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Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

Relationships Between QBO in the Lower Equatorial Stratospheric Zonal Winds and East African Seasonal Rainfall

M. Indeje and **F. H. M. Semazzi**

With 10 Figures

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Summary

Teleconnections between the seasonal rainfall anomalies of March through May ("long-rains") over eastern Africa (Uganda, Kenya and Tanzania) and the lower equatorial stratospheric (30-mb) zonal winds for the 32-year period 1964–1995 are examined using statistical methods. The analysis is based on the application of the simple correlation method and QBO/rainfall composite analysis. A statistical study of spatial correlation patterns is made in an effort to understand the climatic associations between the equatorial stratospheric zonal wind and regional rainfall at the interannual scale. The aim of this analysis is to establish whether this global signal can be employed as predictor variable in the long-range forecasts. The study is part of an ongoing investigation, which aims at designing a comprehensive and objective, multi-variate-forecast system of seasonal rainfall over eastern Africa. The correlation parameters include simultaneous (zero lag), and the non-zero lag correlations. The statistical significance of the correlation coefficient [r] is tested based on the Monte Carlo t-statistical method, and the standard correlation tables.

Our results indicate significant positive simultaneous and non-zero lag correlations between rainfall over parts of East Africa and lower equatorial stratospheric zonal wind during the months of March–May and June–August. Significantly high correlations are concentrated over the western regions of eastern Africa with peak values of (+ 0.8) observed over these areas. These associations have been observed to be more prominent during lag than in the simultaneous correlations. Strong month to month lag coherence is observed after June prior to the onset of the March to May seasonal rainfall and persists for more than 4 months. Correlation indices for the eight homogeneous rainfall regions over eastern Africa which are derived from our Empirical Orthogonal Function/Cluster analysis shows a clear annual cycle with significant relationships between QBO and seasonal rainfall occurring during boreal summer (June–August). The season with the weakest relationship is December–February. It is however, noted that although the coherence between QBO-Index and rainfall during the long-rains is significantly high, there are some wet/dry years for which the relationship between the long rains and the lower equatorial zonal wind are not significant (for example in 1966, 1973 and 1983). These years have been associated with strong and prolonged ENSO events. Preliminary comparison of the QBO-Index and the newly found Indian Ocean dipole mode index (DMI) indicates that the two climate variables may be significantly related. Of the six high dipole mode events in the Indian Ocean that were observed in 1961, 1967, 1972, 1982, 1994 and 1997, all except 1967 coincided with the easterly phase of the QBO-Index and below normal rainfall over western highlands of eastern Africa. Contingency analyses indicate 60 percent likelihood for the occurrence of above normal rainfall during the westerly phase of the QBO and 63 percent likelihood of below normal rainfall during the east phase of the QBO. Our correlation analysis results indicate that about 36 percent of the variability of the long-rains season over eastern Africa are associated with the QBO-Index. Our results further show that the tendency of the lower equatorial stratospheric zonal wind prior to the season is a good indicator of the performance of the long rains of eastern Africa. A positive OND minus JJA QBO trend is a good indicator for the non-occurrence of drought over eastern Africa. Similarly, a negative trend is a good indicator for the non-occurrence of high rainfall over the region. The identified characteristics and domain of influence of the QBO signal in different regions of East

Africa suggests that this global oscillator may offer useful input to objective multi-variate rainfall prediction models for eastern Africa.

1. Introduction

The quasi-biennial oscillation (QBO) is a quasi-periodic reversal in the tropospheric and stratospheric zonal wind from easterly to westerly components and vice versa with periodicity of about 28 months. Several studies have reported the presence of the QBO in various atmospheric parameters and at different regions of the globe. Some of the stratospheric and tropospheric variables that have exhibited QBO include temperature (Rasmusson et al., 1981), ozone (Funk and Garnham, 1962; Hasebe, 1980), Indian monsoon rainfall (Mukherjee et al., 1979, 1985), African rainfall (Rodhe and Virji, 1976; Ogallo, 1982; Nicholson and Entekhabi, 1986; Nicholson, 1996). In studies of QBO it may be important to distinguish between the stratospheric QBO and tropospheric QBO. Studies by Brier (1978), Nicholls (1978) have associated QBO in the troposphere to the air-sea interaction processes. Brier (1978) presented a conceptual model, which suggested that the tropospheric QBO could arise if the sense of either the ocean-to-atmosphere forcing or atmosphere-to-ocean forcing varied seasonally. Nicholls (1978) postulated that air-sea interaction in the Indonesia-North Australia region could provide the required seasonal variation in feedback and could be the source of the tropospheric QBO. Studies by Holton and Lindzen (1972), Plumb (1977), and Holton and Tan (1980) have indicated that the stratospheric equatorial QBO is forced locally by alternating downward propagating patterns of westerly and easterly mean zonal winds which repeat with somewhat irregular period averaging about 26 months. It has been pointed out that the stratospheric QBO is excited primarily by vertically propagating equatorial wave modes, and that these modes excite a quasi-biennial mean zonal wind response through the mechanism of radiative damping which causes the waves to decay in amplitude with height and thus to transfer momentum to the mean zonal flow (Holton and Lindzen, 1972). This mechanism indicates linkage between the tropospheric disturbances and the QBO in the zonal winds of the lower stratosphere over lower latitudes. Schoeberl (1978) postulated that cell eddies, commonly referred to as planetary waves, which formed in the troposphere through baroclinic, orographic and diabatic processes would propagate vertically and affect the stratospheric circulation. Labitzke and van Loon (1988, 1990), Barnett (1990), Ropelewski et al. (1992) have reported the QBO of the stratosphere equatorial zonal winds and its association with the interannual variability of the coupled air-sea system. Lau and Sheu (1988) have indicated that the fundamental period of the Southern Oscillation (SO) is approximately double that of the QBO, which in turn is twice that of the annual cycle. QBO has been found to be strongly phase locked with the annual cycle and it also tends to enhance major negative swings in the SO associated with the El Nino-Southern Oscillation (ENSO) events. Evidence suggests that the development of ENSO tends to be associated with the easterly phase of the lower stratospheric QBO (Lau and Sheu, 1988).

Many attempts have been made to examine the predictability potential of the QBO signals because of its persistence and appearance in many atmospheric parameters (Mukherjee et al., 1979, 1985; Mason and Tyson, 1992; Jury et al., 1994). Mukherjee et al. (1979, 1985) have identified a significant relationship between the phases of the QBO in the zonal wind in the lower stratosphere (30-mb) and the percentage departures of the summer monsoon rainfall of India. They showed that the strong easterly phase of the QBO is associated with weak monsoons and the weak easterly/westerly phase with active monsoons. The weakening of the easterly winds is generally a manifestation of westerly phase of the QBO in the lower stratosphere, as the prevailing winds in the stratosphere during summer monsoon are broadly easterly. Mason and Tyson (1992) have analyzed the phases of QBO and southern Africa rainfall and found a significant correlation ($+0.6$) between QBO and regional rainfall when the QBO is in the west phase. The relationship failed during 1991/92 when the regional drought corresponded with the east phase of the QBO. Jury et al. (1994) have identified a correlation pattern between the QBO and tropospheric winds, which corresponds with upper anticyclonic, Walker cell uplift over southern Africa and the descent over Madagascar in the west phase summers. Ogallo et al. (1994) have investigated the characteristics of QBO over tropical eastern Africa using zonal wind composites from Nairobi, Kenya (1°18′ S, 36°45′ E) for the period 1966–1987. Their results, based on spectral analysis indicated the dominance of a 28 months period in the zonal wind component. The vertical rate of propagation was about 1.2 km per month. The results also indicated some significant (at 5% level) association between rainfall and QBO signal based on the reversal in zonal winds.

Distinct QBO-spectral peaks in the East African rainfall have been reported in several studies (Rodhe and Virji, 1976; Ogallo, 1982; Nicholson and Entekhabi, 1986; Nicholson, 1996). Nicholson and Entekhabi (1986) presented evidence of several quasi-periodicities common to African rainfall, especially over southern and equatorial regions of the continent. In the low latitudes, spectral peaks in the ranges of 2.2 to 2.4 and 5.0 to 6.3 years are common. In the eastern tropical sector spectra show peaks in the ranges 2.2 to 2.4 and 3.3 to 3.8 years. These dominant periodicities may be indicative of different mechanisms in the two sectors. These findings and others have led us to investigate the prospects of adopting the stratospheric oscillator as a potential predictor for regional seasonal rainfall. The regular quasi-periodicity of the QBO of about 2.3 years, further makes it a good candidate for the prediction of rainfall over eastern Africa.

