STRATOSPHERIC OZONE VARIATIONS IN THE NORTHERN AND THE SOUTHERN HEMISPHERE DURING THE PERIOD 1957–1990

JOHN XANTHAKIS,[1] CONSTANTINE POULAKOS[1] and CHRISTOS S. ZEREFOS[2]

[1]*Research Center for Astronomy and Applied Mathematics, Academy of Athens, Greece;* [2]*Physics Department, Laboratory of Atmospheric Physics, University of Thessaloniki, Greece*

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Abstract. The fluctuation and the periodicities of the total ozone layer for the period 1957–1990 is studied. Monthly total ozone data from 32 ground based stations have been analysed. It is shown that the maxima and the minima of the monthly values of total ozone for each year and for the whole period in question do not necessarily occur in March or in April and in September or October but range from March till July and from September till December respectively. Periodicities of 3, 4 and 6 months have been revealed. Finally the maxima and the minima of the total ozone data were examined. The variation of the whole phenomenon is analytically expressed with the help of an algebraic formula and can represent the observed monthly ozone values with an accuracy of 97%.

1. Introduction

Ozone is a triatomic form of oxygen abundant at sufficient concentration mainly in the stratospheric area between 15 and 35 km heights. As it is well known this area is a very vulnerable part of the earth's atmosphere being affected by both natural and man-made activities. Natural phenomena influencing the ozone variability are either quasi periodical or transient. Oscillatory type phenomena include the quasi-biennial-oscillation of winds in the tropical stratosphere and various components of the 11-year solar cycle. Transient phenomena include volcanic eruptions and the El Nino/southern oscillation. There is abundant literature for both phenomena (Funk and Graham, 1962; Dutch and Link, 1973; Wilcox *et al.*, 1977; Zerefos, 1983; Hasebe, 1983; Bowman, 1989; Willet, 1962; Zerefos and Crutzen, 1975; Pittock, 1978; Angell, 1990).

In the present paper we present new results and findings for the total ozone layer based on a long series of measurements, kindly provided by the WMO of Geneva and the whole problem of the fluctuation, the variability and the periodicity of the total ozone layer is examined from a new perspective.

2. Observational Material

Monthly total ozone values obtained from 32 ground based stations of the Northern and Southern Hemisphere for the period 1957–1990 were used to examine the fluctuations and possible periodicities of total ozone for the cited time interval. The data were kindly provided by the WMO being checked up beforehand by

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specialists from NASA and the WMO. The ozone stations are well distributed all over the world and cover the latitude zones from 74° N to 54° S.

However, it should be noted here that due to limited space purposes, we have restricted ourselves to the most important results and the paper includes only a sample of the total figures (the most representative ones) the total number of which is more than 90 while the tables are very long and will be avoided here. We intend to publish the full text with its all tables and figures in one of the Academy of Athens' publications late next year.

3. Mean Monthly Values of Total Ozone

Mean monthly values of the total ozone and for the time interval in question, were calculated for each station. In the relevant bibliography is referred that the ozone presents a yearly variation the maximum value of which appears during March while the corresponding minimum value in September. In the present work it is shown that there is indeed a yearly variation but the maximum values appear during the months March, April, May and July, while the minimum during the months September, October, November and December for the Northern Hemisphere and the inverse phenomenon for the Southern Hemisphere.

For the proper interpretation of the problem, we computed the mean monthly values of the ozone layer for each station and for the entire period (1957–1986) as well as the standard deviation (s.d.) for each monthly value. The results are shown in Figures 1, 2 and 3. Figure 1 illustrates the computed mean monthly values of total ozone for 8 stations of the N.H. The curves represent the ozone values computed with the help of the equations marked below each curve. Bars show the s.d. for each mean monthly value for the whole time interval.

Figure 2 gives the computed mean monthly values of total ozone for the time interval 1957–1986 for 11 stations of the N.H. The curves represent the values computed with the help of the equations marked below each curve. The small bars show the s.d. for each monthly value for the time interval in question. As it is seen the maxima and the minima occur in April and in October correspondingly.

An additional illustration of the monthly values of total ozone computed with the help of quite similar algebraic equations as per Figures 1 and 2 is shown in Figure 3. In this figure the maxima occur from April till July while the minima from October till December. The time interval is the same as per Figures 1 and 2 (1957–1986)

From Figures 1, 2 and 3 we see that the variation of the mean monthly values of total ozone can be expressed analytically with the help of a relation of the form:

$$10 - {}^{3} \cdot O_{\text{mean}} = A + B[\sin(\pi/12)t + W] \,, \tag{1}$$

where W represents the displacement of the maximum of the mean monthly values for each year and varies among the ozone stations. Of particular interest are the parameters A and B of Equation (1). Indeed, as it is shown in Figure 4 the

