An Analysis of the Power Spectra of Total Ozone Data

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ABSTRACT

An analysis is made of the power spectrum of total ozone data using the window closing procedure of Jenkins and Watts (1968). It is concluded that it is presently difficult to distinguish statistically between true periodicities in the data and a "red noise" spectrum for periods greater than one year. Nevertheless, statistical procedures are outlined to distinguish between red noise and a significant quasi-biennial oscillation (QBO) in ozone. Some evidence for a QBO in ozone was found in the Arosa total ozone data, but the period or periods of the QBO could not be firmly established due to the short time span of data available.

1. Introduction

A physical phenomenon which may contribute to variations in total ozone is the quasi-biennial oscillation (QBO) of wind and temperature in the lower stratosphere (see Angell and Korshover, 1973, 1976; Wilcox *et al.*, 1977; Nastrom and Belmont, 1975; Belmont *et al.*, 1974; Reed, 1965). These oscillations in wind, temperature and ozone are usually represented by a polynomial with a period of 26 months (see, e.g., Hill and Sheldon, 1975). However, the QBO is not really a periodic wave because the amplitude and period of the oscillation vary over time. Therefore, the representation of the QBO in ozone by a polynomial with a fixed 26-month period will represent only the average behavior of the phenomenon.

An even more significant problem in establishing a model for ozone trends is whether a harmonic analysis model should be used at all, given the presently limited amount of data available for establishing periodic trends (see Mitchell, 1965). In particular, due to the turbulence of the atmosphere, it is difficult to distinguish the QBO in ozone from long-term persistence in the data which Mitchell (1965) has characterized using first-order linear Markov type "red noise". In this context, red noise means that each term is influenced by its immediately proceeding term according to a Markov-type memory and that the power spectrum shape will become distorted across all wavelengths with the amplitude of the spectrum decreasing at the shorter wavelengths. This paper will utilize a standard statistical procedure for distinguishing between red noise and a statistically significant quasi-biennial oscillation in ozone and then demonstrate what can be reliably determined with the present amount of data.

2. Procedures

In order to resolve information available in the total ozone data, power spectra of monthly mean ozone data were generated using the window closing procedure recommended by Jenkins and Watts (1968). This procedure calls for the use of a broad bandwidth initially and then progressively narrower bandwidths until all important details in the spectrum have been brought out. The bandwidth B for an autocorrelation function generated using a Tukey lag window can be calculated using the relation (Jenkins and Watts, 1968)

$$B = 1.33/M,$$

where M is the truncation point of the Tukey lag window. As a general rule, for high fidelity, the bandwidth must be the same width as the narrowest important detail in the spectrum and should be less than the frequency width of the gap between the peaks.

Associated with the calculation of bandwidth are the calculation of confidence intervals for individual peaks in the spectrum and the calculation of the magnitude of the local continuum. Jenkins and Watts (1968) have shown how to calculate the confidence intervals for individual peaks while Mitchell (1966) has shown how to calculate the local continuum assuming domination by red noise. In both procedures, by narrowing the bandwidth to obtain better spectral resolution, some statistical stability

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TABLE 1. Total ozone data used in the analysis.

Station	Latitude	Time interval used in the analysis
Tromso	70°N	1936–68
Churchill	59°N	1965–72
Oxford	52°N	1951–73
Arosa*	47°N	1932–73
Boulder	42°N	1964–73
Mauna Loa	20°N	1964–73
Kodaikanal	10°N	1958–73
Brisbane	27°S	1958–73
Aspendale	38°S	1958–73

* Also subdivided into intervals 1932–52 and 1953–73.

in estimating the true form of the spectrum is lost. The precision of estimate of the spectrum is related to a chi-square distribution divided by the degrees of freedom ν. For a Tukey window, ν is given by $\nu = 2.67T/M$, where T is the number of data points used in the analysis. The basic problem in statistical analysis of ozone trends lies in deciding what value of M should be used to give an adequately narrow bandwidth and yet establish the local continuum for red noise with adequate precision. Jenkins and Watts (1968) have shown empirically that the choice of M is critical if one wants to gain physical insight from the spectrum. A second problem is deciding if the value of T is large enough to establish a reliable spectrum for a given M.

