The Quasi-Biennial Oscillation and Feedback Processes in the Atmosphere-Ocean-Earth System

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(Manuscript received 17 October 1977, in final form 24 March 1978)

ABSTRACT

Recent investigations indicate that the quasi-biennial oscillation (QBO) in stratospheric winds may be related to variations in the tropospheric circulation in middle and high latitudes. Although the QBO was noticed years ago in a number of worldwide atmospheric phenomena, it is still not well understood. A logical question arises as to whether the oscillation might be a result of the annual forcing by the solar heating, since it is well known that in some nonlinear systems subharmonic oscillations can be produced of order one-half the frequency of the exciting force. A conceptual model is presented to show how a two-year oscillation could be produced by a negative feedback process acting on a two-state system, i.e., winter and summer states. Even for a relatively weak biennial oscillation with stochastic elements involved, the results show that rather strong links must exist in the chain or feedback loop, indicating potential predictability for periods of six months or more. Support for the concept is provided by the analysis of monthly mean observations of the 50 mb zonal winds at Balboa (9°N, 80°W) from September 1950 to October 1976. It is clear that the transitions from an easterly to westerly mode (and *vice versa*) and the duration of a particular mode are closely related to the annual cycle.

1. Introduction

In recent years there has been a considerable amount of interest in the discovery made more than a decade ago that the stratospheric winds over the equator showed a strong tendency to reverse from easterly to westerly from one year to the next. Since the reversal did not always take place and the average period seemed to be a little greater than two years, the phenomenon became known as the quasi-biennial oscillation (QBO). Subsequent investigations by Angell and Korshover (1977), Ebdon (1975), and others indicated that the stratospheric QBO might be related to similar variations in the tropospheric circulation. Although evidence for quasi-periodic fluctuations of around two or three years in surface weather data had been pointed out by a number of investigators during the past 100 years, the weak signal found was usually of doubtful statistical significance. However, Madden (1976) has recently extended the work of Ebdon (1975), making use of the Northern Hemisphere monthly-mean sea-level pressure data for 74 years, and has concluded that in some circumstances the signal-to-noise ratio might be sufficiently high for the biennial oscillation to have predictive value.

Although the so-called biennial oscillation appears to be irregular, varying between two and three years in length, a logical question arises as to whether these oscillations might be a result of the annual forcing by the solar heating. It is well known that in some nonlinear physical systems subharmonic oscillations can be produced of order one-half or one-third the frequency of the exciting force. Although the electrical or mechanical systems where these phenomena occur are much simpler than the atmosphere with its apparent stochastic or nondeterministic elements, we still might learn something by considering the behavior of these less complex systems. The weather-climate system has components (atmosphere, ocean, biosphere, etc.) which are interrelated through complex feedback processes on various time scales. Studies of the annual and biennial cycles and their interrelation should help us to understand and, perhaps, predict the fluctuations on other time scales. This paper gives a few reasons why one might expect the atmosphere to show a tendency toward a biennial oscillation and presents a simple conceptual model, involving a negative feedback process, that provides a possible framework for further theoretical and empirical studies. The concept, along with supporting observations, leads to the suggestion that the QBO may have a much greater importance for understanding and predicting atmospheric fluctuations than that suggested by spectrum analyses of surface observations, which generally indicate only a weak signal.

2. Oscillations in nonlinear systems

It is known that the application of periodic force to a stable linear system results in an oscillation having

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the same frequency as the external force. The forced oscillation depends only on the characteristics of the system and the external force, and it is not affected by the initial condition with which the oscillation was started. However, for nonlinear systems some new phenomena arise where various types of periodic oscillations may exist depending on the initial conditions. The fundamental period of the resulting oscillation is the same as, or equal to an integral multiple of, the period of the external force. These have been termed harmonic oscillation and subharmonic oscillation, respectively. A specific example is systems governed by the Mathieu differential equation

$$\frac{d^2x}{d\tau^2}+(a+16q\cos 2\tau)x=0, \tag{1}$$

where a and q are constants. The equation is a particular case of linear type of the second order with periodic coefficients and has the solution of π or 2π for a proper choice of a and q. The periodic solutions of (1) are known as the Mathieu functions. A more general case is given by the second-order differential equation

$$\frac{d^2\nu}{d\tau^2}+f\left(\nu,\frac{d\nu}{d\tau}\right)=e(\tau), \tag{2}$$

where $e(\tau)$ represents a periodic external force and the function $f(\nu,d\nu/d\tau)$ is in general nonlinear. It is known that a stable solution of (2) is periodic where the least period is equal to the period of the external force or an integral multiple of it. Descriptions of systems governed by (1) and (2) with methods of solving the equations are given by Hayashi (1964). Experimental verifications have been made with electrical circuits containing a saturable-core inductor as a nonlinear element. For example, Hayashi (1964) has produced subharmonics of either order one-half or one-third in a system, the results depending only upon the initial condition which could be controlled precisely by electronic timing devices.[1]

