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Interaction of upper westerly waves with intertropical convergence zone and their effect on the weather over Zambia during the rainy season

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ABSTRACT. Intertropical convergence zone (ITCZ) is normally established over central Africa between 10°S and 20°S during southern hemispheric summer season and is the main feature of general circulation responsible for the rainfall over this region. The eastward moving upper level troughs in the westerlies have a considerable influence on the systems in the lower level easterlies and thus directly or indirectly affect the rainfall patterns over the central Africa.

In the present study the various types of interactions between upper westerly waves and intertropical convergence zone that are noticed on examination of five years of synoptic charts have been discussed and illustrated by presenting typical case studies. A climatology of the movement and northward extension of the westerly trough over the region is also presented.

1. Introduction

The rainfall is of primary importance to agriculture in Zambia. The most of Zambia's rainfall occurs during the southern hemisphere summer season, between November and March. There are large seasonal variations in amounts and durations of rain in any one place ranging from drought to flood and from a long rainy season to a short one.

The main characteristics of the rainfall pattern can be explained in terms of the movement of the large scale pressure and wind systems. However, the day to day variations in the rainfall not only depend on the synoptic scale systems in the low latitudes but also seem to be considerably affected by the systems in the middle latitude westerlies. The outbreaks of rain during pre-rainy and post-rainy seasons and occasionally in winter season are known to occur over Zambia in association with the passage of eastward moving, westerly waves in the lower and middle troposphere (Fox 1969).

Hattle (1970) has given a synoptic model of upper westerly wave in Rhodesia (Fig. 1). This differs from the model described by Riehl (1954) in respect of the relation of upper westerly wave to the underlying surface conditions. Riehl's model considers the inverted V-shaped trough in the surface easterlies as an "impressed" trough, "formed as a reflection of a trough in upper westerlies". Whereas, in Rhodesian model, the upper trough or wave is directly linked with the forward colder half of the advancing anticyclone and usually found some distance behind the surface trough. At the forefront of the cold anticyclone maximum equatorward displacement of polar air is usually taking place.

The westerly waves in the middle and upper troposphere move across the southern Africa throughout the year. During the beginning of rainy season (November and December) and end of rainy season (March and April), these often extend northwards to 10-12 degrees latitude south of the equator and have a considerable effect on the distribution of rainfall over Zambia. A detailed study of the effect of upper westerly wave on the rainfall over Zambia during the rainy season has been made and the results are presented in this paper.

Intertropical Convergence Zone (ITCZ), which is the zone of convergence between northeast and southeast trades, is well defined in the northern hemisphere over west Africa. However, its structure is much more complicated in the southern hemisphere.

During the southern hemisphere summer season, there are three airstreams flowing into central Africa in the lower levels :

(*i*) The southeast trades streaming in from the southwest Indian Ocean;

(*ii*) The northwesterly airstream. This is a branch of deflected southeast trades over the south Atlantic Ocean which after recurving round the seasonal low over Angola arrive over western parts of central Africa as a very moist and unstable northwesterly/northerly airstream. The leading edge of this forms the Zaire Air Boundary (ZAB) and

(*iii*) The northeasterly airstream, emanating from the subtropical anticyclone over Saudi Arabia or north Indian Ocean

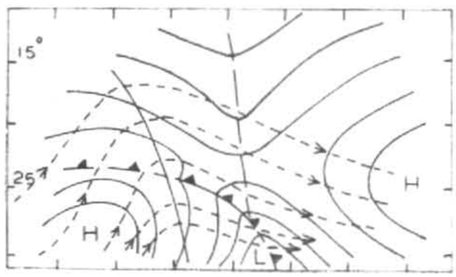

Fig. 1. Rhodesian model of a wave in the upper westerlies (linked with cold forward half of the advancing anticyclone—*After* Hattle)

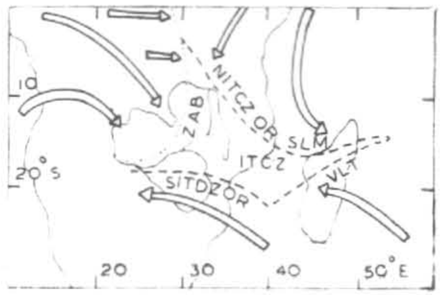

Fig. 2. Intertropical Convergence Zone, Mean position, January (*After* Torrance)

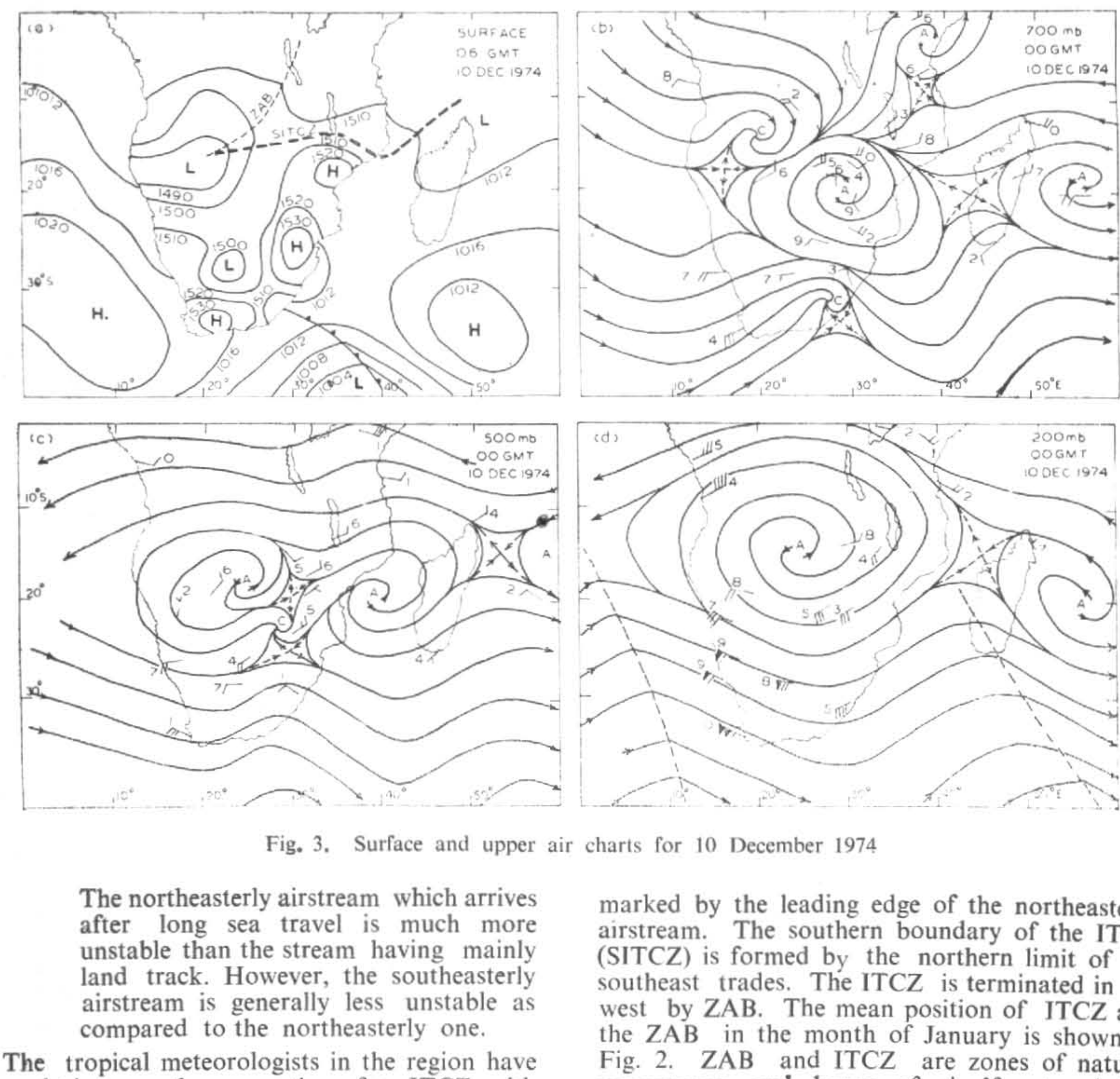

Fig. 3. Surface and upper air charts for 10 December 1974

The northeasterly airstream which arrives after long sea travel is much more unstable than the stream having mainly land track. However, the southeasterly airstream is generally less unstable as compared to the northeasterly one.

