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Low frequency oscillations in wind and circulation fields over India during northern summer monsoon

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सार — यह अध्ययन भारत में ग्रीष्म मानसून के दौरान क्षेत्रीय और याम्योत्तरी पवन और अपसरण और भ्रमिलता में निम्न आवृति वाले दोलनों के परिणाम प्रस्तुत करता है। इस उद्देश्य के लिए विशिष्ट आवर्तिताओं का पता लगाने के लिए प्रसंवादी विश्लेषण को अपनाया गया है। हैडली परिसंरचण की प्रबलता को मानसून की वर्षा से सम्बन्धित रखा गया है। होमोलर डायग्राम की सहायता से दोलनों में अन्तरवर्षीय उच्चावचनों का परीक्षण किया गया है। दोलनों के उत्तेजन में केलविन और रोसबाई तरंगों के योगदान पर विचार विमर्श किया गया। मानसून की स्थापना में पूर्वी और पश्चिमी विसंगतियों की भूमिका और सक्रिय विच्छेद आवर्तन को दर्शाया गया है। आवर्तनों की ऊर्ध्वाधर संरचना का अन्वेषण किया गया है और सत्याभासी व्याख्या, विशेषकर इसके झुकाव और मानसून की सक्रियता के साथ इसमें सम्बन्ध को प्रस्तुत किया गया। भारतीय अक्षांशों पर दोलनों के जनन प्रवर्धन तीव्रीकरण और दुर्बलता के सम्बंध में संभव क्रियाविधि को प्रस्तावित किया गया है।

ABSTRACT. The study presents results of low frequency oscillations in zonal and meridional wind and divergence and vorticity fields during summer monsoon over India. Harmonic analysis has been adopted for this purpose to detect prominent periodicities. Strength of Hadley circulation has been related to the monsoon rainfall. Inter-annual fluctuations in the oscillations have been examined with the help of Hovmöller diagrams. The contribution of Kelvin and Rossby waves in the excitation of the oscillations has been discussed. Role of easterly and westerly anomalies in the establishment of the monsoon and the active-break cycles has been projected. The vertical structure of the cycles has been investigated and plausible explanation offered, particularly on its tilt and its relation to monsoon activity. Possible mechanism on generation, propagation, intensification and weakening of the oscillations over Indian latitudes has been proposed.

1. Introduction

One of the outstanding characteristics of the atmospheric parameters in the tropics is the quasi-periodic oscillations in 30-60 days which was first identified by Madden & Julian (1971). Since then a large number of papers have appeared in meteorological literature (Yasunari 1979, 1980, 1981; Sikka and Gadgil 1980, etc). Recently Murakami *et al*. (1984), Krishnamurti *et al.* (1985), Lau and Chan (1986), Chowdhury *et al.* (1988 a, 1988b), Singh and Kripalani (1985) and De *et al.* (1988) have confirmed that the short-period cycles are rather regular and intense over India during the northern hemispheric summer and have northward propagation.

In the present study, an attempt has been made to detect possible signals in the time scale of 30-60 days during summer monsoon over India. Structure of oscillatory motions in the zonal and meridional wind and circulation features represented by divergence and relative vorticity have also been examined. Association between these low frequency oscillations and active-break phase of the monsoon has also been explored.

2. Data and method of analysis

The study utilises the radio-sonde data of 17 fairly well distributed stations over India. Daily data of 00 GMT for the levels 85, 70, 30 and 20 kPa have been considered from 1 June to 30 September covering a total of 122 calendar days. Ten day normals of zonal and meridional wind based on 1966-1980 data are utilised to find presence of modes, if any in the normal wind and circulation patterns. The daily wind anomalies were obtained as a departure from this 10-day normal. Two worst years of monsoon failure in India, *viz.*, 1979 and 1982 and two years (*i. e.*, 1978 and 1983) in which the rains were exceptionally bountiful were selected. The area under study extends from 8° to 28° N and 70° to 95° E. The basic data were extracted from the records of India Meteorological Department, Pune. Since the aim of the study is mainly to examine oscillations beyond 10 days, random noise in the data was removed through 3-day moving average.

