Double Quasi-Biennial Cycles in Observed Winds in the Tropical Stratosphere[1,2]

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ABSTRACT

Height-time sections of mean monthly observed upper-air zonal winds at stations within 20 degrees of the equator show not only an almost biennial oscillation of the wind in the middle or upper stratosphere but that there is a relative wave, 180 degrees out of phase to the first, which occurs in the lower stratosphere. The two waves are merged near the equator; they are best distinguished from each other from about 9N to 15N and, although still noticeable as separate occurrences of westerlies from 15N to 20N, the intensity of the westerlies is much reduced. Both waves occur at progressively higher levels from one biennium to the next. This observed double cycle is caused by the combination of the fundamental annual and biennial waves, and the upward progression appears due to the difference in phase lags with height of these two component waves.

1. Introduction

Ever since 1883 when Krakatoa in the East Indies erupted and its dust was observed to travel above 25 km from east to west at least twice around the world (Wexler, 1951), meteorologists have been aware of the broad band of tropical easterlies at upper levels. However, in 1908 van Berson in Central Africa and in 1909 Van Bemellen in Batavia found westerlies above 20 km imbedded in this generally easterly low-latitude belt, and, until about 1959, these stratospheric winds still bore their names. The Berson westerlies and Krakatoa easterlies were indeed confirmed in the Pacific stratosphere in the late 1940's and early 1950's, when high-level wind observations were taken in conjunction with atomic tests.

As a by-product of these same observations, an analysis by the group at Hawaii under McCreary (1959) and by Graystone (1959) demonstrated that the westerlies were not found at the same levels from year to year; indeed, easterlies frequently appeared where westerlies were expected. There then followed in the years since 1959 a series of papers by Ebdon and Veryard in England, and by Reed and coworkers, and by Angell in the United States, presenting additional data to describe the behavior of these observed variable winds.

The existence of an apparent quasi-biennial wave, of variable period, in the strength of the observed mean monthly zonal stratospheric winds at low latitudes has now been well documented. [See, for example, Veryard and Ebdon (1961) and Reed and Rogers (1962).] The wave was found in the stratosphere at latitudes up to 30N by Veryard and Ebdon and even at mid-and high latitudes by Angell and Korshover (1962, 1963) who have since traced it down to the lower troposphere.

The phenomenon was first noticed at equatorial latitudes where the observed wind reversed sign at relatively regular intervals of about two years. As pointed out by Reed and Rogers (1962), the observed resultant mean monthly wind wave is composed mainly of waves of two periods: An annual wave, with its maximum at the poles, and a mean 26-month (or "biennial") wave whose maximum lies at the equator. To avoid the present confusion in the use of "biennial" wave or oscillation, we propose the modifiers "observed" and "component" to distinguish these waves. Confusion arises because of the discovery of the observed biennial wave in the equatorial zone where there is no appreciable annual component and the two terms above are synonymous. However, at higher latitudes it is important to distinguish whether one speaks of the total observed oscillation or only its quasi-biennial component.

With further regard to terminology, we will here adopt the term "quasi-biennial wave" (QBW), suggested by Godson, in place of "mean 26-month wave or oscillation" whose precise period it is not yet possible to establish with the short period of record now available. "Biennial wave," even if applied loosely, is still apt to be confused with a 24-month period. Also "quasi-biennial" less strongly implies a constant period than does "26-month" or "biennial."

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[2] Paper prepared at Applied Science Division, Litton Systems, Inc. (formerly General Mills Electronics Division).

