# Quasi-Biennial and Quasi-Triennial Oscillations in the Summer Monsoon Rainfall of the Meteorological Subdivisions of India

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ABSTRACT

The summer monsoon rainfall time series for 29 subdivisions of India from 1951 to 1991 (41 years) were subjected to maximum entropy spectral analysis and showed significant periodicities in a wide range, including quasi-biennial oscillation (QBO 2–3 years) and quasi-triennial oscillation (QTO 3–3.9 years). After filtering out periodicities of 4.0 years or more, the residual series, considered as representative of QBO and QTO only for each series, could be separated into 4 categories (viz., category A of 10 subdivisions having only one strong QBO peak but no QTO, category B of 4 subdivisions having two strong QBO peaks but no QTO, category C of 4 subdivisions having no strong QBO or QTO, and category D of 11 subdivisions having a strong QTO). The 50-mb zonal wind showed two strong QBO peaks at 2.33 years (28 m) and 2.75 years (33 m). A comparison of stratospheric (50 mb) westerly wind and rainfall maxima showed that for many subdivisions, maximum rainfall was associated with the increasing westerly phase of zonal wind and droughts were associated with the easterly phase. A loose relationship with El Niño–Southern Oscillation was also noticed for droughts in some subdivisions (mostly western India), and the two effects (50-mb wind and ENSO) seem to be operating independently of each other.

## 1. Introduction

In India, a major part of the rainfall (75%–90%) occurs during summer months (June–September). The rainfall varies greatly from place to place (400–2800 mm) and the standard deviation of the interannual variability also varies greatly. A power spectrum analysis of the time series of the summer monsoon rainfall (Kane 1990) shows several significant periodicities, but different at different locations. Among these, one often encounters quasi-biennial (QBO) and quasi-triennial (QTO) oscillations (period 2.0–3.9 years). A QBO in the summer monsoon rainfall in various parts of India has been reported by several workers [e.g., Parthasarathy and Mooley (1978); Rangarajan and Rao (1978); and references therein]. Using data for a short period (1971–76), Mukherjee et al. (1979) indicated a possible relationship between QBO phases of the zonal wind in the lower stratosphere (30 mb) and the percentage of deviations of summer monsoon rainfall of India as a whole. Later, Mukherjee et al. (1985) used wind data for a longer period (1951–82), divided the rainfall data into different latitude regions (north and south of 20°N, etc.), and showed significant correlations (+0.3 to +0.4). Though statistically significant, these values are rather low and QBO explains only about 15% of the variability. Recently, Parthasarathy et al. (1987, 1992) have published long time series of monsoon rainfall for 29 subdivisions of India (Fig. 1). In this communication, we examine specifically the QBO and QTO of these series and compare these with the QBO of the 50-mb tropical zonal wind and QTO of the Southern Oscillation index represented by the atmospheric sea level pressure difference between Tahiti and Darwin (T − D).

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## 2. Isolating the QBO and QTO by using spectral analysis

Every rainfall series (1951–91, 41 years) was first subjected to MESA (maximum entropy spectral analysis) (Ulrych and Bishop 1975), which yields periodicities very accurately, especially in the low periodicity region. The inaccuracy is ±2% for periodicities up to about half of the data length. For larger periodicities approaching the data length, the inaccuracy could be as large as ±20% (Chen and Stegan 1974). But the method does detect such large periodicities while conventional methods like Blackman and Tukey (1958) show broad, flat spectra in this range. However, the amplitude estimates in MESA are not reliable (Kane 1977; Kane and Trivedi 1982). Hence, we used MESA only for locating possible peaks $T_k$ ($k = 1-n$) and then used these $T_k$ in the expression

