VARIATION WITH LONGITUDE OF THE QUASI-BIENNIAL OSCILLATION [1,2]

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ABSTRACT

Daily data at 16 stations along five latitudes from 13°N. to 33°S. were carefully examined at the 50-, 100-, and 500-mb. levels for evidence of longitudinal phase progression of the quasi-biennial oscillation (QBO). At 50 mb. there is evidence of west to east progression although there are many irregularities and much uncertainty. The phase dates differ by days at low latitudes. At 100 and 500 mb., it appears that the QBO originates in tropical America and progresses both eastward and westward, occurring last in the Indian Ocean. The progression time ranges from 1 to 2 yr. At 500 and 100 mb., however, a cellular phase progression is possible due to the difficulty of identifying corresponding waves with a very meager network.

It appears now that the QBO may not be simultaneous in longitude and that its speed and even direction of propagation, like its other properties, may vary from cycle to cycle. The analysis is being expanded to other levels and latitudes to obtain better continuity in following each wave.

1. INTRODUCTION

It has been generally assumed that the quasi-biennial oscillation (QBO) in the zonal wind component, observed first in the tropical stratosphere and later at other latitudes and levels, is simultaneous at all longitudes for a given latitude. However, this impression is based on the general use of monthly mean wind data, so if the phenomenon actually has a longitudinal time variation in a shorter period than 1 mo., one could not detect it from monthly mean data. It is the purpose of this study to determine phase dates of individual cycles of the QBO as precisely as possible using daily data, and to see if stations near a given latitude show consistent progression of the wave with longitude. In practice it became advisable not to restrict the study to individual latitudes but to map the phase dates so that the progression with latitude and longitude could be observed.

The assumption of simultaneous occurrence implies a global ring phenomenon whose influence is symmetric to the Equator and is a function only of latitude and altitude. Such a pattern can best be described in terms of north-south oriented standing or traveling waves. As observation has revealed nodal belts typical of standing waves and phase progression characteristic of traveling waves, it is reasonable that the variation along a meridian is a mixture of both. However, if careful examination of data on a daily, rather than a monthly, basis shows that there are indeed longitudinal variations, a more complicated model must be advanced. These variations, if evident, may be due to the longitudinal variability of the properties of north-south components or even possibly to an east-west traveling component which spirals around the earth from high to low latitudes with very rapid velocity.

No theory for the existence of the QBO is yet established, although many tentative proposals have been advanced. (A convenient review of the status of proposed QBO causes can be found in [1].) To assist in ascertaining its origin, its properties must be better known. Whether the results of a detailed study of daily data reveals a regular progression with longitude of this wave or not, they will be of great help in focusing effort onto a reduced number of possible causes.

Far from being a simple, regular, sinusoidal variation, the QBO appears to be a highly irregular phenomenon whose period, amplitude, and phase vary continually at a given station, and which has noticeable intensity in various regions such as the tropical stratosphere, the polar midtroposphere, and the polar midstratosphere, yet is not seen clearly between these regions. A corresponding, although less pronounced, variation in monthly mean temperature is also noted. Despite its cycle-to-cycle irregularity, long-term series of mean monthly surface data also show an average period apparently near 26 mo. on a worldwide basis (Landsberg et al. [2]). Shah and Godson [3], also using monthly means, have mapped the phase and amplitude of the biennial temperature cycle for levels from 10 to 200 mb. on a global scale and recognize a spacing of about 30° of lat. between maxima in amplitude. They found that the tropical maximum (near 30°) is out of phase with the equatorial, temperate (60°), and polar (80°) cycles, confirming results of Angell and Korshover [4].

[1] Research supported under Contract Nonr 4700(00) with Office of Naval Research.

[2] Presented in preliminary forms at American Geophysical Union meeting, Washington, D.C., Apr. 17, 1967, and the Seventh Stanstead Seminar, July 1967.

2. APPROACH

The type of analysis that has been chosen consists of determining the calendar dates of maxima and minima and magnitude of the QBO on an individual cycle basis. Of the usual methods of periodic analysis—harmonic analysis, spectral analysis, and filtering, the latter is the most appropriate.

Harmonic and spectral techniques describe the phase and amplitude of sinusoidal components within the data. However, the quasi-biennial waveform being examined contains appreciable energy which cannot be described in terms of a single sine wave or in terms of harmonic components primarily because of the time variations of amplitude and frequency that are apparent. Therefore, the amplitude and phase of a single quasi-biennial component as given by the spectral techniques will not necessarily describe the properties of the composite waveform.

The digital filter technique which we have chosen does not depend on a single sinusoidal interpretation of the biennial wave. By using a broad-band, low-pass filter, the annual cycle and higher frequencies are greatly attenuated so the lower frequency components with weak amplitude can be identified. The frequency response of the filter in the neighborhood of the biennial peak is almost uniform; therefore, systematic variations of the quasi-biennial waveform are evident in the filtered results. A logical calendar interpretation of the dates of maxima and minima of the filtered waveform is then easily accomplished. (Although it is recognized that the term "phase" refers properly to a single sinusoidal wave, for lack of a more convenient term it will be used here also to refer to the maximum (or minimum) of a particular cycle.) The use of digital filters in the analysis of the quasi-biennial oscillation is not uncommon (Landsberg et al. [2]; Edmond [5]), and numerous investigators have made use of the 12-mo. running mean, another digital filter, for a variety of descriptive analyses.

To obtain times of maximum or minimum with finer resolution than a month, daily data are required rather than monthly means. However, in order to filter a time series, all values must be equally spaced. Missing data were therefore interpolated using a technique discussed in the next section. It is mainly to avoid the need for interpolation that monthly means are commonly used, and therefore there have been no findings concerning shorter period variations in phase date. However, monthly means contain an indeterminable bias due to the nonuniform distribution of few data within a given month, and also are aliased due to the infrequent sampling at high levels within the month.

Hence our approach was to prepare a serially complete daily time series which was then subjected to a digital filter to suppress the unwanted frequencies.