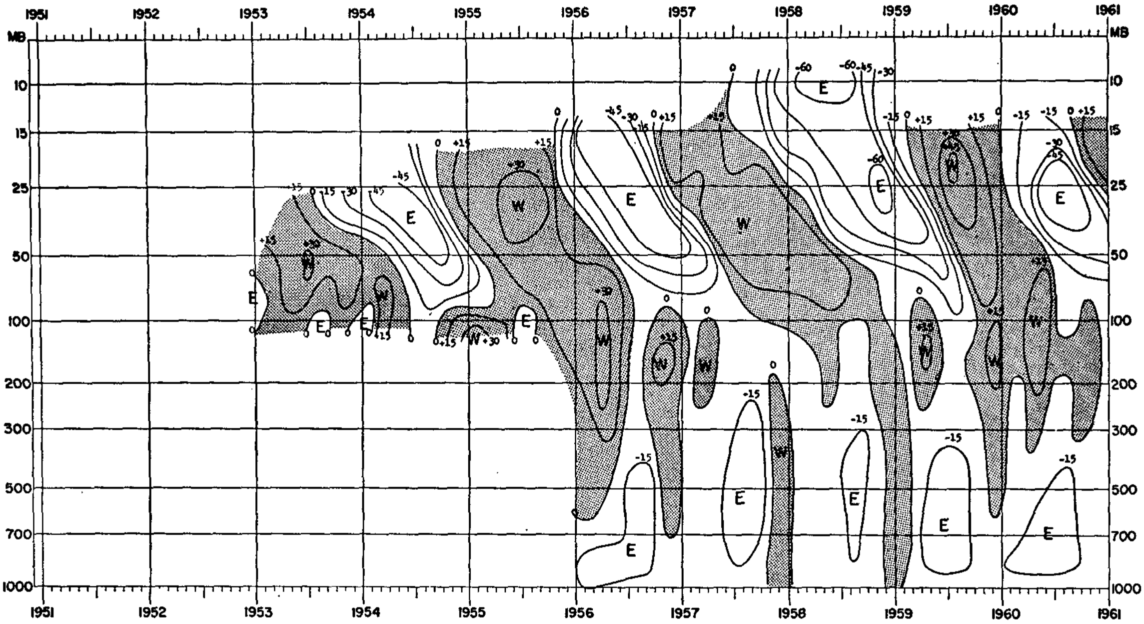

Fig. 1. Time-section of mean monthly zonal wind component, in knots, Canton Island. The 100-, 25-, and 10-mb pressure surfaces (the ordinate) correspond to heights of about 16, 25, and 30 km, respectively.

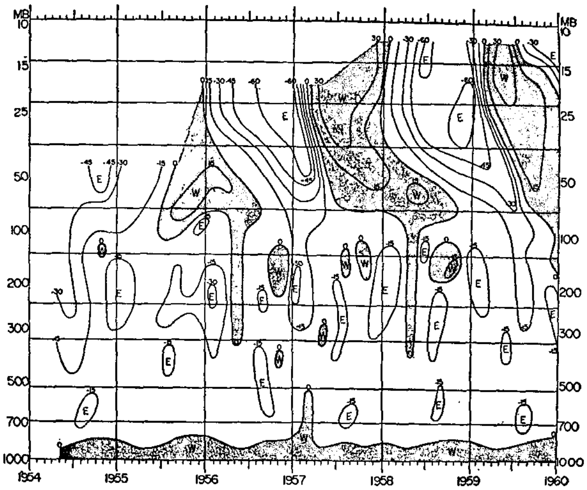

Fig. 2. Time-section of mean monthly zonal wind component, in knots, Leopoldville.

2. Time-sections of the observed wind

It is the primary purpose of this paper to discuss the properties of the observed wind field. The component waves are discussed in detail in other papers, (Reed and Rogers, 1962; Dartt and Belmont, 1963, 1964).

The following rawinsonde data were used:

Canton Island	3S	1954–1960
Leopoldville	4S	1954–1959
Balboa	9N	1951–1960
Kwajalein	9N	1954–1960
Eniwetok	11N	1951–1963
Johnston Island	17N	1951–1961
San Juan	18N	1951–1960

The observed QBW in the equatorial zone is not representative of the observed QBW at subtropical latitudes, because near the equator the alternation between east and west is relatively regular; it was from the frequently reproduced time-section of Canton Island that the impression may have arisen, that periods of 13 months of east wind are followed by an equal 13 months of west wind in the tropical stratosphere. Actually, at stations farther from the equator, both the period of the observed wave and the duration of east and west winds vary considerably from cycle to cycle and with latitude and height. This can be seen in the time-sections of Figs. 1–7. Isotachs of the observed mean monthly zonal wind are given at intervals of 15 knots and periods of westerly winds are shaded.

In the time sections, the cycles are easily recognized at low-latitude stations in the form of westerlies at approximately biennial intervals. Although the average period of the resultant quasi-biennial cycle may be approximately 26 months, we have already seen that the period may vary from one cycle to the next and from level to level. As an example, the variability at Eniwetok is summarized in Table 1. Further, it should be em-

Table 1. Intervals between successive occurrences of maximum westerly winds at constant pressure levels for Eniwetok.