The tropical meteorologists in the region have brought into use the convention of an ITCZ with a southern and northern boundaries in day to day forecasting. In local forecasting terminology the northern boundary of the ITCZ (NITCZ) is referred to as the southern limit of the monsoon and is marked by the leading edge of the northeasterly airstream. The southern boundary of the ITCZ (SITCZ) is formed by the northern limit of the southeast trades. The ITCZ is terminated in the west by ZAB. The mean position of ITCZ and the ZAB in the month of January is shown in Fig. 2. ZAB and ITCZ are zones of natural convergence and hence of significant rainfall. Apart from these, the other low level systems which considerably influence the rainfall distribution are vortices which form along the ITCZ and feeble troughs in the easterlies.

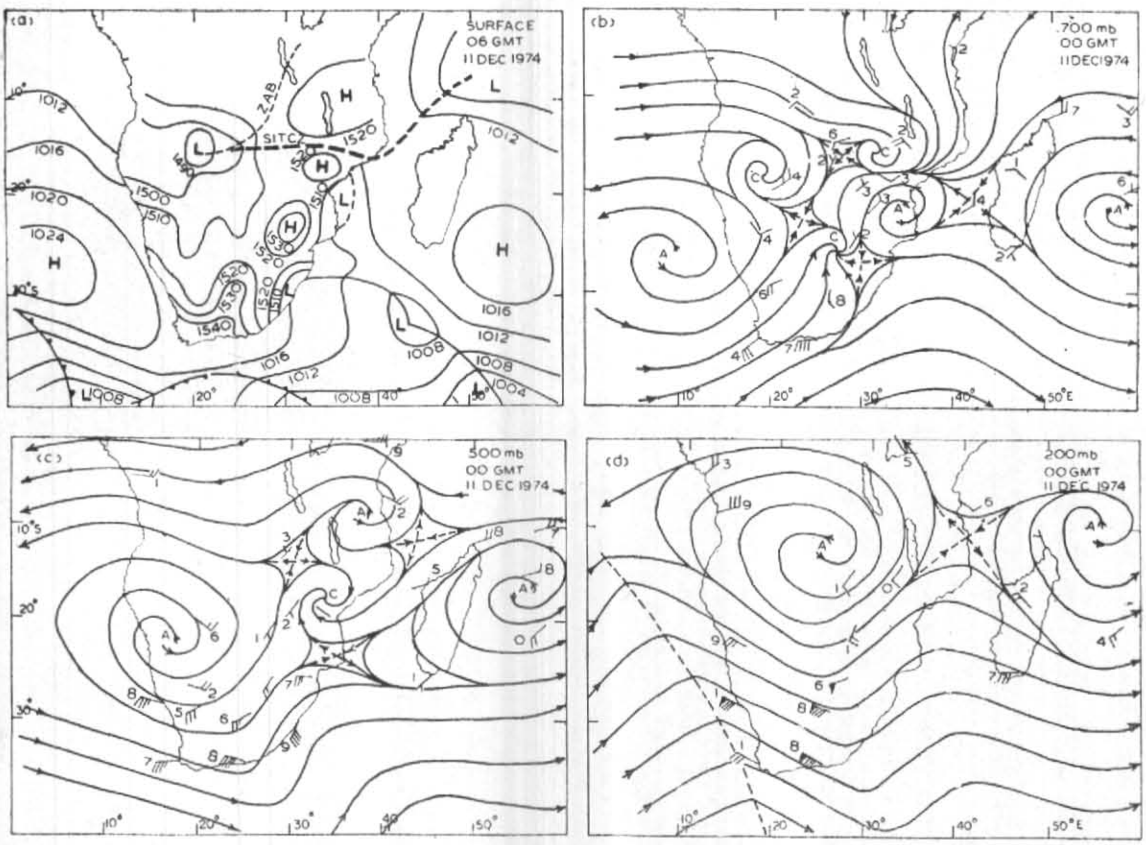

Fig. 4. Surface and upper air charts for 11 December 1974

Rainfall associated with the lower level systems is found to be considerably influenced by the eastward moving waves in the upper tropospheric westerlies.

The airflow is generally divergent ahead of the trough axis and convergent in the rear. Thus, the conditions ahead of the trough line are favourable for low level convergence, cyclogenesis and enhancement of thunderstorm activity.

In order to study the interaction of the westerly waves with ITCZ and their effect on weather over Zambia, the synoptic surface and upper air charts for the months of December, January, February and March during the five rainy seasons 1972-73, 1973-74, 1974-75, 1975-76 and 1976-77 were examined. The different types of interaction of the westerly waves with ITCZ and consequent changes in weather over Zambia were identified. Principally four types of interactions appear to be important. To illustrate each of these types of interactions, typical case studies have been presented in this paper. The climatology of the westerly troughs at 300 mb that moved across the subcontinent of Africa in the southern hemisphere with effect on the distribution of rainfall over Zambia based on the data of the five rainy seasons is also prepared.

2. Types of interaction between westerly wave in the upper troposphere and the lower level systems

The examinations of surface and upper air charts of the five seasons revealed that the waves in the upper tropospheric westerlies affect the distributions of the rainfall in four different types of interaction with the lower level systems as described below.

2.1. *Intensification and displacement of seasonal low*

On certain occasions, under the influence of upper westerly wave, the seasonal low over Angola is intensified. The associated cyclonic vortex at times extends upto 500 mb and moist northwesterly flow becomes the dominating feature over central Africa, particularly over Zambia. This causes generally, a fairly heavy rainfall over Zambia and Rhodesia for few days.

A good example of westerly wave which affected central and southern Africa during 11 December to 14 December 1974 and caused intensification of seasonal low has been discussed below in detail.

On 10 December 1974 at 0600 GMT, the SITCZ was lying over southern parts of Zambia along Lat. 15°S. The seasonal low was situated over southern Angola and adjoining parts of Namibia

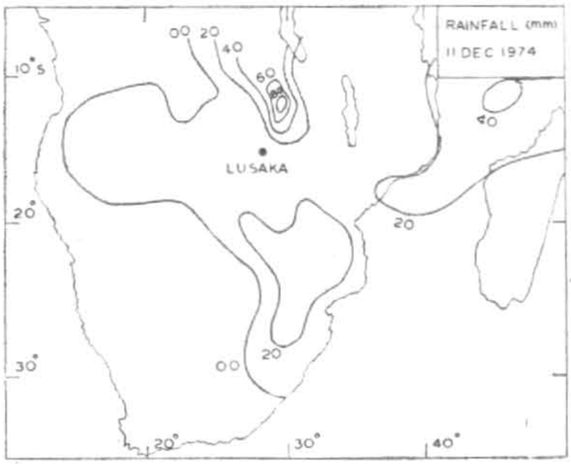

Fig. 5. Rainfall chart for 11 December 1974

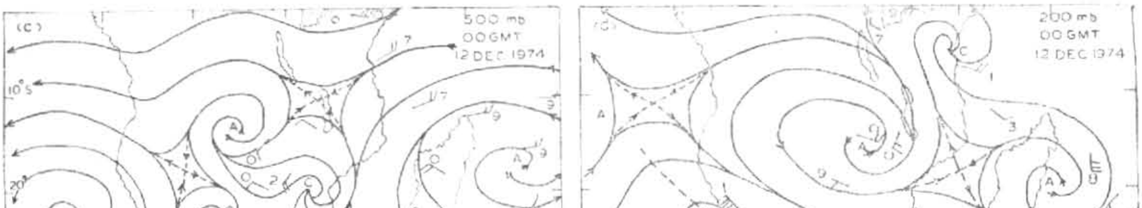

Fig. 6. Surface and upper air charts for 12 December 1974

with its central region near Lat. 17°S and Long. 19°E. The ZAB was lying across northwestern province of Zambia. A cold front was trailing over southeast coast, north of East London and the associated coastal low was situated over Natal Coast (Fig. 3a).

The cyclonic vortex associated with the seasonal low extended upto 700 mb only (Fig. 3b) and the flow was generally anticyclonic easterly in the middle and upper troposphere over Zambia (Figs. 3c and 3d). A trough in the westerlies at 200 mb was approaching the west coast of the subcontinent.

The SITCZ and the seasonal low remained practically stationary during next 24 hours. However, the ZAB moved slightly southeastwards. The cold front was trailing over south Mozambique coast near Maputo and coastal low was near Beira (Fig. 4a).

At 700 mb, apart from the cyclonic circulation associated with the seasonal low, another cyclonic vortex was seen at 00 GMT on 11 December 1974 (Fig. 4b). This was seen also at 500 mb (Fig. 4c).