The systems described above are relatively simple compared to the complex atmosphere and, even though we felt that the atmosphere should have similar behavior, there are a number of reasons why it does not appear practical to pursue this approach much further. We are not able to write the system of equations analogous to (1) and (2) for the atmosphere and, even if we could, we would not have the necessary initialization data nor the mathematical power to solve them. Furthermore, it appears that there may be purely stochastic processes operating in the atmosphere so that random perturbations and shocks would prevent a deterministic solution, at least over long period extensions in time. However, there does appear to be another approach that addresses somewhat the same problem of possible oscillatory behavior of the atmosphere and permits stochastic elements to play a role. A conceptual model along these lines is presented below.

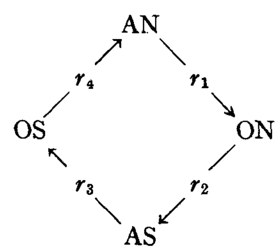
3. A feedback system with a two-year oscillation

The climate system consists of the atmosphere, the oceans, the cryosphere, lithosphere, and biomass. We shall designate (for the sake of simplicity) the atmosphere by A and the remainder by O (oceans), since it it known that the oceans must play an important role in the interactions or feedbacks between the different parts of the system. In the time domain, a two-state system will be represented by N for the season when the sun is in the Northern Hemisphere and by S when it is in the Southern Hemisphere. Thus, the symbol AN_t represents the state of the atmosphere at the time t ($t=1, 2, \ldots, n$ years), ON_t represents the state of the oceans at t, etc. The following table shows the time sequence of A and O with arrows representing the assumptions with regard to the direction of cause and effect:

	N_1	S_1	N_2	S_2
A	AN_1	AS_1	AN_2	AS_2
	$\downarrow\ \nearrow$	$\downarrow\ \nearrow$	$\downarrow\ \nearrow$	
O	ON_1	OS_1	ON_2	OS_2

For example, it is assumed that the atmosphere circulation during a particular season affects the oceans, which in turn can have a carry-over or lag effect on the atmosphere the following season. It is assumed that the memory of the atmosphere is negligible compared with that of the ocean-earth system.

The feedback loop is represented by the following diagram where r_i ($i=1, 2, 3, 4$) indicates the correlation for the individual links in the chain:



The product $R=r_1r_2r_3r_4$ gives a measure of the strength of the entire feedback loop. Under these assumptions it is obvious that if any $r_i=0$ there is no effective feedback, i.e., a chain is no stronger than its weakest link. If all $r_i\neq 0$, then a little analysis will show that there are only two possibilities, a negative feedback or a positive feedback. For example, if all correlations are positive and we start out with a positive anomaly for AN_1, then the expected pattern of anomalies is as

[1] Such systems that permit two or more distinct sets of statistics according to the condition existing when the system first became established have been termed *intransitive* by Lorenz (1976).

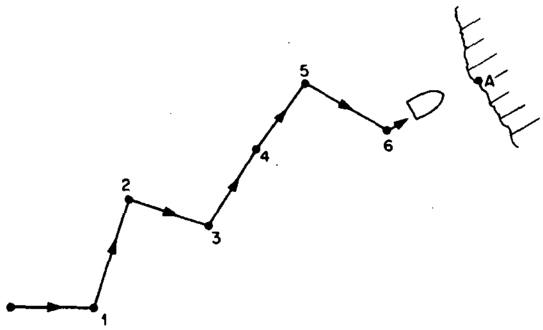


FIG. 1. Illustrations of quasi-periodicity in path of rowboat produced by negative feedback.

follows:

	N_1	S_1	N_2	S_2	N_3	S_3	N_4	S_4
A	+	+	+	+	+	+	+	+
O	+	+	+	+	+	+	+	+

However, if one of these correlations is negative (say r_4), the pattern of anomalies is

	N_1	S_1	N_2	S_2	N_3	S_3	N_4	S_4
A	+	+	−	−	+	+	−	−
O	+	+	−	−	+	+	−	−

which shows two years between anomalies of like sign for either season N or season S. (If r_1 or r_2 is negative instead of r_4, the change in signs in the anomalies would be between N and S, rather than between S and N.) In general the feedback will be negative if one correlation coefficient is opposite in sign to the other three. The effect of random perturbation is to disturb such a perfect pattern and to lengthen the apparent cycle. This is illustrated by the following analogy. If, as shown in Fig. 1, I start rowing a boat toward point A on the shore my path will show a zigzag with a 2 min interval between peaks if I turn my head around and make a correction every minute. If I occasionally forget and make the correction at the end of 2 min, some peaks will be 3 min apart. A typical spectrum analysis of my path will show some kind of an average period in power between 2 and 3 min. A different type of analysis would be needed to adequately summarize the detailed characteristics of the path.