Pressure levels in mb	Intervals in months
10	(22), 25, 26, 21
15	(26), 22, 24, 27, 22
25	(25), 24, 58, 16
50	23, 10, 26, 24, 22, 24

( ) = incomplete or uncertain periods.

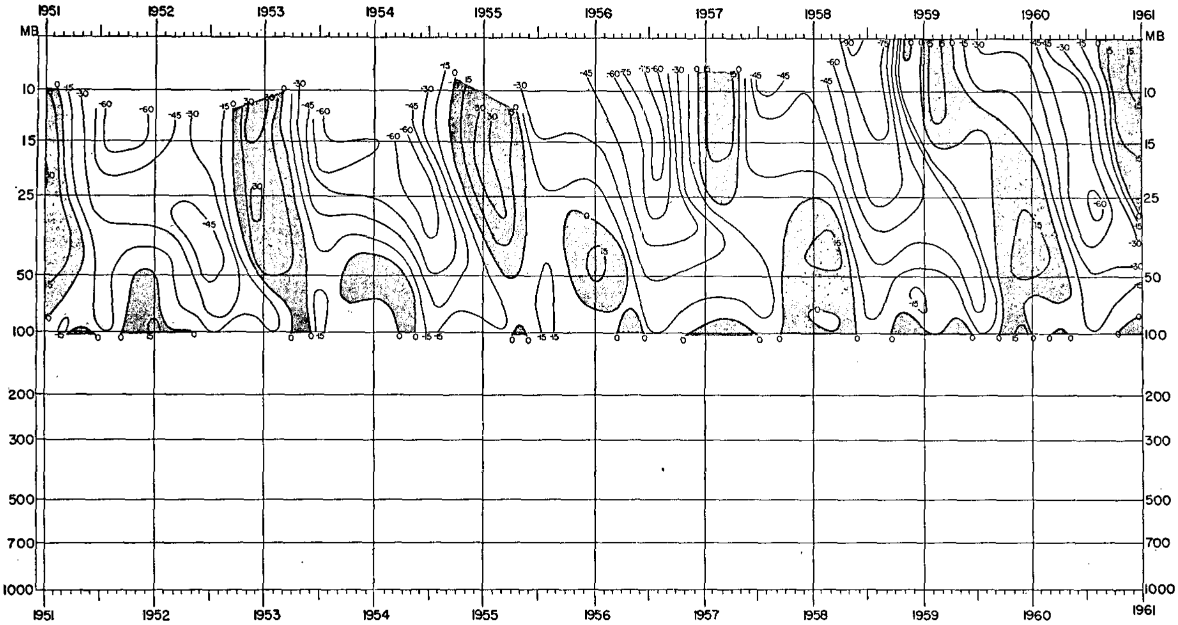

FIG. 3. Time-section of mean monthly zonal wind component, in knots, Balboa.