Significant evidence of the relationships between short-rains over eastern Africa, and Sea Surface Temperature (SST) and ENSO have been observed (Ogallo et al., 1988; Nyenzi and Nicholson, 1990; Semazzi et al., 1996; Mutai et al., 1998; Indeje et al., 2000). Relatively less attention has been directed at the predictive potential of the long-rains season over the region, which is more critical than the short-rains in many parts of the region for the agricultural industry and other social economic activities. The long rains season has been associated with complex interactions between many regional and large-scale mechanisms which generally induce large heterogeneities in the spatial rainfall distribution (Ogallo, 1982; Beltrando, 1990; Semazzi et al., 1996; Nicholson, 1996; Okoola, 1998; Indeje et al., 2000) and virtually negligible correlations with ENSO (Ogallo, 1988). Recent studies of interannual variability in the tropics have largely focused on the ENSO, so much so that other important long-term sources of climate variability may have been overlooked. Recent investigations (Webster et al., 1999 and Saji et al., 1999), have furnished evidence of unusual events in the tropical Indian Ocean that clearly point to the existence of a climate mode of interaction between the ocean and the atmosphere (Anderson, 1999). As noted above, this mode of climate variability may be significant in modulating the climate of eastern Africa. The QBO on the other hand, was well known in the atmosphere long before ENSO became the main focus of the studies on interannual variability (Lau and Sheu, 1988). It has been observed that once there is a change of sign from positive to negative (or vice versa) of the lower stratospheric winds, the particular state persists for at least nine months (Brier, 1978). Although the biennial oscillation appears to have an irregular component, varying between two and three years in length, it provides some measure of order in the otherwise more chaotic behavior of interannual variability of the long-rains of eastern Africa and therefore some hope for predictability. Based on the foregoing observations therefore, the objective of this study is to investigate the relationships between the different QBO phases in the stratospheric zonal wind and the long-rains season of eastern Africa and also explore the predictive potential of the long rainy season using information about the phases of the QBO. We will explore both simultaneous and lag correlation in the search for optimal predictive potential. This analysis represents continuation of an ongoing search for predictor variables, which could be used to predict the East African seasonal rainfall using multi-variate analysis. Here, we will primarily concentrate on the fluctuations in the lower stratospheric (30-mb) zonal wind component which, for purpose of this study, is merely referred to as QBO in the rest of this paper.

2. Data and Methods

The monthly mean climate indices: the Southern Oscillation Index (SOI) and the globally averaged equatorial stratospheric 30-mb zonal wind index (QBO-Index) are obtained from Climate Analysis Center (CAC/NOAA) database. The SOI and QBO-Index covers the period 1964–97 and 1979–97 respectively. Because of the short length (1979–1992) in the equatorial stratospheric 30-mb zonal wind index which is obtained from CAC, it will be supplemented by 30-mb zonal wind observational data set for Singapore (1°20′N). The time series of the monthly mean zonal winds at 30-mb for Singapore used in this study is for a 15-year period (1964–1978). Inspection of the data from any near-equatorial station reveals that the amplitude and phase of the QBO is independent of longitude (Wallace, 1973; Plumb et al., 1984). The stratification of the QBO indices is based on four seasons: March to May (MAM), June–August (JJA), September to November (SON), and December to February (DJF). The standardized departures of the rainfall for East Africa from its 136 stations and 30-year (1964–1993) normals are calculated for the long-rains season of March–May (MAM). Rainfall over eastern Africa exhibits large temporal and spatial variability (Ogallo, 1982; Nicholson, 1996). The spatial variation has been attributed to the complex topography, extreme contrasts in the type of vegetation, the existence of large inland lakes, the proximity of the Indian Ocean, and other regional factors. The use of normalized regionally averages resolves two problems inherent in the analysis of rainfall in subhumid, tropical areas namely the highly diverse means and variabilities and the randomness of the convective process reflected in individual station totals. This problem becomes more significant in subhumid regions where a few disturbances produce most of the season's rainfall. Spatial averages are more representative of the large-scale conditions than are data for individual stations (Nicholson, 1986). In view of the large variability of distribution of rainfall over the region, our analysis is based on subregions in order to examine the relationship of rainfall of those regions with QBO. Further details regarding the identification of the eight homogeneous subregions over eastern Africa (Fig. 1), which are adopted in this study, are described in Indeje et al. (2000).

The methodology employed in this study is based on the application of the simple correlation analysis and rainfall composites based on the phase of the QBO. The aim of these analyses is to establish whether the QBO signal can offer any useful predictor variable information for use in seasonal prediction. Each of the 136 (32-year) rainfall indices and the regional rainfall index time series for eight subregions are first correlated with the equatorial averaged stratospheric zone wind in order to identify the spatial extent of the associations between QBO and rainfall. The subregions that significantly correlate with the QBO are identified and are cross-correlated with the SOI to test the contribution of each of the two global climate indices on the long-rains season. These subregional time series are then generalized into categories using contingency tables based on the west and east phases of the QBO. The primary attributes of our correlation analysis include simultaneous or zero lag, and the non-zero lag correlation analyses. The statistical significance of the correlation coefficient [r] is tested based on the Monte Carlo

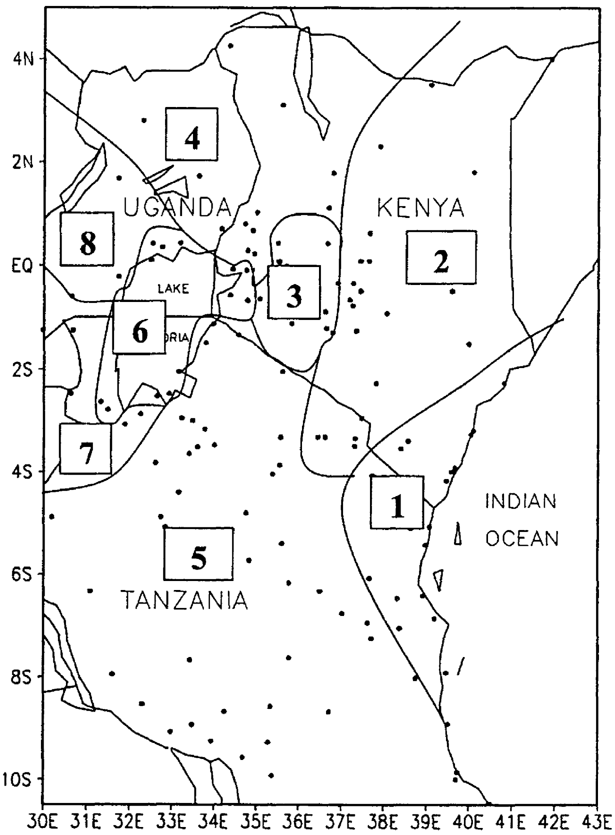


Fig. 1. The eight homogeneous rainfall groupings over East Africa obtained from combined EOF and simple correlation analyses (Indeje et al., 2000)

t-scores that achieve 95% significance and the standard correlation tables (Neave, 1978). Since the data is at varying length, statistical significance is attained at different correlation coefficient [r] levels. The space and time patterns of the significant correlations are then used to investigate the relationships between QBO and SOI, and regional rainfall. The lag cross-correlation maps between rainfall and climate indices offer estimates of the domain and intensity of influence of global oscillators (SOI, QBO and SST) over recent decades (Jury et al., 1994). This study is part of an ongoing investigation, which aims at designing a comprehensive and objective, multi-variate-forecast system of seasonal rainfall over eastern Africa. Results obtained from this study are presented in the next section.

3. Results

3.1 Relationships Between East African Seasonal Rainfall and Equatorial Averaged 30-mb Zonal Wind Index

Spectral analysis has been performed on the rainfall time series in the eight homogeneous rainfall regions over East Africa and the results are shown in Fig. 2. There is a dominant group of periodicities around 4–7 years, which may be associated with the ENSO phenomena. More interestingly, a pronounced QBO, with periods from 20–30 months are also dominant over regions 7 and 8 which corresponds to the western sector of eastern Africa. Nicholson (1996) showed a rainfall spectrum for eastern Africa as a whole that was dominated by a strong peak at 5 to 6 years, but significant peaks at 3.5 to 2.3 years were also evident suggesting that other than ENSO/SST forcing (5–6 years), there are other forcing mechanisms acting quasi-periodically with a time scale of about 2–3 years responsible for the interannual variability of rainfall in East Africa. These findings and others justify our investigation of the stratospheric (QBO) oscillator as an additional influence factor for tropical African climate variability. The basis for using the lower equatorial stratospheric zonal wind index in seasonal prediction are based on its tendency to persist for several months after the phase change from easterly to westerly and vice versa, is established.