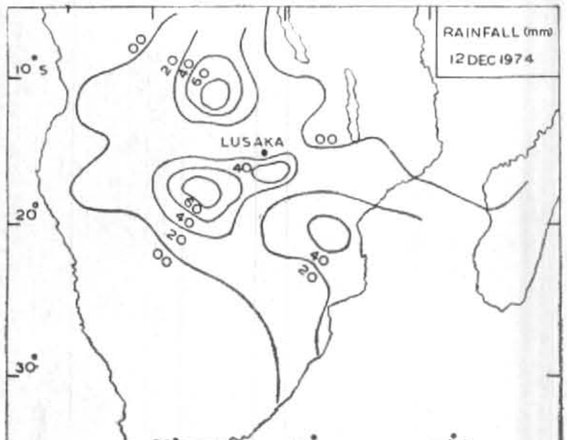

Fig. 7. Rainfall chart for 12 December 1974

The ridge axis at 200 mb was along latitude 12°S and the trough in the westerlies was close to the west coast of the subcontinent (Fig. 4d).

On this day, significant rainfall occurred only near the ZAB over the Copperbelt and Luapula Provinces (Fig. 5). During the next 24 hours, there had been significant changes in the pressure systems and flow patterns. The pressures started falling rapidly and at 0600 GMT on 12 December, pressure falls were occurring over the whole subcontinent.

The 0600 GMT surface chart of 12 December 1974 (Fig. 6a) showed that the seasonal low shifted southeastwards to the central parts of Botswana and intensified, apparently under the influence of the upper westerly trough. There was another low on the SITCZ over southern parts of Rhodesia and adjoining parts of Mozambique.

The moist Zaire air also rapidly advanced southeastwards and was covering the whole of Zambia and northwestern parts of Rhodesia. SITCZ shifted southwards to Limpopo Valley (a jump of about 6° of latitude) and the coastal low had become a part of SITCZ.

The upper air charts of 12 December (Figs. 6b to 6d) showed that the cyclonic vortex associated with the seasonal low extended upto 500 mb. Another vortex was still seen at 500 mb. The trough in the westerlies at 200 mb had flattened.

The rainfall chart for 12 December (Fig. 7) showed two rainfall maxima, one over southwestern parts of Zambia and another over central parts of Rhodesia and adjoining Mozambique, these two being associated with the two cyclonic vortices mentioned above.

By 0600 GMT of 13 December, the cold front moved away eastwards across the Mozambique channel and the pressures had generally risen over the subcontinent with maximum rises of 9 mb over Natal coast. Under the influence of rising pressure, the SITCZ and seasonal low moved northwards and weakened slightly (Fig. 8a).

The associated cyclonic vortices were extending only upto 600 mb. The westerly trough at 200 mb was oriented northwest-southeast across south Africa but an area of marked diffluence was noticed over the southern parts of Zambia and adjoining parts of Rhodesia (Figs. 8b to 8d).

The rainfall chart for 13 December (Fig. 9) showed that the rainfall maximum belt also moved northwards and extending from northern half of Rhodesia to southwestern and central parts of Zambia. The rainfall distribution was associated with the SITCZ and the seasonal low and did not decrease, despite the weakening of the systems, apparently due to the favourable influence of the upper diffluent flow.

2.1.1. *Discussion*

The salient features of this type of interaction can be briefly summarised as follows :

(*i*) As the deep westerly trough in the upper troposphere approached the west coast of southern Africa, pressures started falling over the whole of the subcontinent.

(*ii*) Under the influence of the pressure falls, the seasonal low and SITCZ shifted southwards about 5 to 6 degrees of latitude.

(*iii*) The seasonal low intensified when the divergence field ahead of the trough in the upper troposphere became superimposed above it.

(*iv*) The intensification of the seasonal low caused a deep northwesterly flow over whole of Zambia.

(*v*) This synoptic situation caused well distributed rainfall over the whole of Zambia with scattered heavy falls over northwestern, western, southern and central provinces.

2.2. *Direct enhancement of rainfall*

On many occasions, the eastward movement of westerly waves do not cause the intensifications of seasonal low, especially when it is situated over northern and central Angola, outside the influence of the westerly troughs. However, the passage of westerly wave causes increase in rainfall over central and southern parts of Zambia, ahead of the upper trough.

To illustrate this fact, an interesting case of westerly wave in the upper troposphere which moved very slowly across the central Africa between 14 March and 19 March 1977 has been discussed below.

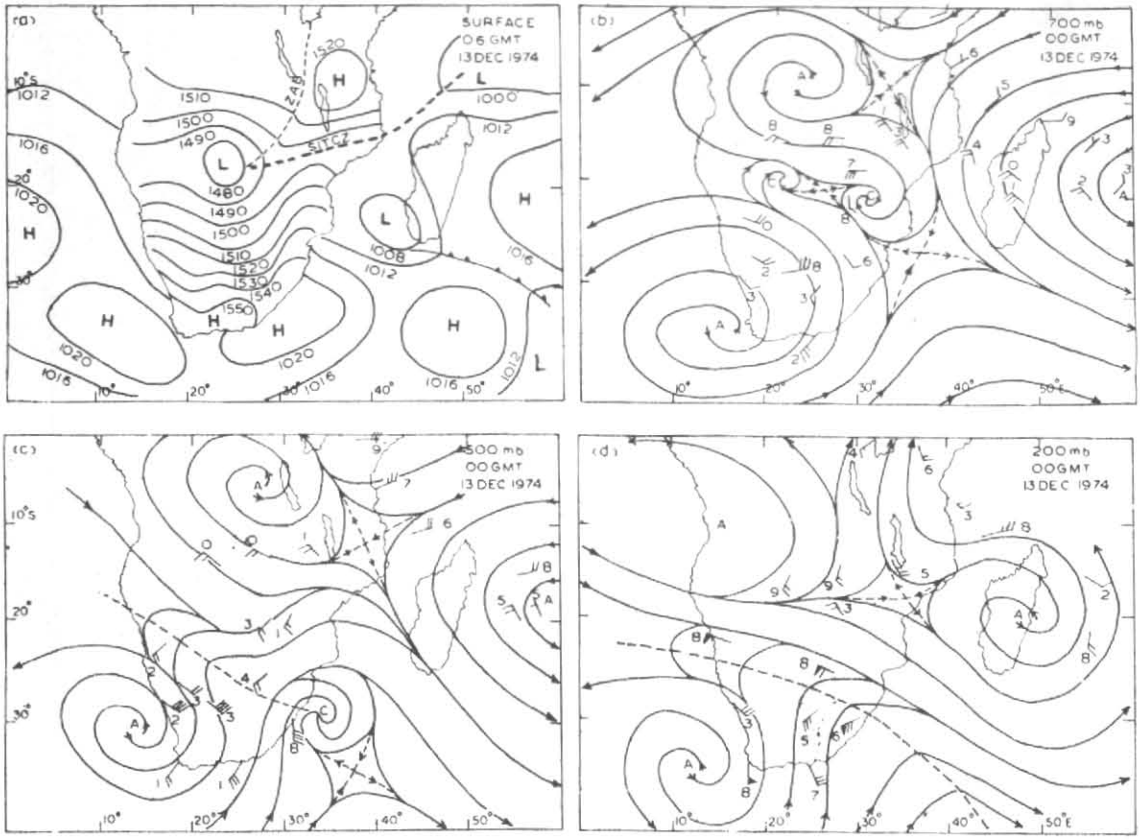

Fig. 8. Surface and upper air charts for 13 December 1974

Fig. 9. Rainfall chart for 13 December 1974

The SITCZ was lying over northern parts of Zambia and ZAB across the northwestern province as seen at 850 mb on 14 March 1977 (Fig. 10a). A cold front was trailing across the central parts of South Africa.

In the upper troposphere a deep trough in the westerlies extended upto 14°S into Zambia at 0000 GMT on 14 March (Fig. 11a). The rainfall for the same date (Fig. 12a) showed that the maximum rainfall had occurred close to ZAB and SITCZ. However, the secondary maximum was found over southwestern parts of Zambia in the forward sector of westerly trough at 400 mb.

During the next 24 hrs. the SITCZ shifted rapidly southwards to central parts of Rhodesia but ZAB almost maintained its position. The cold front moved over to south Mozambique coast close to Maputo (Fig. 10b).

The trough in the westerlies at 400 mb remained practically stationary but deepened in amplitude. The 400 mb chart for 0000 GMT, 15 March 1977 (Fig. 11b) showed it was extending northwards upto Lat. 12°S and an intense anticyclone had formed over Malagasy. This was blocking the eastward movemet of the westerly trough.

A fairly well distributed rainfall had occurred on 15 March (Fig. 12b) ahead of the upper air trough.

By 0000 GMT on 16 March, the cold front had moved away eastwards and pressures rose in the rear of the front. Under the influence of rising pressures the SITCZ moved to northern parts of Rhodesia and slightly weakened (Fig. 10c).

