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Characteristics of quasi-biennial oscillation over Kenya and their predictability potential for the seasonal rainfall

L. J. OGALLO, R. E. OKOOLA and D. N. WANJOHI

Dep. of Met., University of Nairobi, Nairobi, (Kenya)

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सार — इस अध्ययन में, 1966-1987 की अवधि के नैरोबी (कीनिया) की मासिक कटिबंधीय पवनों के घटकों का प्रयोग करते हुए, उष्णकटिबंधीय पूर्वी अफ्रीका पर अर्द्ध द्विवार्षिक दोलन की विशेषताओं की जांच की गई है। समताप मंडल की पूर्वी और पश्चिमी पवनों के फेज और मौसमी वर्षा की विसंगतियों की भी जांच की गई है।

स्पेक्ट्मी विश्लेषण के परिणाम से कटिबंधीय पवन के घटकों में 28 माह की अवधि की प्रधानता का पता चला है। पश्चिमी और पूर्वी दोनों पवनों के फेजों के उर्ध्वाधर प्रसार की दर लगभग —1.2 कि० मी०/माह पाई गई।

सांख्यिकी विश्लेषण के परिणाम से वर्षा की विसंगतियों (सामान्य से अधिक, सामान्य और सामान्य से कम) के साथ पूर्वी और पश्चिमी पवनों के फेज के मध्य उल्लेखनीय संबंध (5 प्रतिशत स्तर पर) का पता चला है।

ABSTRACT. In this study the characteristics of the Quasi-Biennial Oscillation (QBO) over the tropical eastern Africa were investigated using monthly zonal wind components from Nairobi (Kenya) within the period 1966-1987. Relationships between the stratospheric easterly and westerly wind phases and the seasonal rainfall anomalies were also investigated.

Results from spectral analysis indicated the dominance of a 28 months' period in the zonal wind component. The vertical rate of propagation of both westerly and easterly wind phases was about —1.2 km/month.

Results from statistical analysis indicated significant (at 5% level) association between rainfall anomaly class (above normal, normal, and below normal) and easterly and westerly wind phases.

Key words — Quasi-biennial oscillation, Season forecasting, Spectral and cross-spectral analysis.

1. Introduction

One of the well known quasi-periodic phenomena in the atmosphere is the regular alternation of zonally symmetric westerly and easterly winds in the mean winds of the tropical stratosphere. The reversal period of the easterly and westerly winds is about 23-30 months. The successive westerly/easterly wind regimes first appear around 30 hPa and then propagate downwards. The phenomenon has been generally known as the Quasi-Biennial Oscillation(QBO). Evidences of QBO in both stratospheric, tropospheric together with the extra-tropical variables have been presented by Palmer (1954), Reed *et al.* (1961), Angell and Korshover (1964), Angell *et al.* (1969), Dartt and Belmont (1970), Miller, *et al.* (1974), Ebdon (1975), Brier (1978), Coy (1979), Trenberth (1980) among many others.

The stratospheric and tropospheric variables which have exhibited QBO include temperature (Rasmusson *et al.* 1981), ozone (Funk and Garnham 1962, Hasebe 1980), Indian monsoon rainfall (Mukherjee *et al.* 1985), African rainfall (Rodhe and Virji 1976, Ogallo 1979, 1982), ENSO phenomenon (Berlage 1966) and many others. A historical review of the QBO phenomenon may be obtained from Landsberg (1962) and Lamb (1972), while some of the best theories which may be used to describe QBO characteristics have been presented by Holton and Lindzen (1972), Plumb (1984) among many others in terms of the upward propagating equatorial waves like mixed Rossby-gravity and Kelvin waves.

Due to the regularity in the phases of the QBO and the appearance of QBO spectral peak in many atmospheric parameters, many attempts have been made to examine the predictability potential of the QBO signals. The major objectives of this study are two fold—the first part examines the characteristics of QBO over the equatorial eastern African region using zonal stratospheric wind records from Nairobi. The predictability potential of the observed QBO signals for the seasonal rainfall forecasting is investigated in the final part of the study. The data used in the study consisted of mean monthly zonal wind records from Nairobi, Kenya (1° 18'S, 36° 45'E) for the period 1967 to 1987 at 100, 70, 50 and 30 hPa levels (Fig. 1).

2. Methodology

This section highlights the various methods which were used in this study to investigate the characteristics of QBO over Kenya. Methods which were used to investigate the relationship between the stratospheric QBO phases and the observed surface climatic fluctuations are also presented. The methods include spectral, correlation and cross-spectral analyses. Time-height cross-sections were also used.