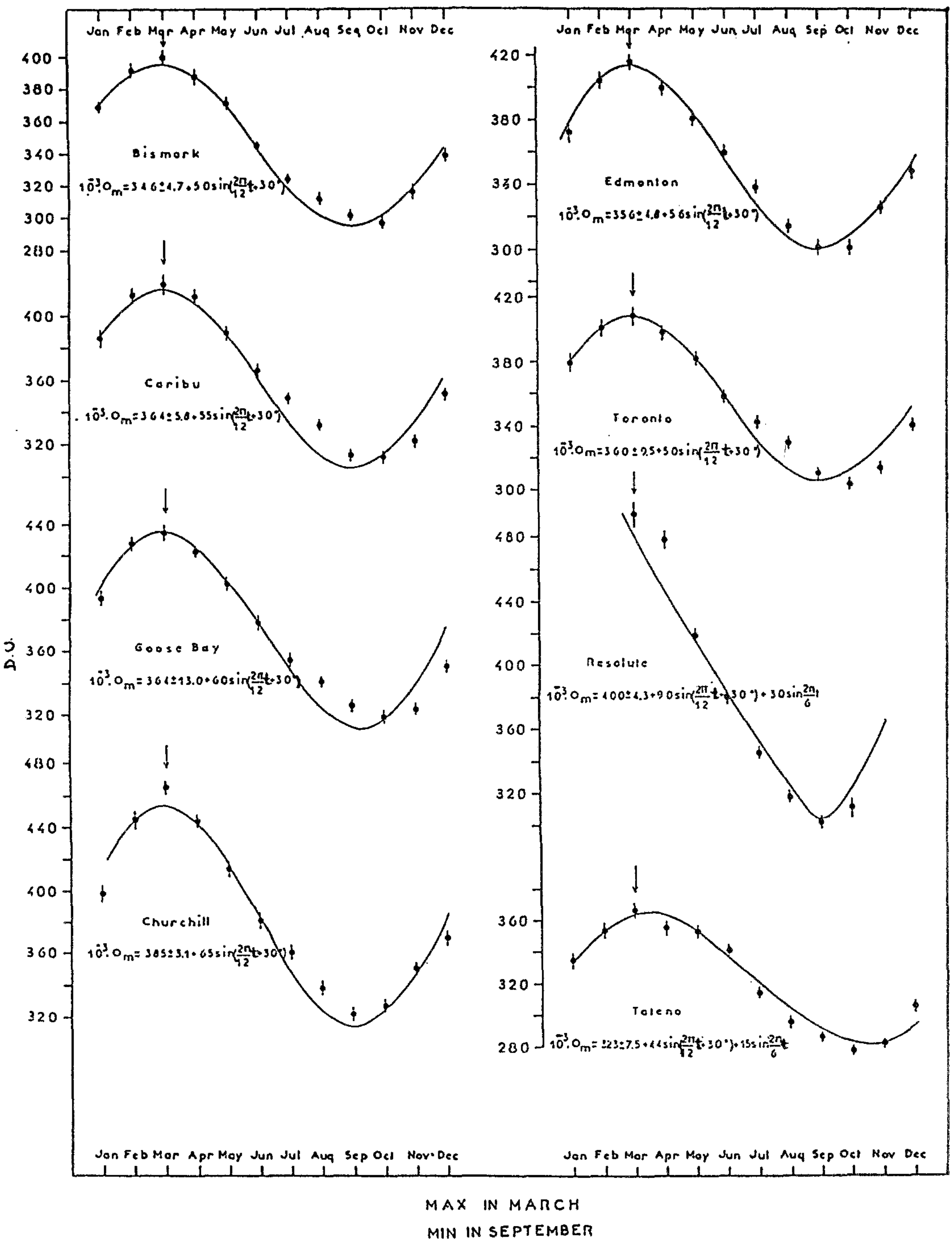

Fig. 1. Computed mean monthly values of the total ozone (continuous curves) for the period 1957–1986. Maxima appear in March and minima in September. The curves were computed with the help of the equations marked below each curve. The small bars indicate the computed s.d. for each mean monthly value for the whole time interval.