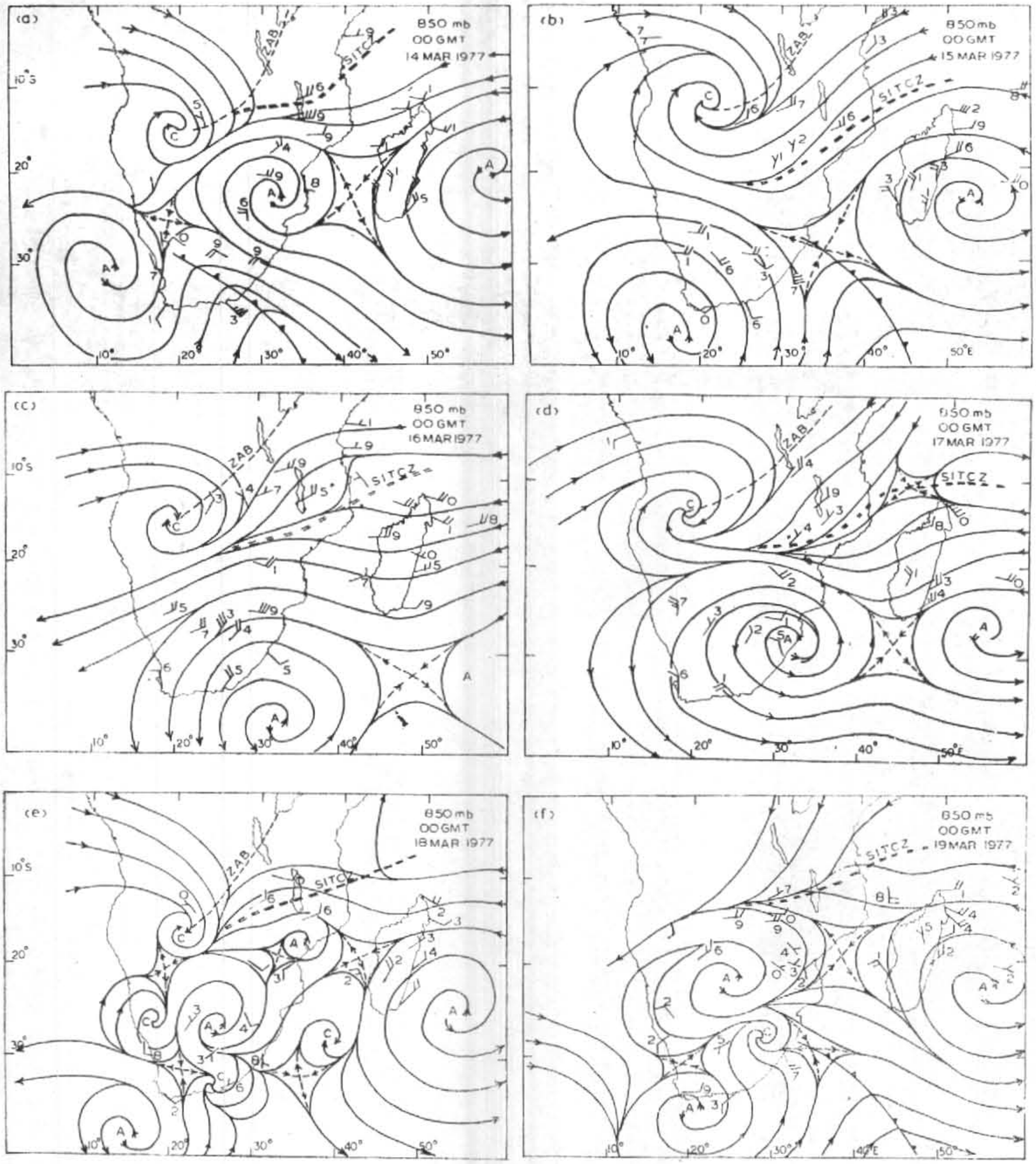

Fig. 10. 850 mb charts (14 March to 19 March 1977)

The westerly trough at 400 mb continued to be almost stationary (Fig. 11c). Most of the rainfall on 16th occurred ahead of westerly trough over central and eastern parts of Zambia. The rainfall was moderate to rather heavy despite the fact that SITCZ was weak (Fig. 12c).

The SITCZ continued to be weak and gradually moved northwards from northern parts of Rhodesia to the central parts of Zambia between 16 and 19 March (Figs. 10c to 10f).

The anticyclone over Malagasy continued to block the eastward movement of the westerly trough. Thus, the trough remained over southwestern parts of Zambia on 17 and 18 March 1977 and by 19 March it had moved slightly eastward (Figs. 11d to 11f).

The rainfall charts for 17 to 19 March (Figs. 12d to 12f) showed that the fairly large amounts of rainfall had occurred on 17 and 18 March in areas which fell in the forward sector of the trough at 400 mb.

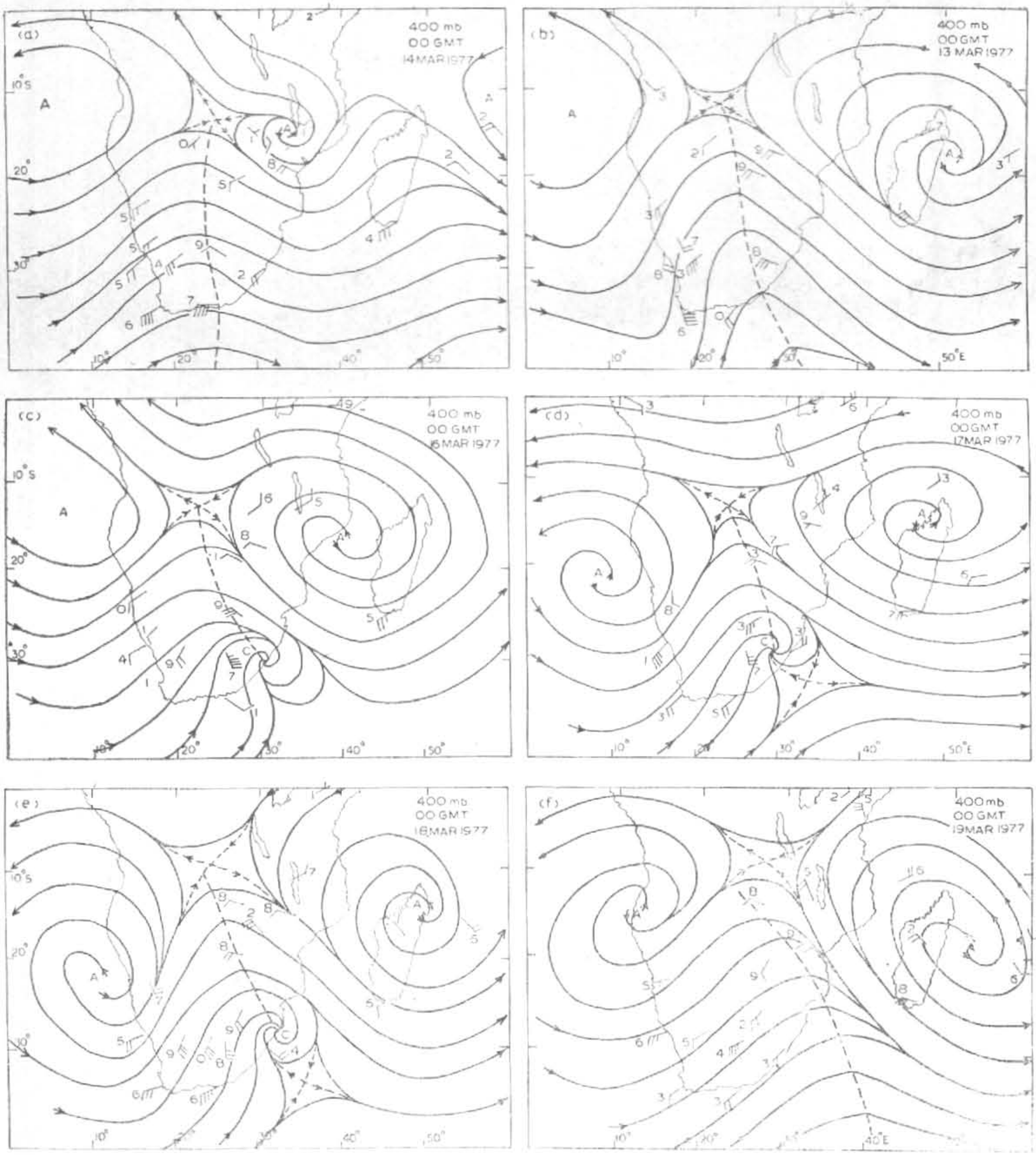

Fig. 11. 400 mb charts (14 March to 19 March 1977)

However, there had been no rainfall over southern half of the country on 19 March.