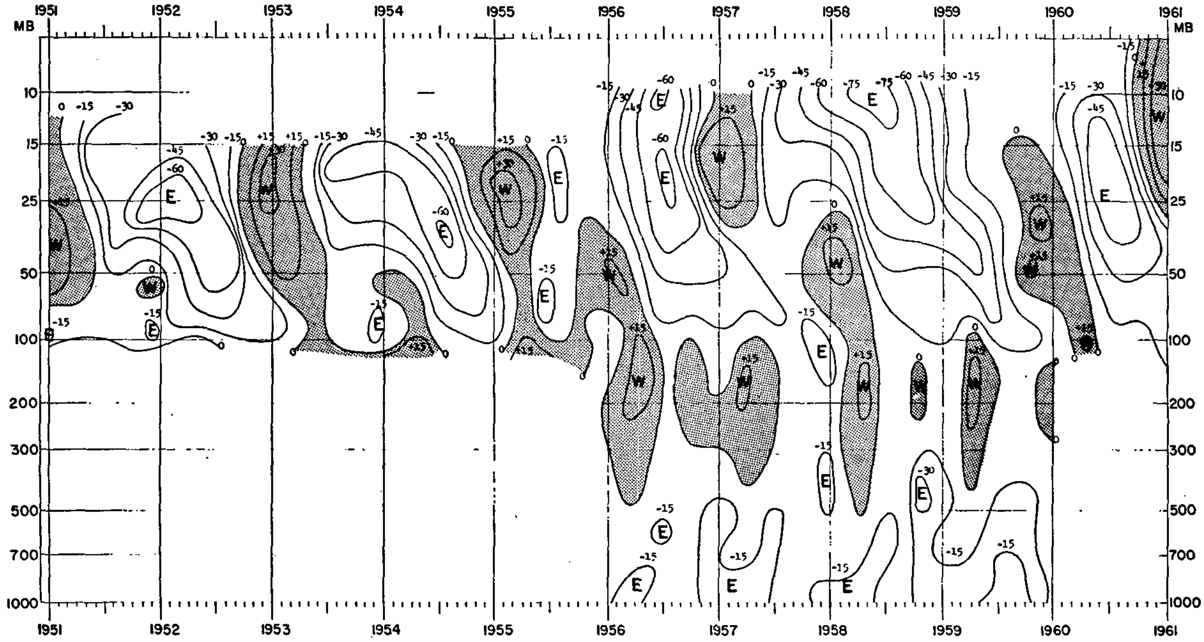

FIG. 4. Time-section of mean monthly zonal wind component, in knots, Kwajalein (Reprinted with permission of the *Journal of Geophysical Research*).

phasized that whatever the period may be, it should not be implied that there are equal intervals of easterlies and westerlies. A glance at Table 2 will show how irregular the distributions may be, not only in time but from level to level, as measured from a sample time, section for Balboa.

The observed zonal wind, or its periodic components, have generally been examined only at discrete levels. Only time-sections for the equatorial stations Canton Island and Nairobi (Reed *et al.*, 1961), have so far appeared in the literature. Time-height sections at higher tropical latitudes, however, (Belmont and Dartt, 1963), show that the interference of the component quasi-biennial and annual waves produces yet another ob-

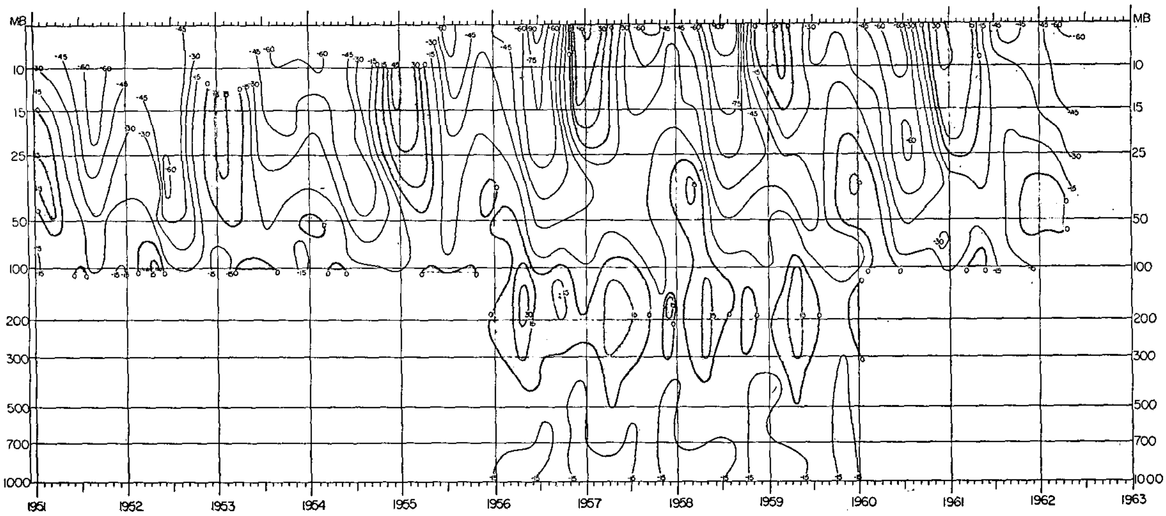

FIG. 5. Time-section of mean monthly zonal wind component, in knots, Eniwetok.

