into deep depression by 17 June.

The third frontal system of the month was seen at 1200 GMT on 18 June approaching the west coast of southern Africa. The pressure started falling over south Africa. As a result, the pressure ridge (1030 mb) and the high over southwest Indian Ocean (1032 mb) weakened only slightly. The deep depression moved westnorthwestwards and became a cyclonic storm. The ITCZ continued its northwards progress and advanced to 17 N. During the next 24 hours the front was seen slipping southeastwards south of the Cape, thus causing only slight weakening of the high over southwest Indian Ocean (1028 mb). The high in the rear of the front was also of central pressure 1028 mb. There was slight decrease in the cross equatorial flow. The ITCZ had advanced to 18 N. The cyclonic storm moved rapidly westnorthwestwards. The high over southwest Indian Ocean remained weak upto 20 June. The strength of westerlies reduced to 35 kt and depth was now upto 400 mb only. The rear high associated with the third frontal system moving eastwards merged with the high over southwest Indian Ocean resulting in its gradual intensification by 21 June (central pressure 1032 mb). The ITCZ had by now moved to Gujarat (22 N) and the monsoon covered the entire west coast of India by 21 June.

6. The intensity of pressure ridge over southeast Africa and northward progression of ITCZ

The association between the passage of cold fronts and the northward movement of ITCZ is better seen from the daily variation of the index for the intensity of pressure ridge over southeast Africa. The index for May and June 1979 is shown in Figs. 5 & 6 respectively. In Fig. 6, the daily position of ITCZ has also been plotted.

The normal intensity of the pressure ridge is 1022 mb. It may be seen that in the month of May, there was considerable variation in the pressure index in the first fortnight and insignificant fluctuation in the second fortnight. The ITCZ, therefore, remained weak and disorganised during the month.

However, in June, the pressure index fell rapidly from the normal value on 7 June to 1005 mb by 10 June. Thereafter, it rapidly increased to 1036 mb

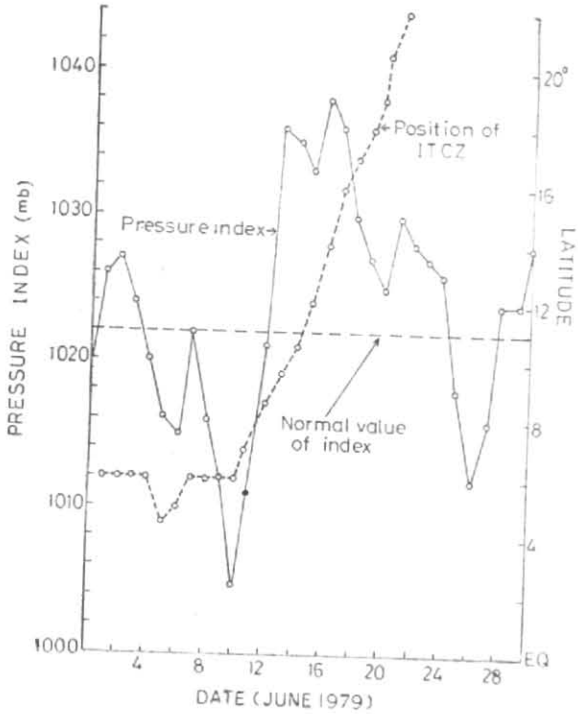


Fig. 6. Index for intensity of pressure ridge and advance of ITCZ during June 1979

by 13 June and continued to be high upto 17 June, with slight weakening between 18 and 20 June. It will be evident from Fig. 6 that the increase in the pressure index is followed by a northward progression of ITCZ.

7. Discussion and conclusions

The passage of moderate/deep frontal systems across southern Africa followed by intense Atlantic Ocean anticyclone and period of sustained strong pressure ridge over southeast Africa determine the strength of cross equatorial flow into south Arabian Sea and south Bay of Bengal leading to organisation of ITCZ.

The following salient features emerge from this study :

(*i*) During the period of movement of the frontal systems from the west coast of south Africa to the Mozambique channel, pressure ridge over southeast Africa remains weak or disappears for 2-3 days, leading to a decrease in the cross equatorial flow. Along with the frontal system, the IOA also moves eastwards from Long. 55 E-60 E to Long. 80 E-85 E in two to three days and its contribution to the cross equatorial flow into Arabian Sea becomes insignificant. The ITCZ, therefore, remains weak/disorganised. With the further eastward movement of the frontal system across the Mozambique channel, the Atlantic Ocean anticyclone crosses into southwest Indian Ocean and stagnates over oceanic area south of Malagasy, establishing the pressure ridge again.

(*ii*) Within 24 hours of the strengthening of the pressure ridge and increase in the cross equatorial flow, the ITCZ intensifies abruptly and begins to move northwards. At the same time, a low pressure area forms in the zone of ITCZ and gradually concentrates into a depression due to increase in horizontal shear and resultant cyclonic vorticity. As this system intensifies and moves northwards, the onset of monsoon occurs over the west coast of India.

(*iii*) If the southern hemisphere cold fronts follow in quick succession (3-4 days) such that before the first frontal system moves across the Mozambique channel, the next one approaches the west coast of southwest Africa, the pressure ridge is not maintained and as a result the cross equatorial flow is also not sustained. Under such conditions, their effect on ITCZ is insignificant.

(*iv*) The absence of frontal systems of moderate and strong intensity in the second fortnight of May, can lead to a delay in the onset of the monsoon.

(*v*) In association with the movement of deep frontal systems, the intensity of pressure ridge can vary by 10-15 mb in 24 hours. However, with a moderate system, the variation of 6-9 mb from the mean pressure (1022 mb) can occur and is considered significant for increase or decrease in cross equatorial flow.

(*vi*) The sequence of changes in the intensity of pressure ridge over southeast Africa in association with the passage of frontal systems lasts for about seven days and is generally broken with the approach of another frontal system from the west. The variation of pressure index may serve as a useful parameter for the prediction of the onset of the monsoon over Kerala and rest of the west coast four to seven days in advance.

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