Figure 3 show plots of simultaneous and lag correlations between the long-rains over homogeneous rainfall regions in eastern Africa and 30-mb QBO-Index for the period 1979–1992. Based on a the standard correlation tables (Neave, 1978) on a sample size of 14 years, correlation coefficients $[r] \geq 0.532$ are above 5 percent confidence level. Table 1 gives a summary of the seasonal and monthly correlation indices between the two variables. Results indicate significant simultaneous and lag correlations between the QBO-Index and rainfall over region 3, which covers the central and western highlands of Kenya ($+0.8$), the western parts of Uganda (region 8) of about $+0.8$, the lake Victoria basin (region 6) and the northern parts of Kenya and Uganda (region 4). The QBO/rainfall correlations in these regions are significantly high for at least six months prior to the MAM rainfall season. The highest significant correlations between seasonal rainfall and the QBO-Index of $> +0.8$ are observed between the MAM rainfall index and the JJA QBO-Index of the previous year and decreases towards the target rainfall season (MAM). These lagged relationships between the two variables indicate high prospects for using them in the development of prediction methodology. However, the correlations suddenly collapse between 3 and 2 seasons lag for regions 7 and 8. The sudden collapse in correlations suggests that long-term prediction (of two seasons or more in advance) may not be feasible in these two regions. The JJA QBO-Index of the previous year can be used to predict the MAM rainfall season with significant skill. Significantly high zero lag and lagged correlations between the QBO-Index and MAM seasonal rainfall were also obtained in some stations over central parts of Tanzania of about 0.8. This pattern is positive during JJA and SON seasons and reverses sign to negative during the boreal winter. In these areas of Tanzania, some caution should be exercised in using the correlations for forecasting purposes because of the sudden reversal in the sign of correlation coefficient from JJA and SON seasons. Negative significant correlations are observed over the southern coast of East Africa. The observed areas of significant lag correlations suggest that seasonal prediction may be feasible in those areas. The physical aspects of the linkage

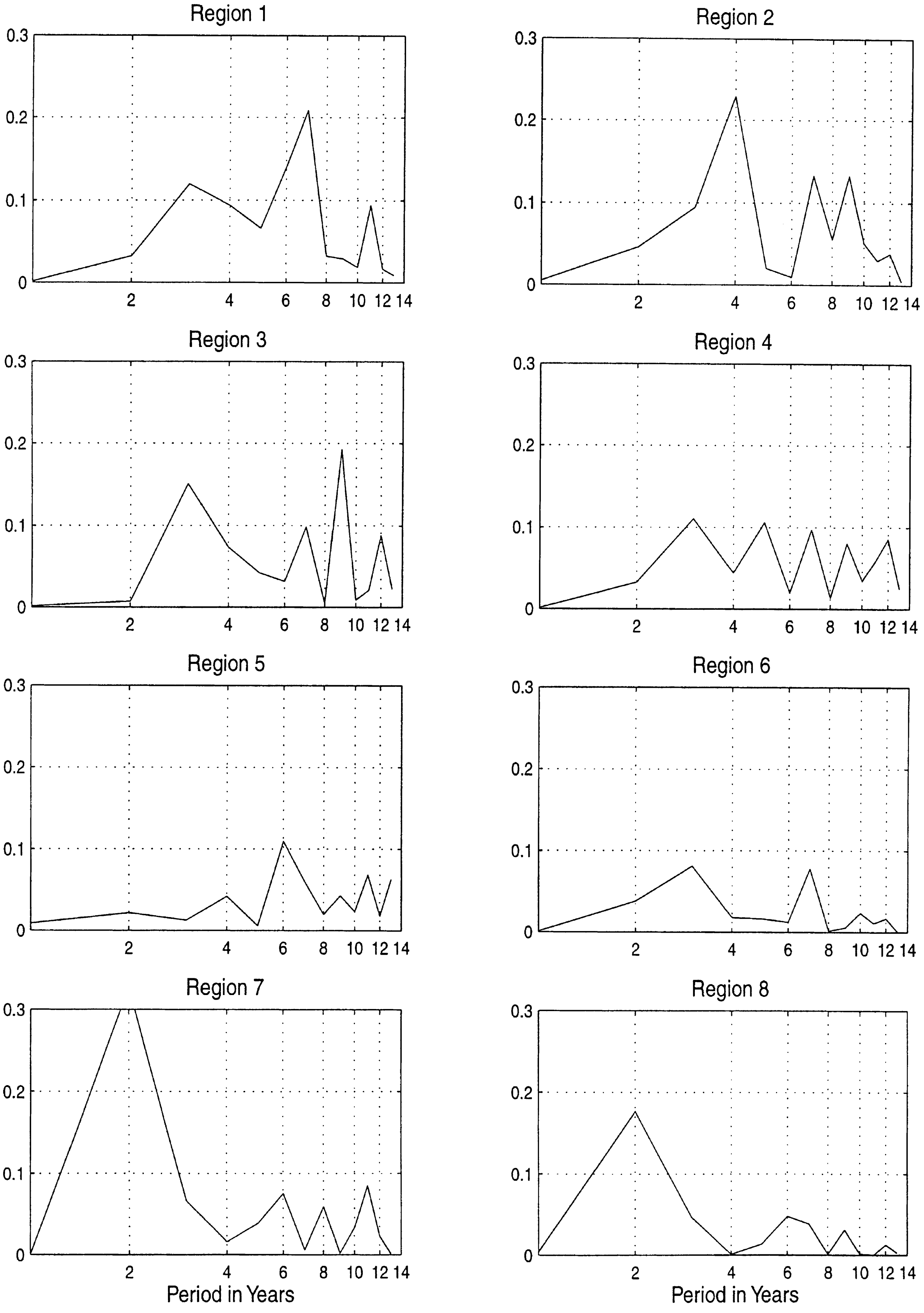


Fig. 2. A power spectrum of annual rainfall time series for the eight homogeneous regions over eastern Africa. Values ≥ 0.1 on the *y*-axis are above confidence level of 95 percent

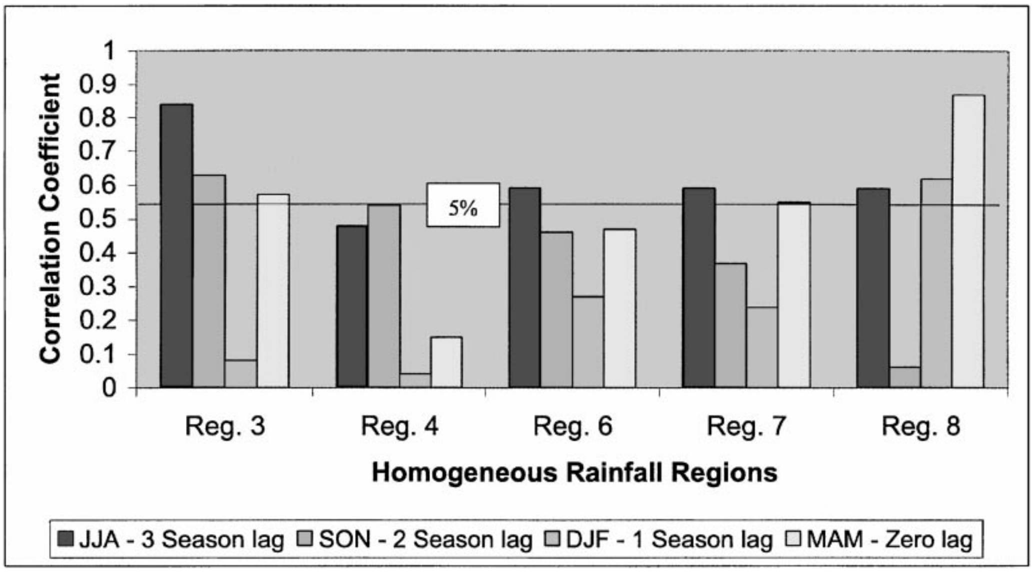


Fig. 3. The mean correlation patterns of three seasons lag, two seasons lag, one season lag and zero lag between the QBO-Index and March–May (long-rains) season over East Africa. Correlation values above 5% significant levels are also indicated

Table 1. *Simultaneous and Lag Correlations [r], Between the Averaged Equatorial Stratospheric 30-mb Zonal Winds (QBO-Index) and March–May "Long-rains" Rainfall Season Over the Eight Homogeneous Regions Over East Africa. Bold and Underlined Values are Above Significant Level of 10 Percent Based on a Sample Size of 14 years*