2.1. *Spectral analysis and time-height cross-sections*

Under this section time series of the mean monthly zonal winds at 100, 70 50 and 30 hPa were subjected to spectral analysis in order to determine the period of recurrences of the westerly (positive zonal winds) and easterly (negative zonal winds). A twelve month difference filter was used to remove the seasonal fluctuations. The filter further ensured stationarity in the time series. Details of the difference filter together with the corresponding response functions can be obtained in many standard references including WMO (1966). The differenced time series were subjected to spectral analysis using Maximum Entropy Method (MEM). The computed spectral estimates were smoothed using Parzen and Tukey windows independently. Details of spectral analysis may be obtained from Burg (1972), and Jenkins and Watts (1968). Peaks in the smoothed MEM spectra were used to determine the dominant recurrence periods in the stratospheric westerly and easterly phases over Kenya.

The characteristics of the time-height cross-sections within the period of study were also used to investigate the recurrence patterns of the easterly and westerly wind phases at the various levels.

2.2. *Relationship between QBO phases and rainfall*

In the final part of this study, relationships between the westerly/easterly QBO phases and rainfall have been examined using simple correlation coefficient (r), cross-spectral analyses and contingency tables. Cross-spectral analysis involved the computation of cross-correlation $R(k)$ coherence $C(f)$, and phase $Q(f)$ functions.

The simple correlation coefficient (r) may be expressed as :

$$r = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\left(\sum_{i=1}^{n} X_i^2 \sum_{i=1}^{n} Y_i^2\right)}} \tag{1}$$

$$-1 \leqslant r \leqslant 1$$

$$x_i = X_i - \overline{X}_i, \quad y_i = Y_i - \overline{Y}_i$$

where X_i and Y_i, represents monthly values of rainfall and easterly/westerly wind phases at the individual levels respectively while $\overline{X}_i$ and $\overline{Y}_i$ are their corresponding

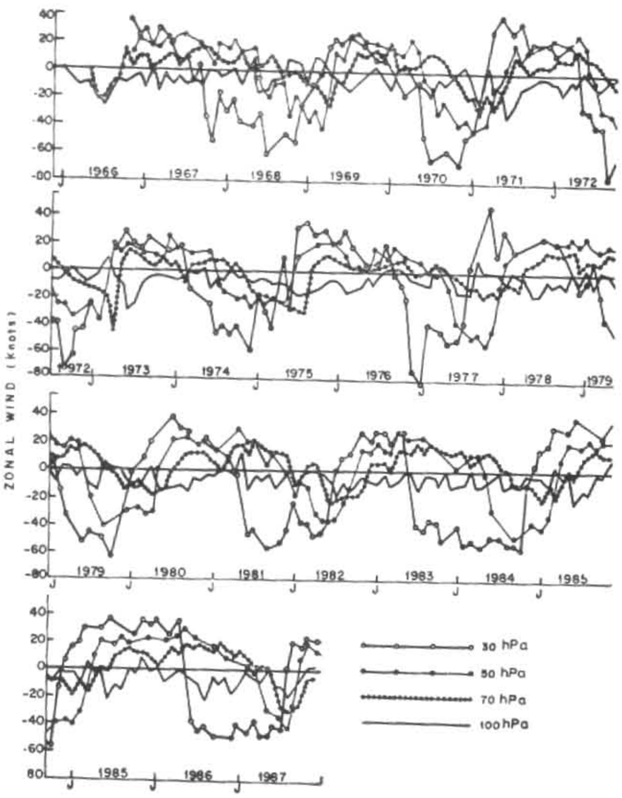


Fig. 1. Mean monthly zonal wind record for Nairobi for period 1967 to 1987 at 100, 70, 50 and 30 hPa levels

long-term averages based on 1967-87 records. The statistical significance of r was tested using t-test at 95% confidence level. Pairs of variables are correlated if r is significantly different from zero. Positive/negative values indicate positive/negative relationships respectively. Unit r value represents perfect correlation between the pair of variables.