In the analysis of divergence and relative vorticity of the normal wind field, finite difference method, on 2.5° $\times$2.5° grid points, has been used. Chowdhury *et al.* (1988b) found the presence of prominent oscillations of low frequency in the rainfall over the area between 15° and 20°N and west of 80°E. In order to find out the differences in the divergence and vorticity patterns in years of contrasting monsoon, and area close to this area has been considered. Bellamy's method was used to calculate these parameters. The area enclosed by three different triangles, *viz.*, Bombay-Hyderabad-Nagpur, Hyderabad-Nagpur-

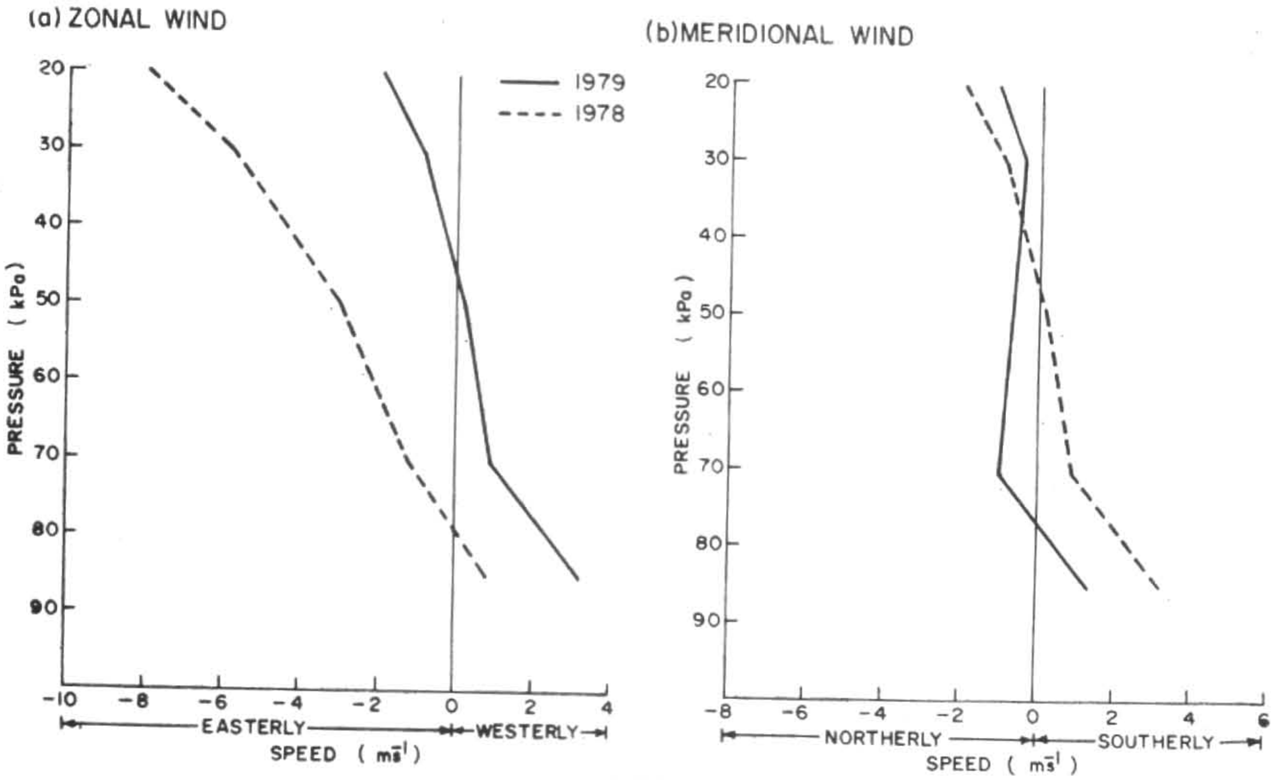

Fig 1. Mean wind in the 24°-28°N belt during July

Bhubaneshwar and Hyderabad-Nagpur-Visakhapatnam were considered. The mean divergence and relative vorticity of these triangles were obtained for only one pair of good and poor monsoon, *viz.*, 1978 and 1979 respectively.