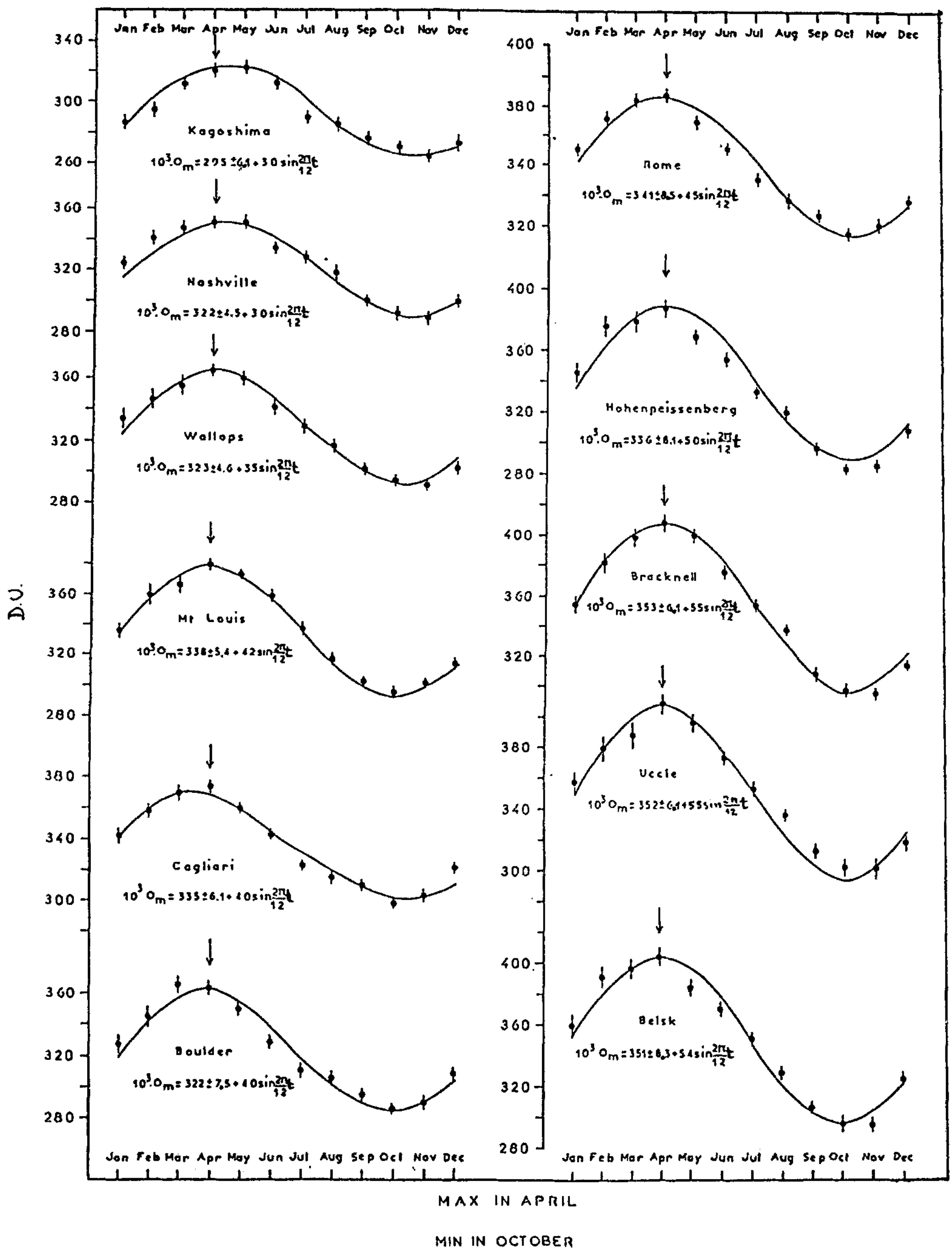

Fig. 2. Computed mean monthly value total ozone (continuous curves) for the period 1957–1986. Maxima appear in April and minima in October. The curves were computed with the help of the equations marked below each curve. The small bars indicate the computed s.d. for each mean monthly value for the whole time interval.

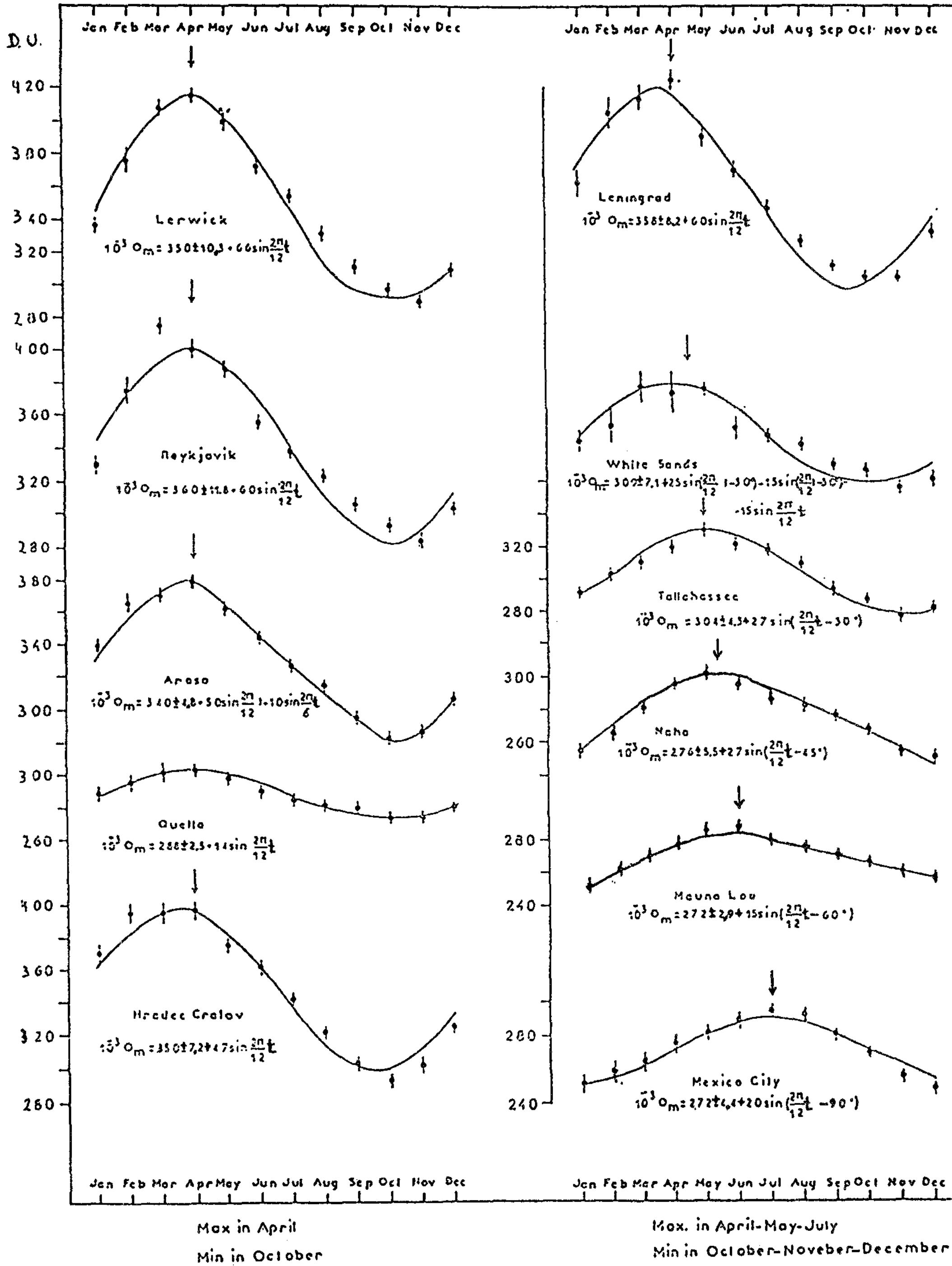

Fig. 3. Computed mean monthly values of total ozone (continuous curves) for the period 1957–1986. Maxima appear from April to July and minima from October till December. The curves were computed with the help of the equations marked below each curve. The small bars indicate the computed s.d. for each mean monthly value for the whole time interval. The names of the considered 11 ozone stations are also marked.