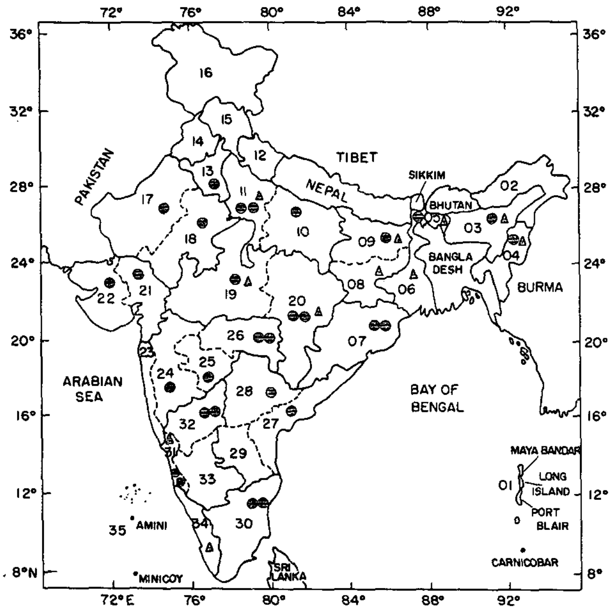



FIG. 1. Latest meteorological subdivisions of contiguous India. Full circles represent the presence of a QBO and triangles represent the presence of a QTO.

$$f(t) = A_0 + \sum_{k=1}^{n} \left[ a_k \sin\left(\frac{2\pi t}{T_k}\right) + b_k \cos\left(\frac{2\pi t}{T_k}\right) \right]$$

$$+ E = A_0 + \sum_{k=1}^{n} r_k \sin\left(\frac{2\pi t}{T_k} + \phi_k\right) + E, \quad (1)$$

where $f(t)$ is the observed time series and $E$ is an error factor. An MRA (multiple regression analysis) (Bevington 1969) was then carried out, which yielded the best statistical estimates (by the method of least-squares fit) of the parameters $A_0$, $a_k$, and $b_k$. Their standard errors were also obtained by the method of residuals and were the same for all $a_k$, $b_k$. From these, the parameters $r_k$, $\phi_k$ and their standard errors (same for all $r_k$) were calculated. A priori, every $r_k$ exceeding $2\sigma_r$ is significant at a 95% confidence level. Every amplitude $r_k$ accounts for a percentage variance $50r_k^2/\sigma^2$ where $\sigma^2$ is the variance of the series $f(t)$. This method has been tested with artificial samples and yields very accurate results (Kane 1977, 1979; Kane and Trivedi 1982).

Table 1 shows the periodicities that were significant at a $2\sigma_r$ a priori level for the rainfall series of the 29 subdivisions from 1951 to 1991. These values are slightly different from those given in Kane (1990), which referred to a longer series (1871–1970). Here, we are restricted to 41 recent years only, since the 50-mb wind data (Venne and Dartt 1990) are available to us only from 1951 onward. In Table 1, the following may be noted:

1) Almost all of the series show significant periodicities in more than one spectral range. Some of these are significant at a $3\sigma_r$ level and some even at a $4\sigma_r$ level.

2) The periodicities are not the same, even in nearby subdivisions.

3) In the larger periodicity regions, some occur frequently, [e.g., 4.7–4.8 years, 11–12 years (solar cycle), 20–23 years (Hale magnetic cycle)]. However, these will not be studied in this paper.

4) In the QBO region (2.0–2.9 years), almost all subdivisions show periodicities significant at a $2\sigma_r$ level and sometimes with even larger significance (exceptions are subdivisions 14, 23, 29, and 33 where no significant QBO is observed). However, at other locations, the QBOs are not similar. Some have only one strong peak while others have two peaks. The bottom part of Table 1 gives periodicities for the four-station, average monthly mean 50-mb zonal winds at Gan, Balboa, Singapore, and Canton (Venne and Dartt 1990, updated) and shows only two strong peaks, namely, a very prominent peak at 2.33 years (28 months, amplitude 8 m s$^{-1}$) and a comparatively smaller peak at 2.75 years (33 months, amplitude 5 m s$^{-1}$). Some subdivisions do seem to have two peaks very near these two peaks of 50-mb wind. Incidentally, even though annual values are used for rainfall series, MESA is capable of distinguishing between such pairs of QBO peaks if they exist. This has been tested by using artificial samples.