3. Results and discussion

3.1. *Strength of Hadley circulation*

Over the Indian area, in July, though ITCZ fluctuates in association with the active-break conditions, normally, it is located between 24° & 28°N (Ananthakrishnan 1977). In order to bring out contrast in meridional circulation the vertical profile of the zonal and meridional winds, averaged between 24° & 28°N and 70° & 90°E for July is presented for a good monsoon year and a year of monsoon failure (Fig. 1). The figure distinctly exhibits the northern hemispheric summer Hadley circulation in both the years, but it is much more pronounced during the year when monsoon is active. Evidently during good monsoon years the northern hemispheric Hadley cell penetrates much to the north over the monsoon region. During years of monsoon failure the Hadley cell is perhaps more localized. The corresponding distribution of the mean zonal components (Fig. 1 a), shows weak westerlies in the lower layer and strong easterlies aloft in a good monsoon year. In years of monsoon failures, westerlies predominate in lower and middle troposphere and feeble easterlies in the upper troposphere. These results are in agreement with the circulation features observed in the 24°-28°N latitudinal belt during spells of active and weak monsoon conditions.

3.2. *Wind oscillations*

In the first instance, the 10-day normal wind was analysed with a view to determining climatologically prominent modes in the propagation of the wind. Contribution of different cycles was sought by averaging the winds for 4° latitude belt. Results of the analysis have been summarised in Table 1 for zonal and meridional wind components.

As may be expected, the first harmonic, *i. e.*, seasonal mode dominates the zonal wind field at nearly all levels in all latitudes. This is particularly so north of 20°N and in upper troposphere where 80-90% of the variance is explained by the seasonal mode. In the lower latitudes, *i.e.*, south of 20°N, the middle and upper troposphere exhibit significant fluctuations associated with 30-60 day periodicities.

A rather complex pattern emerges in the normal meridional wind field. No doubt, in nearly three fifth of the levels/latitude zones, the seasonal mode continues to dominate the circulation, in the rest of the cases, 30-60 day fluctuations emerge as the most conspicuous modes. In some cases, the 30-60 day fluctuations explain nearly 60% of the variance while the 120-day mode, in sharp contrast, explains less than 5%. Variance explained by 20-25 day periodicities is also substantial, particularly south of 24°N and between 70 & 30 kPa.

TABLE 1

Variance (%) explained by normal winds

Levels (kPa)	Periodicity (days) 08°-12°N			12°-16°N			16°-20°N			20°-24°N			24°-28°N		
	120	30-60	20-25	120	30-60	20-25	120	30-60	20-25	120	30-60	20-25	120	30-60	20-25
(a) Zonal component															
20	66	31	3	55	40	5	88	12	0	94	6	0	95	5	0
80	67	24	9	33	52	15	40	57	3	86	13	1	92	8	0
50	64	34	2	59	40	1	55	41	4	39	42	19	87	12	1
70	71	27	2	75	25	0	82	16	2	58	30	12	76	22	2
85	71	27	2	75	24	1	72	26	2	63	29	8	71	21	8
(b) Meridional component															
20	74	26	0	1	78	21	82	16	2	59	29	12	75	23	2
30	65	33	2	13	86	1	18	71	11	55	20	25	53	38	9
50	25	53	22	47	38	15	4	58	38	13	64	23	31	61	8
70	52	45	3	43	9	48	33	41	26	20	70	10	88	7	5
85	60	37	3	56	14	30	86	11	3	65	31	4	83	14	3

TABLE 2

Variance (%) explained by zonal wind anomaly

Year	Periodicity (days) 08°-12°N			12°-16°N			16°-20°N			20°-24°N			24°-28°N		
	120	30-60	10-20	120	30-60	10-20	120	30-60	10-20	120	30-60	10-20	120	30-60	10-20
(a) Level 85 kPa															
1978	10	35	22	4	27	31	8	30	27	2	28	24	2	16	50
1979	21	49	14	16	41	21	14	51	15	4	31	35	11	40	17
1982	3	22	46	6	38	36	44	43	12	1	36	27	15	37	18
1983	7	23	32	6	50	19	11	24	31	2	29	33	1	13	58
(b) Level 20 kPa															
1978	10	26	25	37	28	17	9	20	48	14	23	47	30	19	33
1979	4	15	50	6	13	39	21	34	22	28	41	10	21	45	8
1982	15	25	30	10	25	30	7	23	42	6	37	29	15	35	37
1983	10	34	24	17	37	25	1	48	36	7	38	28	37	18	29

The normal pattern is, more often than not, realised in different years. This is clearly brought out in Table 2 (a) which contains variance explained by zonal wind anomalies at 85 kPa. Irrespective of the activity of the monsoon, 30-60 day modes ramain the largest contributor to the total variance in nearly all latitude zones. Shorter periodicities, however, appear to control monsoon rainfall during good monsoon years, particularly north of 20°N.