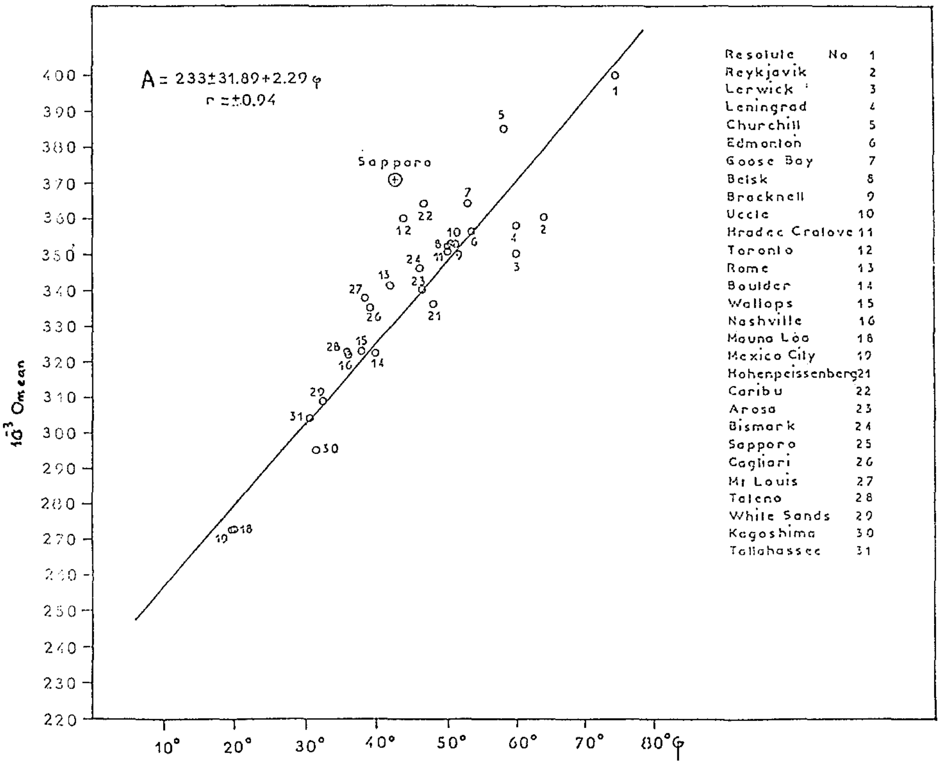

Fig. 4. Correlation between A, and φ for 31 stations of the N.H. Equation giving the parameter A, is marked on the left. Sapporo station is not included in the calculations.

parameter A increases linearly along with latitude φ i.e. the higher the latitude the thicker the ozone layer is. This is clearly shown by the theoretical variation which is represented by the straight line in Figure 4 and which has been computed by means of the least square method. From this figure we see that at $\varphi = 20°$ corresponds total ozone of the order of 272 Dobson Units (DU) while at $\varphi = 60°$, 372 DU and at $\varphi = 74°$ the corresponding value of total ozone is 400 DU. We see then that the variation of the parameter A, which represents the mean ozone value for each station can be analytically expressed as a function of the latitude φ with the help of Equation (2)

$$A = 233 \pm 31.89 + 2.29\varphi\,, \tag{2}$$

where the standard deviation (s.d.) σ was estimated to be $\sigma = \pm 31.89$ and the correlation coefficient r equal to $r_{A,\varphi} = 0.94$.

Figure 5 shows the correlation between the parameter B, which represents the amplitude of the mean ozone variation for each station, and the latitude φ for 30 ozone stations of the Northern Hemisphere. The station Sapporo has not been included in the calculations due to its large deviation from the rest of the stations.

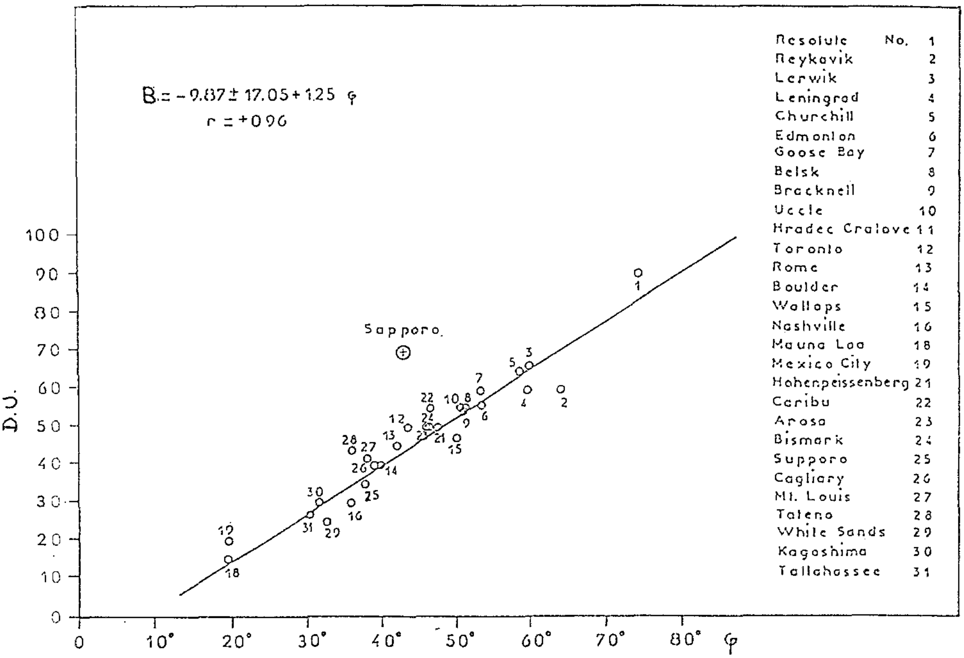

Fig. 5. Correlation between the parameter B, which represents the amplitude of the mean ozone variation for each station, and the latitude φ for 31 ozone stations of the Northern Hemisphere. The station Sapporo has not been included in the calculations due to its large deviation from the rest of the stations.

The straight line in Figure 5 shows that the parameter B, is well correlated with the latitude φ ($r_{B,\varphi} = 0.96$). It is therefore obvious that the parameter B, can be analytically expressed as a function of the latitude φ with the help of Equation (3)

$$B = -9.87 \pm 17.05 + 1.25\varphi\,. \tag{3}$$

It is worth mentioning that as far as we know this is the first time that Equations (2) and (3) are presented in the literature by the present work, although there was a suspicion that there should exist a relationship between the mean variation of total ozone and φ.

Figures 6 and 7 are quite similar to Figures 4 and 5 but they are referred to the Southern Hemisphere. However the results which are graphically shown in Figures 6 and 7 should be considered with due caution because they are based on observational data referring to only 4 stations of the Southern Hemisphere. Figures 6 and 7 show that following the same procedure as for the Northern Hemisphere the parameters A, and B, can be also expressed analytically as function of the latitude φ.