The following general principles were used in establishing the maximum lag M for the spectral analysis. These principles are similar to those suggested by Mitchell *et al.* (1966):

1) The maximum lag used for identifying periods should not exceed one-eighth the total number of years of record involved in the analysis. Turbulence in the atmosphere will preclude using a smaller bandwidth (see Mitchell, 1965).

2) A Tukey lag window was utilized to help in eliminating spurious periodicities. Note that when using a Tukey lag window which covers one-eighth the total number of years involved in the analysis, the spectral resolution which can be achieved is equivalent to using a rectangular lag window covering one-third the total number of years involved in the analysis. This is because the standard bandwidth of a Tukey window is 1.33 (Jenkins and Watts, 1968) while the standard bandwidth of a rectangular window is 0.5. The broader bandwidth of a Tukey window produces smaller biases in the amplitudes of the periodicities as well as eliminates some spurious periodicities at the cost of poorer spectral resolution. Jenkins and Watts (1968) have fully discussed the advantages of using a broad bandwidth and Tukey filter for establishing statistically significant periodicities and a narrow bandwidth for establishing a more exact period.

3) If two periodicities are suspected, the maximum lag should not exceed one-third the beat period P_B of the periodicities, where P_B is defined by

$$\frac{1}{P_B} = \frac{1}{P'} - \frac{1}{P},$$

where P' is the first suspected period and P the second suspected period (note: $P > P'$). This guideline was established because Probert-Jones (1964) once suggested that the QBO in tropical stratospheric winds could be resolved into two periodic com-

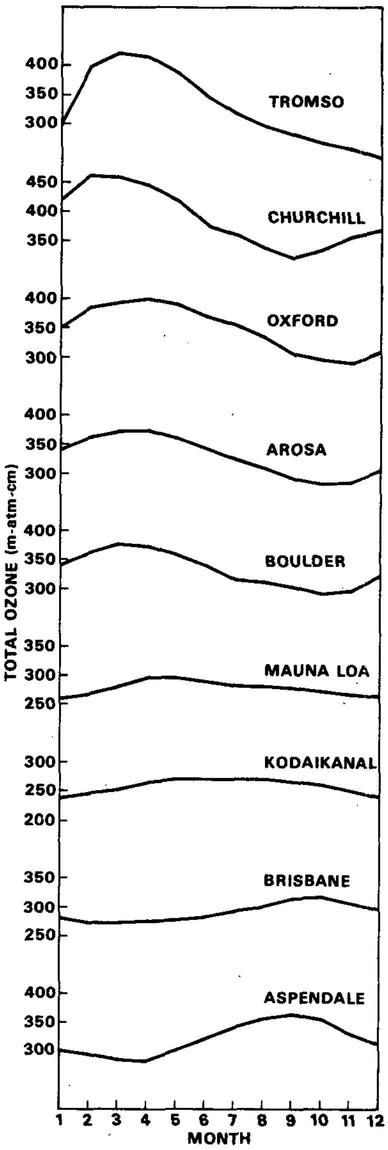

FIG. 1. The mean annual variation in total ozone for a number of stations at various latitudes.