This was due to the fact that a southeasterly airstream, emanating from an anticyclone over central Botswana was reaching over the southern half of Zambia on 19 March 1977.

The following salient points emerge out of this study :

(*i*) The movement of westerly wave in the upper troposphere caused the increase in rainfall activity ahead of the trough over central, southern and eastern parts of Zambia.

(*ii*) Due to the formation of an intense blocking anticyclone over Malagasy in the higher levels, the westerly wave practically remained stationary from 14 to 18 March. As a result, the spell of increased rainfall over southern half of the country continued for these five days.

(*iii*) Despite, the fact that the westerly trough was still present on 19 March, the rainfall decreased over the southern half of Zambia, due to the anticyclonic southeasterly flow in the lower level emanating from high over central Botswana. This

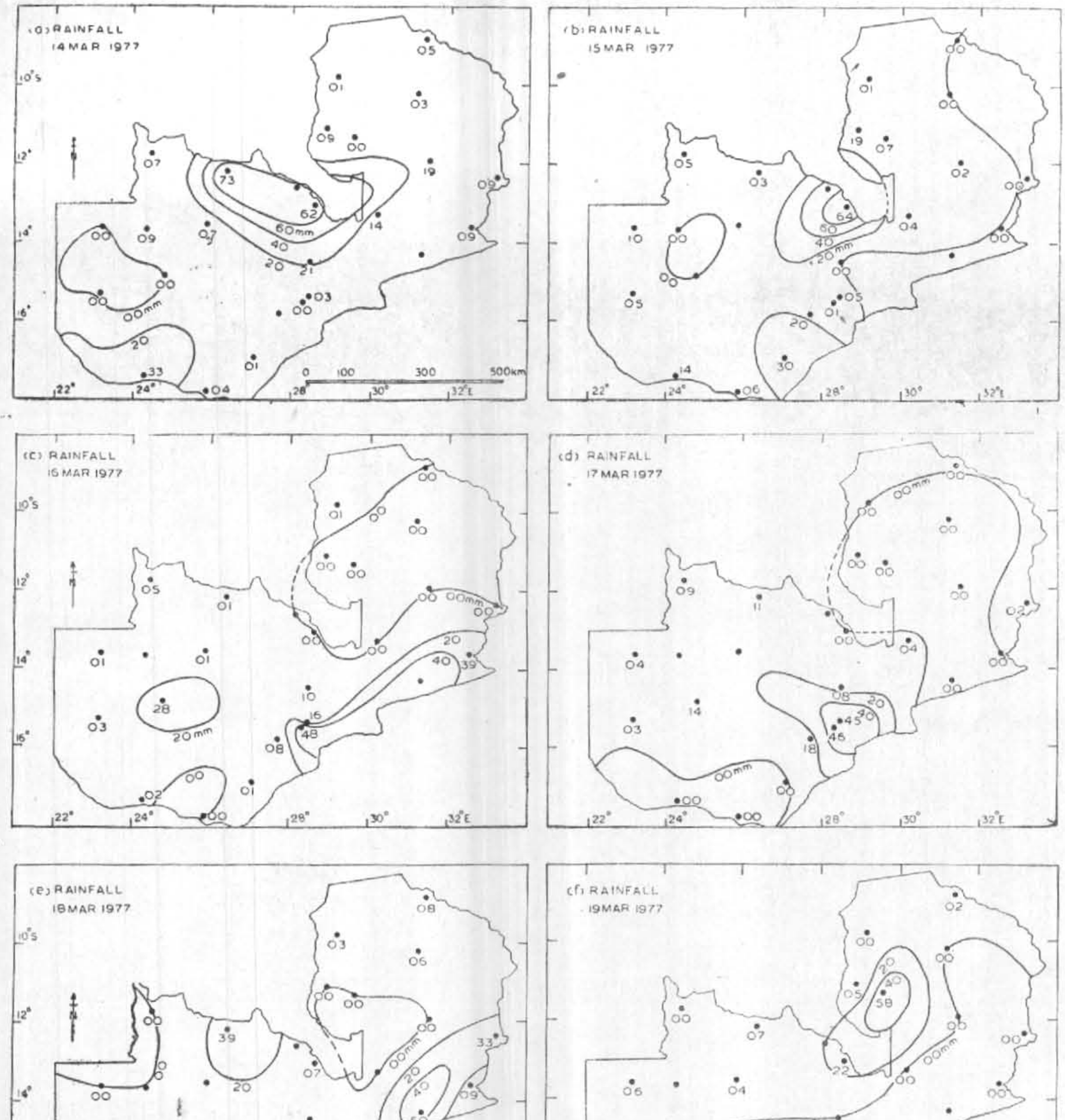

Fig. 12. Rainfall charts (14 March to 19 March 1977)

subsiding airstream with mainly land track is relatively dry and stable.

3. Temporary disintegration of ITCZ over the subcontinent

On rare occasions, deep cold fronts with associated westerly waves extending into the upper troposphere, penetrate as far north as southern parts of Zambia. The movement of such westerly wave causes temporary disintegration of ITCZ over the subcontinent and the flow patterns become similar to that are found in the early winter season.

During the rainy season 1976-77, a very deep cold front with associated westerly wave rapidly moved across the central and southern Africa between 30 December 1976 and 2 January 1977. This resulted in complete disintegration of ITCZ over central Africa, on 31 December and 1 January. Fair weather conditions prevailed over most parts of the country on 31 December and the New Year day.

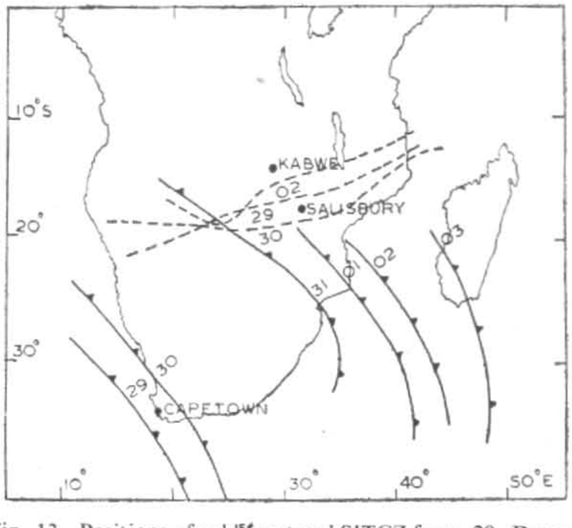

Fig. 13. Positions of cold front and SITCZ from 29 December 1976 to 2 January 1977

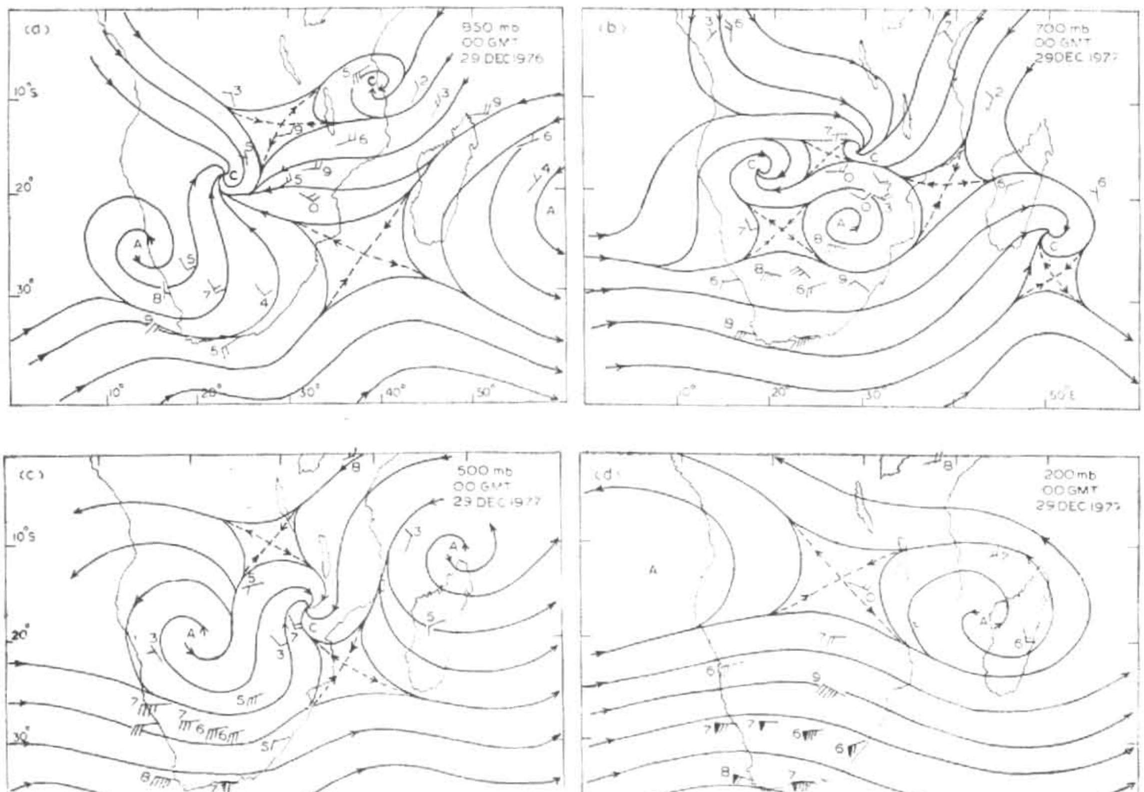

Fig. 14. Upper air charts for 29 December 1976

At 0600 GMT of 29 December, SITCZ at the surface was situated at close to the southern borders of Zambia with Rhodesia and a deep cold front was approaching the southwest coast (Fig. 13). The ITCZ was quite active as it had embedded vortices extending upto 500 mb. It was overlain by weak easterly flow in the upper troposphere (Figs. 14a to 14d).