The cross-correlation coefficient $R(k)$ which determines the degree of relationship between X_t and Y_t at time lag k may be expressed as :

$$R_{xy}(k) = \frac{\sum_{t=1}^{n-k} X_t Y_{t+k}}{\left(\sum_{t=1}^{n-k} X_t^2 \sum_{t=1}^{n-k} Y_{t+k}^2\right)^{\frac{1}{2}}} \tag{2}$$

where, k is the time lag

$$x_t = X_t - \overline{X}_t \text{ and } y_t = Y_t - Y_t$$

Another function which has been widely used to describe the time lagged relationships is the coherence function $[C_{xy}(k)]$:

$$C^2_{xy}(f) = \frac{F^2_{xy}(f)}{|F_x(f)|\ |F_y(f)|} \tag{3}$$

where, $0 \leqslant f \leqslant \frac{1}{2}$ and $-1 \leqslant C(f) \leqslant 1$

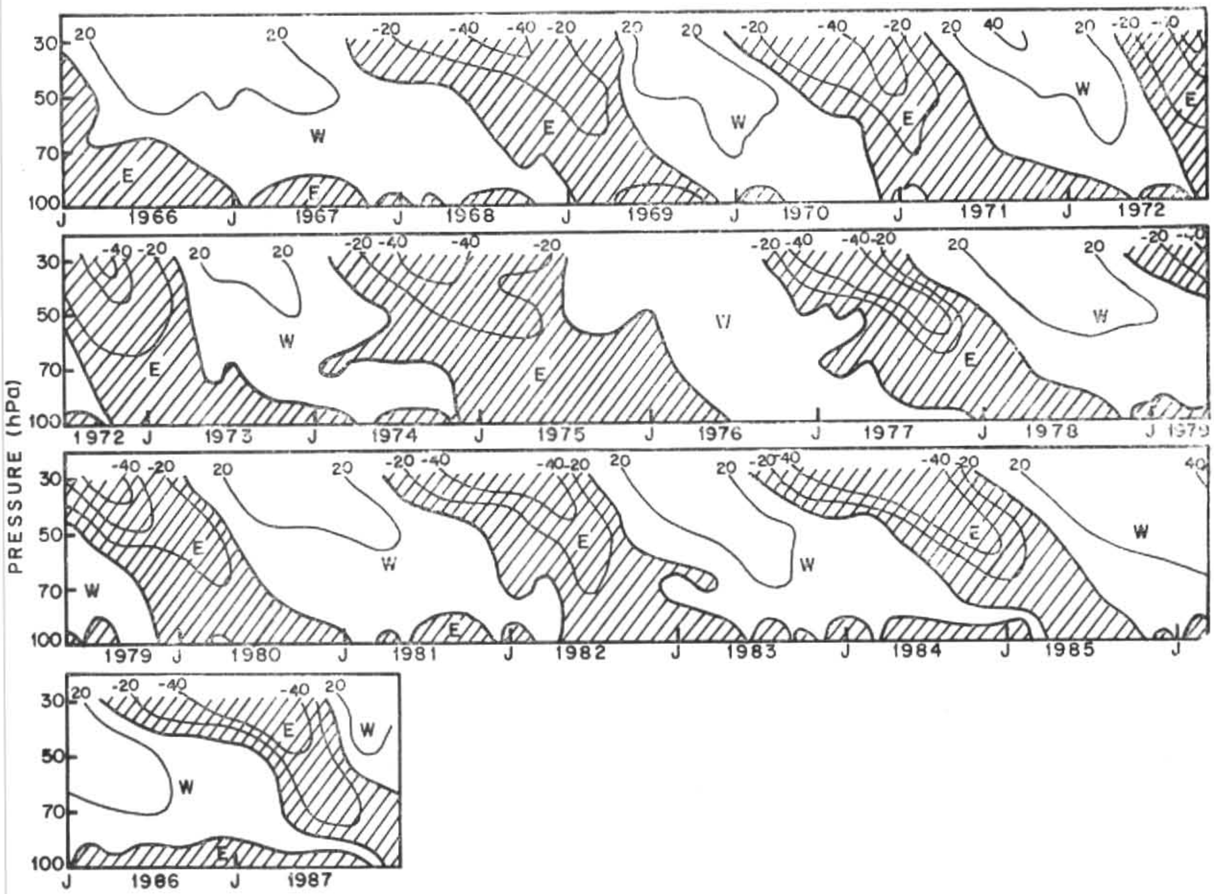


Fig. 2. Time-height cross-sections of the 30-100 hPa zonal winds for the period 1966-1987

where, f is frequency and $F_{xy}(f)$ are the cross-spectral density estimates for the time series X_t and Y_t while $F_x(f)$ and $F_y(f)$ are the independent spectral density estimates for the time series X_t and Y_t.