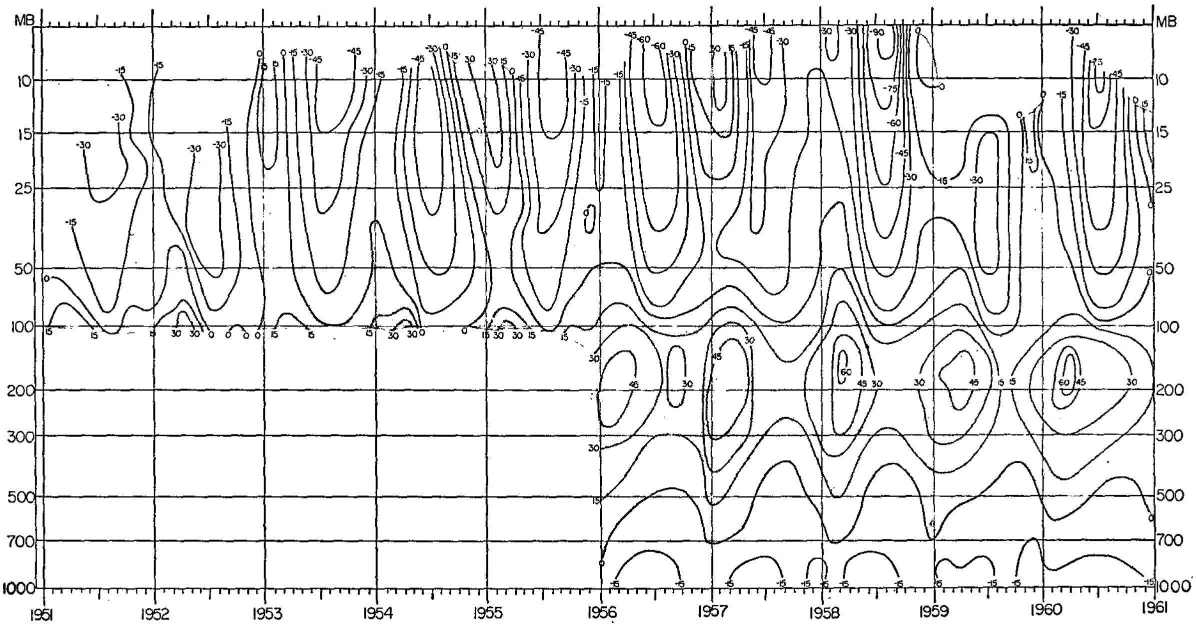

FIG. 6. Time-section of mean monthly zonal wind component, in knots, Johnston Island.

served quasi-biennial wave which should be of interest to those concerned with both practical and theoretical aspects of westerly flow in the tropics.

In addition to the usual properties, two new features can be noted from the time-sections:

1. There appear to be at least two quasi-biennial stratospheric waves, which occur in opposite phase to each other, and at different heights. They are most easily distinguished at subtropical stations such as Balboa, Eniwetok, Johnston, and Kwajalein. Note that westerlies occur each winter, although at different heights each year.

Lower stratospheric westerlies appear as a separate quasi-biennial occurrence in the lower stratosphere or upper troposphere. Note how they occur at the phase opposite to the quasi-biennial upper stratospheric cycle and appear to be distinct from it. These lower level westerlies may be related to the upper tropospheric quasi-biennial period reported by Angell and Korshover (1962) at mid-latitudes.

These waves are most clearly separated at subtropical stations (9N to 15N). At the equatorial stations of Canton Island and Leopoldville, where the annual wave is very small, the observed wave is almost entirely the quasi-biennial component, and the second wave is not