In the complex atmosphere-ocean system one might expect a number of feedback loops, some positive and some negative, with interactions between them. One might think of the positive feedback loops producing long-term trends and the negative feedback loops producing the higher frequency quasi-oscillation with periods of several years. Many analyses of long meteorological time series suggest both mechanisms operating, but in the presence of a large amount of noise. If in the model presented here each $r_i=0.5$, then $R=0.0625$—not very useful for prediction. But in some cases larger negative correlations ($R\approx-0.25$) are observed in the atmosphere, which imply links in the chain with $|r_i|=0.70$, and these might be well worth exploring for scientific and practical reasons. A particular case is the QBO in the stratospheric tropical winds which will be examined next in connection with the hypothesis of subharmonic oscillations.

4. Analysis of supporting data

The data used in this analysis are the monthly means of the 50 mb zonal winds at Balboa (9°N, 80°W) from September 1950 to October 1976 inclusive. This record was chosen as the longest continuous set of stratospheric observations available to the author, being kindly supplied by Dr. J. Angell of the Air Resources Laboratory, NOAA, Silver Springs, MD. The 30 mb level could have been chosen but the quality of the record was not as good as the 50 mb level. The choice appears to be fortunate since the dominating cycles have large amplitudes with very little noise and no smoothing or filtering of any kind was needed. Furthermore, the data clearly show a small but distinct annual cycle which makes it possible to study possible interactions between the QBO and the annual forcing.

TABLE 1. Periodogram for 50 mb mean monthly zonal wind components at Balboa, based on 26 years of data. The raw estimates are given without smoothing, and there were no appreciable peaks beyond $F=29$ with the exception of the semi-annual period which accounted for 1.3% of the total variance.

Frequency (312 months)	Period (months)	Variance (%)
1	312	0.01
2	156	2.11
3	104	0.34
4	78	0.48
5	62.4	0.17
6	52.0	2.05
7	44.6	0.46
8	39.0	1.53
9	34.7	8.23
10	31.2	2.96
11	28.4	21.16
12	26.0	2.60
13	24.0	17.75
14	22.3	0.96
15	20.8	3.35
16	19.5	0.51
17	18.4	0.57
18	17.3	0.26
19	16.4	0.92
20	15.6	1.01
21	14.9	0.08
22	14.2	0.28
23	13.6	0.53
24	13.0	0.71
25	12.5	0.08
26	12.0	24.26
27	18.6	0.84
28	11.1	0.12