The phase function $Q(f)$ gives the time lag/lead between X_t and Y_t values at any given frequency (f)

$$Q_{xy}(f) = \tan^{-1}\left(\frac{Q_{xy}(f)}{P_{xy}(f)}\right) \qquad (4)$$

where, Q_{xy} and P_{xy} are the quadrature and real part of the co-spectrum respectively. Details of the cross-spectral functions may be obtained from Jenkins and Watts (1968). $Q(f)$ and $C(f)$ were used here to determine lagged relationships between rainfall and easterly/westerly winds at 100, 70, 50 and 30 hPa levels. They were also used to determine the rate of downward propagation of the stratospheric easterly/westerly wind phases.

Relationships between rainfall characteristics and the easterly/westerly winds were further examined using χ^2-test derived from contingency tables which summarized the rainfall characteristics associated with the various easterly/westerly wind phases. The rainfall characteristics examined in the study included the duration magnitude, onset and withdrawal dates. These are examined for three years, 1984 (poor long rains), 1985 (poor short rains) and 1986 (normal rainfall for both seasons). The duration, onset and withdrawal dates were obtained from cumulative decadal rainfall mass curves. These analyses were done for both long and short rainy seasons. The long and short rainy seasons are observed during March-May and October-November respectively.

3. Results and discussion

Time-height cross-sections of the 30-100 hPa zonal winds within the period 1966-1987 are given in Fig. 2. The figure indicates successive recurrences of the easterly and westerly wind phases. The successive phases appear at 30 hPa and propagate downwards. The average rate of the downward propagation of the westerly and easterly winds were about —1.5 km/month and —0.9 km/month respectively giving an average rate of —1.2 km/month. This rate is close to the value which has been observed by other authors (Plumb 1984, Holton and Lindzen 1972).

TABLE 1

Observed characteristics of the easterly westerly wind phases

Easterly wind component at 30 hPa level				Westerly wind component at 30 hPa level			
Onset date for easterly	Withdrawal date for easterly	Duration of persistent easterly (months)	Recurrence period for easterly (months)	Onset date for westerly	Withdrawal date for westerly	Duration of persistent westerly (months)	Recurrence period for westerly (month)
Sep 1967	Apr 1969	20	—	Apr 1969	Jan 1970	10	—
Jan 1970	Mar 1971	15	29	Mar 1971	May 1972	17	24
May 1972	Mar 1973	11	29	Mar 1973	Mar 1974	13	25
Mar 1974	May 1975	15	23	May 1975	Oct 1976	18	27
Oct 1976	Aug 1977	11	32	Aug 1977	Dec 1978	17	28
Dec 1978	Feb 1980	15	27	Feb 1980	Apr 1981	15	31
Apr 1981	Jul 1982	16	29	Jul 1982	Jun 1983	12	30
Jun 1983	Nov 1984	18	27	Nov 1984	May 1986	19	29
May 1986	Aug 1987	16	36	Aug 1987	—	—	—
Average		15.2	28.9			15.1	27.7

The time-height cross-sections given in Fig. 2 were used to determine the onset and withdrawal dates together with the durations of the individual easterly/westerly wind phases at 30hPa. The observed dates are given in Table 1. The table indicates that the onset and withdrawal dates were distributed throughout the year. The reversal of the westerly/easterly wind phases at Singapore has, however, been observed to be concentrated within the period November-April (Plumb 1984). Table 1 further indicates that the maximum and minimum durations of persistence of the easterly wind phase at 30 hPa level were about 20 and 11 months respectively. The corresponding values for the westerly phase were 19 and 10 months respectively.