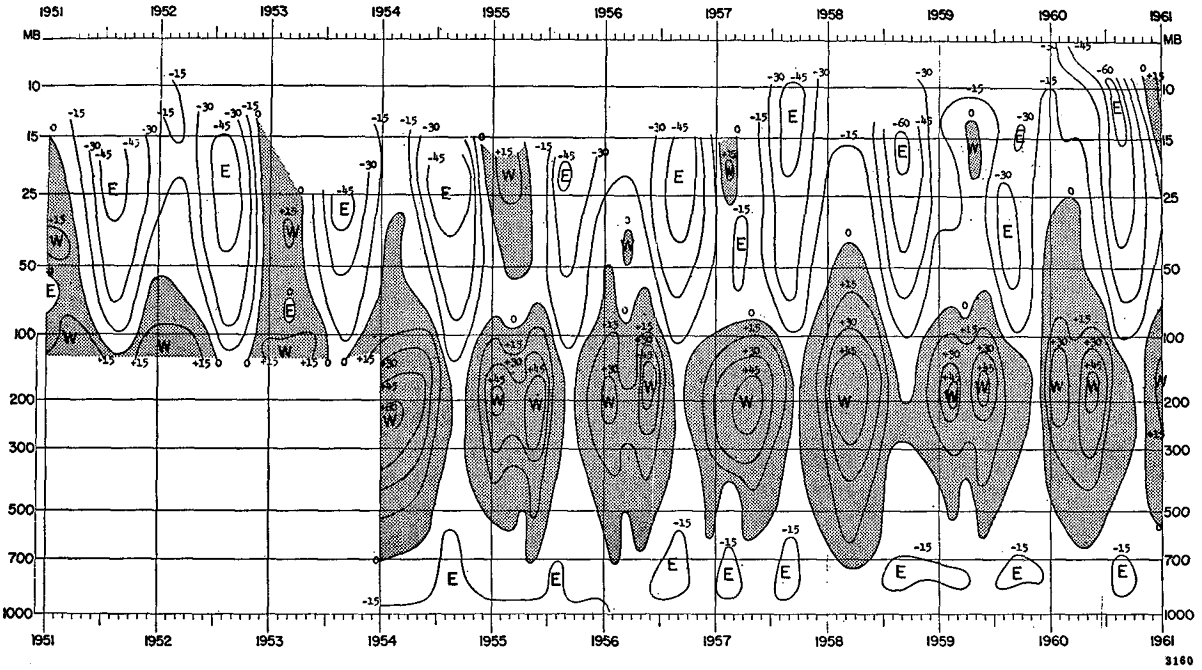

FIG. 7. Time-section of mean monthly zonal wind component, in knots, San Juan.

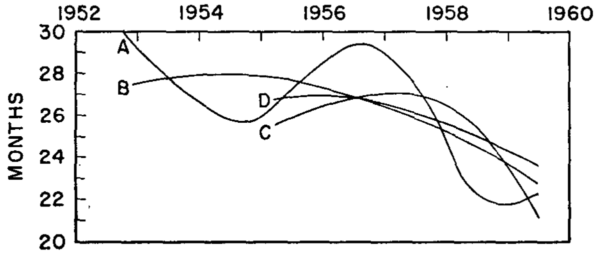

FIG. 8. Variation of period of quasi-biennial waves at (A) San Juan (1951–1961); (B) Balboa (1951–1961): (C) Canton Island (1954–1961); and (D) Kwajalein (1954–1961).

TABLE 2. Durations of westerlies and easterlies at constant pressure levels for Balboa.

Pressure levels in mb		Durations in months						
10	W	(6)	(7)	5	5			
	E	(18)	18	20	20	15		
15	W	6	8	5	3	4		
	E	18	18	19	21	3	9	
25	W	7	6	2	6			
	E	18	19	21	29	9		
50	W	2	5	7	2	6	8	8
	E	7	11	4	11	5	18	16

( ) = incomplete or uncertain periods.

separately identifiable. At higher subtropical latitudes (Johnston Island and San Juan) the distinction in the two observed waves is clearly seen but the centers are much less pronounced.

2. At stations at least 5 degrees from the equator, both waves progress upward from one cycle to the next from 1951-1960. The position of the 1961 center of maximum westerlies does not appear to follow this trend and may mark the start of a new progression. Notice the upward trend of the maximum wind centers of the upper wave series, both east and west, and also of the lowest level of the zero wind isoline in the upper waves. The trend of the lower wave train can be seen by following the upper edge of the shaded westerlies.

The decrease in amplitude of the running mean zonal wind cycle at many stations in the years since 1958 was pointed out by Veryard and Ebdon (1961) for low latitudes where the quasi-biennial wave is strong. This decrease may be caused by the upward movement of the maximum wind centers with respect to a given pressure level, and also by the selection of wind speeds from two different series of waves.

3. Time-sections of the isolated biennial wave

The above observed wind time-sections include the effects of both the annual and quasi-biennial waves, as well as irregularities due to nonrepresentative data. It is of interest to compare these observed patterns with that of the component QBW alone. To do this, the annual component must be eliminated.