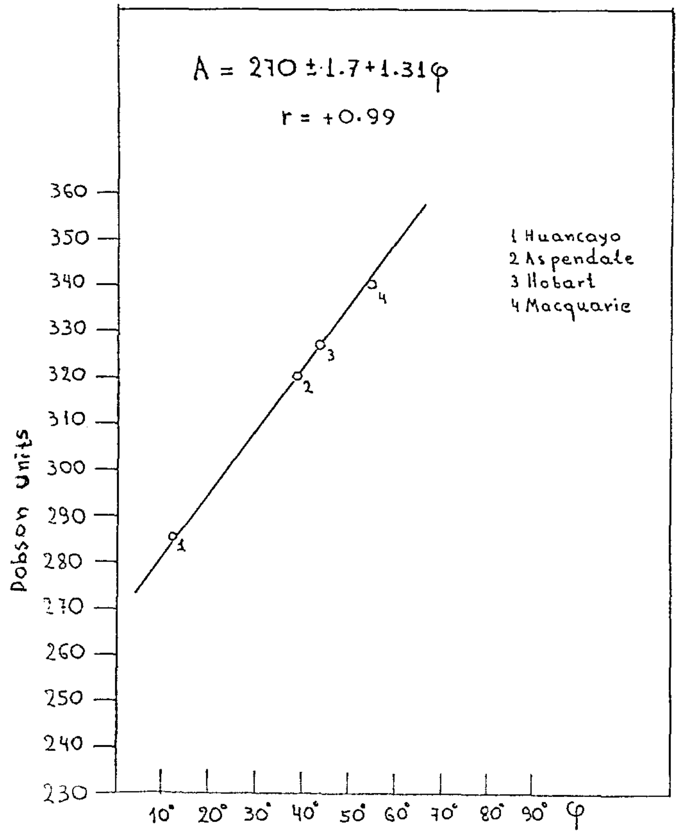

Fig. 6. Correlation between A, and φ. Ordinate represents DU. and abscissa latitude φ. Equation giving the parameter A, is marked as well as the the correlation coefficient r. (S. Hem.)

$$A = 270 \pm 1.7 + 1.31\varphi \qquad (r_A,\varphi = 0.99)\,, \tag{4}$$

$$B = -7.85 \pm 1.5 - 0.8\varphi \qquad (r_{B,\varphi} = 0.99)\,. \tag{5}$$

In the following paragraphs a study will be made of the phenomenon of the mean variation of the total ozone layer with time for each station. It is well known, that the ozone layer is unstable and varies from year to year. It is, therefore, very important that this variation with time is investigated and, if possible, to be expressed with the help of a mathematical expression. To this end for each station the differences

$$D = 10^{-3} \quad O^{\text{obs}} - [A + B\sin(2\pi/12)t + W]\,, \tag{6}$$

were calculated. The spectrum analysis showed that these differences do not seem to be of random origin but appear, for almost all the stations, short periodical variations. The periodicities revealed through the spectral estimate of the differences (6) have short periods of 6, 4 and 3 months. For brevity reasons, reference

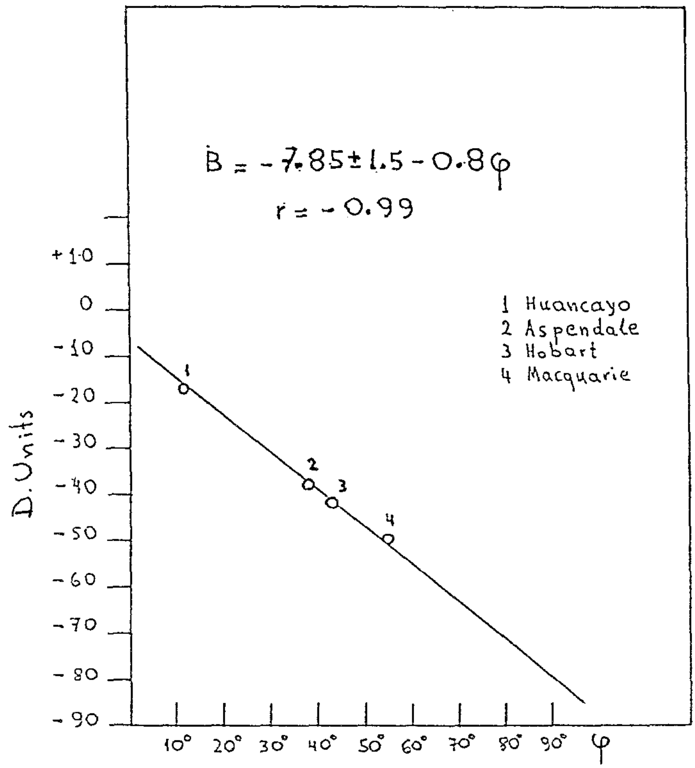

Fig. 7. Correlation between the parameter B, and the latitude φ. Symbols are as in Figure 6. The parameter B, is given with the help of Equation (5). $r = -0.99$. (S. Hem.)

is made here to only three stations. The above cited short periodicities are shown in Figures 8, 9, and 10. Similar figures exist for all the stations of Northern and Southern Hemisphere.

Unfortunately the spectrum analysis does not give the position and the amplitude of the short-term periodicities. This can be achieved only by applying the method of the successive approximations. This can be clearly seen in Figures 11 and 12 for the stations Rome and Boulder which are a representative sample of the total figures. In these figures periodicities of 6, 4 and 3 months as well as their position and amplitude for the period 1957–1986 are clearly shown. In some cases these periodicities are superimposed or show semi-periodicities overlapping each other.

From the above discussion we see that it is possible to express the monthly values of the total ozone with the help of the analytical Equation (7) giving the variation of the ozone layer from year to year for all the stations and the time interval considered here. Indeed, Equation (7) is of particular importance because it represents the variation of the monthly values of total ozone from station to station as function of time and represents the observational data with an accuracy equal to 97%.