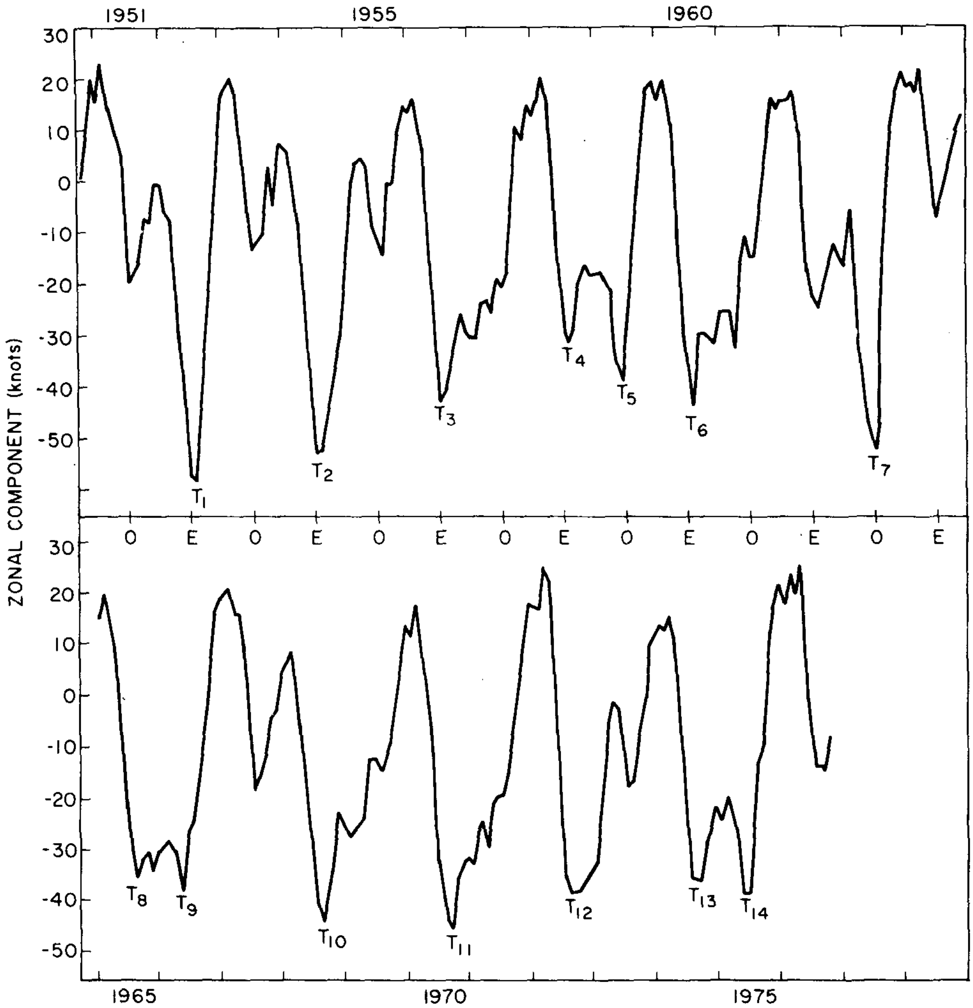


FIG. 2. Mean monthly zonal wind components at 50 mb for Balboa, Canal Zone, 1950–76. Major troughs (easterly winds) occur near July and August in even (E) or odd (O) years.

These data plotted in Fig. 2, with the months of major maxima in easterly winds marked as troughs T_1, T_2, etc. These troughs occur close to July, and for convenience, the time scale is marked O for each July in the odd years and E for each July in the even years. The graph clearly shows the annual cycle, although it is not always present and varies in amplitude (but not in phase). A two-year cycle is evident from T_1 to T_2 and from T_2 to T_3. Things then become a little ambiguous, with three years from T_3 to T_5, or four years from T_3 to T_6, if you prefer. It is two years from T_7 to T_8, but, there are two major oscillations in the five years from T_7 to T_{10}. The important point is that all T_i occur near the month of July and August, and are not distributed randomly throughout the year which would be the case if the QBO were independent of the annual heating cycle. The 30 mb mean zonal wind components at Canton Island/Gan shown by Ebdon (1975) indicate very much the same pattern with an important exception. There is no appreciable annual cycle at Canton Island and although one sees a trough minimum at T_2, T_3 and T_6, for example, there are no minima at T_4 and T_5 but instead a single minimum between T_4 and T_5.

The harmonic analysis was next made of the 26 years of data (October, 1951–September, 1976). Table 1 shows the variance accounted for by each frequency from one to twenty-eight cycles in the 312 month period. Over 94% of variance was accounted for by these first 28 terms and there were no appreciable peaks in the periodogram at any of the higher frequencies. The band between 21–30 months accounted for 45.8% of the total variance and the band between 11–13 months accounted for 26.0%. The semi-annual period (6 months) accounted for a non-significant 1.3% of the variance, although it was higher than any other of the remaining ones. It is difficult to see how anyone could claim a real physical period of 26.0 months or 28.36 months, even though they are much higher than the continuum, accounting for a disproportionate share of the variance.

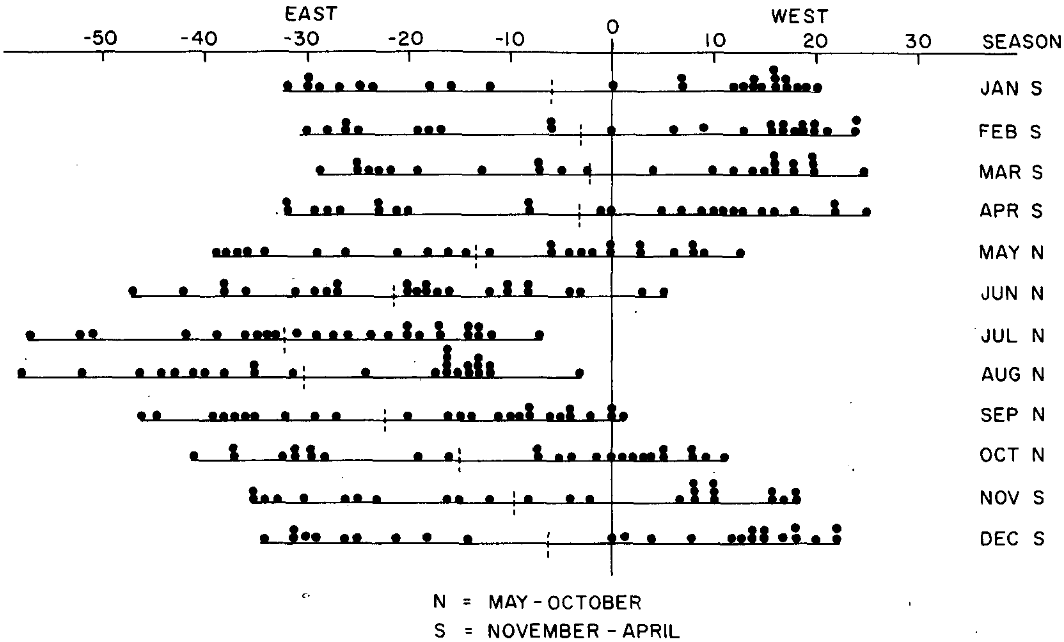


FIG. 3. Frequency distributions for mean monthly zonal wind components at Balboa, Canal Zone, 1950–76. The dashed vertical lines are at mid-range.