	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8
JJA	– 0.41	0.24	**0.84**	**0.48**	0.13	**0.59**	**0.59**	**0.59**
SON	– 0.40	0.06	**0.63**	**0.54**	– 0.02	**0.46**	0.37	0.06
DJF	0.32	0.36	0.08	0.04	– 0.02	0.27	0.24	**0.62**
MAM	– 0.08	0.33	**0.57**	0.15	0.11	**0.47**	**0.55**	**0.87**
JUNE	– 0.37	0.21	**0.76**	0.30	0.09	**0.48**	**0.61**	**0.71**
JULY	– 0.38	0.27	**0.84**	**0.49**	0.17	**0.59**	**0.60**	**0.61**
AUG.	– 0.41	0.20	**0.79**	**0.58**	0.11	**0.61**	**0.47**	0.35
SEPT.	– 0.42	0.12	**0.70**	**0.57**	0.05	**0.53**	0.39	0.18
OCT.	– 0.39	0.06	**0.62**	**0.54**	– 0.02	**0.46**	0.36	0.05
NOV.	– 0.39	– 0.02	**0.55**	**0.50**	– 0.10	0.37	0.34	0.06
DEC.	– 0.43	– 0.10	**0.46**	**0.46**	– 0.08	0.26	0.24	– 0.20
JAN.	0.29	0.36	0.12	– 0.02	– 0.04	0.28	0.25	**0.63**
FEB.	0.20	0.33	0.20	0.00	0.04	0.31	0.39	**0.70**
MAR.	0.13	0.36	0.39	0.06	0.15	0.43	**0.48**	**0.83**
APR.	– 0.06	0.36	**0.53**	0.16	0.12	**0.47**	**0.54**	**0.87**
MAY	– 0.26	0.25	**0.67**	0.20	0.06	0.45	**0.56**	**0.80**

between QBO and convection over eastern Africa are further discussed in Sect. 4.

Figure 4 shows the comparison of the time series for rainfall (long-rains) over western highlands of East Africa, the QBO-Index and the SOI for March and July (previous year). Cross-correlation between the QBO-Index, rainfall and SOI was computed and the resulting indices are summarized in Table 2. These results show some good associations between QBO-Index and the regional rainfall with significant simultaneous and lag correlations of + 0.53 (explaining about 26% of the variance) and + 0.84 (explaining about 70% of the variance), respectively. The fact that the two global climate indices (QBO and SOI) are statistically unrelated

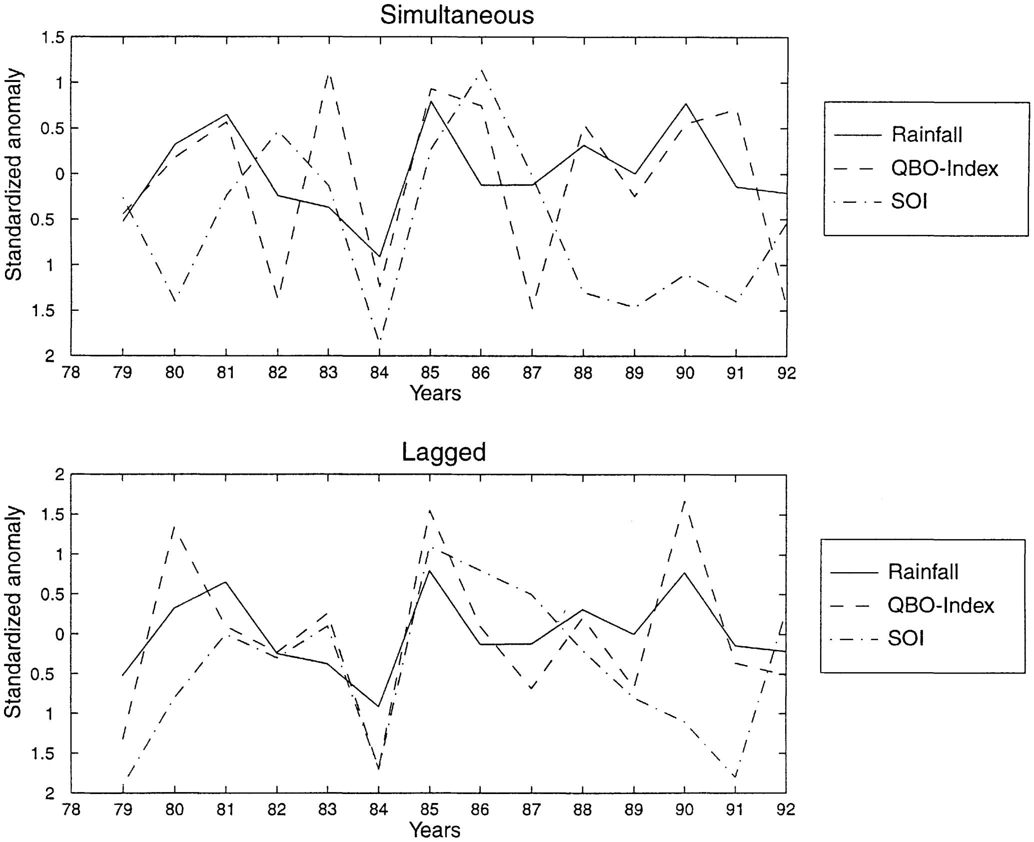


Fig. 4. Time series of March–May (long rain) seasonal rainfall over central and western highlands of Kenya (region 3), and March QBO-Index, and March SOI index (top) and, previous year July QBO-Index, and previous year July SOI index (bottom)

Table 2. *Simultaneous and Lag Cross-Correlation Matrix for Rainfall, QBO and SOI Indices. The Sample Size is 14 years (1979–92) and Correlation Coefficient [r] > 0.53 is Significant at 5 Percent Level. Significant Correlation Values are Underlined*

	Rainfall Index (Region 3)	QBO Index (MAM)	SOI Index (MAM)	QBO Index (July)
QBO Index (MAM)	**0.57**			
SOI Index (MAM)	0.07	0.07		
QBO Index (July)	**0.84**	**0.62**	0.13	
SOI Index (July)	0.38	0.13	**0.69**	0.39

at both simultaneous and lagged time, gives more confidence of using them as predictors of the seasonal rainfall with low risk of introducing artificial skill. The QBO-Index and SOI are found to be out of phase for most of the analysis period. The notable phase locking of the two variables occurred during the year 1984. This year followed one of the strongest ENSO of the century, which was associated with severe drought over most parts of the East African region. Our results clearly indicate the potential of using the QBO information for the prediction of the long-rains, which have a poor relationship with ENSO.

Having demonstrated the associations between the equatorial averaged 30-mb zonal wind index and the seasonal rainfall over some regions of eastern Africa, the next step is to test the stability of these relationships by using a longer time series of equatorial lower stratospheric zonal winds and rainfall anomalies. We employed the Singapore observed 30-mb zonal wind to supplement the QBO-Index. Examination of the two data sets indicates that they are very highly correlated. Wallace (1973) indicated that due to the zonal symmetry, the QBO in the equatorial stratosphere could be well represented by a single station. This station being close to the equator, the annual cycle is dominated by distinct oscillation with average periodicity of slightly more than 2 years. In the next sub-section we examine the robustness of our conclusions based on the QBO index as well as examining the prediction potential of the seasonal rainfall based on the phases of this index.

3.2 Predictability Potentials of East African Rainfall Using the Equatorial Stratospheric QBO-Index

Figure 5 shows the time evolution of the QBO-Index and the SOI for the period 1964–1997. The figures show years with westerly and easterly phases of the QBO-Index and SOI. The west phases of the QBO-Index were observed during 1963, 1966, 1969, 1971, 1973, 1975, 1978, 1980, 1983, 1985, 1986, 1988, 1990, 1993, 1995 and 1997 and, east phases during 1965, 1968, 1970, 1972, 1974, 1976/77, 1979, 1982, 1984, 1987, 1989, 1992, 1994 and 1996. These observations agree with those of Mukherjee (1995), and Brier (1977) using 30-mb zonal wind data from Balboa (9° N, 80° W) and, Ogallo et al. (1994) using zonal wind components for Nairobi, Kenya (1°18′ S, 36°45′ E). The QBO was relatively stationary during the years 1964–74. During recent period 1975–1994 there was a strong westerly event followed by two consecutive easterlies. The SOI on the other hand, exhibited a positive phase in the 1960's and early 1970's. From the early 1980's to-date, the