INTERPOLATION

Several techniques for estimating the missing data were examined. These included the use of polynominals, band-limited functions, and linear regression. Of these methods, the latter was most appropriate because the regression technique very nearly conserves most of the statistical properties of the existing data, namely the mean, variance, autocorrelation, and power spectrum. Also, this interpolation is compatible with all time series from different stations regardless of the density of sampled data and gives a measure of interpolation error in terms of the number and geometry of neighboring data utilized to estimate the missing value.

As linear regression, commonly referred to as "optimum interpolation," has been discussed widely in various texts and its application to meteorological data has been examined by Gandin [6], Peterson and Middleton [7], and Buell [8], the analytic formulation is not given here. Qualitatively, this technique utilizes the autocorrelation function of the data to determine a set of optimum linear weights to be attached to surrounding sample points to give the best least squares estimate of the interpolated value. A statistical estimate of interpolation error can then be determined in terms of these optimum linear weights and the variance and autocorrelation function of the sampled data. The weights have the property of point orthogonality, that is interpolation error vanishes at all sample points.

In using this technique, the autovariance function of a zonal wind time series was first determined for periods somewhat greater than the longest gap in the wind data record utilizing lags of 12- or 24-hr. multiples depending on the basic sampling rate for a given station. (It is to be noted that the autovariance function is equivalent to to the autocorrelation function multiplied by the variance of the data.) This was done by normalizing the resulting correlations with respect to the number of data pairs that were available from the incomplete data for that given lag.

For each autovariance function, a pilot study of statistical interpolation errors was then made for various sample configurations in the neighborhood of an interpolated point. This was necessary to choose how many samples might be utilized for the interpolation scheme for that particular time series. (In practice, as a matrix inversion is involved in determining the weighting functions for each interpolated value, only a few samples can be economically used.) As might be expected, interpolation errors were most sensitive to the nearness of sample points to the interpolated value. In fact little improvement in this statistical error was realized if other than the most recent sample point was utilized. Naturally, smaller errors occurred with two-sided interpolation than with one-sided interpolation (extrapolation).

From this preliminary study, a method was obtained for choosing the optimum number of observations to be utilized in the interpolation program for each time series. This consisted of an iterative technique for examining observations on each side of the interpolated point so that: 1) a minimum number of observations were utilized as determined from the decay of interpolation error with increased number of measurement, 2) more observations than necessary are not used as the matrix inversion determining regression coefficients can become a time consuming operation, and 3) two-sided interpolation is used whenever possible. Usually from four to 10 samples were used for interpolating a missing data point; fewer data are used when the samples are quite dense. The optimum weights were then computed and the interpolation in terms of existing data was accomplished. In addition, statistical interpolation errors were determined for each estimated value.

FILTERING

As discussed previously, it is desired to pass the combination of interpolated and sampled data through a digital filter in order to isolate the quasi-biennial oscillation. This filter must be chosen to attenuate the annual cycle and higher frequencies where much of the spectral energy of the wind is located. However, the selection of the filter must also consider the number of weights involved because the length of the transient-free filtered output is equivalent to the length of the time series being analyzed minus the number of filter weights. For many stations there are only enough sampled data to contain one or two cycles of the quasi-biennial oscillation, therefore the number of filter weights must be conserved in order to examine any maximum or minimum. This creates a further problem as many filter weights are required to produce a filter whose frequency response has a sharp cutoff without any undesirable side lobes.

Because of the necessity of masking almost entirely the annual cycle, it appeared that filters with side lobes would have to be considered. Examination of several filters showed one particular truncated cosine filter to be promising because of its zero response at the frequency of the annual variation and because of the relatively few weights required. The weights of this filter are given by:

$$\mathrm{wt}(n)=1.65(\pi/2N)\cos(\pi/2N)(N-2n)\qquad n=0,1,2,\ldots,N, \qquad (1)$$

where N is the total number of weights required over an 18-mo. period. The frequency response of the filter, $R(w)$, is given by:

$$R(w)=1.65(\pi/4)\left(\frac{\cos(9w)}{9w+\pi/2}-\frac{\cos(9w)}{9w-\pi/2}\right), \qquad (2)$$

where w is radial frequency. Both the above equations have been normalized so that the frequency response of the filter at $w=2\pi/26$ mo. is 1. Figure 1 indicates the weighting and response functions of the cosine filter. This filter and a 365-day running mean were considered for analysis of the data. Figure 2 shows the result of passing a time series of data for Nairobi through both filters. As higher frequencies are significantly more evident in the filtered output of the running mean, the cosine filter was chosen for use on all data.

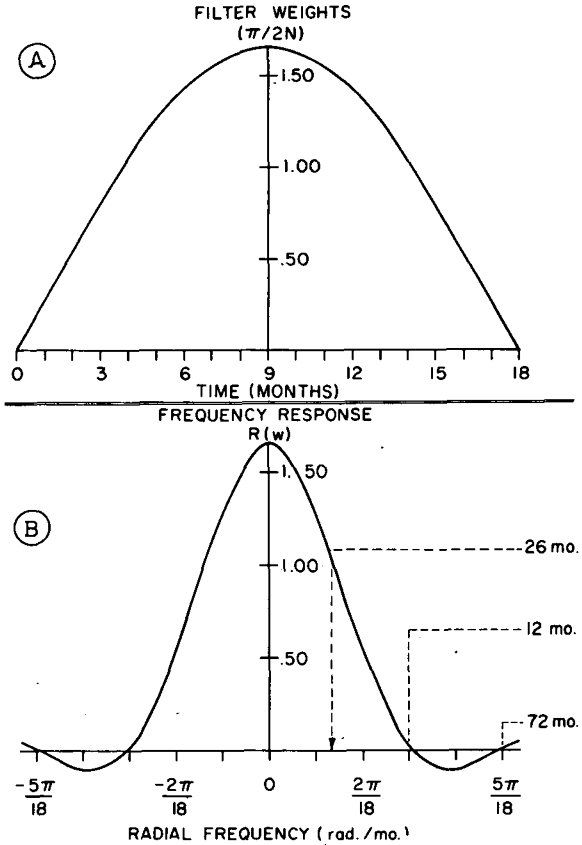

Figure 1.—(A) Cosine filter weights and (B) frequency response of cosine filter.