If a different length of record had been chosen for analysis, the peak at 28.36 months could easily disappear and show up elsewhere. The spectrum or periodogram does not give a very good picture of what is going on in this case, and might be quite misleading regarding clues to possible physical processes. Presumably, a higher noise level would only make it more difficult to interpret apparent peaks in a spectrum.

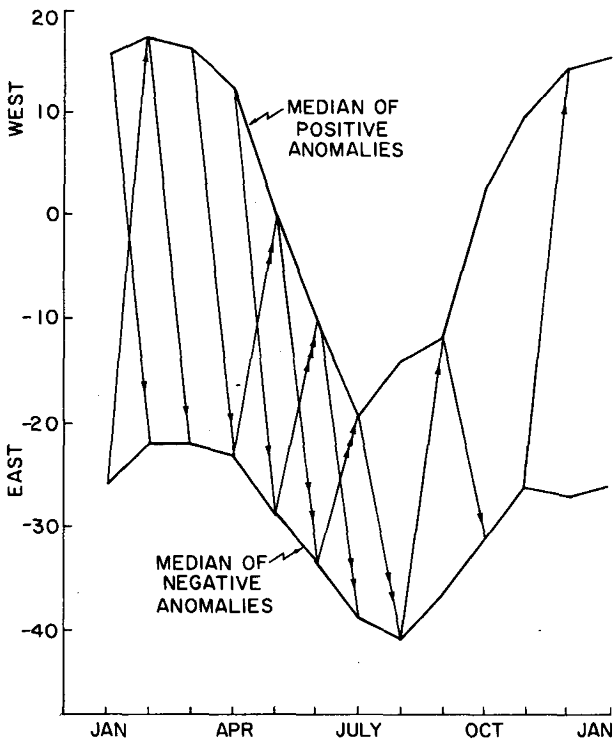


FIG. 4. Months of transitions from positive to negative anomaly, or vice versa. *Direction of change and frequency of winds is* represented by the number of arrowheads.

Since the data show an obvious annual cycle in addition to the QBO, the next step was an attempt to remove this component before further analyses. Examination of the frequency distributions for the individual months showed a very pronounced tendency for U-shaped distributions, with a deficiency of observations in the middle ranges. These phenomena are clearly shown by the plot of the monthly values in Fig. 3. In these circumstances the mid-range (halfway between the lowest and highest values each month) of the distribution is a more appropriate statistic to use for a location parameter than the sample mean. These mid-ranges are shown in Fig. 3 and were used to compute a departure anomaly for each month of the series. These values are given in Table 2, where a positive anomaly means a departure in the direction of a more westerly component while a negative sign means a departure in the easterly direction. This table also shows the average anomaly for season S (November–April) and for season N (May–October).

Referring to the monthly anomalies in Table 2, it is noticed that once there is a change of sign from positive to negative (or *vice versa*) the particular state will persist for at least nine months or more. Furthermore, there appears to be a preferred time of the year for the transitions to take place, with 16 of the 22 changes in sign taking place in the N season. Fig. 4 shows the direction of these transitions during the year with the arrowheads indicating the number of cases. For