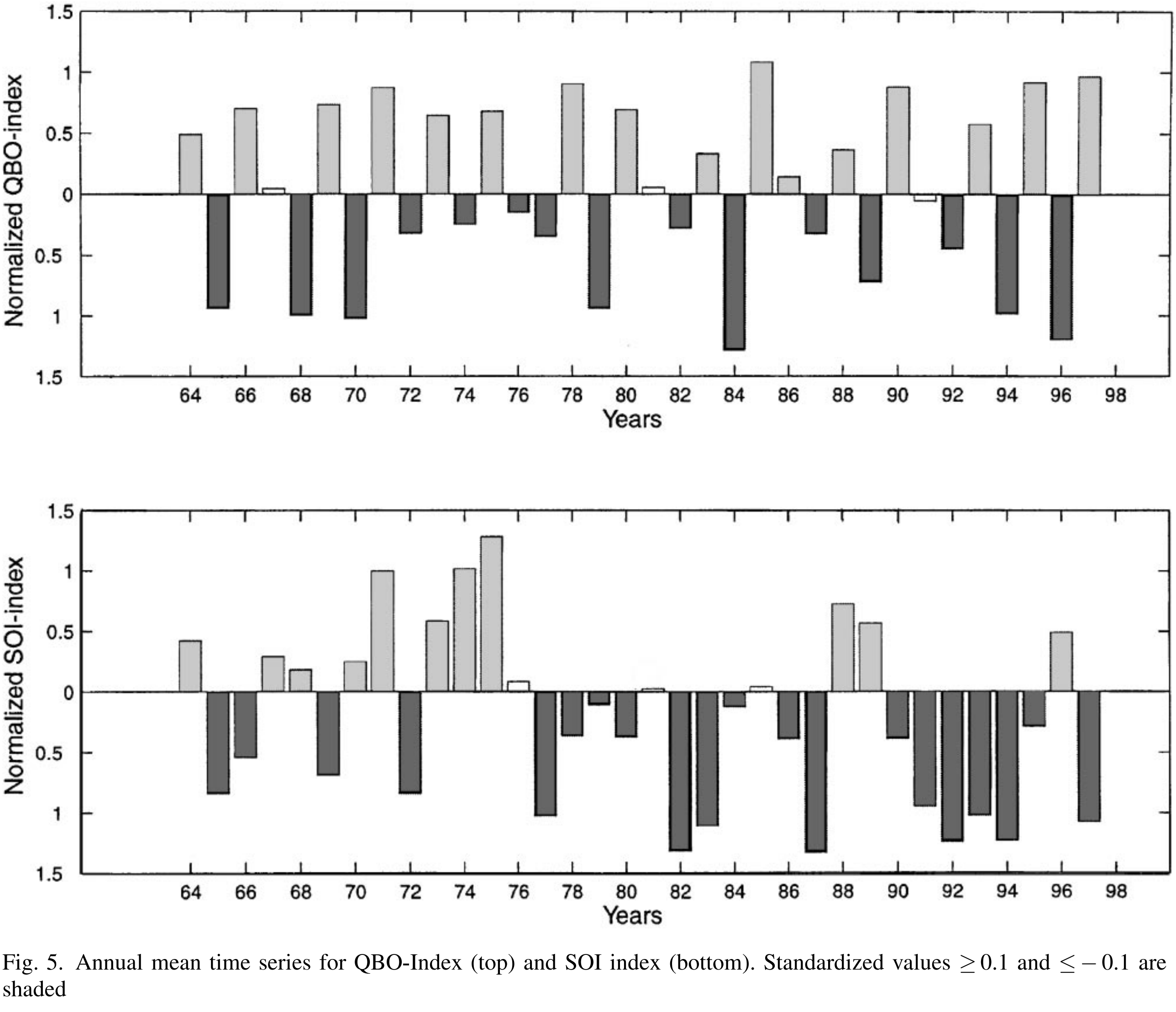


Fig. 5. Annual mean time series for QBO-Index (top) and SOI index (bottom). Standardized values ≥ 0.1 and ≤ -0.1 are shaded

frequent negative phases have been dominant in the SOI. During the years: 1965, 1972, 1977, 1979, 1982, 1984, 1987, 1992 and 1994, the east phase of the QBO-Index coincided with the low (negative) phase of the SOI. All these years with exception of 1984 and 1994, have been classified as ENSO years (Trenberth, 1997). This observation is consistent with the notion that ENSO tends to be associated with the east phase of the QBO.

Figure 6 shows the time series of rainfall from three regions of East Africa that we have identified to have significant correlation with the QBO-Index. Generalizations of the seasonal rainfall in these three regions into categories using contingency tables and the west and east phases of the QBO are summarized in Table 3. Based on these three regions, stratospheric westerly wind phases corresponding to above normal rainfall, were observed during 8 of the 13 cases for region 3, 6 out of 13 for region 7 and, 7 out of 13 for region 8, giving conditional probabilities of about 0.6, 0.5, and 0.55 for the associations of above normal rainfall during the long-rains over eastern African region and west phase of the QBO. Similar results were observed by Ogallo et al. (1994). Years with below normal rainfall coinciding with the westerly phase of the QBO were observed during 1966, 1973 and 1983. These years have been classified as strong and prolonged ENSO years (Trenberth, 1997). Many studies have been done on ENSO/rainfall

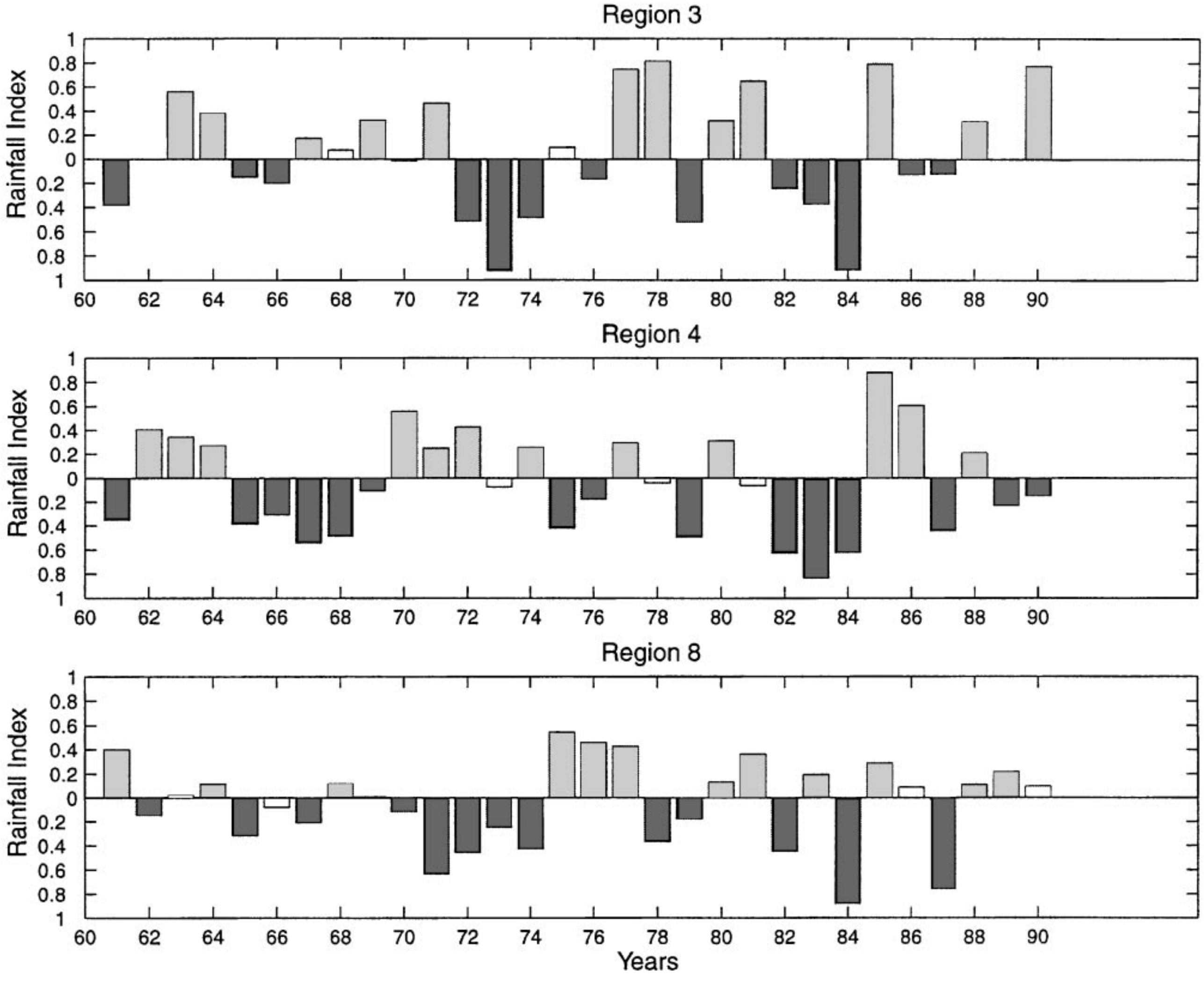


Fig. 6. Time series of standardized rainfall for three homogeneous regions: region 3; central Kenya (top), region 4; northwestern Kenya and northern Uganda (middle), and region 8; western Uganda (bottom). Shading information is similar to that in Fig. 5