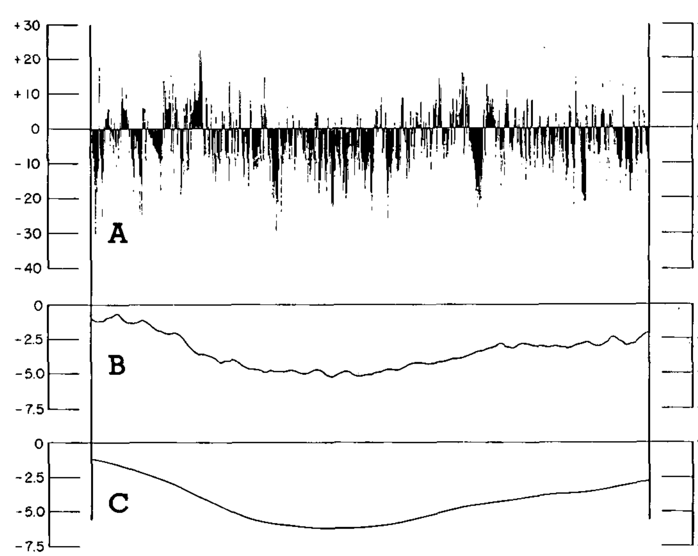

Figure 2.—(A) 100-mb. zonal winds at Nairobi for the period July 1, 1958, through September 15, 1960; (B) 365-day running mean winds for the same period; (C) winds obtained by using 547-day cosine filter for the same period.

ACCURACY OF THE FILTERED TIME SERIES

It is of prime importance to analyze the accuracy of the filtered record with regard to errors introduced by using interpolated data. This is because comparisons of the calendar dates of corresponding extreme values are to be made for the filtered time series of various stations. As each time series has a different time-dependent ratio of interpolated data to observational data, the reliability of

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the extreme values will vary accordingly. The mean square error, σ^2, of a single point in the filtered time series can be represented (after Cramer [9]) as:

$$\sigma^2=E\left\{\left[\sum_{i=1}^{N}a_i\epsilon_i\right]^2\right\}=\sum_{i=1}^{N}\sum_{k=1}^{N}\lambda_{ik}a_ia_k, \tag{3}$$

where E is the statistical expectation, a_i are the N filter weights, ϵ_i are the interpolation errors for the N data points underneath the filter and λ_{ik} is the covariance error matrix of the N data points. A property of the optimum interpolation method utilized is that the interpolation errors are orthogonal among themselves and also to the existing observational points. As a result only the diagonal of the covariance error matrix needs to be considered and equation (3) may be written:

$$\sigma^2=\sum_{i=1}^{N}a_i^2\lambda_{ii}. \tag{4}$$

Thus the error of a single-filtered output value can be simply represented as a weighted average of the mean square errors, ϵ_i^2, of the interpolated points underneath the filter. It is to be noted that where observational points occur, their mean square error is zero.

The above technique was utilized to determine the accuracy of extreme values in the filtered time series. Instrumental errors were not considered, as their magnitude and behavior are not generally known. These errors, if known, could be incorporated into the analysis; however, a correlation would then exist between the errors in the interpolated values and the instrumental errors associated with sample points. As a result, the error in the filtered output would be tedious to compute as equation (3) must be used.

It is desirable that the RMS error of extreme values in the filtered time series, σ, be transformed into corresponding errors in time, of the calendar dates of these minima and maxima. This would permit a direct comparison among time series of the reliability of respective extremes. However, to do this, it is necessary to know the joint probability density function of the filtered data. This requires knowledge of the true functional form of the zonal wind data and of the joint probability density function of the errors associated with the points in the filtered time series. As these are not known, the assumption was made that the density function of an element of the filtered time series was "Gaussian normal" with a mean equivalent to the value of that element, and with a standard deviation, σ. When applied to extremes, the probability that a maximum (minimum) is greater (less) than the mean minus σ (plus σ) is therefore 84 percent. The time interval in which the extreme value is known with 84-percent confidence is then found by examining the filtered data in the neighborhood of this point. For a maximum, this interval is defined as the time difference between those filtered values equal to the extreme value minus σ, located on either side of the extreme point. (For a minimum, the filtered values involved are equivalent to the extreme value plus σ.) Because the filtered data are not necessarily locally symmetric with respect to the extreme point, the time difference may not be equally distributed with respect to this point.

TABLE 1.—*Available percentage of all scheduled 12- or 24-hr. observations, for the time interval from 9 mo. before to 9 mo. after the periods of record shown in figures 3 and 4. An asterisk indicates stations taking 12-hr. observations.*

Stations	Latitude	Longitude	Percentage of Complete Data		
			50 mb. (65,000 ft.)	100 mb. (55,000 ft.)	500 mb. (20,000 ft.)
Guantanamo*	19°54′N.	75°09′ W.	47	53	70
Swan Island*	17°24′N.	83°56′ W.	67	76	96
San Andreas*	12°35′N.	81°40′ W.	47	59	85
Niamey	13°29′N.	02°10′E.	57	67	77
Aden	12°50′N.	45°01′E.	46	71	85
Bangkok	13°44′N.	100°30′E.	26	33	49
Guam	13°33′N.	144°50′E.	85	92	97
Kwajalein*	08°43′N.	167°44′E.	41	53	88
Balboa*	08°56′N.	79°34′ W.	61	73	96
Canton*	02°46′S.	171°43′ W.	84	92	98
Guayaquil*	02°12′S.	79°53′ W.	45	53	68
Nairobi	01°18′S.	36°45′E.	10	77	94
Lima*	12°00′S.	77°07′ W.	46	54	70
Cocos	12°05′S.	96°53′E.	49	86	96
Darwin	12°26′S.	130°52′E.	62	87	96
Quintero*	32°47′S.	71°32′ W.	68	68	97
Capetown	33°58′S.	18°36′E.	18	45	95
Williamtown	32°49′S.	151°50′E.	40	79	95