TABLE 2. Monthly anomalies for 50 mb zonal wind components for Balboa, expressed in terms of deviation from the mid-range value.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Seasonal averages November–April	Seasonal averages May–October
1950									20	16	19	24		
51	22	27	18	15	21	26	12	13	7	8	1	6	20.8	14.5
52	6	−3	−5	−17	−23	−21	−25	−28	−15	−14	−6	7	−2.0	−21.0
53	23	22	22	21	19	18	19	19	12	18	5	14	14.8	17.5
54	13	9	−3	−5	−16	−15	−20	−22	−24	−26	−26	−20	5.5	−20.5
55	−6	3	6	8	16	13	20	16	22	15	17	21	−5.8	17.0
56	20	20	14	10	−1	−7	−10	−10	−14	−16	−16	−23	17.0	−9.7
57	−24	−27	−21	−20	−13	3	12	14	18	26	17	21	−21.8	10.0
58	19	19	22	18	13	3	6	−1	−5	−4	−7	−12	19.3	2.0
59	−12	−14	−17	−18	−21	−17	1	14	22	23	27	26	−13.3	3.7
60	22	22	17	14	7	−6	−4	−11	−7	−14	−21	−25	21.3	−5.8
61	−19	−22	−23	−29	−3	11	18	16	18	19	25	20	−23.0	13.2
62	22	19	20	16	16	5	10	6	2	−1	−3	−8	17.0	6.3
63	−10	−3	−11	−25	−26	−26	−19	−16	6	24	26	28	−10.0	−9.5
64	25	23	20	25	22	24	25	27	23	20	19	19	24.5	23.5
65	21	23	16	12	10	1	3	−5	−10	−16	−25	−24	18.3	−2.8
66	−23	−25	−27	−29	−24	−6	8	14	14	20	25	25	−25.5	4.3
67	26	24	18	19	21	13	15	15	11	11	7	10	22.8	14.3
68	13	12	0	−5	−5	−8	−7	−14	−17	−17	−14	−19	6.2	−11.3
69	−21	−23	−23	−20	1	9	18	18	16	15	17	20	−20.0	12.8
70	18	21	12	3	7	−10	−3	−13	−23	−22	−24	−25	15.2	−10.7
71	−26	−23	−22	−26	−8	2	13	17	17	17	16	24	−24.3	9.7
72	23	20	27	25	13	4	−1	−8	−16	−22	−26	−28	22.5	−5.0
73	−24	−15	−5	2	11	11	15	14	14	10	19	18	−16.0	12.5
74	20	16	18	13	9	1	−2	−5	−13	−13	−17	−15	17.3	−3.8
75	−18	−16	−20	−24	−25	−17	5	17	13	23	27	28	−18.3	2.7
76	24	27	22	28	26	17	19	17	8	8			26.0	15.8
MR	−6	−3	−2	3	−13	−21	−32	−30	−22	−15	−9	−6		

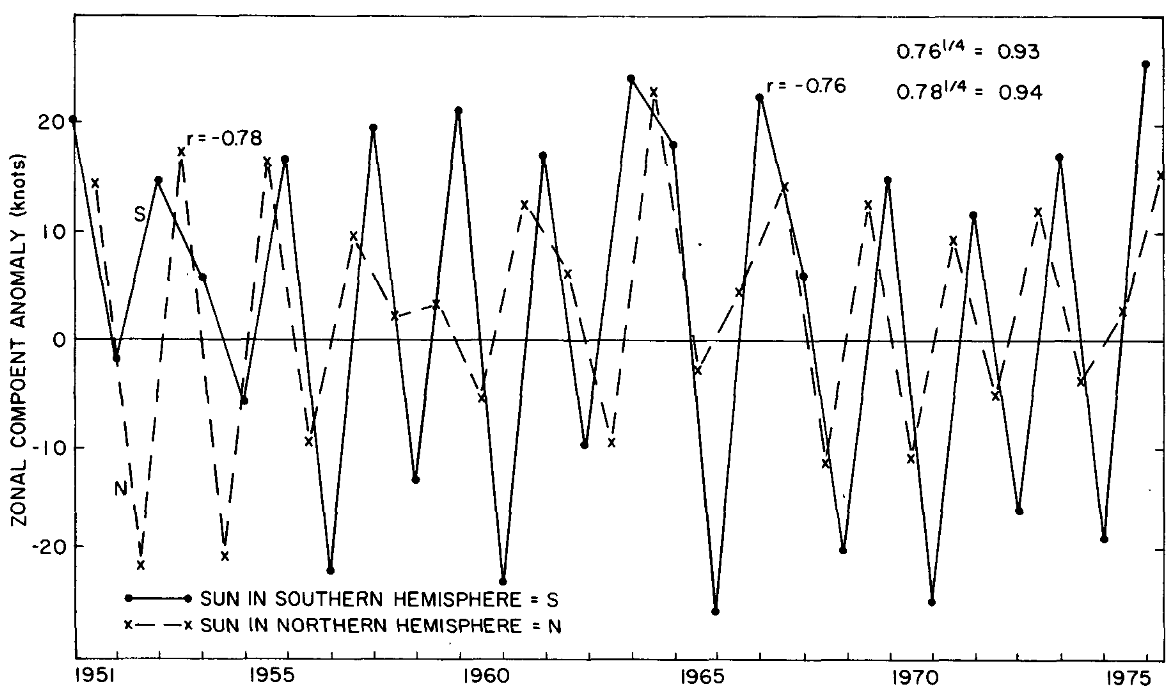


FIG. 5. Seasonal averages of mean monthly zonal winds anomalies for Balboa, Canal Zone, 1960–76. The months November–April are designated by S and the May–October season as N.

TABLE 3. Sequence of seasonal anomalies, plus or minus. Usual pattern of anomalies is disturbed at points $D_1, D_2, \ldots, D_5$.

Year	1951	1952	1953	1954	1955	1965	1957	1958	1959	1960	1961	1962	1963
Season	S N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S
Anomaly	+ + −	− +	+ +	− −	+ +	− −	+ +	+ −	+ +	− −	+ +	+ −	− +
Disturbance	↑ D_1							↑ D_2				↑ D_3	

Year	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Season	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S	N S
Anomaly	+ +	− −	+ +	+ +	− −	+ +	− −	+ +	− −	+ +	− −	+ +	+
Disturbance				↑ D_4									↑ D_5

example, from May to June there are three changes from easterly to westerly anomaly. Especially notable is the nearly complete absence of transitions from October to January.