The most of rainfall over Zambia on 29th have occurred close to the zone of convergence between northwesterly and northeasterly airstreams in the lower levels (Fig. 15a).

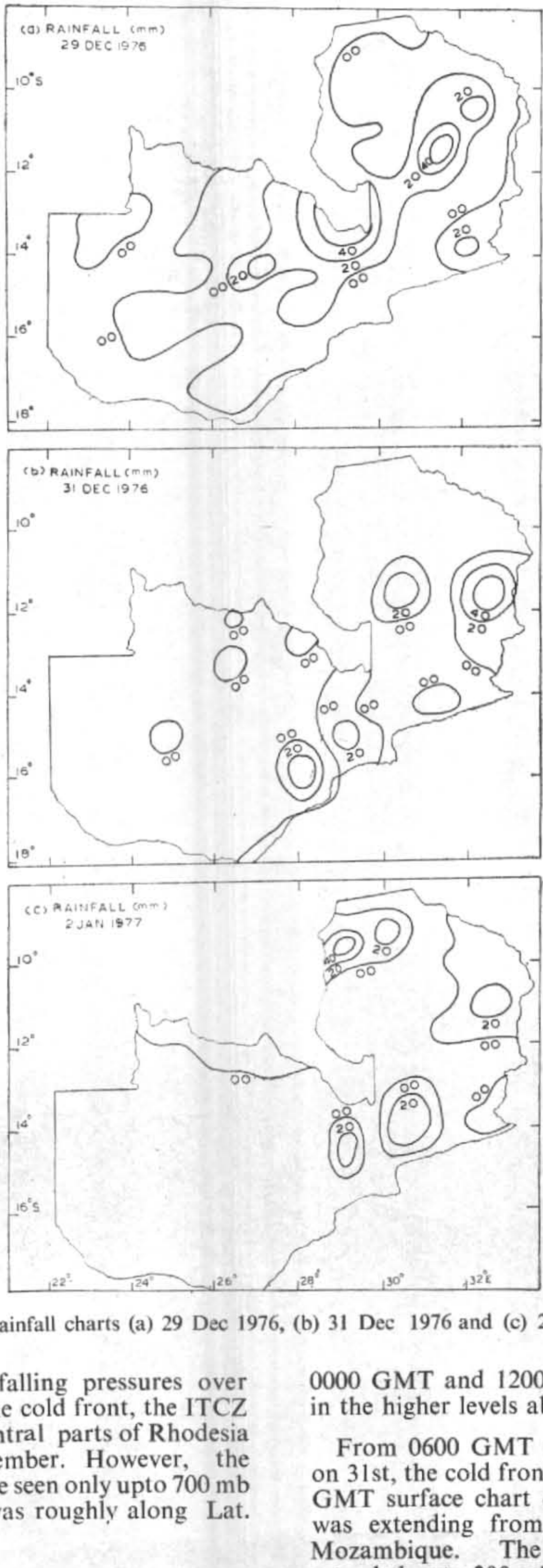

Fig. 15. Rainfall charts (a) 29 Dec 1976, (b) 31 Dec 1976 and (c) 2 Jan 1977

Under the influence of falling pressures over southern Africa, ahead of the cold front, the ITCZ moved southwards to the central parts of Rhodesia by 0600 GMT of 30 December. However, the vortices on the ITCZ could be seen only upto 700 mb and ridge axis at 200 mb was roughly along Lat. 17°S.

The time section of Cape Town (Fig. 16) showed that the cold front with associated wave upto the middle troposphere crossed Cape Town between 0000 GMT and 1200 GMT of 30 December and in the higher levels about six hours later.

From 0600 GMT on the 30th to 0600 GMT on 31st, the cold front moved rapidly. At the 0600 GMT surface chart of 31 December (Fig. 17), it was extending from southern Angola to south Mozambique. The associated westerly wave extended upto 200 mb (Figs. 18a to 18d).

It is to be noted that the ITCZ had completely disappeared from the mainland and the upper level

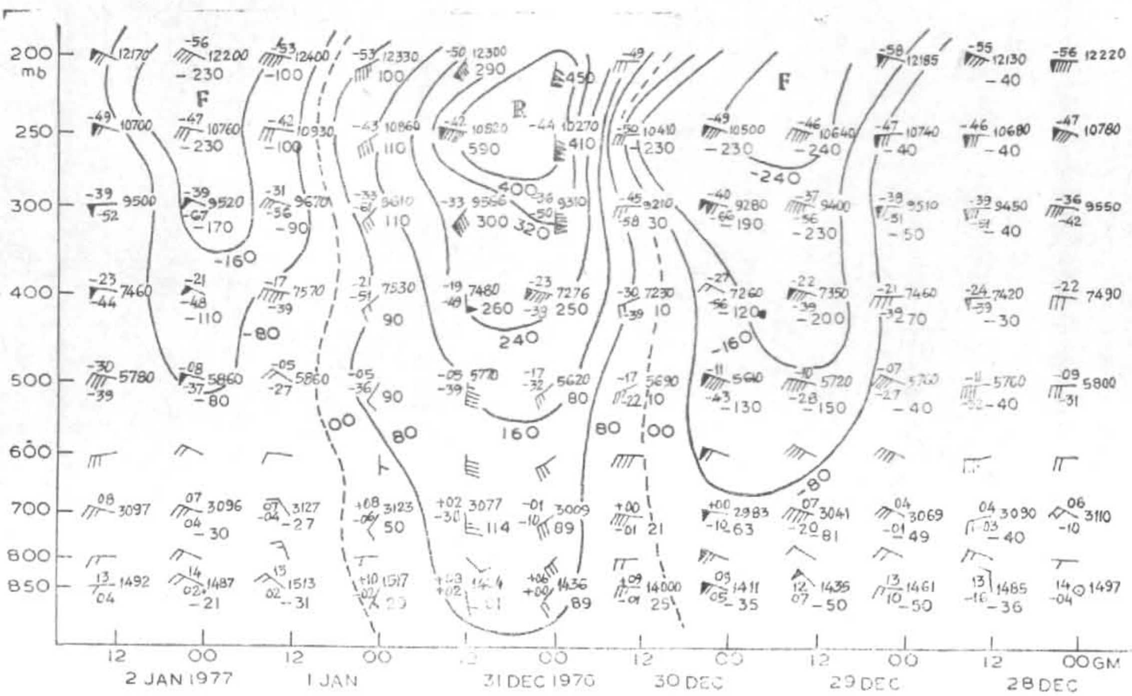

Fig. 16. Time cross-section Cape Town

flow patterns became similar to those found in the early winter season (the month of May).

The rainfall had considerably decreased over Zambia on 31 December (Fig. 15b).

At 0600 GMT of 1 January, the cold front was trailing over surface chart across central Rhodesia and southern Mozambique and was still a predominating feature. ITCZ continued to be unidentifiable. However, the seasonal low over Angola had reappeared and the ZAB was seen across the northern parts of Zambia.

The time section of Kabwe (Fig. 19) showed that the cold front with associated wave in the lower and middle levels had crossed Kabwe between 0000 GMT and 1200 GMT of 1st. The dry air had spread over the central parts of Zambia at all levels.

The similar chart of Salisbury revealed that the cold front with associated wave upto 600 mb crossed Salisbury between 1200 GMT of 31 December and 0000 GMT of 1 January (Fig. 20). The westerly wave at 500 mb and above continued to be west of Bulawayo.