At subtropical latitudes both annual and quasi-biennial waves have appreciable amplitude and, therefore, the period of record must be chosen to contain an integral number of each wave. Twelve-month running means are frequently used, but at higher latitudes where the amplitude of the QBW is very weak, 12-month running means may almost completely erase the wave. Even near the equator, where the annual wave is very small, the use of running means seriously reduces the amplitude of the QBW. Its only use is to reveal the variable period of the QBW.

Fig. 8 shows how variable this component QBW is at San Juan, Balboa, Kwajalein, and Canton Island. The periods are taken from 12-month running means at 50 mb and values are plotted at the midpoint of the measured periods. [In another article, the writers show that neither the annual nor quasi-biennial waves can be assumed to be sinusoidal nor of fixed wave form from cycle to cycle (Dartt and Belmont, 1964)].

To avoid unreasonable assumptions of period and to avoid decreasing the amplitudes, the following procedure was used:

Twelve-month running means were used to find the periods of the individual QBW's; for a seven year period containing an integral number of both annual and QBW's, a mean annual wave was estimated by averaging Januaries, Februaries, etc.; this mean annual wave was then subtracted from the observed wave to yield the QBW plus residual irregularities. Only the 50-mb data were used to determine the years containing an integral number of waves. The mean annual wave was found for each level during this period, and assumed representative of the entire period of record. This method has been applied to data from Balboa and San Juan. These stations represent, respectively, a latitude where the two waves are both strong, and a latitude where the annual wave is stronger than the QBW. For comparison, the running mean method was also used for Balboa.

Fig. 9, Panel A, for Balboa, shows that when the annual wave is removed only a single quasi-biennial pattern remains. The weak QBW at San Juan (Panel B) is proportionately much more disturbed by data "noise" than at Balboa, and, therefore, appears less regular. Panel C was obtained by taking the twelve-month running means at Balboa, and to make the results more truly comparable to Panel A, the long-term mean at each level was also removed. At 25 mb the amplitude of the QBW in this graph is on the average about 60 per cent of that in Panel A.

The explanation of the apparent second biennial wave is evidently the interference of the annual and biennial waves. The cause of the rise in height of the QBW peaks is the difference in the phase lags with height of the two waves. To demonstrate this, two families of waves, at four levels, with different phase lags from level to level, were combined numerically. The waves were propagated for about ten biennial cycles and produced a pattern of height changes similar to that observed in the actual wind data.

One prominent set of loci of the coincidence of the maxima of two such families of waves are parallel lines sloping upward in time. Both the distance between these lines and their slope decrease as the relative lag with height of the two wave families increases. Thus, we can expect to find not only two lines of ascending waves but more, from the surface to the highest levels, wherever the amplitudes of both waves are detectable.

It must be realized that there are numerous other orientations of the resultant double maxima of the two wave families, depending upon how many intervening secondary maxima are accepted between the primary maxima of the resultant pattern. One could see the westerly centers, for example, aligned in at least four different directions, without having intermediate secondary maxima, if the data existed over a sufficiently deep layer of the atmosphere to show the repeat pattern. In our time-sections the upward sloping one is the most prominent because the horizontal (time) dimension is the longest on the diagram.

The reason for the out-of-phase relation of the two series of ascending waves is the effect of the annual wave maximum occurring alone between the coincidences with the QBW's maxima.

Although the entire discussion here has concerned only the wave pattern of the zonal wind speed variations, it is well to keep in mind that these wind waves must be associated with temperature waves.

In summary, there are at least two QBW's in the observed stratospheric wind field between 15–30 km at tropical stations at least 5 degrees from the equator, each of which progresses upward from one biennium to the next. As westerlies are found where easterlies might have been expected, this is of direct application to practical forecasting problems and calls for interpretation in terms of circulation patterns (Belmont and Dartt, 1962 and 1964). A systematic tracing of the variability of the amplitude and phase of the observed wind patterns in height and time, as well as of the component QBW cycles with latitude and elevation, is also required. The former patterns are not obvious because the annual wave is of opposite phase in the two hemispheres while the QBW, so far as is now known, is of the same phase. Hence, the phase of the resultant wave at corresponding latitudes differs, and the interesting question presents itself of possible cross-equatorial phase interference.