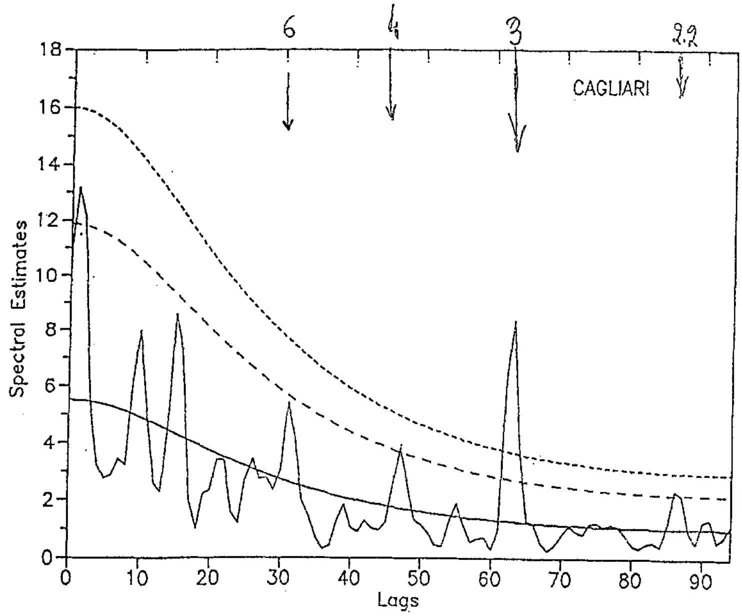

Fig. 8. Spectral estimate of the differences given with the aid of relation (6) for the station Cagliari. Periodicities of 6, 4 and 3 months are predominant.

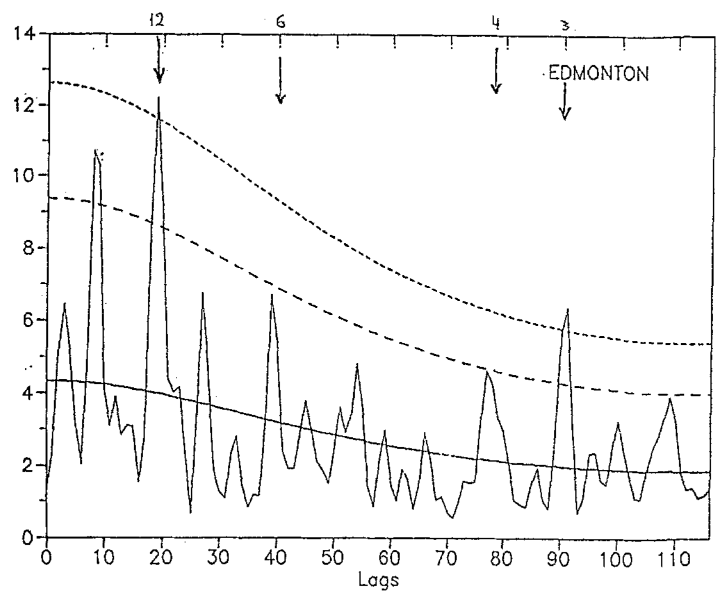

Fig. 9. Spectral estimate of the differences given by means of (6) for the station Edmonton. Short-term periods are predominant. The confidence level is above 99% and 95%.

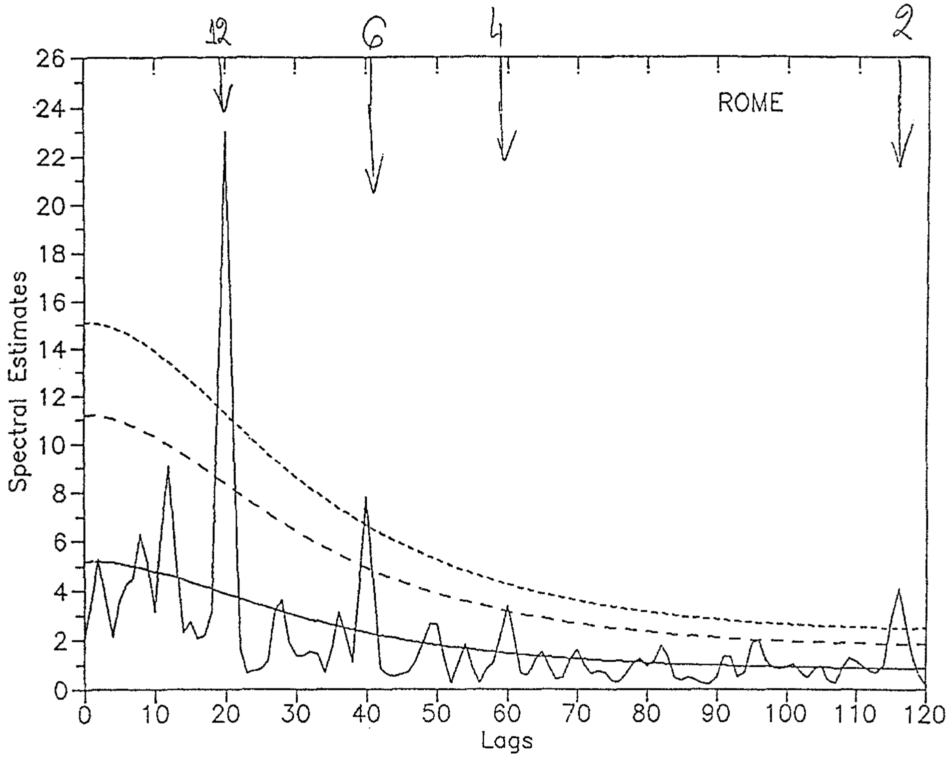

Fig. 10. Spectral estimate of the differences given by means of (6) for the station Rome. Short-term periods are predominant. The confidence level is above 99% and 95%.

$$O = A + B[\sin(2\pi/12)t + W] + a\sin(2\pi/3)t + \\ + b\sin(2\pi/4)t + c\sin(\pi/6)t\,. \tag{7}$$

Equation (7) describes the total ozone data of all stations and express the whole phenomenon of the fluctuation, the variability and the periodicities of the monthly values of total ozone layer dor the time interval in question.