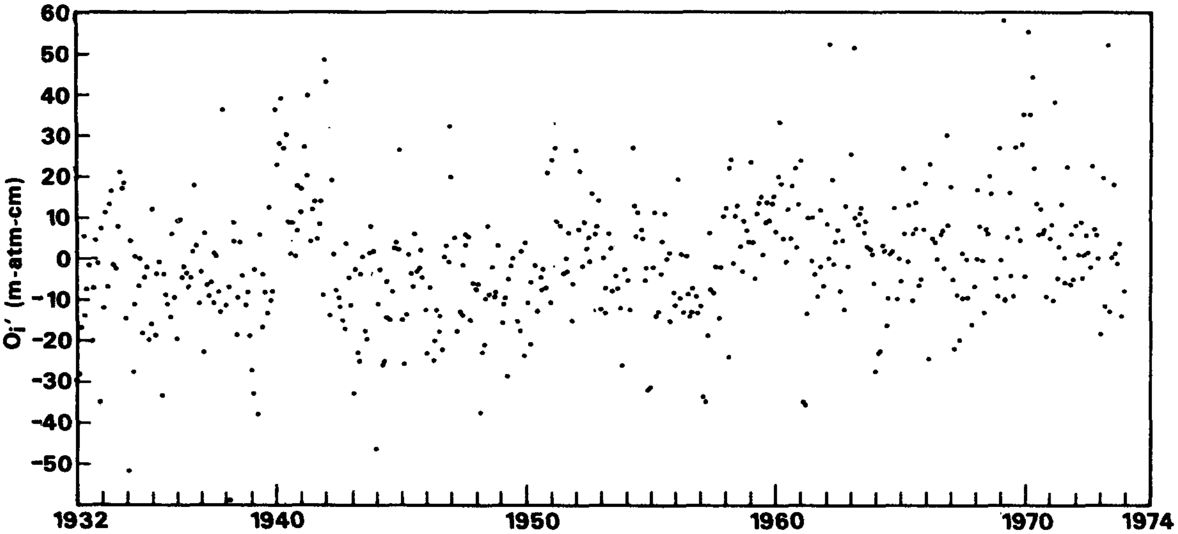

FIG. 2. Monthly total ozone data from Arosa, Switzerland for the period 1932–73. The average mean annual variation has been removed from the data.

ponents of 27 and 22.5 months. This work was later criticized by Mitchell (1964) who felt that there was no *a priori* physical reason why the data could be resolved into two periodicities and that the periods found by Probert-Jones could be mathematical artifacts arising from the turbulence in the atmosphere. If one accepts the use of this guideline, then it is necessary to have at least 27.5 years of data to establish periods of 27.5 and 22 months using the autocorrelation function and a Tukey lag window.

3. Results

The autocorrelation functions of monthly mean total ozone data from the stations shown in Table 1 were generated using a Tukey lag window with truncation points of 1/12, 1/8, 1/4 and 1/2 the amount of available data. As noted earlier, the broader bandwidths were used to establish the existence of the periodicities while the narrower bandwidths were used to establish a more exact period.

The data were selected so that information from a wide range of geographic latitudes could be sampled. In all cases, the data were first prewhitened by subtracting the mean annual variation from the data. This was accomplished by transforming the original total ozone series O_i into a new series O_i' by means of the equation

$$O_i' = O_i - \bar{O}_i.$$

Here $\bar{O}_i$ is the record-mean total ozone value for all values of the series pertaining to the same calendar month as this particular O_i. The value of $\bar{O}_i$ for each month of the year and for each station in Table 1 is shown in Fig. 1. Note that the prewhitening not only removes the mean annual variation in the data but other harmonics of the annual variation as well. In particular, Newell *et al.* (1972) have discussed extensively how the annual and semiannual modulations in the amount of sunlight received at the equator will cause corresponding modulations in both the zonal winds and the total ozone. The bell-shaped change in the amount of sunlight received at high latitudes causes ozone to be transported in such a way that total ozone varies in the manner shown (see Cunnold *et al.*, 1975). In any case, it is not expected that the prewhitening procedure will result in any spurious periodicities at other frequencies as does the "running mean" type of filter (see Holloway, 1958; Reynolds, 1978).

After these procedures were implemented, it became obvious that it is impossible to distinguish between periodicities in the data and "red noise" when data other than those taken at Arosa, Switzerland are used due to the short time span of data available from other stations. An examination of the Arosa data after the mean annual variation has been removed (see Fig. 2) shows that, even with these data, it is not easy to distinguish periodicities in the data. Power spectra of the Arosa data using different lags (see Fig. 3) show a typical red noise spectrum with a possible QBO component when a lag window of one-eighth the data interval is used. When a lag window of one-half the data interval is used, it is found that the most likely period for the QBO in ozone at Arosa, if it exists, is 20 months. This spectrum indicates that there are possibly other periodic components in the range from 3 to 12 years. These components, however, cannot be considered statistically significant at this time due to lack of