5) Many locations show significant peaks in the QTO region (3.0–3.9 years). This may be indicative of a possible connection with the phenomenon of El Niño, warm water episodes along the Peru–Equador coast, which occur with a frequency of about 2–5 years. El Niño is intimately connected with SO (Southern Oscillation), represented by the sea level atmospheric pressure difference between Tahiti (T) (18°S, 150°W) and Darwin (D) (12°S, 131°E). Lowest values of (T − D) coincide with El Nino occurrences. A power spectrum of the time series of 12-month running averages of (T − D) from 1951 to 1991 gave periodicities $T$ = 2.60, 3.6, 5.3, 10, and 17 years (Table 1, bottom), but $T$ = 3.6 is most prominent and may be related to similar peaks in the Indian rainfall data, at least for some regions as outlined in an earlier communication (Kane 1990).

To isolate the QBO and QTO, the ($a_k$, $b_k$) of periodicities of 4.0 and larger years were added and the series so obtained was subtracted from the original series. This is our high-pass filtering. The residuals should now contain only peaks in the QBO and QTO regions (2.0–3.9 years). These series (41 values) were then correlated with the 50-mb wind series for DJF (December–February), MAM (March–May), JJA (June–August), and SON (September–November) separately. Thus, each of the 29 divisional rainfall series gave four correlation coefficients as given in Table 1.

TABLE 1. Rainfall characteristics for 29 subdivisions of India.