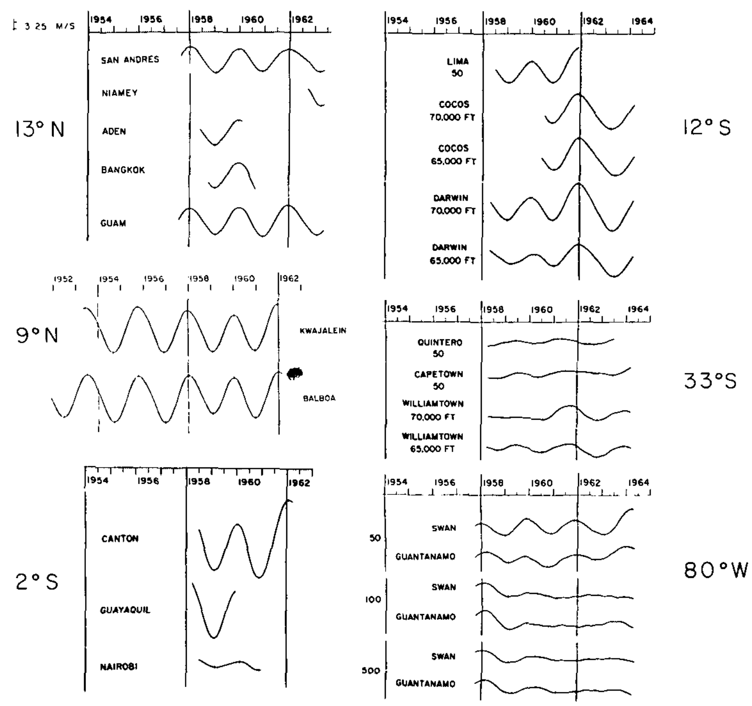

FIGURE 3.—Filtered zonal winds, 50 mb., for all stations, plus 100 and 500 mb. at Swan and Guantanamo.

3. DATA

Table 1 indicates the 16 stations at five selected latitudes between 13°N. and 33°S. for which daily data were examined at the 50-, 100-, and 500-mb. levels. Because of the strong dependence of QBO phase on latitude, stations were selected along each latitude so that each station was not more than 1° from that latitude. Obviously this severely limited the stations which could be used and they were not those with the longest and most complete or reliable observations. Further, it was necessary to limit analysis to common periods of record at all stations along a given latitude as we intended to compare phase dates of the same wave. Swan Island and Guantanamo were originally included along 80°W. to establish a latitudinal correction that could be used to correct for small latitude variations within each station group. However, the results showed so much time variation of the QBO with latitude from one cycle to the next that it was decided such corrections were inadvisable. Rather, phase dates of each cycle were plotted on maps. This permitted isochrones to be drawn which showed the progression of the wave both in longitude and latitude without the need to make assumptions concerning rate of latitudinal progression.

4. RESULTS

50 MB.

Graphs of the quasi-biennial oscillation at 50 mb. are shown in figure 3 for those periods of record which were common to stations at the same latitude. The amplitudes of the QBO have been restored (at 26 mo.) to compensate for the attenuation of the filtering process, and are drawn to the same scale so that stations and levels may be compared directly. In doing this, however, the maxima and minima at 100 mb. and 500 mb. become indistinct at times. As the Australian data were available only for constant heights, the waves at the nearest 5,000-ft. level both above and below the 50-mb. level are shown. All phase dates were extrapolated for the mean 50-mb. height which at Darwin was 67,850 ft., at Cocos 67,750 ft., and at Williamtown 67,950 ft.

The magnitudes of the 50-mb. filtered time series show predominately the normal amplitude variation with latitude described in the literature. The wave appears strongest near the Equator and progressively weaker at subtropical latitudes. However, there are some noticeable exceptions to this general pattern. For instance, near the Equator, Nairobi exhibits a magnitude (3 m./sec.) much weaker than Canton Island (20–40 m./sec.). Further, at 32°S. Williamtown's variation (5–10 m./sec.) is stronger than the variation at either Quintero or Capetown (3 m./sec. or less). The apparent increase with time of the magnitude of the QBO leading to extreme variations in 1962 and 1963 can be seen at all stations; higher latitude stations indicate this increase at somewhat later times. The asymmetry of the amplitude about the Equator can be seen by comparison of the magnitudes of the variation at 13°N. (13 m./sec.) and 12°S. (13–20 m./sec.). Further, the magnitude at those stations along 33°S. (3–10 m./sec.) is somewhat larger than at Guantanamo, 21°N. (3–7 m./sec.).

The interpolation errors, when interpreted in terms of days, result in uncertainties of the phase date which at 50 mb. ranges from about 15 days at Guam, Balboa, and Canton to as high as about 50 days at stations where the amplitude of the wave is weak or where the data are very incomplete, such as at Guantanamo, Aden, and Quintero. At Capetown and Williamtown the possible errors are so large as to make the filtered waveform highly uncertain. So many observations are missing at these stations that the average time variation of a maximum or minimum is about ±75 days. In almost every instance the uncertainty varies from cycle to cycle as the amplitude of the wave changes and the density of observations varies. These uncertainties make time and space variations of the QBO very difficult to interpret. No solution to this problem seems possible without complete and accurate observations at high levels. Nor can these uncertainties be ascribed to the interpolation methods used. In fact Gandin [6] has shown that the optimum interpolation technique utilized is superior to other methods, particularly in regions of sparse data. Further, one of the merits of this technique is that errors in interpolation may be approximated, whereas in several other interpolation or averaging schemes, such errors are intrinsically present in the result but cannot be determined. It should also be realized that the calendar dates of the extreme values are still the most probable times of occurrence.

In view of these problems one must rely as usual in meteorology on consistent results from independent data in a given area. Hence, we can only hope to suggest directions of progression where the data appear to be consistent and not to prove them. By the same token, inconsistent results at this time are simply inconclusive.

Figure 4 maps the dates of the four minima and maxima at 50 mb. given in columns 2–5 in table 2. The letters E and L refer to relatively early and late phase dates. Month and day are indicated at 10-day intervals. In addition to the usual progression from subtropical toward equatorial latitudes there is an apparently strong tendency for a west to east movement from southern Asia toward the South Pacific. Further, the dates in the Caribbean appear to be consistently earlier than those anywhere else. The stations near 33°S., if they can be believed at all, are in a completely different regime from lower latitude stations.

100 MB.

Figure 5 shows the filtered time series at 100 mb. and also 500 mb. Zonal winds at 55,000 ft. were analyzed at the Australian stations. As the mean 100-mb. heights for these stations are within approximately 1,000 ft. of this level, no interpolation was used.