For studying oscillations in the zonal component of wind in upper troposphere, 20 kPa level has been chosen. At this level, in both good and poor monsoon years the contribution to variance by fluctuations of 60 days or less (Table 2b) is generally found to exceed 50%. In years of deficient monsoon, south of about 20° N, contribution of quasi-biweekly oscillations (*i. e.*, 10-20 days) is significantly larger than that of 30-60 day oscillations. In years of good rainfall, over the Peninsular India, the contribution of 10-20 day modes, though smaller than 30-60 day modes, is nevertheless comparable to the latter in magnitude. A reverse trend is seen in the northern latitudes.

The results emanating from the anlysis of meridional winds were similar to that for the zonal winds and are not discussed.

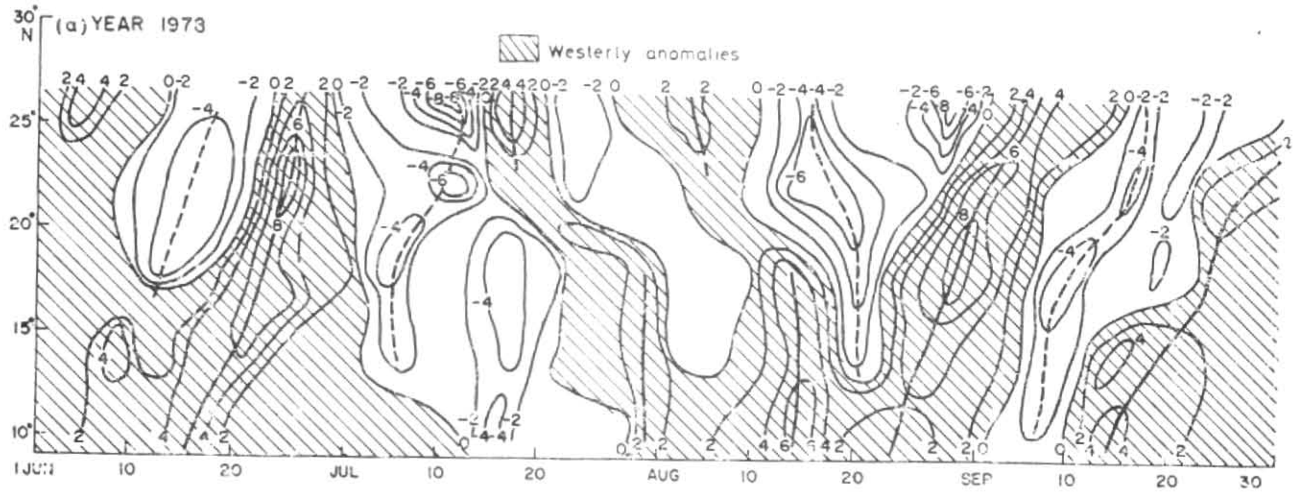

Fig. 2 (a). Hovmöller diagram of zonal wind anomalies at 85 kPa : year 1978

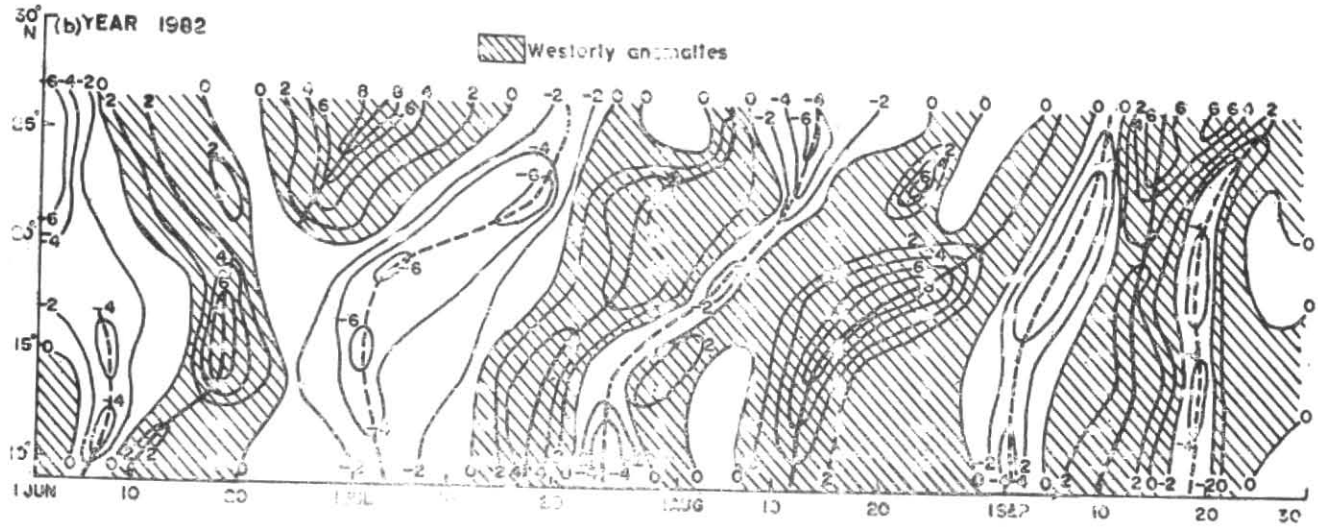

Fig.2 (b). Hovmöller diagram of zonal wind anomalies at 85 kPa : year 1982

TABLE 3

Different epoches of monsoon

Year	Date of monsoon onset				Period of weak monsoon	
	As per India Met. Dept.		As per the study		As per India Met. Dept.	As per the study
	10°N	20°N	10°N	20°N		
1978	28 May	10 Jun	2 Jun	21 Jun	10-21 Jul, 15-25 Aug	3-22 Jul, 18-28 Aug
1979	11 Jun	19 Jun	15 Jun	24 Jun	15 Jul-5 Aug, 19 Aug-14 Sep	4-25 Jul, 17 Aug-21 Sep
1982	30 May	17 Jun	8 Jun	14 Jun	1-7 Jul, 3-7 Aug, 25 Aug-7 Sep	29 Jun-10 Jul, 3-6 Aug, 29 Aug-8 Sep
1983	14 Jun	20 Jun	16 Jun	17 Jun	1-7 Jul, 25-31 Jul, 1-12 Sep	1-15 Jul, 27 Jul-5 Aug, 20 Aug-1 Sep, 7-11 Sep