On 1st, the weather was dry on the southern half of Zambia. However, the northern parts of the country experienced well distributed rainfall. This may be attributed to the ZAB. The cold front thereafter moved slowly eastwards and was moving across Mozambique Channel on 2nd. By 0600 GMT of 2nd, the continental high over Transvaal had reformed in the rear of the cold front and SITCZ had re-established itself along Zambezi Valley as a weak feature. The seasonal low was situated near Caprivi Strip.

The flow patterns became normal in the lower levels. The westerly wave in the middle levels was moving across Mozambique. But, in the upper troposphere, it was still over extreme eastern parts of Rhodesia (Figs. 21a to 21d). The most of the rainfall on 2nd had occurred over the eastern and northern parts of the country (Fig. 15c). The decrease in rainfall might be due to the fact that the dry air had spread in the western, central and southern parts of Zambia.

3.1. *Discussions*

The chief features of this type of interaction can be summarised as follows :

(*i*) As the deep cold front crossed Cape Town, the ITCZ became slightly weak and moved south on 30 December.

(*ii*) With further rapid eastward movement of the cold front and its associated westerly wave as it was extending from southern Angola to south Mozambique across central Botswana, the ITCZ was completely disintegrated over the subcontinent and remained so for next 48 hr till the cold front crossed the subcontinent.

(*iii*) The upper air flow patterns had completely changed and were similar to that found in the early winter season (May).

(*iv*) The southern half of Zambia received hardly any rainfall for two days.

(*v*) When the cold front moved into Mozambique Channel on 2nd, SITCZ re-established and the flow patterns in the lower level returned to normal over central Africa.

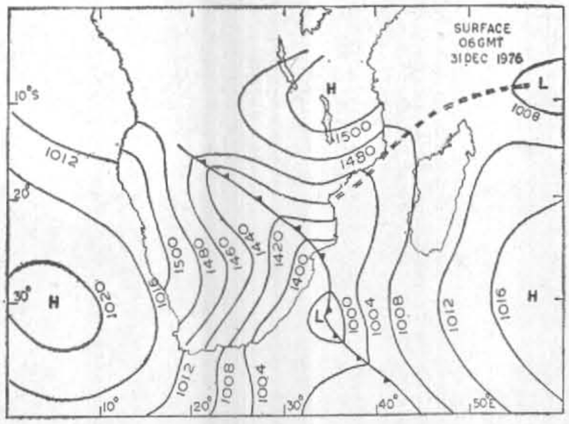

Fig. 17. Surface chart for 0600 GMT' 31 December 1976

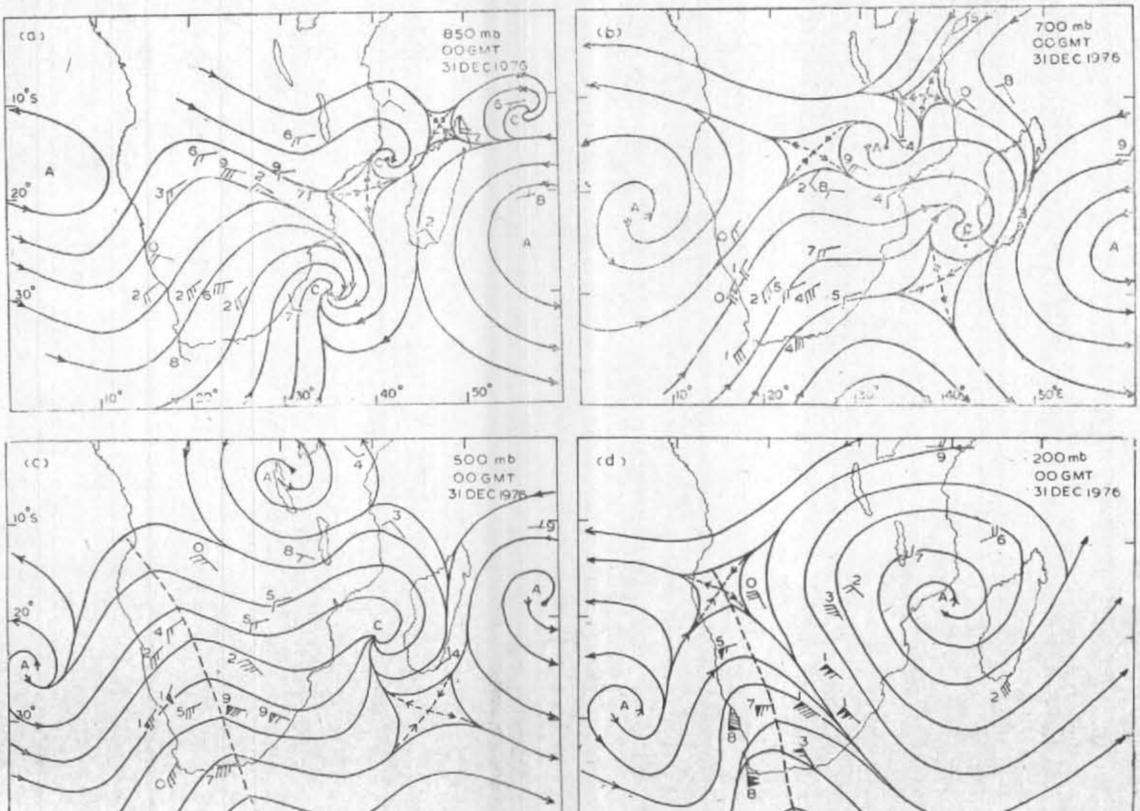

Fig. 18. Upper air charts for 31 December 1976

4. Intensification of coastal low and southward displacement of ITCZ

Sometimes, the coastal low moving northwards along the southeast coast of the subcontinent may be intensified when the divergence field ahead of the troughs in the upper troposphere becomes superimposed above it. The well marked low or depression is advected inland.

ITCZ invariably jumps suddenly southwards and the depression or well marked low becomes the part of the ITCZ. An unusual case of such a deep depression has been discussed by Kumar (1977).