The seasonal averages were examined next and are plotted in Fig. 5 with the solid lines connecting successive S seasons and dashed lines connecting the N seasons. The biennial oscillation is evident, along with occasional phase reversals. The majority of major peaks are two years apart with an occasional three-year interval. The lag one correlation for S is $r=-0.76$, and $r=-0.78$ for season N. If these correlations are the result of a feedback process with four links in the chain, then the individual links must have correlations near $0.76^{1/4}=0.93$. If one cares to argue that things are more complicated and there should be more links, say 6, then $r_1=0.76^{1/6}=0.96$. With noise levels this low, one might hope to find some of the links in the chain with good physical guidance if the right data are available.

The pattern of seasonal anomalies is shown by the sequence of plus and minus signs in Table 3. The dominant pattern is $++--++--$ with the changes in sign taking place between S and N. The negative anomalies *never* persist for more than two seasons, and only at disturbance points D_1, D_2, D_3, D_4 and D_5 does a change in the general pattern take place. The apparent

TABLE 4. Frequency of occurrence of positive or negative anomalies for eight seasons following specified initial anomalies and two previous seasonal anomalies.

Previous seasons		Initial season		Following seasons							
N_1	S_0	N_0	Anomaly	S_1	N_1	S_1	N_2	S_3	N_3	S_4	N_4
+	+	−	+	0	8	8	4	1	5	6	4
			−	8	0	0	4	6	2	1	3
−	−	+	+	8	4	1	5	6	4	2	4
			−	0	4	6	2	1	3	4	2
+	+	+	+	1	1	2	2	2	1	1	3
			−	2	2	1	1	1	2	2	0
−	+	+	+	2	0	0	2	2	1	1	1
			−	0	2	2	0	0	1	1	1
+	−	−	+	2	2	2	0	0	2	2	1
			−	0	0	0	2	2	0	0	1
+	−	+	+	1	0	0	1	1	1	0	0
			−	0	1	1	0	0	0	1	1
S_1	N_0	S_0		N_1	S_1	N_2	S_2	N_3	S_3	N_4	S_4
−	+	+	+	4	1	6	7	5	2	4	5
			−	5	7	2	1	3	7	3	2
+	−	−	+	8	8	4	1	5	6	4	2
			−	0	0	4	6	2	1	3	4
+	+	+	+	0	0	3	3	1	1	2	2
			−	3	3	0	0	2	2	1	1
+	+	−	+	1	3	2	2	1	1	3	2
			−	2	0	1	1	2	2	0	1
−	−	+	+	2	2	0	0	2	2	1	1
			−	0	0	2	2	0	0	1	1

effect of these disturbance points is to prolong the persistence of the positive anomaly and delay the negative feedback mechanism. In only one case (1965–66) does the positive anomaly persist for more than three seasons. It is interesting to consider the predictability of these sequences from the point of view of a Markoff process with two states, i.e., a plus or a minus anomaly. Table 4 shows the frequencies of the subsequent states of the system according to the initial states at S_0 or N_0 and the conditions for the two preceding seasons. For example, the first lines of the table show that eight cases were observed in the historical record where the S season had a negative anomaly preceded by a negative anomaly in the previous N season and a positive anomaly in the preceding S season. In *all* of these cases, the anomalies in the next two seasons were positive, and even five or six seasons ahead the anomalies were predominately positive, with return to negative anomalies in between. This evidence of nonrandomness suggests predictability for a season or more.

5. Discussion

When the QBO was first noticed over a decade ago it was felt by some investigators that it might be some sort of a statistical accident or fluke and would eventually disappear. The Balboa data shown here indicate that this is not the case since the variations in the 50 mb winds show essentially the same pattern from 1970–76 as they did for the previous two decades. The statistical analysis and arguments presented here suggest that the apparent cycles of around 25–30 months are not oscillations of unknown origin, but closely related to the annual cycle, perhaps resulting from negative feedback processes and interactions involving the atmosphere-ocean-earth system.

The tendency toward U-shaped and nonsymmetrical distributions of the monthly means strongly suggests that the tropical stratosphere has two distinctly preferred modes with a relatively short transition period between these modes. The lack of a semi-annual period and the distinct preference for the transitions to take place between April and October indicate the importance of the annual forcing, perhaps involving the stratospheric and tropospheric circulation in higher latitudes. If only local equatorial solar heating was involved, one might expect to find some evidence of a semi-annual period. The tendency for the anomalies to persist for a while and then suddenly change suggests that both negative and positive feedback mechanisms are operating and, in a sense, competing with each other for dominance or control of the climate system at every point in time. It may simplify the problem if some of these controls are seasonally dependent, as indicated here by the evidence of the QBO. The pattern of seasonal anomalies shown by the tropical stratospheric winds appears to resemble a combination of those hypothesized by the model described in Section 3.