Table 3. *Contingency Tables for Zonal Wind Phases at 30-mb Level and March to May (Long-Rains) Rainfall Anomalies Over Three Regions of Eastern Africa*

			Rainfall Anomaly		
	QBO Phases	AN	NN	BN	Total
Region 3	West Phase	8	1	4	13
	East Phase	1	3	8	12
	Total	9	4	12	25
Region 4					
	West Phase	6	1	6	13
	East Phase	4	0	8	12
	Total	10	1	14	25
Region 8					
	West Phase	7	2	4	13
	East Phase	4	0	8	12
	Total	11	2	12	25

AN – Above Normal rainfall ($X_i \geq X_{\text{mean}} + 0.1\sigma$).
BN – Below Normal rainfall ($X_i < X_{\text{mean}} - 0.1\sigma$).
NN – Near Normal rainfall ($X_{\text{mean}} - 0.1\sigma \leq X_i \leq X_{\text{mean}} + 0.1\sigma$).
σ is the standard deviation.
x_i denotes an observation.

relations in the region. Stratospheric east wind phases and below normal rainfall shows 8 out of 12 for region 3, 8 out of 12 for region 4 and, 8 out of 12 for region 8, giving conditional probabilities of about 0.7 for below normal rainfall in the three regions and the east phase of the stratospheric zonal wind. Associations between the two variables (rainfall and QBO) are more marked after the year 1979 onwards. The results obtained in this study support the notion that above/below normal rainfall is associated with the stratospheric westerly/easterly zonal wind phases. About 60 percent probability is found between the west phase of the QBO and rainfall over eastern Africa. The relationship fails during years of strong ENSO events. The low-level easterly transport of moisture in the region from the Indian Ocean by the monsoonal wind system maybe responsible for the association between upper level westerly (easterly) wind phases and the corresponding above (below) normal rainfall conditions over eastern Africa (Ogallo et al., 1994). These good associations between phases of QBO and seasonal rainfall indicate encouraging potential for rainfall predictability using the information about the QBO phases.

Significant correlations between rainfall in regions 3 and 4 and the QBO-Index persists for two seasons prior to the long-rains season, but collapses in regions 6, 7 and 8. We note that the tendency analyses (shown in Fig. 8) may work well for the two regions (3 and 4), but perhaps not for regions 6, 7 and 8. In the rest of the analyses, we use the rainfall index for region 3 as an example for testing the prediction potential of rainfall using the QBO-Index. In Fig. 7, we present the July QBO-Index prior to the onset of the long-rains which indicated a high significant correlation with the MAM seasonal rainfall over the central and western highlands of eastern Africa. It is evident from this figure that about 60 percent of the large positive/negative anomalies in the rainfall were observed during the periods of large positive/negative QBO anomalies. Some of the extreme rainfall anomalies were however, not related to the QBO anomalies. Using a time series of 32 years (1964–1995), for the QBO-Index and sub-regional rainfall, the correlation coefficient is found to be 0.55, which is above significant level of one percent based on the standard correlation tables (Neave, 1978). This highly significant correlation with a time series of more that 30 years, indicate some robust associations between the seasonal rainfall and the QBO. The shown robust relationship between the long-rains and the QBO-Index shows high predictive potential.

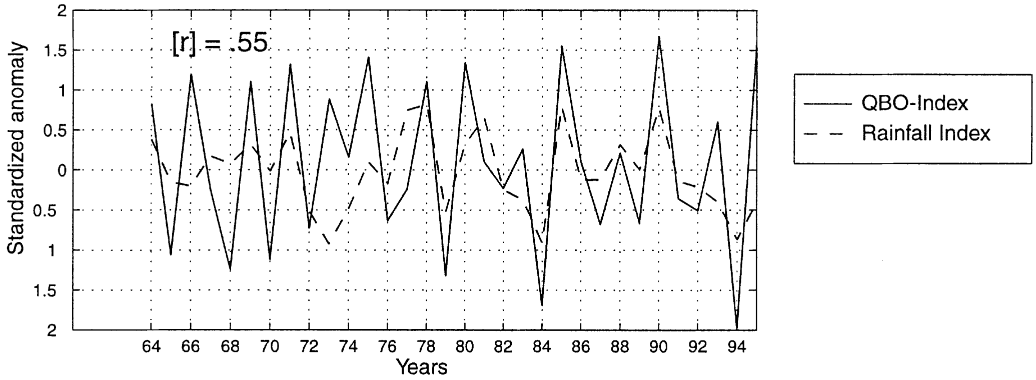


Fig. 7. Time series of rainfall over central and western highlands of Kenya (region 3) and the QBO-Index

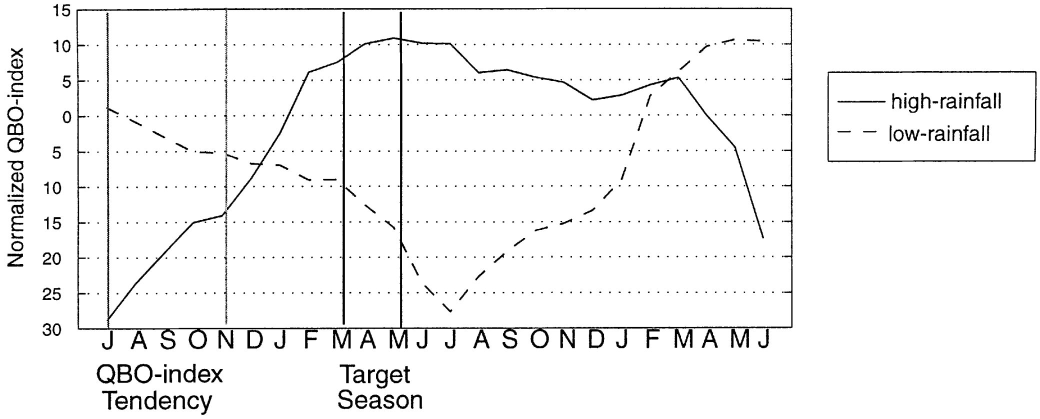
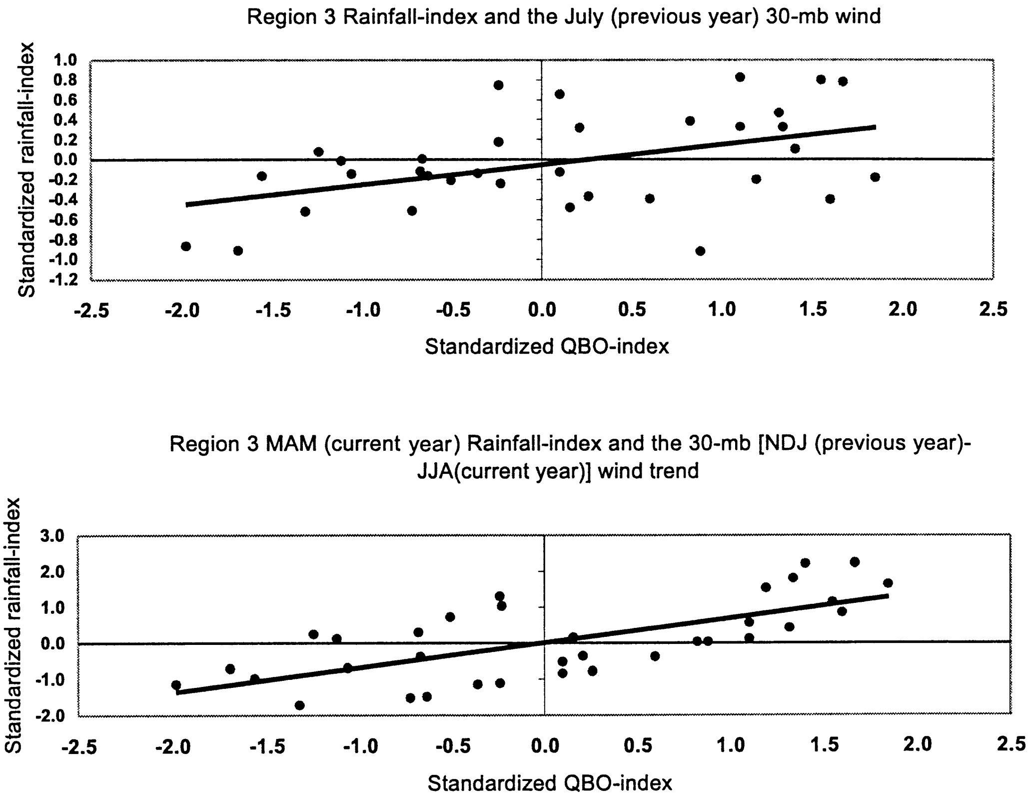