| Subdivisions | 1871–1970 Mean summer monsoon (Jun–Sep) rainfall (mm) | Standard Deviation (mm) | Standard Deviation (%) | Periodicities (years) significant at a $2\sigma$ a priori level: 2.00–2.33 | 2.34–2.66 | 2.67–2.99 | 3.0–3.5 | 3.6–3.9 | 4.0–36.0 | PVE: QBO | QTO | Correlations (×100) with 50-mb wind in different seasons: DJF | MAM | JJA | SON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3. N. Assam | 1454 | 164 | 11 | 2.14 | | 2.69* | 3.5* | | 12**, 17 | 28 | 10 | +02 | −01 | −09 | +01 |
| 4. S. Assam | 1471 | 170 | 12 | | | 2.69 | 3.2 | | 4.7*, 14, 20 | 10 | 23 | +21 | −11 | −41 | −42 |
| 5. Sub-Him, W. Bengal | 2008 | 296 | 15 | 2.09 | | | 3.3 | | 11, 23* | 10 | 10 | +04 | +07 | −01 | −09 |
| 6. Gangetic W. Bengal | 1138 | 162 | 14 | | | | 3.1 | 3.6* | 17** | 3 | 33 | −06 | +01 | −05 | −08 |
| 7. Orissa | 1182 | 158 | 13 | 2.19* | | 2.75** | | | 4.2**, 4.8*, 6.0, 31** | 39 | 0 | −22 | −06 | +15 | +24 |
| 8. Bihar Plateau | 1101 | 151 | 14 | | | | 3.3 | | 6.8, 8.9, 14 | 2 | 12 | −06 | −06 | 0 | −01 |
| 9. Bihar Plains | 1036 | 195 | 19 | 2.29* | | 2.69 | 3.4 | | 15 | 16 | 18 | −03 | +04 | −03 | −08 |
| 10. E. Uttar Pradesh | 907 | 202 | 22 | | | | | | 4.7, 7.4 | 24 | 6 | −28 | +07 | +40 | +44 |
| 11. W. Uttar Pradesh Plains | 771 | 179 | 23 | | 2.34 | 2.75** | 3.5 | | 6.9 | 34 | 10 | −29 | +02 | +37 | +46 |
| 13. Haryana | 451 | 134 | 30 | | 2.57 | | | | | 11 | 0 | −15 | +03 | +34 | +37 |
| 14. Punjab | 480 | 159 | 33 | | | | | | 4.4, 15 | 6 | 2 | −25 | +11 | +41 | +32 |
| 17. W. Rajasthan | 252 | 98 | 39 | | | 2.82* | | | 15 | 23 | 2 | +02 | +16 | +29 | +20 |
| 18. E. Rajasthan | 639 | 169 | 26 | | 2.34 | | | | 18 | 8 | 5 | −26 | −09 | +19 | +25 |
| 19. W. Madhya Pradesh | 920 | 167 | 18 | | 2.40* | | 3.1 | | 7.2*, 15 | 22 | 10 | −27 | 0 | +26 | +31 |
| 20. E. Madhya Pradesh | 1219 | 186 | 15 | | 2.40* | 2.75* | 3.2 | | 7.2, 20 | 38 | 12 | −43 | −21 | +20 | +34 |
| 21. Gujarat | 876 | 268 | 31 | | | 2.75 | | | 19 | 11 | 7 | −02 | −19 | +01 | +06 |
| 22. Saurashtra & Kutch | 437 | 191 | 44 | | | 2.88 | | | 11, 21 | 13 | 0 | +04 | −04 | +10 | +03 |
| 23. Konkan and Goa | 2367 | 478 | 20 | | | | | | 6.9*, 22* | 9 | 0 | −02 | +06 | +16 | +16 |
| 24. Madhya Maharashtra | 582 | 122 | 21 | | 2.40 | | | | 4.8, 6.6, 30 | 10 | 0 | +02 | +12 | +28 | +17 |
| 25. Marathwada | 696 | 186 | 27 | | 2.51 | | | | 4.8*, 36 | 11 | 3 | −01 | 0 | +23 | +23 |
| 26. Vidarbha | 906 | 177 | 20 | 2.19* | 2.63 | | | | 11, 18 | 27 | 5 | −05 | +04 | +29 | +21 |
| 27. Coastal Andhra Pradesh | 503 | 107 | 21 | | 2.63* | | | | 17 | 20 | 2 | +05 | +23 | +42 | +31 |
| 28. Telengana | 716 | 158 | 22 | | | 2.75** | | | 6.6* | 26 | 2 | +08 | +15 | +42 | +39 |
| 29. Rayalseema | 422 | 122 | 29 | | | | | | 4.8*, 6.6 | 7 | 7 | +20 | +27 | +27 | +14 |
| 30. Tamilnadu | 306 | 72 | 24 | 2.09 | 2.51 | | | | 5.5, 11* | 25 | 0 | +07 | +22 | +16 | +08 |
| 31. Coastal Karnataka | 2821 | 494 | 18 | | 2.40 | 2.75* | 3.5 | | 4.4, 6.9**, 11*, 14 | 23 | 8 | −17 | −04 | +28 | +30 |
| 32. N. Karnataka | 601 | 119 | 20 | | 2.40 | 2.75** | | | 4.8*, 6.3*, 13* | 37 | 0 | +15 | +18 | +36 | +25 |
| 33. S. Karnataka | 500 | 103 | 21 | | | | | | 6.9 | 13 | 2 | −04 | 0 | +29 | +24 |
| 34. Kerala | 1939 | 372 | 19 | | | | 3.5* | | 6.9 | 5 | 24 | −23 | −12 | +19 | +20 |
| (a) 50-mb wind | | | | 2.33** | | 2.75* | | | | 68 | 2 | | | | |
| (b) T − D | | | | | | 2.60 | 3.6** | | 5.3, 10, 17* | 6 | 9 | | | | |

* Significant at $3\sigma$
** Significant at $4\sigma$

As can be seen, positive correlations reaching up to $+0.45 \pm 0.12$ are seen for some subdivisions for JJA and SON months (i.e., during and after the monsoon months) and, hence, do not have any prediction potential. In DJF and MAM months, correlations are low.