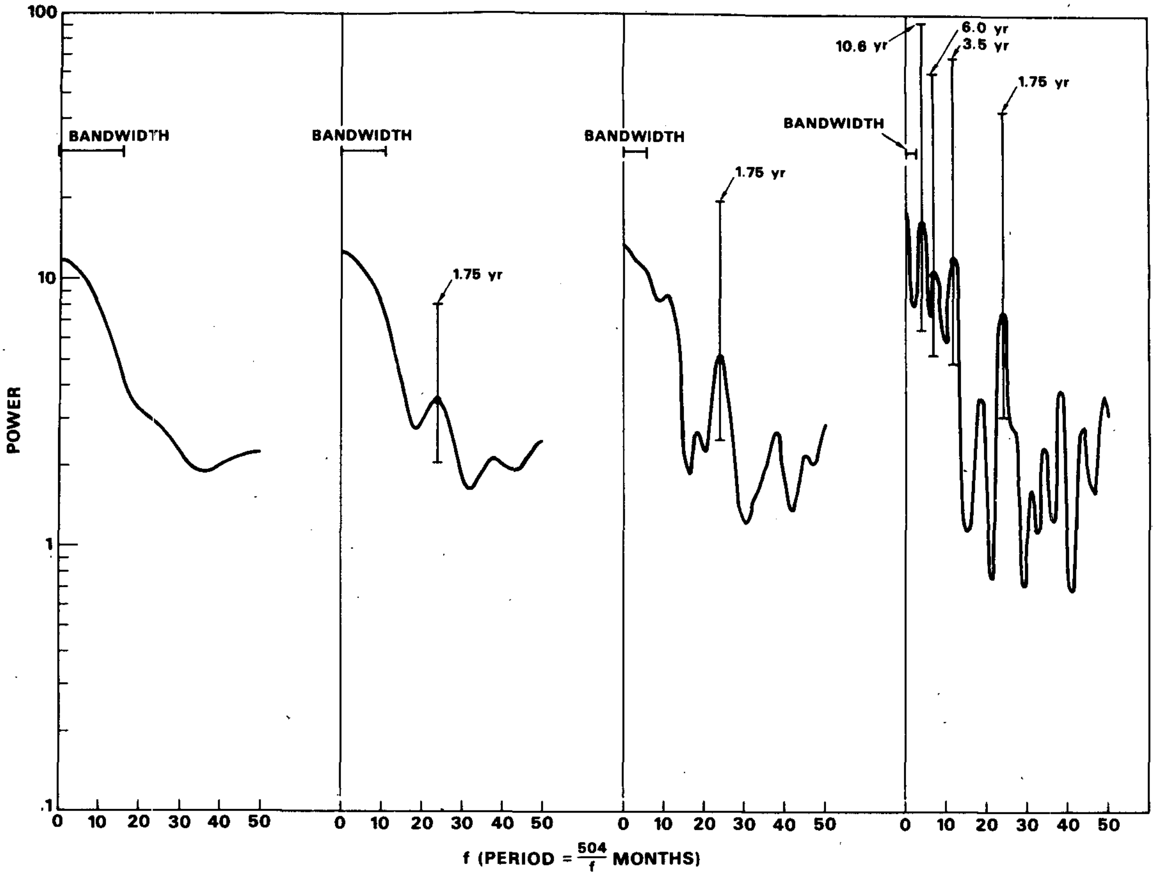

FIG. 3. Low-frequency portion of the autocorrelation function of Arosa total ozone data for the period 1932–73 (504 months) using a Tukey window with lags of (from left to right) 32, 63, 126 and 252 months. The mean annual variation has been prewhitened from the data as described in the text. The 95% confidence interval for selected peaks also is shown.

enough data to verify their statistical significance. It is estimated that 100 years of data (i.e., $T = 100$ years) would be needed to distinguish between red noise and periodic components in the range from 3 to 12 years.

As mentioned earlier, the autocorrelation functions of total ozone data were generated using the data from the other stations shown in Table 1 and the same techniques used in the analysis of Arosa total ozone data. The autocorrelation functions showed definite evidence of red noise at time intervals greater than one year. Some evidence is found for a QBO in total ozone for the data taken at Boulder, Mauna Loa, Kodaikanal, Brisbane and Aspendale when a Tukey filter covering one-fourth the total number of years was used in the analysis. However, the evidence from the statistical technique used in this paper is judged to be statistically insignificant at this time because the time period in which the data were taken was not long enough to establish statistical significance. On the other hand, when the same method was used with Balboa east zonal winds at 50 mb, a strong quasi-biennial periodicity with a period of 26 months was found as shown in Fig. 4.