It can be seen that the 100-mb. waveform is generally weaker and intermittently biennial as compared to 50 mb. For some periods the series at these two levels are well correlated, i.e. Swan Island and Guantanamo, 1958–1960; other time intervals show practically no similarity between the 50- and 100-mb. levels, i.e. Balboa, 1956–1962. Near the Equator the 100-mb. time series exhibit a fairly regular QBO with a magnitude of about 5 m./sec. Farther north, however, the time series are more irregular and with generally a weaker variation. In the Southern Hemisphere the magnitude of the filtered waveform is much the same as at the Equator, however, the biennial pattern is less regular. For instance, Williamtown exhibits a marked 4-yr. period for the segment of data analyzed.

Table 3 shows that the time separation among respective maxima and minima of various stations at 100 mb.

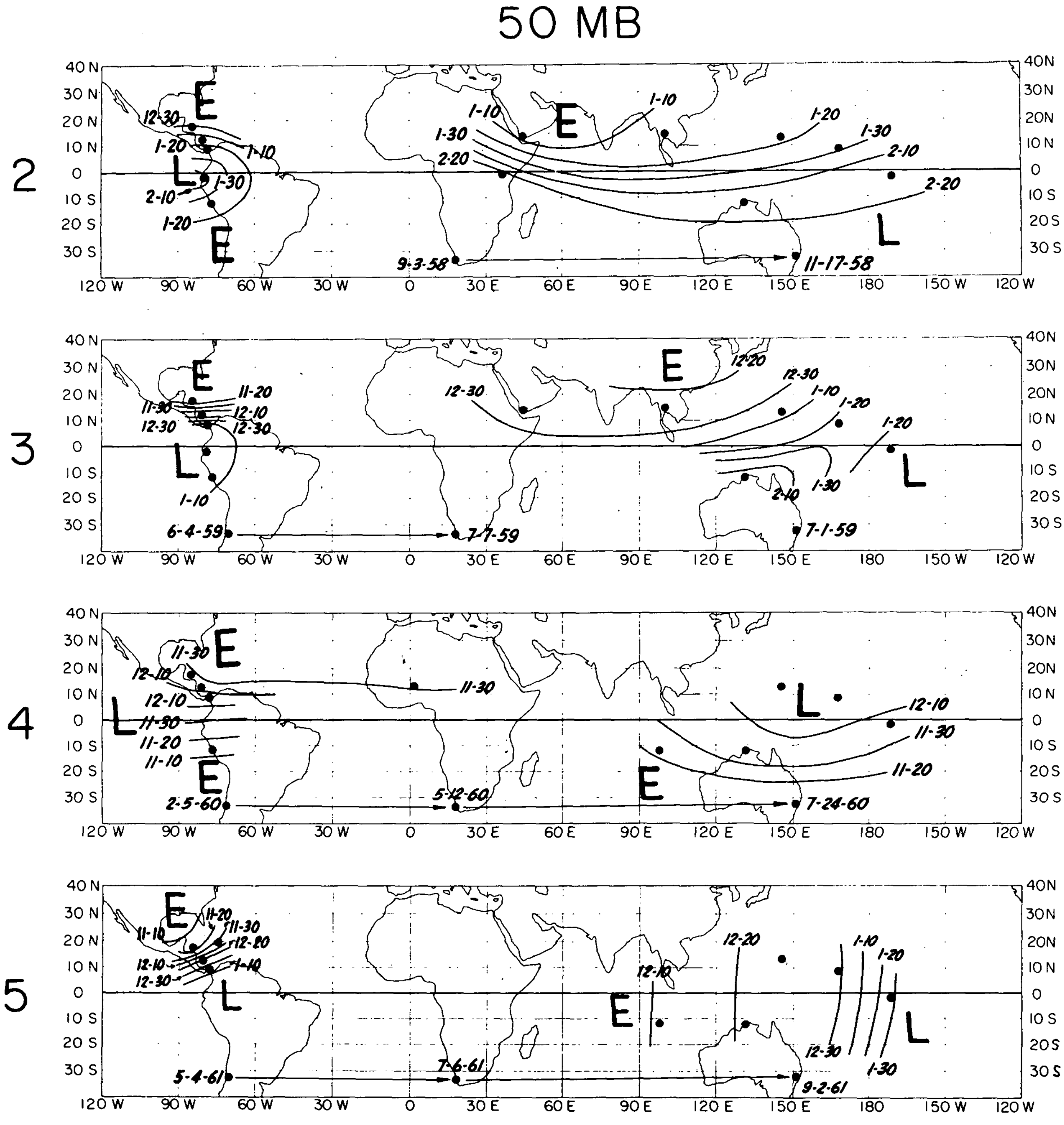

FIGURE 4.—Phase progression of the quasi-biennial oscillation at 50 mb. in the Tropics. The particular maximum or minimum analyzed is indicated by a correspondence of map number in the above figure and column number in table 2.

is of the order of months rather than days as was evident at 50 mb. As a result there is more difficulty in identifying corresponding extremes for different stations. This selection of corresponding maxima and minima was done subjectively by comparing the total time history of extremes for neighboring stations and taking into account the similarities of the filtered waveforms at the 50-, 100-, and 500-mb. levels. The uncertainty of phase dates is larger at 100 mb. than at 50 mb. This reflects a proportionally larger loss of amplitude of the QBO between 50

TABLE 2.—*Calendar dates (yr., mo., and day) of 50-mb. maxima and minima*

Stations	Phase Dates (+ Max; − Min)											
	−	+	−	+	−	1+	2−	3+	4−	5+	6−	+
Guantanamo						580403	590221	591031	600929	611130	620930	631213
Swan						571222	590101	591119	601201	611116	630208	640401
San Andreas						571231	590118	591216	601201	611222	630325	
Niamey											630412	
Aden							590106	591225				
Bangkok							590113	591222				
Guam						580107	590117	600103	601214	611225	630220	
Balboa	520610	530705	540903	551013	561216	580109	590124	600110	601212	620106		
Kwajalein		530621	540902	551011	561205	571227	590129	600122	601229	611229		
Guayaquil							590210					
Nairobi							590222	600223	601129			
Canton							590217	600116	601202	620129		
Lima							590125	600108	601112			
Cocos									601123	611210	630516	
Darwin							590207	600207	601206	611220	630527	
Quintero								590604	600205	610504	620624	
Capetown							580903	590707	600512	610706	630625	
Williamtown							581130	590701	600725	610907	621102	631227