## 3. Geographical distribution of rainfall QBO and QTO and phase relationship with wind QBO

As mentioned by Mukherjee et al. (1985), the intraseasonal rainfall fluctuations of the Indian monsoon are due to the north–south fluctuations of the axis of the monsoon trough, which normally passes through northwestern India in the west and the Gangetic Valley in the east. Hence, in their analysis, they combined data for different regions as (i) north of 20°N, (ii) south of 20°N, (iii) south of 15°N, and (iv) Himalayan foothills (north of 25°N) but found low correlations (+0.25 to +0.42) with the wind data for all of these regions. From our spectra in Table 1, the subdivisions can be divided into four major categories, with respect to QBO and QTO, as follows:

category A: No QTO peak but only one strong QBO peak for 10 subdivisions largely in the western part of India.

category B: No QTO peak but two distinct QBO peaks for four subdivisions (viz., 7, 26, 30, and 32).

category C: No prominent QBO or QTO peaks for four subdivisions (viz., 14, 23, 29, and 33).

category D: Significant QTO peaks, mostly associated with QBO peaks also for 11 subdivisions, largely in the eastern part of India.

In Fig. 1, full circles represent the presence of a strong QBO and triangles represent the presence of a QTO. Figure 2a shows a plot of the rainfall series (one value per year) for category A (one QBO, no QTO) of subdivisions. The top plot is for East Uttar Pradesh (number 10). The series showed only one prominent QBO peak at $T = 2.29$ years. The full dots mark the rainfall maxima. Plots for other category A subdivisions follow, and at the bottom we show the 50-mb zonal wind as 12-month running averages, centered 3 months apart (i.e., four values per year). The vertical lines mark the westerly wind maxima. There are 17 wind peaks during 1951–91 (40 years) indicating an average spacing of about 2.35 years (28 months). However, this spacing varied between 24 and 36 months. Hence, the power spectrum analysis of the 50-mb wind shows two prominent QBO peaks, one at 2.33 years and another at 2.75 years.

To study the phase relationship between wind peaks and rainfall peaks, the dots (rainfall maxima) were compared with the vertical lines (westerly wind maxima). Figure 3a shows the frequency distribution of lags and leads. The top plot is for East Uttar Pradesh. Zero means coincidence and $-1$ means rainfall maximum occurred earlier than westerly wind maximum by one unit (~6 months). As can be seen, from the 15 peaks, 10 peaks occurred at $-1$, 3 peaks at 0, and 2 peaks at $+1$. Thus, a large fraction occurred at 0 or $-1$, indicating that rainfall maxima tended to occur where the westerly wind was approaching a maximum. The other plots in Fig. 3a are for other subdivisions of category A. Subdivisions 13, 17, and 18 also show a substantial number of peaks (11, 12, and 12, respectively) in the 0 and $-1$ category. For other locations (e.g., 21) the lags or leads are spread in a wide range, indicating a lack of clear relationship between rainfall and the 50-mb wind for these subdivisions.

It may be noted, however, that this relationship is rather weak and has most probably very little prediction potential. In Fig. 2a, the East Uttar Pradesh rainfall series has 15 peaks while the zonal wind series has 17 peaks. But both have a QBO around $T = 2.3$ years. Thus, in the rainfall series, 2 peaks have been missed (for 1962 and 1982) presumably because other factors are occasionally operative to cancel the QBO signal. As a result, the percentage variance explained (PVE) by these QBOs hardly exceeds 30% (see Table 1), a poor level for prediction purposes.