Fig. 8. Composite plot for the QBO-Index corresponding to high- and low-March to May seasonal rainfall years

Figure 8 shows a composite of normalized seasonal rainfall and mean monthly stratospheric wind phases for high- and low-rainfall years. In the composite analysis we used the years with above normal rainfall and coinciding with west phases of the QBO and years with below normal rainfall and coinciding with the east phases of the QBO. The years 1964, 1969, 1971, 1975, 1978, 1980, 1985, 1988 and 1990 having a standardized rainfall index of $\geq +0.10$ were classified as high-rainfall and the years 1965, 1972, 1974, 1976, 1979, 1982, 1984, 1986, 1987, 1989 and 1994, having a standardized rainfall index ≤ -0.1, classified as low-rainfall years. The choice of this range of the standardized rainfall index is based on a student t-test applied on a sample size of 32 years. The t-scores on the high- and low-rainfall indices indicate that the two series are significantly different at 95 significance level. In the figure, the months are presented along the abscissa and the vertical axis corresponds to the normalized QBO-Index. The central block of the graph denotes the boreal spring months for which the seasonal rainfall was considered while the block to the left indicates the QBO-Index tendency prior to the rainfall season. The QBO-Index trend increases/decreases from JJA to DJF before the occurrence of high/low MAM seasonal rainfall. Large positive anomalies of the long-rains are found to coincide with the maximum westerly phase of the lower equatorial stratospheric zonal winds when maximum heating due to the overhead sun occurs, thus suggesting possible role of the annual cycle in modulating the QBO. Because of this striking QBO-Index anomaly in the pre-rainfall months and the composite MAM seasonal rainfall, we have examined the association between pre-MAM QBO trend and MAM seasonal rainfall over eastern Africa. For the purpose of predicting the regional rainfall, the most useful index appears to be the trend for QBO-Index before the rainfall season. The positive OND minus JJA QBO trend could be a good indicator for the non-occurrence of drought over eastern Africa. Similarly, a negative trend could be a good indicator for the non-occurrence of high rainfall over the region.

Figure 9 shows a scatter diagram between March–May seasonal rainfall anomaly over central and western highlands of East Africa (top panel) and, the October to December minus June to August trend in the QBO-Index (lower panel). The correlation coefficient between the East African rainfall anomaly from region 3 and the difference between OND and DJF QBO-Index is 0.6 (explaining about 36% of the rainfall variance) which is higher than that for JJA season (0.5). As shown on Fig. 9 (bottom panel), most of the severe drought years are in the lower left quadrant, and most of the very heavy rainfall years are in the upper right quadrant of the scatter diagram. The near absence of points in the lower right corner of this scatter diagram suggests that a positive QBO-Index trend should be a very useful predictor for non-occurrence of droughts over eastern Africa. An ENSO phenomenon is known to be a fundamental and periodic part of the ocean-atmosphere system, with periodicity of about 3 to 8 years (Rasmusson and Carpenter, 1983). Some extreme rainfall anomalies in East Africa have been associated to ENSO (Ropelewski and Halpert, 1987; Janowiak, 1988; Ogallo, 1988; Nicholson, 1996), among others. If an El Niño has already been observed in the preceding winter and spring, a prediction of deficient MAM seasonal rainfall over eastern Africa can be made with some degree of confidence (Nicholson, 1996; Indeje et al., 2000). But the relationship between the MAM seasonal rainfall and El Niño applies to a limited number of years, the ones when El Niño occurs, whereas the relationship between the QBO-Index and seasonal rainfall is applicable in all years. Monitoring of both the parameters can provide very useful guidance for the long-range forecasting of seasonal rainfall over the region. This observation suggests a conditional probability; thus during the westerly phases of QBO and when a strong ENSO episode is not expected in the following boreal winter, then there are high chances for the occurrence of above normal


Region 3 Rainfall-index and the July (previous year) 30-mb wind

Region 3 MAM (current year) Rainfall-index and the 30-mb [NDJ (previous year)-JJA(current year)] wind trend

Fig. 9. Scatter diagram between March–May seasonal rainfall anomaly over central and western highlands of East Africa (top), and the October to December minus June to August trend in the QBO-index

MAM seasonal rainfall conditions over eastern Africa and vice versa for the easterly phase of the QBO. Results from correlation analysis ([r] = 0.55 based on 32-year period) indicate that QBO could explain a maximum of about 36 percent of the rainfall variance over the central and western highlands of East Africa during March to May season. These areas being highly agricultural productive, accurate seasonal climate prediction would be a step toward improving the planning stages in the industry. Monitoring of the equatorial lower stratospheric zonal wind phases can hence provide useful guidance for the long-range forecasting of the long-rains over eastern Africa.

4. Discussion

There are two primary questions which arise from our analysis, (i) the physical mechanisms responsible for the strong teleconnections between the "long-rains" of eastern Africa and the lower equatorial stratospheric (30-mb) zonal winds, and (ii) the weakening of this relationship with decreasing time lag between the two phenomena. As noted above, the physics of the stratospheric equatorial QBO has been extensively investigated (Holton and Lindzen, 1972; Plumb, 1977; and, Holton and Tan, 1980). The traditional explanation for the development of this type of the QBO is based on the alternating downward propagating patterns of westerly and easterly mean zonal winds which repeat with somewhat irregular period averaging about 26 months. However, recently Webster et al. (1999) have proposed a coupled ocean-atmosphere mechanism over the Indian ocean sector which may offer an alternative explanation, and which seems to have been responsible for the prolonged SST anomaly conditions during the recent 1997/98 ENSO event. Their results show that this mechanism which involves a sequence of thermal and dynamical processes may also account for the major warming event of 1961–62 when the normal SST gradient across the Indian Ocean reversed and resulted in substantial warming in the western basin and flooding over eastern Africa. Webster et al. (1999) and Saji et al. (1999) have shown that the summer monsoons following west Indian Ocean warming should have stronger winds in the western basin, which would induce greater mixing, greater Ekman transport forcing coastal upwelling, and greater evaporation, all of which would contribute to rapid cooling. They refer to the large-scale interactions between the Indian Ocean and the overlying atmosphere as the dipole mode index (DMI). During the low phase of the DMI, there is massive cooling over the western Indian Ocean and relative warming over the eastern sector of the Indian Ocean. A reversed Walker-like atmospheric circulation associated with the low DMI is a consequence of this temperature gradient over the ocean with rising/sinking motion over the eastern/western parts of the ocean. Between 1950 and 1998 there were 16 years in which the equatorial SST gradient reversed with spectral peaks around 2 years (Webster et al., 1999). We postulate that the reversal in the SST gradient associated with the Indian Ocean climate system may also provide an alternative explanation for the reversal in the upper air winds, usually explained in terms of the alternating downward propagating patterns of westerly and easterly mean zonal winds.

Figure 10 is a schematic representation depicting the interaction among, the basic Walker circulation overturning over the Indian Ocean region, the anomaly circulation associated with the Indian Ocean SST dipole, and the equatorial winds associated with the QBO. Under normal conditions the Indian Ocean is warmer in the east and slightly cooler in the west, thus inducing low level winds blowing from the west to the east, and easterlies aloft (Webster et al., 1999). Therefore, the normal SST conditions over the Indian Ocean are in phase with the easterly phase of the QBO. This flow pattern is coupled with the two major ascending branches of the Walker circulation over Africa and the Maritime continent (i.e., the Indonesia region). The net result is a vertical cell structure characterized by rising motion and upper level outflow over central Africa and the Maritime continent, and the compensating descending motion over the western region of the Indian ocean (Holton, 1972). During the opposite phase of the Indian ocean SST dipole, the conditions are warmer over the western part of the ocean basin than in the east, and therefore tend to induce low/upper level easterlies/westerlies, thus consistent with the westerly phase of the