Figures 13 and 14 are a representative ample of the total figures. They illustrate the close correlation between the observed and the computed monthly values of the total ozone for the stations Rome and Boulder.

Finally the monthly minima and maxima per year for the period 1957–1990 are illustrated in Figure 15. This figure shows that the monthly minima per year for the time interval in question do not fall below the limit of 240 DU. Conversely, the monthly maxima per year for 16 out of 28 ozone stations of the Northern Hemisphere show a slight linear decrease with the time. (In Figures 15 only 5 ozone stations were included for brevity reasons).

It is concluded that this is the only evidence which provides some indication of the human impact upon the stratospheric total ozone layer, e.g. CFC, CO, NO, etc.

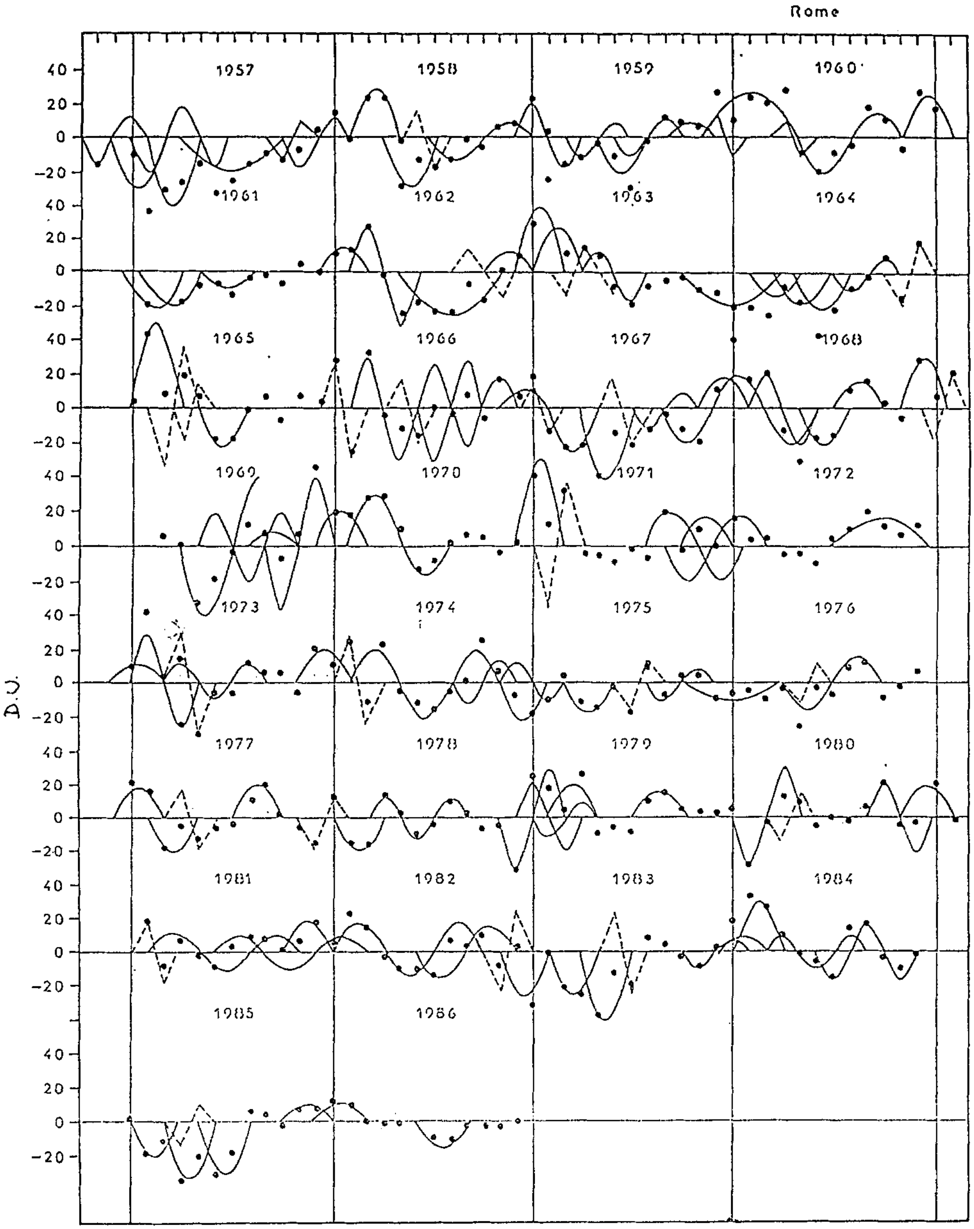

Fig. 11. Short-term periodicities with period equal to 6, 4, and 3 months are shown for the station Rome. The periodicities appear as a network of periodicities and in some cases are overlapping with each other. The time interval is from 1957 to 1986.