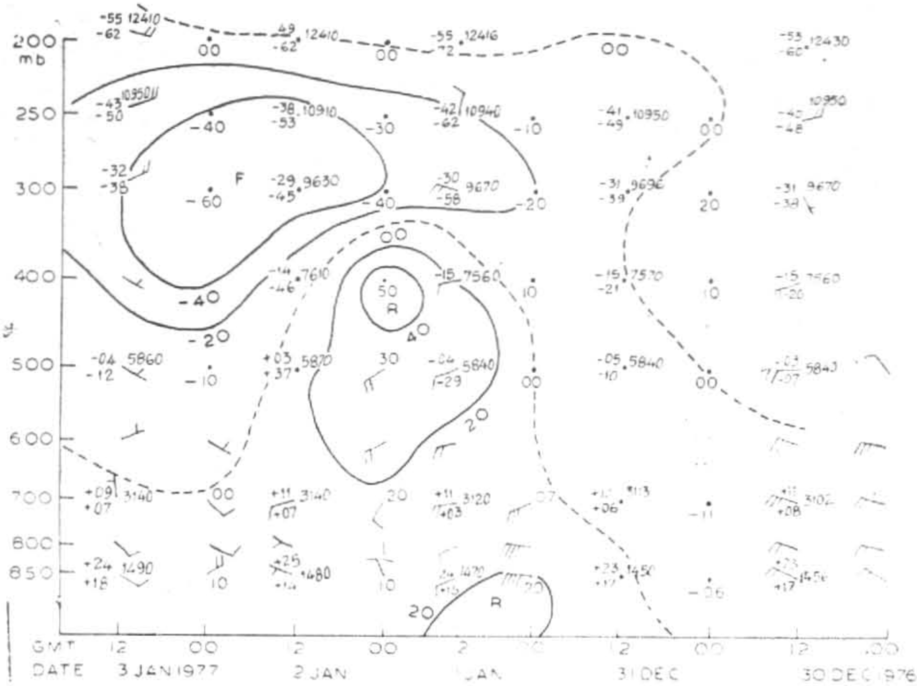

Fig. 19. Time cross-sections, Kabwe

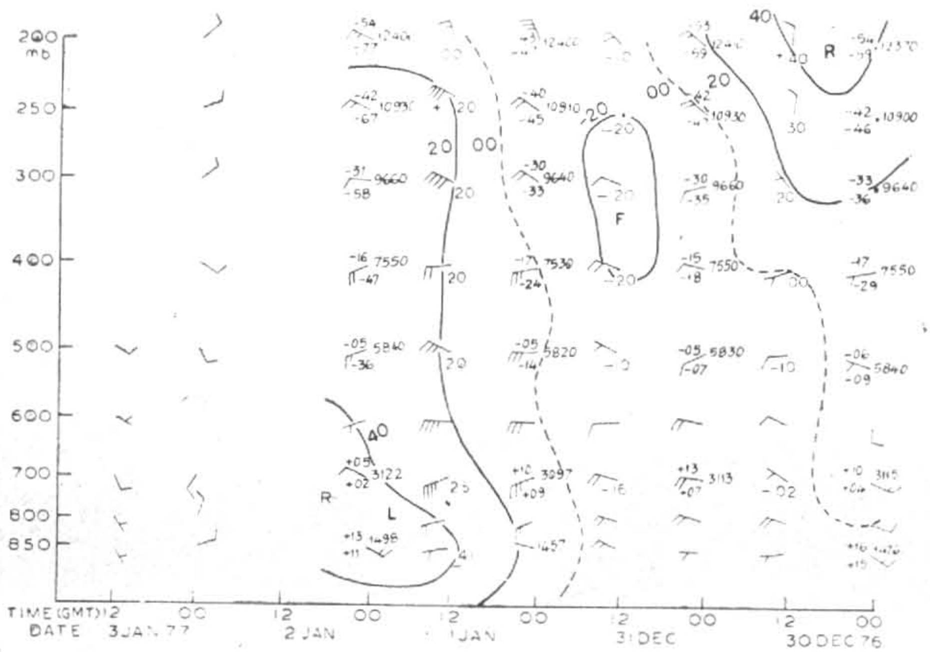

Fig. 20. Time cross-sections, Salisbury

4.1. *Synoptic climatology of westerly trough*

Thus, we find that the westerly waves in the upper troposphere can have considerable influence on the rainfall distribution over the subcontinent in general and Zambia, in particular. Hence a climatological knowledge of the movement, durations and northward extension of the waves in the upper tropospheric westerlies is of considerable use. A statistical study of the westerly troughs at 300 mb has been made and findings are discussed below.

Table 1 gives the data on the northward limit of the troughs in the westerlies at 300 mb at 0000 GMT over southern Africa and adjoining sea areas within

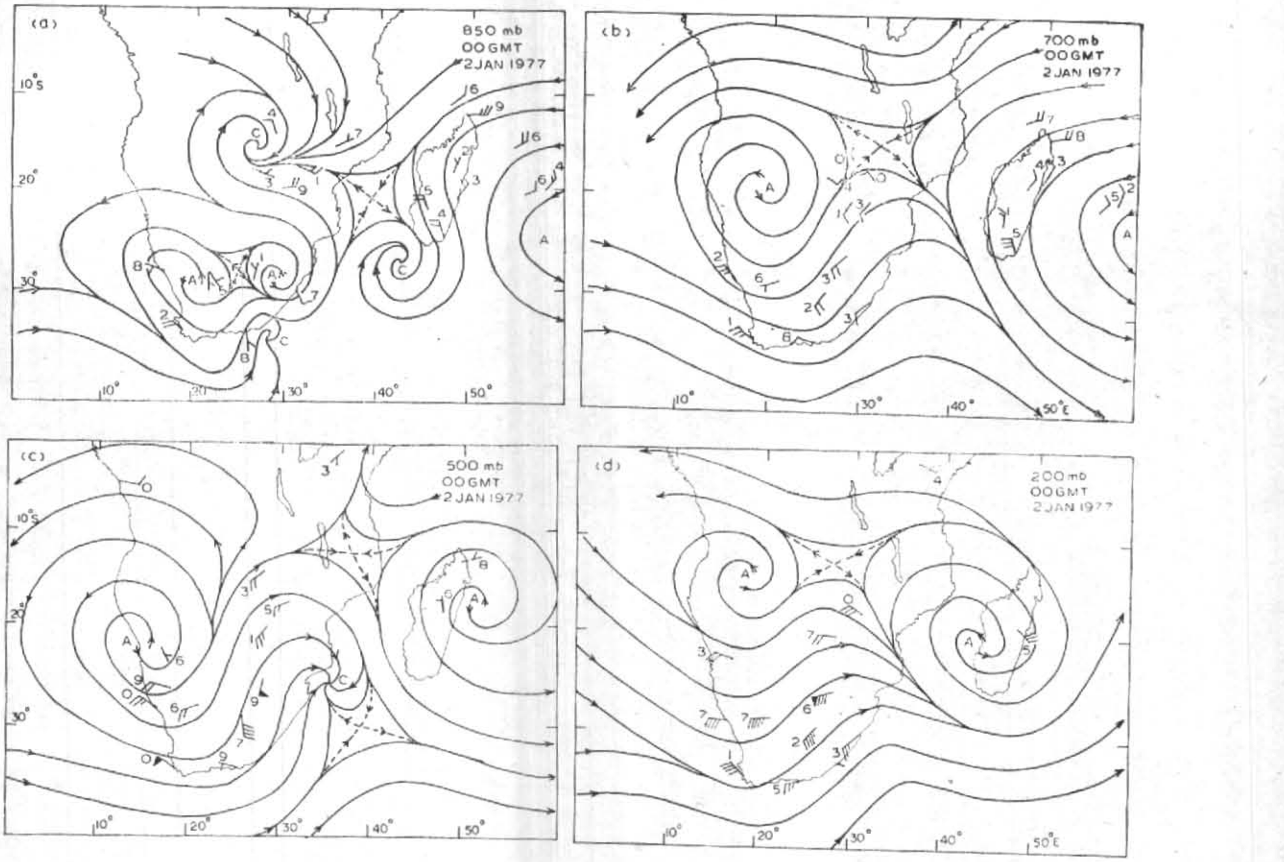

Fig. 21. Upper air charts for 2 January 1977

five degrees of longitude from the coast during the four months from December to March, for the five rainy seasons from 1972-73 to 1976-77. It is seen from the table on about 60 per cent of days westerly trough are found over the area and on 25 per cent of days in December and March and 15 per cent of days in January and February they actually extend into Zambia. On an average 5 to 7 troughs may move across the area per month, and each trough passes across the area in 3 days.

Table 2 gives the data on troughs which extended into Zambia at the 300 mb level and the associated increase in rainfall over Zambia. It can be seen from the table that on about 80 per cent of the days in the months of December, February and March and about 70 per cent of the days in January, when a high level westerly trough extends into Zambia, there is an increase of rainfall over the country. In December the increase is more often associated with the accentuation of the seasonal trough. In all the months the increase in rainfall is generally in the forward sector of the upper trough.

TABLE 1

Number of days on which westerly trough extended into each latitudinal class in each of the months

Lat. Class	Dec	Jan	Feb	Mar
10-12° S	4	2	0	5
13-15	10	11	9	15
16-18	24	11	13	13
19-21	27	18	16	21
22-24	12	23	14	11
25-27	9	15	21	12
28° or more	8	11	11	6
Total No. of days	94	91	84	83
Total No. of troughs	31	34	23	26
Average No. of troughs	6.2	6.8	4.6	5.2
Average No. of days per trough	3.0	2.7	3.6	3.2

TABLE 2

The movement of the westerly troughs at 300 mb which extended into Zambia and their effect on rainfall during the months of December, January, February and March in five rainy seaons (1972-73 to 1976-77)

	Total No. of days of troughs	No. of days of increase in rainfall: Total	Ahead of the trough line	Behind the trough line	Due to the accen-tuation of the seasonal low	% No. of days of increase of rainfall
Dec	38	31	10	1	20	81
Jan	24	16	10	3	3	63
Feb	22	18	15	0	3	82
Mar	33	26	19	3	4	79

TABLE 3

The movement of the westerly trough at 300 mb extending to Lat. 19°S to 24°S and their effect on rainfall over Zamia during the months of December, January, February and March in five rainy seasoons (1972-73 to 1976-77)

	Total No. of days of troughs	No. of days of increase in rainfall: Total	Ahead of the trough line	Behind the trough line	Due to the accentua-tion of the seasonal low	% No. of days of increase of rain-fall
Dec	39	26	7	0	19	66
Jan	41	24	13	2	9	58
Feb	30	22	17	0	5	73
Mar	32	24	17	0	7	75

Table 3 gives the data on trough which extended between Lats. 19° and 24° (south of Zambia) and the associated increase of rainfall over Zambia. It is seen from the table, even in the case of upper westerly troughs moving eastwards to the south of Zambia, on a significant percentage of occasions, an increase of rainfall is noticed over the country.

5. Conclusions

The synoptic cases discussed in this paper clearly indicate that even in the height of the rainy season, the systems in the extra-tropical westerly belt in the higher levels can penetrate well into the tropical areas of Zambia and considerably influence the day to day rainfall patterns associated with the low level systems there. The statistical data indicate that such influence can be experienced quite often. Thus one can conclude the systems in the extra-tropical westerlies in upper levels can play significant part in the seasonal rainfall distribution over Zambia.

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