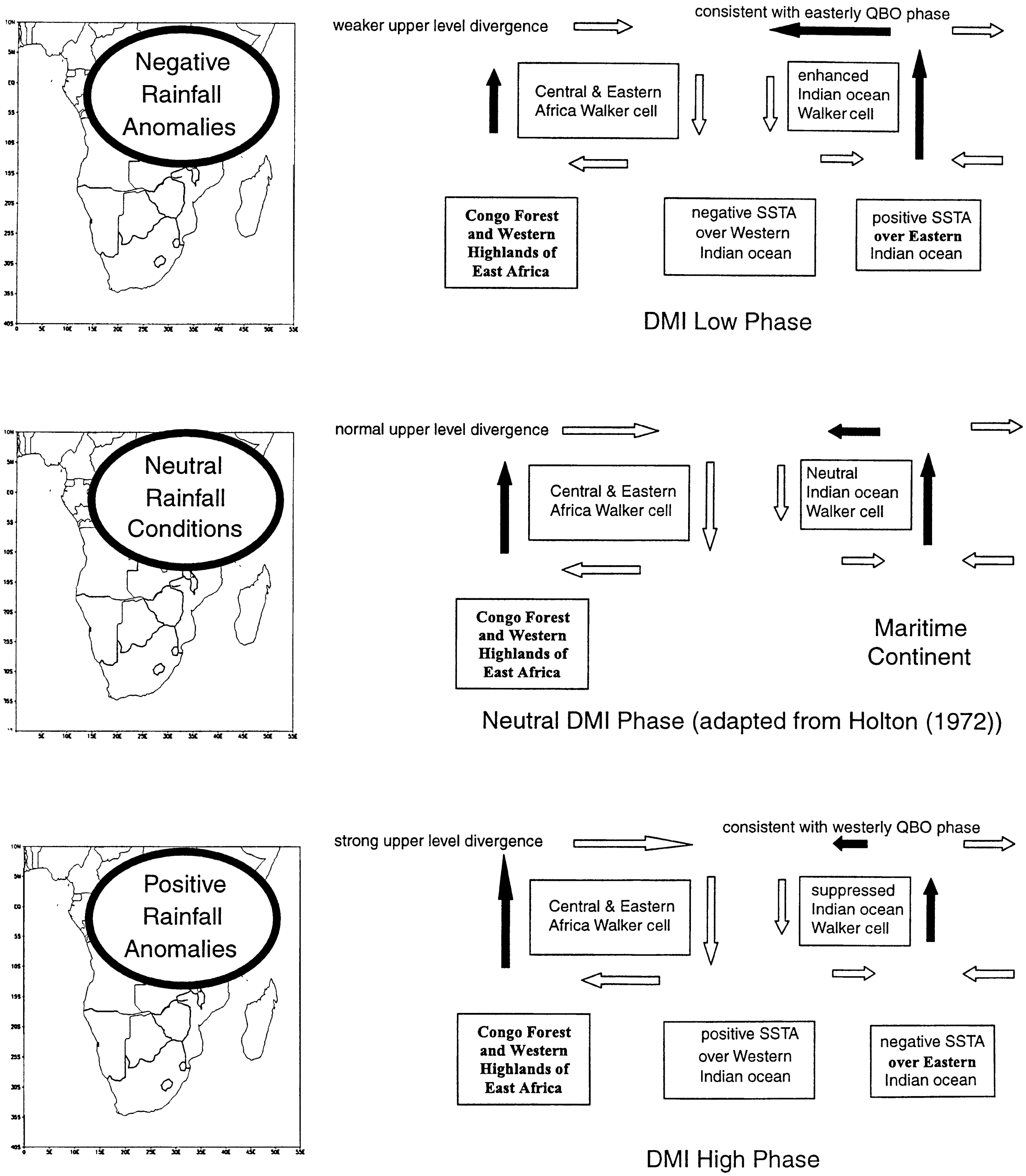


Fig. 10. Schematic of large-scale horizontal interaction between circulation systems over the African-Indian Ocean sector

QBO. We envisage that this flow structure would lead to a sequence of events, characterized by enhanced upper level divergence from the African continental land-mass, and increased ascending motion and rainfall over the Congo tropical rain forest and the western Highlands of East Africa. This conceptual model is consistent with our analysis which indicates that the westerly phase of the QBO is associated with abundant rainfall over eastern Africa and reduced precipitation during its easterly phase. The simple framework proposed here, indicates that the quasi-biennial variability of the DMI could induce upper level flow which may partly explain the QBO phenomenon. The three-way co-variability among, the rainfall over East Africa, the QBO and DMI, may provide an important clues regarding the dynamical links which should be examined more comprehensively in the future, using theoretical and numerical models to understand the physical mechanisms involved.

The reasons for the weakening of the correlation between the QBO-Index and rainfall over eastern Africa, with decreasing time lag are not entirely clear based on the hypothesis proposed above. However, we believe this observation may provide important clues regarding the physical mechanisms involved. We speculate that the primary factor responsible for modulating the "Long Rains" is the Indian Ocean "warm pool" which propagates across the ocean basin and completes the cycle on a quasi-biennial time scale. Its propagation appears to be phase locked with the annual cycle, with maximum amplitude along the coast of Africa occurring during the months of the "Long Rains". Several recent studies (Nicholson, 1996; Jury et al., 1994) provide indirect support for our proposed conceptual model. Nicholson (1996) also described evidence that the low-level divergence and sinking motion over the cool western Indian Ocean may be associated with low- and mid-tropospheric moisture transport in the interior of the East African region. This advected moisture would support the convective activities over the western highlands of eastern Africa, which through the release of latent heat would sustain the east–west Walker-like circulation between the western highlands of eastern Africa and the western Indian Ocean. Over the Indian Ocean, the reversed DMI circulation would be accompanied by rising/sinking motion over eastern/western parts of the ocean.

5. Summary and Conclusions

We have examined the coupled variability between the East African seasonal rainfall and the different QBO phases in the equatorial stratospheric zonal wind. Our analyses were based on the application of the simple correlation and composite analyses. Both simultaneous and lag correlations were examined, in order to explore the optimum associations between equatorial stratospheric zonal winds and East African seasonal rainfall.

This study has revealed an important relationship between equatorial stratospheric quasi-biennial structure and East African seasonal rainfall, which raises the prospects for using the 30-mb zonal wind for prediction of East African seasonal rainfall. Our main results can be summarized as follows: (a) a distinct seasonal cycle exists in the correlations, (b) boreal summer (June–August) is the season with the strongest relationships, (c) boreal winter (DJF) shows the weakest relationships, (d) in some seasons especially boreal summer, the lag correlations are strong enough to suggest the possibility of seasonal rainfall prediction, (f) the strongest correlations are found in western part of East Africa, (g) the correlations remain reasonably stable with time for several seasons, (h) the OND minus JJA trend of the equatorial zonal wind offers a useful index for seasonal climate monitoring of the long-rains over East Africa and, (i) there is high chances of above/below normal rainfall during the west/east phases of the QBO. The relationships failed during the years 1966, 1973 and 1983 when drought was experienced in the region that was modulated by strong and prolonged ENSO events. Similar observations have been made in the monsoon rainfall (Mukherjee et al., 1985) and in the South African rainfall (Mason and Tyson, 1992). Our visual inspection of the QBO-Index and the newly found Indian Ocean dipole mode index (DMI) indicate that the two climate variables might be related significantly. Of the six extreme DMI events that were observed in 1961, 1967, 1972, 1982, 1994 and 1997, all except 1967 coincided with the easterly phase of the QBO-Index.

The present study has further clarified the seasonal relationships, as well as proving general robustness of these relationships, and thus of their use in seasonal prediction. The apparent superior associations between the QBO-Index and seasonal rainfall after 1979 to date, means that the use of relatively short periods of recent data might provide better forecasts than the use of all available historic data. In this study, we have proposed and explained the underlying mechanisms responsible for the QBO/convection over western parts of eastern Africa, and also presented some observational evidence, which may be useful for operational forecasting. We have proposed mechanisms that accounts for observed link between the ocean-atmosphere-coupled mode in the Indian Ocean (DMI) and the QBO/convection over parts of eastern Africa. The high/low DMI phase is associated with easterly/westerly phases of the QBO-Index and low/high convective activities over the western highlands of East Africa. It would be worthwhile to investigate further the QBO in the stratospheric zonal winds, the East African rainfall and the DMI events over the Indian Ocean by adopting a dynamical modeling approach.

This study has further indicated that about 36 percent of rainfall variability over eastern Africa during the long-rains is associated with the quasi-biennial oscillation in the lower equatorial stratospheric zonal winds. If the natural cyclical pattern of the QBO could be anticipated, the present finding may have some value in the general context of the long-range forecasting of the East African long-rains season. Our results suggest that the relative role of QBO and rainfall over eastern Africa is stronger in the time-lag sense than the simultaneous relationship. The present study has further demonstrated that the phase of the QBO prior to the season is also a useful predictor index for the seasonal rainfall. This is particularly the case for the long-rains for which ENSO provides only limited skill in the predictability of the rains. This observation should be explored further in the search for more effective seasonal climate predictors over eastern Africa and the other regions of Africa.

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Author's address: M. Indeje and Fredrick H. M. Semazzi, North Carolina State University, Dept. of Marine, Earth, and Atmospheric Sciences, Raleigh, NC 27607-8208, USA (E-Mail: fsemazzi@foamv.ncsu.edu).