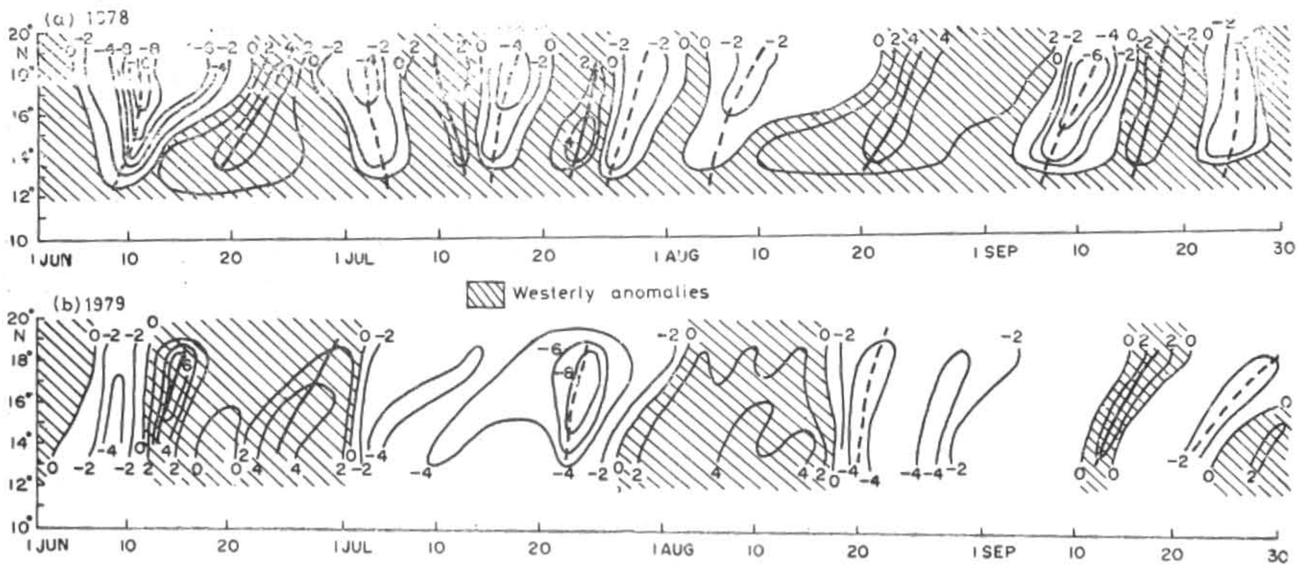

Fig. 3. Hovmöller diagram of zonal wind anomalies at 30 kPa

3.3. *Inter-annual fluctuations*

During monsoon the seasonal mean state is often modulated by low frequency oscillations (LFO). Though LFO is a global scale phenomenon, both longitudinally and latitudinally (Lorenc 1984), the oscillations have their greatest amplitude in the summer hemisphere of south and southeast Asia and Western Pacific. Influence of quasi-periodic fluctuations, the major components of northern hemispheric summer over India and neighbourhood has been studied by examining a Hovmöller diagram of 85 kPa zonal wind anomalies for 1978 (good) and 1982 (bad) (Fig. 2). A train of zonal westerly and easterly anomalies seems to propagate. During the good monsoon year (1978), their periods vary from a tri-weekly to more than 40 days (Fig. 2a) while for a drought year (1982), the periodicities are comparatively larger (Fig. 2 b), suggesting that prolonged breaks characterise drought in the monsoon zone.

The most noteworthy feature observed is the northward movement in the wind anomalies with a period of 30-60 days. Mehta and Ahlquist (1986) observed a steady northward movement in the zonal wind, divergence and vorticity over India during 1979 at 85 kPa level but less so in 1977, 1978 and 1980. The meridional fluctuations in zonal wind anomalies observed in this study are northward repetitive shift from the southern latitudes towards the north Indian plains. The first phase of the northward movement of westerly anomalies perhaps coincides with the onset of the summer monsoon over India. The oscillations travel with a phase speed of about 2° Lat./day. Other major fluctuations seen, are of 10-20 days duration. The propagation is somewhat faster south of 20°N.

For the four monsoon years, *viz.*, 1978, 1979, 1982 and 1983, the onset of monsoon at 10° & 20°N is given in Table 3 alongwith periods of weak or break monsoon. Monsoon onset is found to coincide remarkably well with the arrival of low frequency westerly anomalies over the region. Many studies have found that the 30-60 day oscillations are related to onset of monsoon(Hendon 1988). Commencement of weak monsoon in the study have been observed when the prevailing westerly anomalies are replaced by easterly anomalies and last till the reversal takes place.

We have seen in an earlier section that the 30-60 day modes are most pronounced between 12° & 20°N at 30 kPa. Progression of zonal anomalies in this belt for 1978 and 1979 are depicted in Fig. 3. As in the lower levels, at 30 kPa also, in the beginning and towards the end of the monsoon season, easterly anomalies prevail. In the rest of the season, alteration between easterly and westerly anomalies is seen. In 1978 these anomalies have periodicities in quasi-biweekly time scale and are related to the active-break cycle. On the other hand, in 1979 during a major part of the monsoon season, easterly anomalies are prevailed. They are not only more intense but prevail for a longer duration, exceeding even 40 days.

Madden (1986) has shown that the LFO possesses a substantial meridional propagation. The present observational study also indicates that the oscillations possess a substantial meridional wind propagation thereby suggesting that it is not entirely a Kelvin wave.

In order to explore possible interaction between 30-60 day oscillations in the zonal wind anomalies and link them to the summer monsoon, Hovmöller diagrams of wind anomalies at 85 kPa along 70°-90°E cross-section, for 20°N have been prepared. The results are depicted in Fig. 4, for two contrasting monsoon seasons only. Some broad scale common features observed are described below :

Significant large scale quasi-stationary easterly anomalies over 70°-90°E belt appear towards the beginning of June in association with the monsoon onset. Replacement of the easterly anomaly by the westerly one, heralds the monsoon onset.