4. Conclusions

Because only a limited amount of total ozone data exists, it is difficult to make a generalized statement on how to establish statistically significant ozone trends. In addition to the problem caused by the paucity of data, if one tries to take into account the atmospheric circulation patterns caused by the distribution of land and ocean surfaces, it will be many years before an ozone trend model can be developed from the data. This presents a serious problem if one wants to provide an early warning of ozone depletion. It is apparent that the best one can do at the moment is to indicate if ozone is deviating from what would be predicted from the existing ozone data using statistical procedures such as those developed by Hill *et al.* (1977). These predictions should be compared with an ozone trend

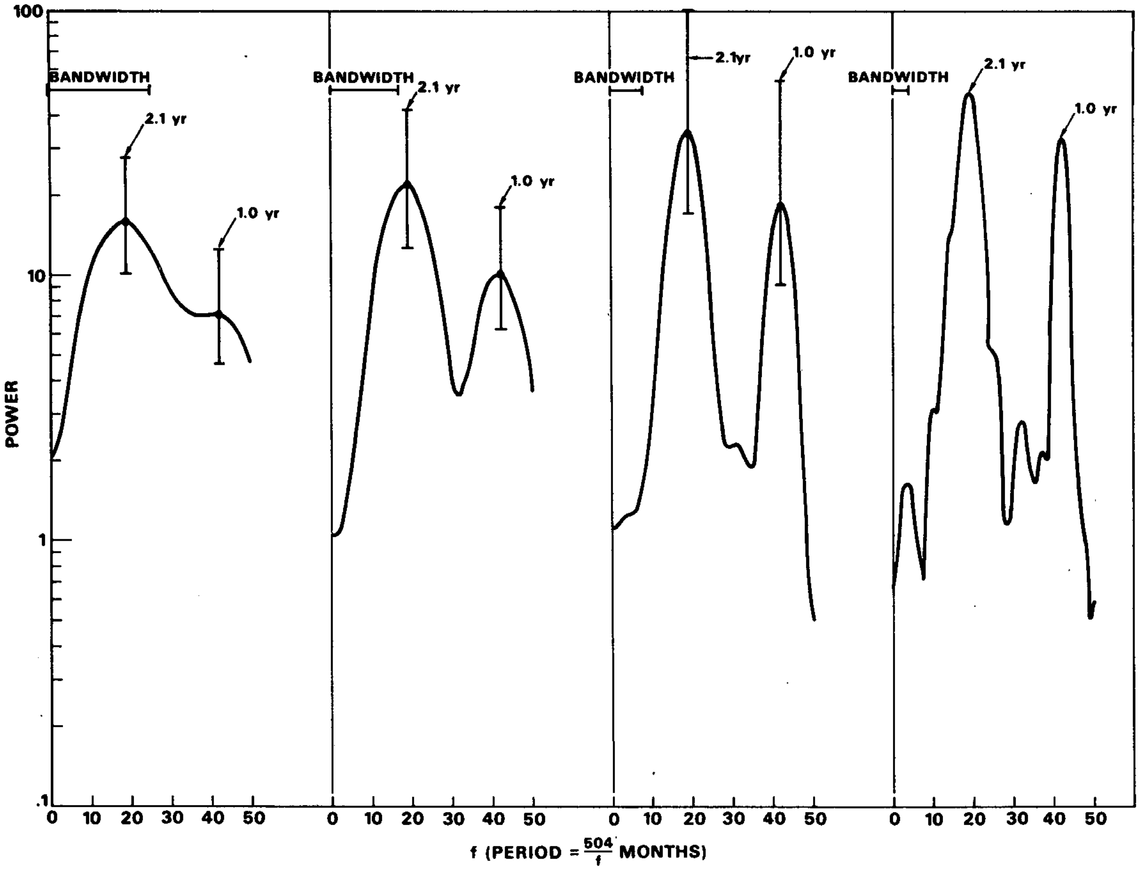

FIG. 4. Low-frequency portion of four autocorrelation functions of Balboa east wind data at 50 mb for the period 1951–77 (324 months) using a Tukey window with lags of (from left to right) 27, 40, 81 and 162 months. The 95% confidence interval for selected peaks also is shown. The autocorrelation function was generated at the frequencies shown in the figure to facilitate comparing this figure with Fig. 3.

model based on our present theoretical understanding of the physical processes which affect ozone production and depletion. However, new theoretical ozone trend models are needed which include the effects of the QBO, turbulence and the solar sunspot cycle. Those models will compliment the data gathering procedures which are presently in progress.

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