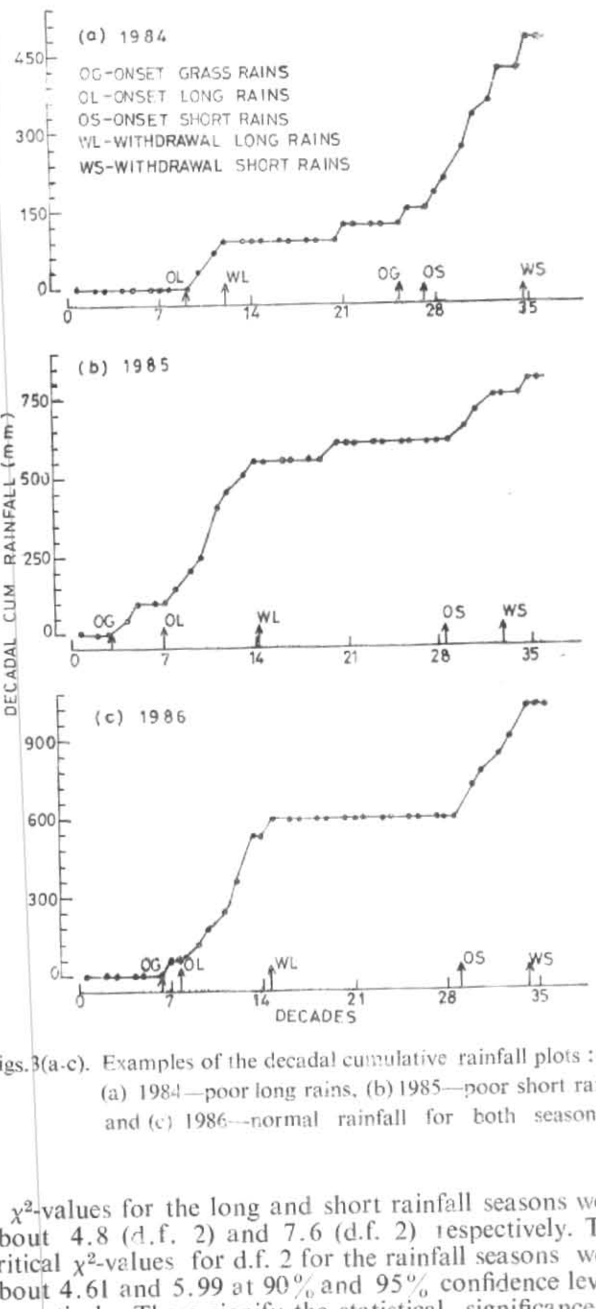
Results from spectral analysis indicated existence of distinct quasi-periodic characteristics in the inter-annual pattern of the westerly and easterly wind phases. The patterns of the time series within the period 1966-87 are given in Fig. 1. The dominant spectral peaks which were discernible from spectral analyses were centred around 28 months for the zonal wind component.

The recurrence dates for easterly and westerly wind phases at 30 hPa within the period of study are given in Table 1. The table indicates that observed recurrence periods ranged from 23-32 months. One case, however, had relatively larger value which was close to 36 months for both easterly and westerly wind phases.

It should be noted that the onset and withdrawal dates of the individual wind phases were extrapolated from the time-height cross-sections. The subjectivity of this graphical method may induce some errors in all parameters which were derived from the onset and withdrawal dates, like the duration and recurrence periods which are given in Table 1.

Results from correlation analysis indicated that most of the correlation coefficient values between rainfall and the stratospheric zonal wind component were less than 0.3 at all levels including the 30, 50, 70 and 100 hPa levels. The t-test indicated that most of those correlation values were statistically not different from zero which indicates no significant correlation between the stratospheric wind phases and rainfall anomalies which were observed during the period of study. Example of the decadal cumulative rainfall values (mass curves) which were used to determine the onset, withdrawal and duration data for rainfall are given in Fig. 3, for cases of (*i*) poor long rains, 1984,(*ii*) poor short rains, 1985, (*iii*) normal rainfall for long and short rains,1986.

Table 2, however, reveals some interesting information when the rainfall and stratospheric wind anomalies were generalized into categories using contingency tables. It is evident from the study that nine cases of above normal rainfall were recorded within the period of study during the long rainy season. Stratospheric westerly wind phases were observed during seven of these nine cases giving a probability of about 0.8 for the association between above normal rainfall and stratospheric westerly wind phase during the long rains. Table 2(b) however indicates that stratospheric westerly wind phases were observed during all six cases when above normal rainfall was observed within the short rainy season.