A period of persistent easterly anomalies is also seen towards the middle of September which generally prolongs till the end of the monsoon season. This is most pronounced during a drought year. On the other hand, in years of good monsoon, westerly anomalies seems to persist even till the end of September. In between these two periods of prominent easterly anomalies, intra-seasonal oscillations (both easterly and westerly anomalies) are seen. Though major oscillations have a periodicity of 30-40 days, minor disturbances of 10-15 days are also seen. These anomalies generally propagate west to east with a speed of 2°-3° Long. day^{-1}. The alteration between westerly and easterly anomaly is generally associated with active-break phase of monsoon. Also, though the eastward movement is most prominent, westward moving transient wind anomalies on smaller scale, is also observed. The east to west movement is perhaps due to a retrograde motion in the anomalies. Ratrogation in deep convection has been reported by Murakami *et al.* (1984) and in pressure anomalies by Singh and Kripalani (1986). Considering local oscillating heat source, Lau and Peng (1987) found westward expansion of the wind perturbation in their primitive equation model. Hendon (1988) also found westward propagation to occur in fully nonlinear model with large values of efficiency factor. The westward propagation of the LFO observed in the study is thus easily reconciled. The westward anomalies, perhaps, correspond to the easterly wave disturbances (Yasunari 1979).

Also observed in the study is a general concentration of predominant westerly anomalies between 80° & 85° E, an area where monsoon depressions generally develop.

3.4. *Vertical structure*

The vertical profile of the zonal anomalies from 85 to 30 kPa for 12° to 16° N and 16° to 20° N Lat. belts for two constrasting years 1978 and 1982, was examined. It has been observed that during 1978 there is a phase lag of 15 days in the easterly and the westerly anomalies in the upper troposphere (30 kPa) and the lower troposphere (85 kPa) causing a tilt in the vertical structure. In contrast, during years of monsoon failure, no such phase lag is noticed. This phase lag is less marked in higher latitudes both during good and bad monsoon years. This suggests that the quasi-biweekly oscillations and the monsoon activity depend to a great extent on the tilt of the lower and middle tropospheric wind anomalies.

3.5. *Oscillations in divergence and relative vorticity*

In the normal divergence field at 85 kPa. 30-60 day oscillations are the most prominent modes south of about 20° N, explaining 50 to 75% of the total variance.