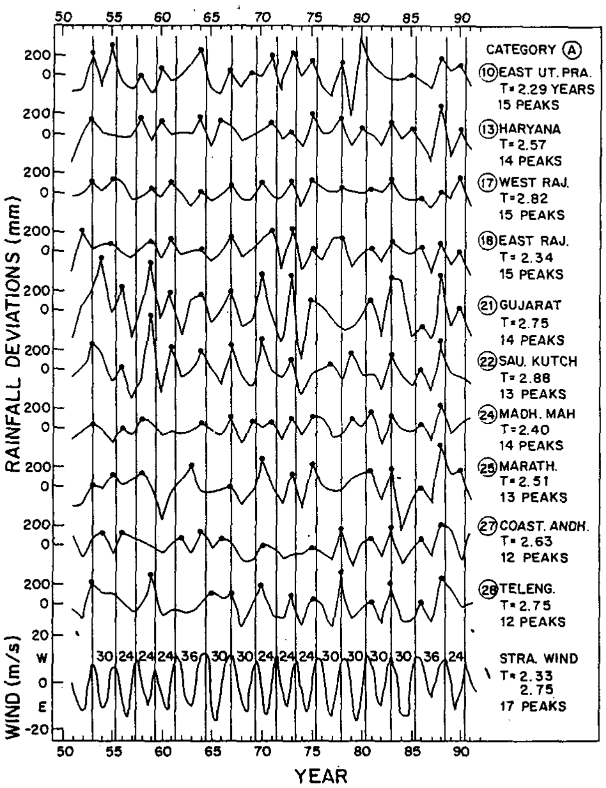
The upper half of Fig. 2b shows a plot for subdivisions of category B (two QBOs, no QTO). Here again, the patterns are irregular and some beats are missed. The upper half of Fig. 3b shows the lags and leads. There is a slight indication of excess at $-1$. The 0 and $-1$ categories together have 11, 10, 8, and 10 peaks for subdivisions 7, 26, 30, and 32, respectively.

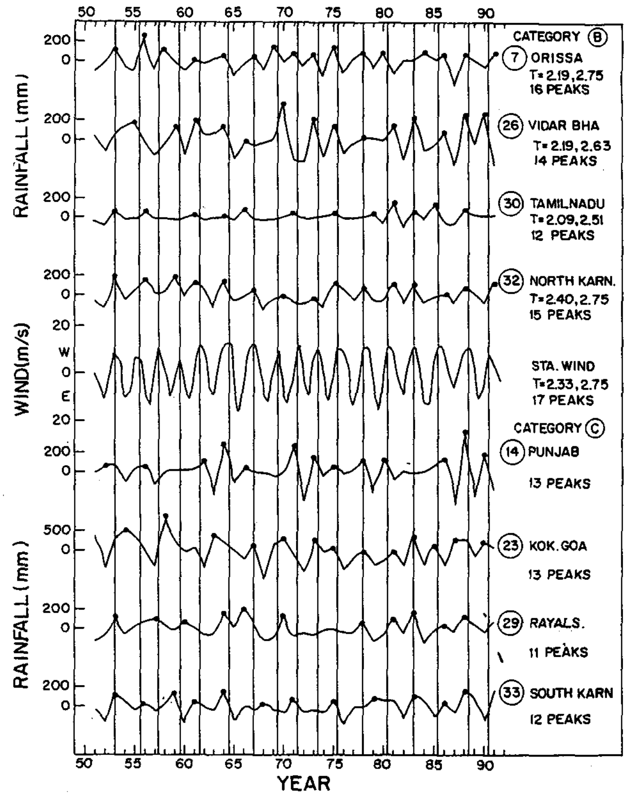
The lower half of Fig. 2b shows a plot for subdivision of category C (no predominant QBOs or QTOs). Thus, one would have expected very little fluctuations. As it seems, some QBOs are still seen but interspersed between larger intervals (4–5 years) of negligible fluctuations. Thus, QBO seems to be present in all subdivisions but intermittently. The lower half of Fig. 3b shows the lags and leads. As expected, the scatter is large, but even here, a slight bias for $-1$ is indicated.