The conceptual model presented here does not deny the possibility of other feedback processes (positive or negative) operating on various time scales, nor does it address the question of detailed physical mechanisms to explain the QBO, such as the theory proposed by Holton and Lindzen (1972). The important point is that if detectable and appreciable oscillations of around two or three years in the atmospheric circulation are the result of negative feedback processes in the climate system, then there must be some strong links in the chain with the possibility of finding and understanding them. The tropospheric oscillations on this time scale are much weaker and difficult to detect, and may be unrelated to the QBO. However, a number of investigators have found evidence to support the view that the QBO is related to similar variations in the troposphere and to high latitude stratospheric variations. The connection is not very clear and more study is needed to determine how much of the atmosphere-ocean-earth system is participating in the QBO and the extent to which negative feedback on this time scale might be important.

Questions regarding the annual and biennial oscillation also appear to be relevant to the points made by Lorenz (1976) in considering nondeterministic theories of climatic change. In discussing transitive and intransitive systems, he remarks that there is "one aspect of the real atmosphere . . . which should appear to hinder the production of periods of several years or longer. This is the strong normal seasonal variation of the thermal forcing . . . . Almost intransitivity might thus favor persistence throughout a season, but not persistence from one year to another." It would appear that a strong negative feedback process producing oscillations with a period of two or three years would tend to have the same effect as the annual forcing and reduce the importance of almost-intransitivity of the atmosphere as an important factor in long-period climatic fluctuations.

6. Conclusions

In nonlinear systems it is known that various types of periodic oscillations may exist where the fundamental period is the same as, or equal to an integral multiple of, the period of the external force, depending on the initial conditions which happen to exist when the system first became established. Such systems are called intransitive, and there is some evidence that the atmosphere-ocean-earth system shows some characteristics of intransitivity, or at least almost-intransitivity. The existence of a quasi-biennial oscillation in the stratospheric winds over the equator is well established, and an analysis of the 50 mb zonal winds at Balboa indicates that the normal seasonal variation of the thermal forcing may play an important role in the period and phase of the phenomena. A simple conceptual negative feedback model with four links in the chain shows that oscillations might be produced in the atmosphere which are comparable in amplitude, period and phase to those observed. Presumably, ocean-atmosphere interactions are among the important links in the feedback process but stochastic elements or random disturbances may weaken the feedback loop and reduce the amplitude and regularity of the oscillation. However, it is shown that even for relatively weak oscillations there may be some rather strong and detectable links in the chain which hold promise for useful prediction of some atmospheric parameters on the time scale of a season or more. Feedback mechanisms requiring correlations as high as 0.90 for individual links in the chain may not appear very attractive in view of the much weaker correlations found in meteorological data. However, there must be a strong memory somewhere in the system since the evidence presented here and elsewhere in support of the strength and reality of the QBO is so strong, if not overwhelming.

Although the relationship between the QBO and the biennial oscillation reported in many tropospheric parameters is not well understood, a number of investigators have reported evidence that the complete reversal of winds in the equatorial stratosphere does play a part in determining the character of the tropospheric circulation in middle and high latitudes. It does seem important to study these relationships more thoroughly and to develop realistic models of the general circulation that take account of possible feedback mechanisms operating on a scale of several seasons and the interactions with the annual forcing. Possible alternatives to feedback processes should be explored, but whatever mechanism is proposed for the QBO, it should be capable of explaining the basic biennial oscillation and the disturbance or disturbances that cause it to deviate from this basic frequency.

Acknowledgments. This research was supported in part by the National Science Foundation under Grant ATM 76-18860. The author wishes to thank two referees for useful comments.

REFERENCES

Angell, J. K., and J. Korshover, 1977: Variation in size and location of the 300 mb north circumpolar vortex between 1963 and 1975. *Mon. Wea. Rev.*, **105**, 20–25.

Ebdon, R. A., 1975: The quasi-biennial oscillation and its association with tropospheric circulation patterns. *Meteor. Mag.*, **104**, 282–297.

Hayashi, C., 1964: *Nonlinear Oscillations in Physical Systems*. McGraw-Hill, 392 pp. (see Chaps. 3 and 4).

Holton, J. R., and R. S. Lindzen, 1972: An updated theory for the quasi-biennial oscillation. *J. Atmos. Sci.*, **29**, 1070–1080.

Lorenz, E. N., 1976: Nondeterministic theories of climatic change. *Quaternary Res.*, **6**, 495–506.

Madden, R. L., 1976: Estimates of the natural variability of time-averaged sea-level pressure. *Mon. Wea. Rev.*, **104**, 942–951.