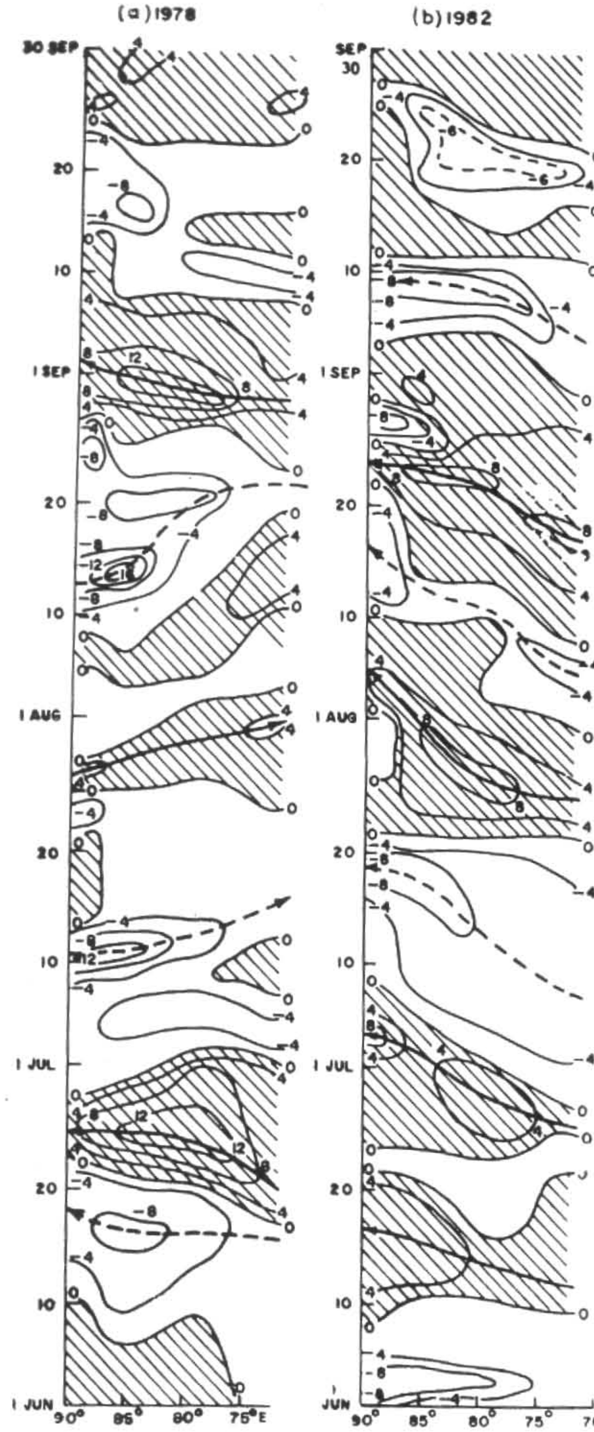

Fig. 4. Hovmöller diagram of zonal wind anomalies at 85 kPa along 20°N

Elsewhere, seasonal mode appears to dominate. At 30 kPa, over large parts, the 120-day mode emerges conspicuously while the 30-60 day oscillations remain prominent only over a small portion in south Peninsula.

The lower troposphere exhibits a complex pattern in the normal relative vorticity field. Over large parts, the 30-60 day fluctuations remain the most important mode of relative vorticity accounting, 50-60% of the total variance. In the upper troposphere the pattern of prominent mode appears more organised. Whereas in northwest India, the seasonal mode is prominent at 30 kPa, in rest of the areas, north of 20°N, 60-day cycle appears most conspicuous. South of 20°N, oscillations of 20-30 day periods generally dominate over other time scales.

Areas between 15°& 20°N and west of 80°E remarkably revealed presence of low frequency modes (Chowdhury *et al.* 1988 b). An attempt, therefore, was made to find out whether in the circulation pattern too, these characteristics are reflected. For this purpose, divergence and relative vorticity were worked out by Bellamy's method for the triangle mentioned in Sec 2. The area of the triangles more or less corresponds to the area where low frequency modes are mostly prevalent. This was done for the three levels, *viz.*, 85, 50 and 20 kPa.

In the divergence field, no unique pattern was observed in any level. However, in relative vorticity, the following features came out prominently.

(*i*) In the lower tropospheric levels, cyclonic vorticity peaks have a periodicity ranging from 10 to 20 days in years of good monsoon. Similar periodicities were also observed at 20 kPa in the anticyclonic vorticity field.

(*ii*) In bad monsoon year the periodicities were, however, of longer duration.

Thus, an in-phase relationship exists between appearance of anticyclonic vorticity at 20 kPa and the appearance of cyclonic vorticity in the middle and lower troposphere in a good monsoon year. This coupling between the lower and upper tropospheric relative vorticity, however, breaks down in years of bad monsoon.

4. Possible physical explanation