TABLE 3.—*Calendar dates (yr., mo., and day) of 100-mb. maxima and minima*

Stations	Phase Dates (+ Max; − Min)											
	−	+	−	+	−	1+	2−	3+	4−	5+	6−	+
Guantanamo						580226	590311	591125	610116	630612		
Swan						580211	590211	591212	610221	621025	630905	
San Andreas						571109	590212	591008	600625	620521	630228	
Niamey						571104	590808	601026	611208	621004	630406	
Aden						571006	600127	601022	620107	630417		
Bangkok						571110	601028	611010	620710	630408		
Guam						580301	590820	600824	610403	630116		
Balboa	530111	531111	550119	no	no	571017	no	no	610908			
Kwajalein		540402	540813	551025	570726	580511	590728	600525	610211	611202		
Guayaquil						580617	590910					
Nairobi							590526	601008	611209			
Canton						580828	590321	600422	610215			
Lima						581014	591024	601005	610825	620804		
Cocos							600808	611003	620813	631104		
Darwin						581203	600211	601125	610821	620517	630216	
Quintero							580512	590522	591113	610507	620401	630427
Capetown							590116	590923	600429	620512	630531	
Williamtown							581003	600818	no	no	621021	

and 100 mb. than can be compensated for by the increased sampling rate at the lower level. (The relative uncertainty can be interpreted in terms of a simple signal-noise ratio.) It is to be noted that even though the uncertainty is larger at 100 mb. than at 50 mb., wave progression may be more reliable at 100 mb. because the time interval of progression between stations generally exceeds the phase date error, whereas at 50 mb. these time intervals are about the same. The 100-mb. phase date variability is also much more asymmetric with respect to the mean extreme date than at 50 mb. This is due to the increased irregularity of the filtered waveform. At 100 mb. the QBO is not only weak, but apparently skips a cycle occasionallly so that a 4-yr. cycle appears at Balboa (but not at Kwajalein at the same latitude) and at Capetown and Williamtown, during the limited period of record.

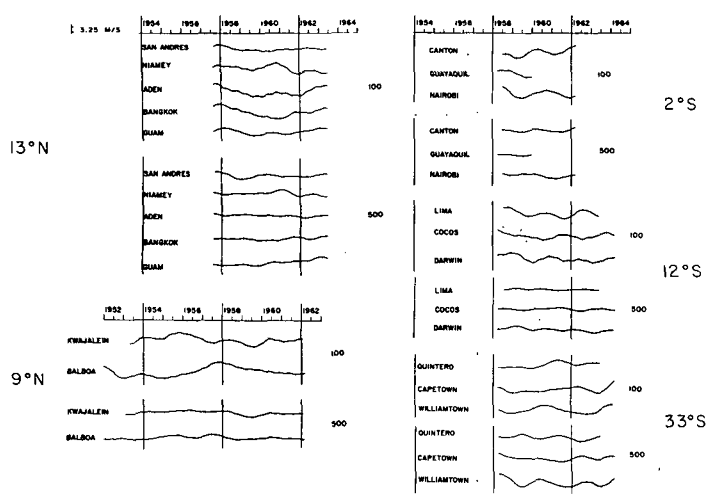

FIGURE 5.—Filtered zonal winds, 100 and 500 mb.