Figs. 3(a-c). Examples of the decadal cumulative rainfall plots : (a) 1984—poor long rains, (b) 1985—poor short rains, and (c) 1986—normal rainfall for both seasons

χ^2-values for the long and short rainfall seasons were about 4.8 (d.f. 2) and 7.6 (d.f. 2) respectively. The critical χ^2-values for d.f. 2 for the rainfall seasons were about 4.61 and 5.99 at 90% and 95% confidence levels respectively. These signify the statistical significance of the associations only during the short rainfall period when 95% confidence level is considered. Evidence of significant relationships between rainfall during short rainy season and SST, ENSO, and other general circulation parameters have been observed by Ogallo (1988), Ogallo *et al.* (1988) among others. Many studies have noted higher degrees of spatial correlations in the rainfall patterns during the short rainy season. The long rainfall season has been associated with complex interactions between many regional and large scales systems which generally induce some heterogeneity in the spatial rainfall characteristics. Table 2 further indicates that the probability of below normal rainfall associated with the stratospheric easterly wind phases were about 0.75 and 0.71 for the long and short rainfall seasons respectively. The corresponding probability of above normal rainfall being associated with stratospheric westerly wind phases is higher, being

TABLE 2 (a & b)

Contingency tables for the rainfall anomalies and zonal wind phase at 30 hPa level

Wind Component	Rainfall anomaly			
	A	N	B	Total
(a) Long rainy season				
Easterly	2(4.5)	13(12.5)	6(4.0)	21
Westerly	7(4.5)	12(12.5)	2(4.0)	21
Total	9	25	8	42
(b) Short rainy season				
Easterly	0(3.0)	16(14.5)	5(3.5)	21
Westerly	6(3.0)	13(14.5)	2(3.5)	21
Total	6	29	7	42

A — Above normal rainfall ($X_i > \overline{X} + \sigma$),
B — Below normal rainfall ($X_i < \overline{X} - \sigma$)
N — Normal rainfall ($\overline{X} - \sigma < X_i < \overline{X} + \sigma$),
σ — is the standard deviation,
$\overline{X}$ — Seasonal arithmetic mean of rainfall.

Figures in parentheses are cell frequencies on hypothesis of no association.

much higher for short rainfall season. It is, however, noted that the samples under categories A and B in Table 2 were small and hence rather large sampling fluctuations in probabilities cannot be ruled out.

Nairobi lies on eastern part of the central highlands making the Indian Ocean the major source of the moisture for precipitation formation transported by the low level easterly monsoonal wind systems. These monsoonal wind systems can be used to explain the observed associations between the upper level westerly/easterly wind phases and corresponding above/below normal rainfall conditions. Table 2 also indicates that only two cases had below normal rainfall with upper level westerly wind phases, in each of the two rainy seasons. These were observed during 1983-84. It should be noted that the period 1982-83 was one of the warmest *El-Nino* event this century.

Results from cross-correlation analysis indicated that time lagged correlations between rainfall and the wind phases were generally low. Few of these time lagged cross-correlations $R(k)$ were, however, significant at the 5% level but the variance explained by the significant cross-correlation functions, was, however, very low. Statistically significant coherence was also obtained at 30 and 50 hPa levels. The phase angle values indicated rainfall leading QBO wave at 30 and 50 hPa levels by 1.4 and 1.2 months respectively.

Cross-spectral analysis further indicated high coherence between inter-level easterly and westerly wind phases. The phase angles gave the average rate of downward propagation of the westerly and easterly wind phases as −1.3 km/month. This is close to the value which was obtained from time-height cross-sections as discussed earlier in the text.

4. Conclusions

The results from the study indicated that the average period of the stratospheric quasi-biennial oscillation over Kenya is about 28 months. The period was dominant in zonal wind component. The westerly/easterly wind phases first appeared around 30 hPa and propagated downwards with an average rate of about −1.2 km/month.

Results from the study further indicated that simple and cross-correlation analyses could not reveal any associations between rainfall and the various stratospheric zonal wind phases. Few cross-correlation functions were, however, significant, but the variance accounted for by the significant cross-correlation functions were, however, very low at 5% significance level. Some significant relationships were, however, discernible when contingency tables were used to generalise the observed rainfall anomalies into categories. The contingency tables indicated that probability of about 0.8 was associated with the stratospheric westerly wind phases and above normal rainfall. The corresponding probability for below normal rainfall cases and stratospheric easterly wind phase was about 0.7 coherence and phase angle values derived from cross-spectral analysis showed that rainfall was leading QBO wave at 30 and 50 hPa levels by 1.4 and 1.2 months respectively. It should be noted that although coherence values between rainfall and the 30 and 50 hPa winds were statistically significant, QBO at these levels accounted for relatively low percentage of seasonal rainfall variance in both seasons. The observed association between the rainfall anomalies and the stratospheric zonal wind phases could provide useful long range signals for the expected seasonal rainfall anomalies for the short rainy season. Further studies using pentad or decadal zonal wind data is however required in order to provide more information on the predictability potential of the stratospheric easterly and westerly wind phases.

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