Although many aspects of the oscillations are well known, mechanism for development and translation of the LFO have not yet been fully understood. Yamagata and Hayashi (1984) and Salby and Garcia (1987) suggested that a plausible mechanism is stationary cumulus convective heating which drives the oscillations. Numerical models have also confirmed that the convective heating in the tropics generates two different modes of disturbances, the Kelvin wave with a phase velocity of 35 m s^{-1} eastwards and the Rossby wave with a velocity 10 m s^{-1} westwards (Lau and Peng 1987). The Kelvin wave being divergent, is affected more by the disturbance than the rotational dominated Rossby wave. Subsequently, the Kelvin wave gets amplified by the CISK mechanism and generates the eastward movement of 30-60 days mode. However, when the central disturbance is away from the equator, the divergence due to Kelvin wave and the wave —CISK mechanism get subdued. In such cases, the rotational component of Rossby wave is more dominant resulting westward propagation of the mode.

5. conclusions

Based on the above studies the following conclusions could be drawn :

(*i*) The Hadley circulations is substantially large when the monsoon rainfall is normal or above normal while in years of monsoon failure the circulation is localised.

(*ii*) Second to fourth harmonics in the lower latitudes, winds appear as the major component of northern hemispheric summer circulation fields over India. It acts as a catalyst in activating the monsoon.

(*iii*) A train of anomalies, both easterlies and westerlies, alternates during the summer monsoon season over India. Advent of westerly anomalies heralds the monsoon onset and is also precursor of active monsoon conditions. Appearance of easterly anomalies normally results in break monsoon conditions.

(*iv*) The westerly anomalies, while travelling eastwards, get amplified when they reach the Bay of Bengal.

(*v*) The low frequency oscillations possess a meridional propagation phase speed of about 2° Lat. per day.

(*vi*) A westward movement of transient wind anomalies also occurs during the monsoon.

(*vii*) The anomalies have generally a vertical tilt.

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