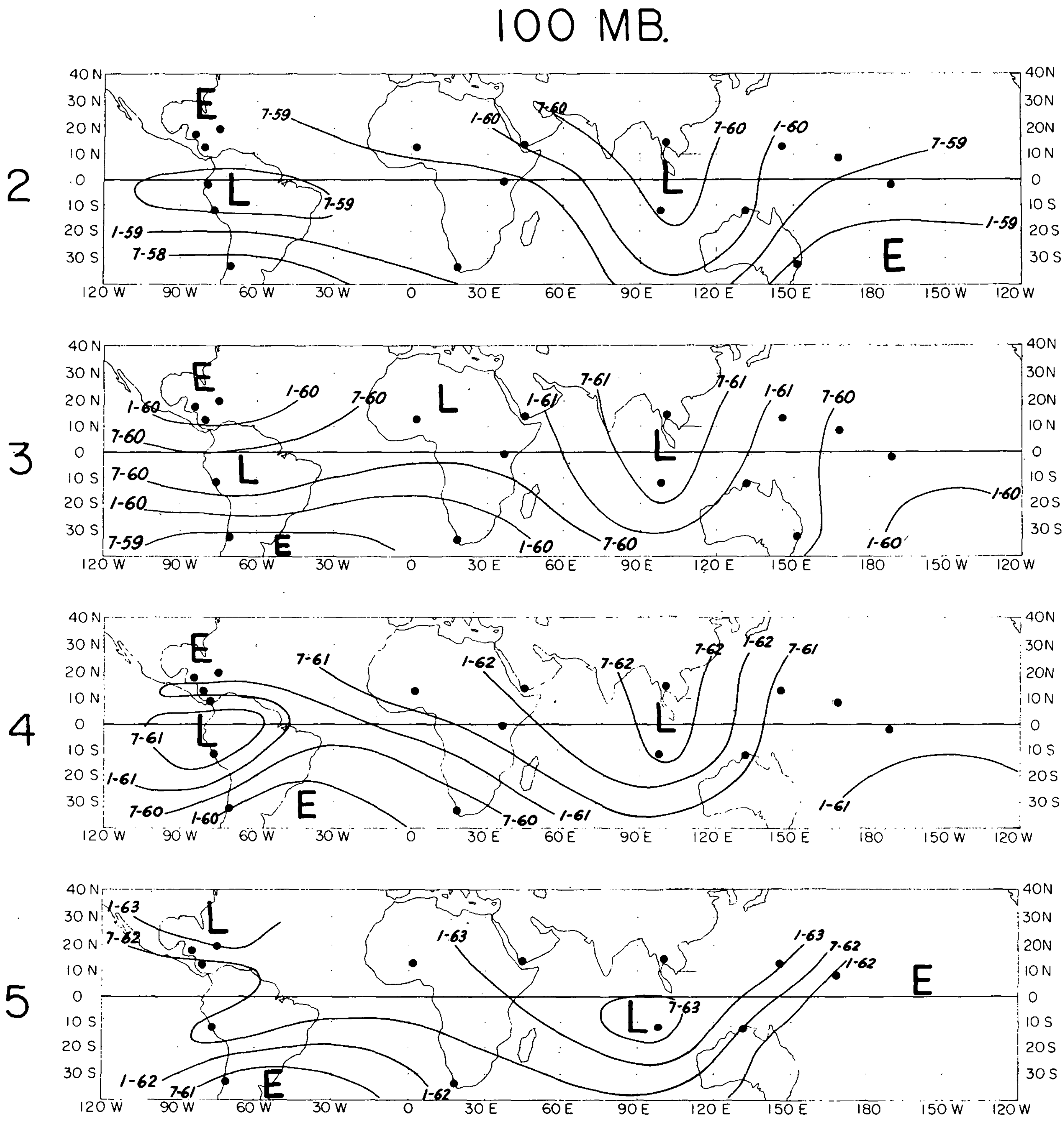

FIGURE 6.—Phase progression of the quasi-biennial oscillation at 100 mb. in the Tropics. The particular maximum or minimum analyzed is indicated by a correspondence of map number in the above figure and column number in table 3.

Figure 6 shows that at 100 mb., as at 50 mb., the areas of earliest occurrence are in the Caribbean, and possibly southern South America. The wave progresses both eastward and westward and appears last over southern Asia, with a time lag of 6 mo. to 2 yr. Neighboring stations show continuity even in the presence of quite large statistical interpolation uncertainties. In general, the patterns are more cellular than they are simple functions of latitude or longitude.

The analysis of phase progression at 33°S. is somewhat complicated as Williamtown does not exhibit a biennial wave at 100 mb. Rather, this station appears to have a 4-yr. cycle at least during the interval from 1958 to 1963. However, some of the extremes at 100 mb. appear well

TABLE 4.—*Calendar dates (yr., mo., and day) of 500-mb. maxima and minima*

Stations	Phase Dates (+ Max; − Min)											
	−	+	−	+	−	1+	2−	3+	4−	5+	6−	+
Guantanamo						580226	590427	600527	610324	631024		
Swan						580111	590213	600404	610808	630517		
San Andreas						571013	590111	600404	610223	630503		
Niamey					580331	600101	600502	610218	611227	620904	630423	
Aden				570815	580410	590308	601216	610512	620403			
Bangkok						590211	601107	610830	620610			
Guam					580124	590214	591109	600911	611228	630218		
Balboa	520204	521112	530803	550924	560725	570603	580910	600503	610206			
Kwajalein		540414	550122	560519	570218	571220	590705	600505	610121			
Guayaquil							590727					
Nairobi					581116	590804	610329					
Canton						580713	590719	600312	610712			
Lima						590313	591030	600531	610501	620730	630429	
Cocos						580709	590803	610616	620717	630519		
Darwin					580415	590325	600217	601026	610804	620312	630215	
Quintero							580718	590617	600604	610508	620623	
Capetown									610618	620807	630530	640203
Williamtown						580421	590619	600418	610831	620925	630709	

correlated in time with the quasi-biennial oscillation at 50 mb. Also, these extremes appear to be more closely related to the neighboring stations, Darwin and Canton, than to Quintero and Capetown. It can be noted that for every extreme the filtered waveform at Quintero leads that at Capetown.

500 MB.

Figure 5 and table 4 indicate the filtered time series at 500 mb. zonal winds at 20,000 ft. were analyzed for the Australian stations. The mean 500-mb. height is generally 800–1,300 ft. lower than this level.

The 500-mb. filtered time series shows intermittent quasi-biennial features similar to those at 100 mb. However, the 100-mb. levels at Balboa and Williamtown did not exhibit quasi-biennial waveforms, yet these stations do have quasi-biennial features at 500 mb. Also, the magnitude of the QBO is somewhat weaker at 500 mb. as compared to the higher level. A tendency exists for the magnitude of this fluctuation to increase with latitude, the reverse of what is normally found in the stratosphere.

The relative errors at 500 mb. are somewhat smaller than at 100 mb. Thus, the increase of measurements at the lower level overcompensates for the slight decrease in magnitude of the QBO, but the lack of vertical correlation of this level with 100 and 50 mb. makes it more difficult to identify corresponding maxima and minima.

In figure 7, the features are quite similar to those observed at 100 mb. Extremes appear to originate in either or both the Northern and Southern Hemisphere in the vicinity of 80°W. andpropagate both eastward and westward, finally occurring latest in the Indian Ocean.

It should be realized that the large-scale map features at 500 and 100 mb. depend a great deal on how the stations along 32°S. are incorporated into the analysis. At 500 mb. Williamtown is in phase with Capetown but out of phase with Quintero. Further, Williamtown is approximately in phase with stations at other latitudes in the southwestern Pacific. However, Quintero is out of phase with Lima, the closest neighboring station. As a result, several interpretations of extreme progression are possible: (a) Williamtown and Capetown lagging Quintero, (b) Williamtown and Capetown leading Quintero, and (c) Williamtown leading Quintero leading Capetown. Which one of these interpretations is preferred depends on whether one assumes vertical continuity, horizontal continuity, or a combination of both. For instance, (a) is the analysis we have chosen and utilizes vertical continuity to establish the relationship between Lima and Quintero and primarily horizontal continuity to fit Williamtown to neighboring stations. An analysis based on (b) would tend to establish more or less uniform horizontal progression from Northern to Southern Hemisphere and does not take into account vertical continuity. The pattern (c) would produce a more or less uniform progression pattern in both hemispheres, but, with separate areal origins and terminations in each hemisphere. This case demands that horizontal continuity be maintained in a certain preconceived fashion. As the QBO exists at higher latitudes than is shown on these maps, the global pattern cannot be described at this time. Data from all available upper air stations are now being plotted, however, and the analysis will be reported in a later paper.