Figure 2c shows plots for subdivisions of category D (prominent QTO, with or without QBO). In almost all cases, there are prominent QBOs also. Figure 3c shows the lags and leads. Whereas some subdivisions show a large scatter, some show a striking bias for $-1$. An overall glance at Fig. 3 shows that the bias for $-1$ is shown by a substantial part of India. On the other hand, some in-between regions do not seem to have any particular bias for $-1$.

## 4. Relationship with El Niño and Southern Oscillation (ENSO)

Since ENSO, as represented by (T − D) atmospheric pressure, has a strong periodicity at $T = 3.6$ years and a smaller one at $T = 2.60$ years, it is likely to match with the rainfall of the subdivisions of category D (strong QTO, with or without QBO). In Fig. 2c, the bottom part shows (T − D), and the rectangles indi-



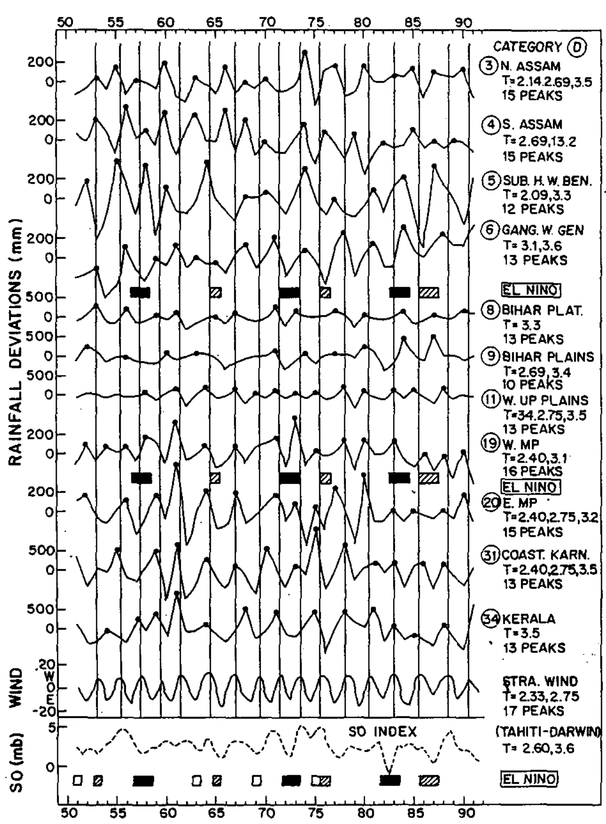




FIG. 2. (a) The QBO–QTO rainfall variations from 1951 to 1991 for 10 subdivisions in category A (one QBO peak, no QTO peak). Full dots indicate rainfall maxima. The bottom plot shows the 50-mb zonal wind (+ve, westerly; −ve easterly) and the vertical lines indicate westerly wind maxima. (b) Upper half: for four subdivisions of category B (two QBO peaks, no QTO peak); and lower half: for four subdivisions of category C (no QBO or QTO). The middle plot shows the 50-mb wind. (c) For 11 subdivisions of category D (prominent QTO, generally with QBO also). The bottom plots are for the 50-mb wind and Southern Oscillation index (Tahiti-minus-Darwin atmospheric pressure). El Niño occurrences are indicated by rectangles (full, strong; hatched, moderate; open, weak).