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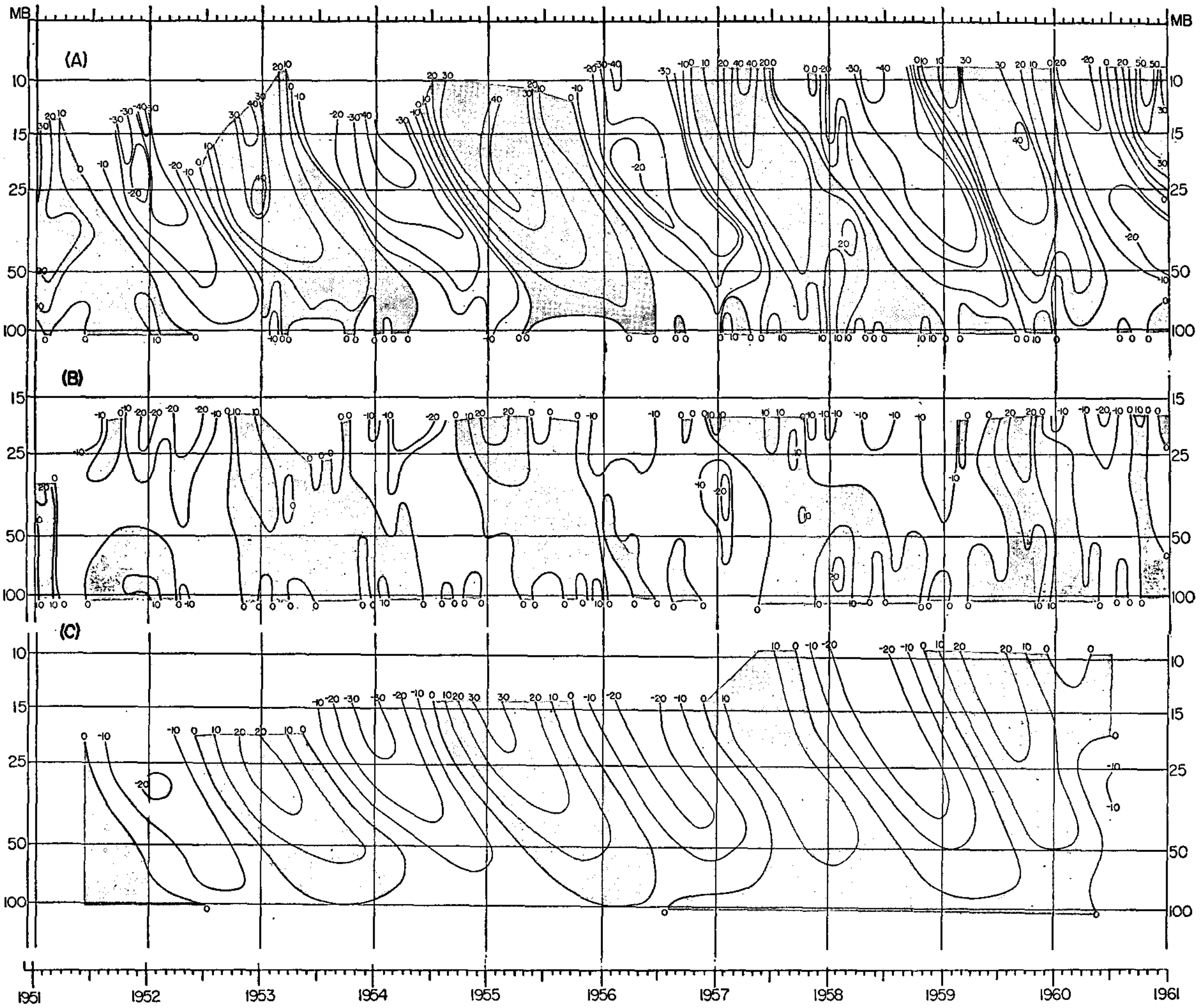

FIG. 9. (A) The component quasi-biennial wave at Balboa obtained by subtracting the mean annual wave from the observed pattern (B) Same for San Juan. (C) The component quasi-biennial wave at Balboa resulting from running 12-month means of observed data with long-term mean at each level removed.

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