5. SUMMARY

At 50 mb. evidence of longitudinal progression of maxima and minima of the quasi-biennial zonal wind is present. The progression generally appears to be from west to east, although many irregularities from one cycle to the next are apparent. Differences in phase dates for stations located at approximately the same latitude range from a few days for equatorial stations to 5 mo. for locations along 32°S. Uncertainties in phase dates due to the use of interpolated data are usually larger than the differences in arrival times of maxima or minima at neighboring stations. However, because consistent progression behavior is found within certain areas, even in the presence of such large errors, the analysis may still suggest real features of the circulation.

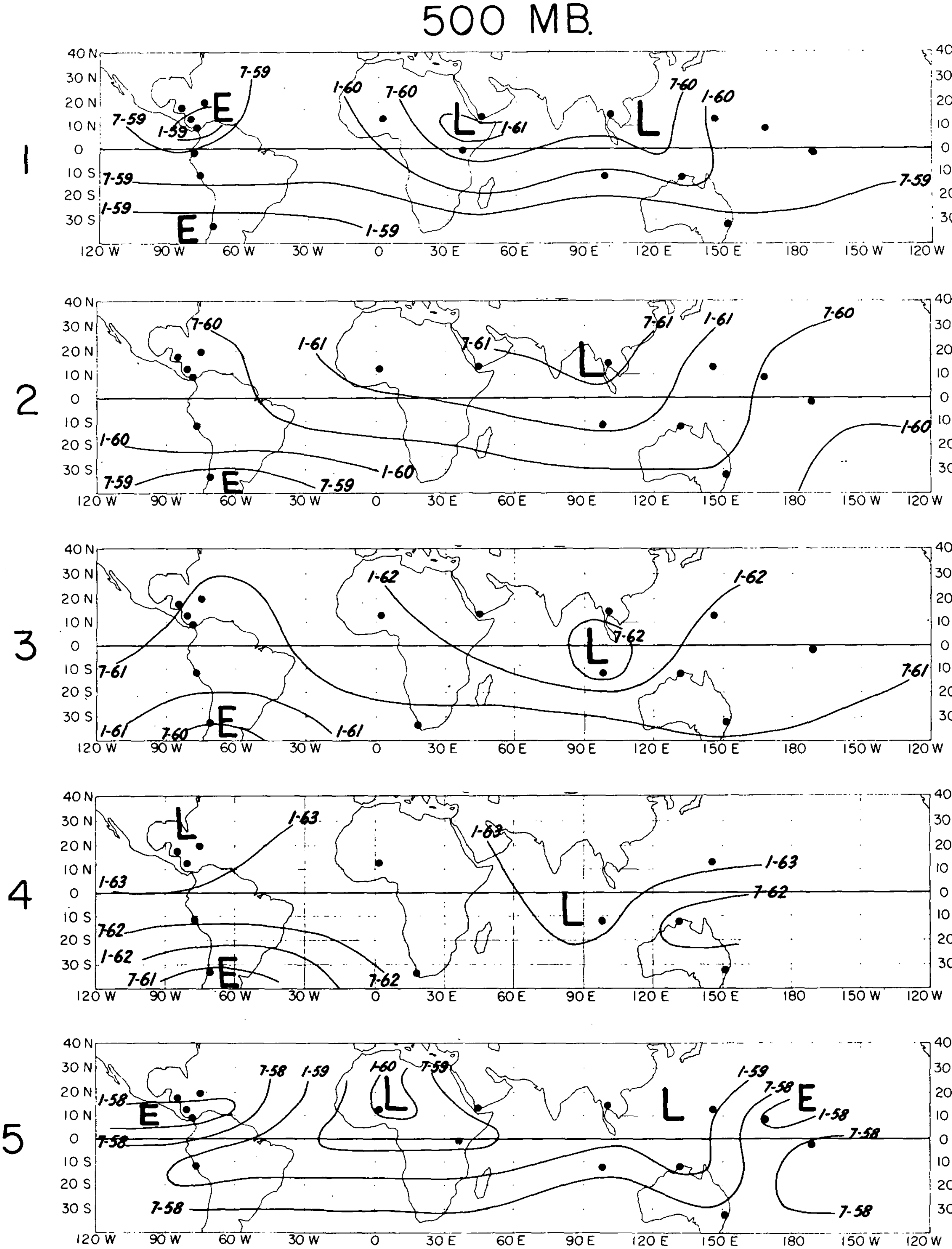

FIGURE 7.—Phase progression of the quasi-biennial oscillation at 500 mb. in the Tropics. The particular maximum or minimum analyzed is indicated by a correspondence of map number in the above figure and column number in table 4.

At 500 and 100 mb., although the quasi-biennial oscillation is intermittent and weak in magnitude, progression is still evident. Tentatively, at these levels, the wave appears to originate in subtropical latitudes in the vicinity of 80°W. of both hemispheres and progresses both eastward and westward, occurring last in the Indian Ocean. The entire progression time generally ranges from 1 to 2 yr.

Due to the irregularity at these levels and slow speed of the QBO between stations, it is sometimes quite difficult to trace corresponding maxima and minima on a global basis. It is quite possible that the QBO at 100 and 500 mb. has a cellular rather than a continuous pattern of phase progression. Analyses of additional stations will clarify the interpretation. In general, interpolation uncertainties at 500 and 100 mb. are somewhat larger than at 50 mb. The decrease in magnitude of the QBO with decreasing altitude is not completely compensated for by the increase in the number of observations available for analysis at the lower levels. However, the results may still be more significant at the lower levels than at 50 mb. because of the much longer transit time of the QBO between stations.

The above analysis apparently does not indicate any new properties that confirm or deny either an external or internal origin of the QBO in the atmosphere. Rather, it shows the natural irregularity in the atmosphere at low frequencies that of course has been observed many times at shorter time scales.

Future work includes the expansion of the analysis to higher latitudes and other levels utilizing a more dense station network to obtain better continuity and to help identify corresponding waves.

It is recommended that a series of long-term, scientific, upper air stations be arranged carefully along a few chosen latitudes and one meridian to obtain more compatible, accurate and complete data concerning this global phenomenon whose properties are still poorly described and whose cause is still completely unknown. Perhaps after 10 or 20 yr. with such data its properties can be described properly.

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NOTICE TO AUTHORS

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