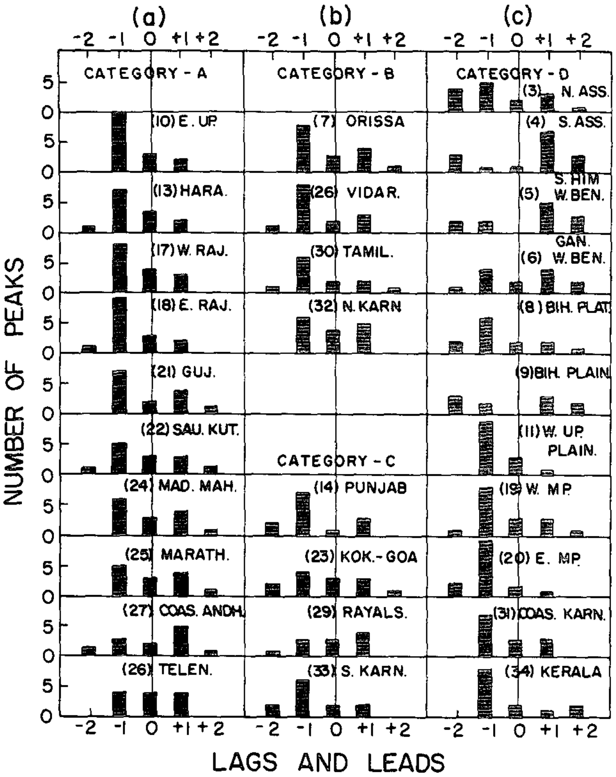



FIG. 3. (a) Phase difference between westerly wind maxima and rainfall maxima for 10 subdivisions in category A. The −1 mean rainfall maxima occurred approximately 6 months before the westerly wind maxima. (b) Upper half: for 4 subdivisions in category B; lower half: for 4 subdivisions in category C. (c) For 11 subdivisions in category D.

cate, El Niño events. During 1951–91, there were three strong El Niños, each as a double event (i.e., occurring in two successive years). Also, there were five moderate El Niños and four weak El Niños (Quinn et al. 1987, updated). Even for the strong El Niño years, the rainfall was not predominantly large or small for any subdivision during 1951–91, implying essentially a poor relationship. Our analysis (Kane 1990) with a longer dataset (1871–1986, 116 years) showed that for western India and a few regions in the north and east, a large number of El Niños was associated with below normal rainfall. For 27 years of strong and moderate El Niños, 15 or more were associated with droughts in 10 subdivisions. However, there were many drought years not accompanied by El Niño occurrence, indicating that some other factors were simultaneously operative. Stratospheric zonal wind could be one of these factors.

## 5. Conclusions and discussion

When the summer monsoon rainfall series for 29 subdivisions from 1951 to 1991 (41 years) were subjected to maximum entropy spectral analysis, several significant periodicities in the quasi-biennial and quasi-triennial range were noted. Ten subdivisions had only one prominent QBO and no QTO. Four subdivisions had two prominent QBOs (significantly different from each other) and no QTO. Four subdivisions had no significant QBO or QTO. Eleven subdivisions had a prominent QTO, generally with significant QBOs also. When the relative positions of rainfall peaks (maxima) were compared with those of stratospheric zonal westerly wind maxima, the rainfall maxima generally occurred a few (about 6) months earlier. Also, the rainfall minima (droughts) were generally associated with strong easterly winds, in agreement with Mukherjee et al. (1985).

The rainfall QBO hardly accounts for approximately 30% variance and, hence, the prediction potential of the above phase relationship is not high. But it would be interesting to investigate how the stratospheric zonal wind comes into picture to affect low-altitude phenomena. Yasunari (1989) reported a QBO in the upper- and lower-tropospheric zonal winds and hinted at a possible link between the QBOs of the stratosphere, troposphere, and sea surface temperature (see also Quiroz 1983). It seems to us, however, (see Kane 1992) that the ENSO phenomenon (including its QBO part) is probably not related to the stratospheric wind QBO. A link between ENSO and Indian monsoon rainfall deficits has been investigated by several workers [e.g., Ropelewski and Halpert (1987), Parthasarathy and Sontakke (1988), and references therein] and even much earlier by Walker (1924). However, this relationship is one-sided, that is, whereas a large fraction of El Niño years is associated with below normal rainfall in many parts of India, many droughts occurred when there was no El Niño activity. These may have a relationship with the stratospheric winds in an altogether independent way, probably through the 200-mb May meridional wind index, which alone seems to explain about 50% variance of rainfall (Parthasarathy et al. 1991). This needs further investigation.

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