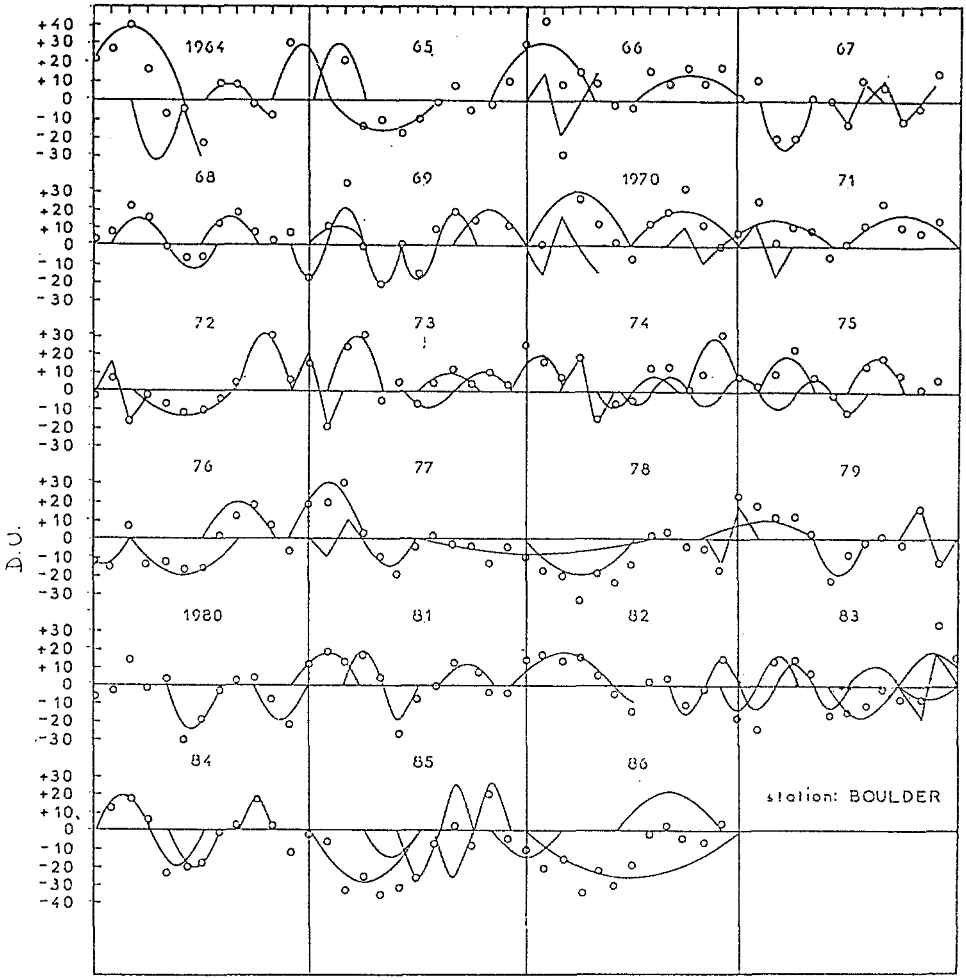

Fig. 12. Short-term periodicities with period equal to 6, 4, and 3 months are shown for the station Boulder. The periodicities appear as a network of periodicities and in some cases are overlapping with each other. The time interval is from 1964 to 1986.

4. Conclusions

On the basis of the present analysis which has utilized all total ozone observations ever made in the Northern and in the Southern Hemisphere during the period 1957–1990 the following are the main findings regarding the fluctuation, the variation and the periodicity of the stratospheric ozone layer.

1. The mean monthly values of total ozone for the period 1957–1990 do not always exhibit their maximum in March and their minimum in September but these values range from March to July and from September to December respectively. The inverse phenomenon is observed in the Southern Hemisphere.

2. The variation of the mean monthly values of the total ozone for the period 1957–1990 can be expressed analytically with the aid of a relation of the form

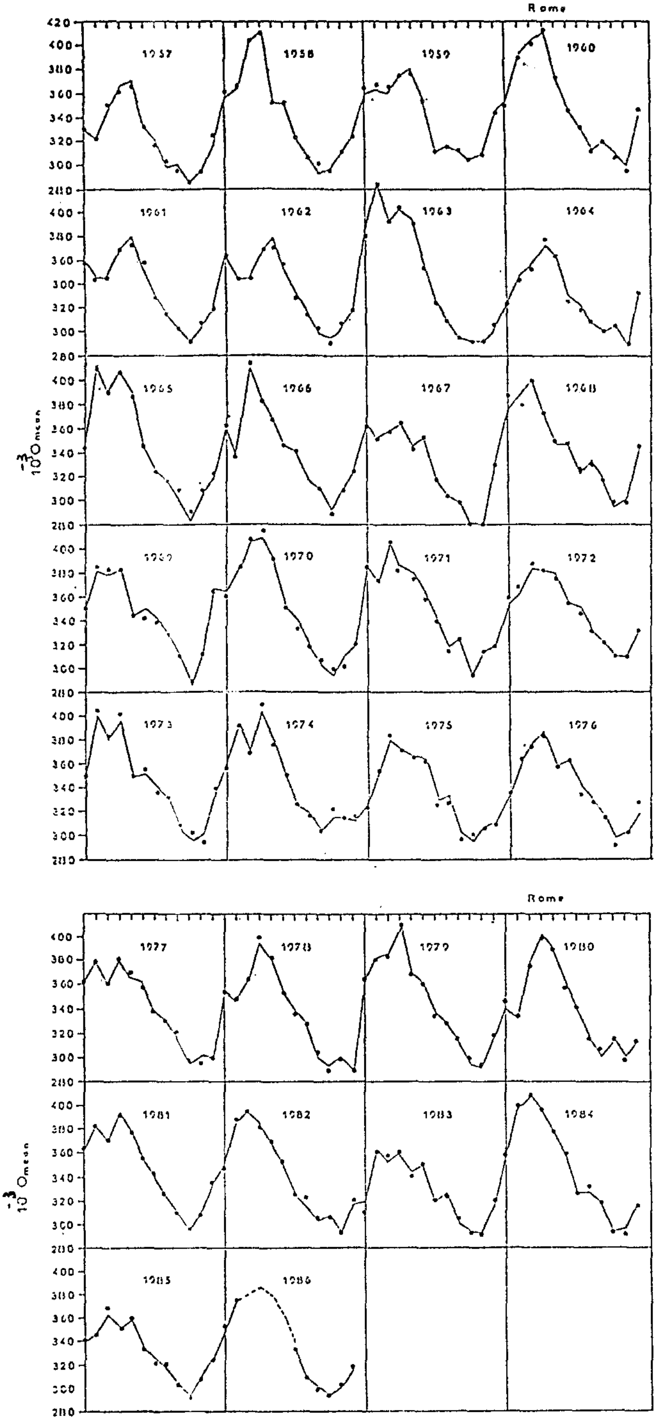

Fig. 13. The small circles represent the observed monthly values of total ozone for the station Rome. The time interval covers the period 1957–1986. The continuous line represents the monthly values of total ozone computed with the aid of Equation (7). The accuracy is equal to 97%.

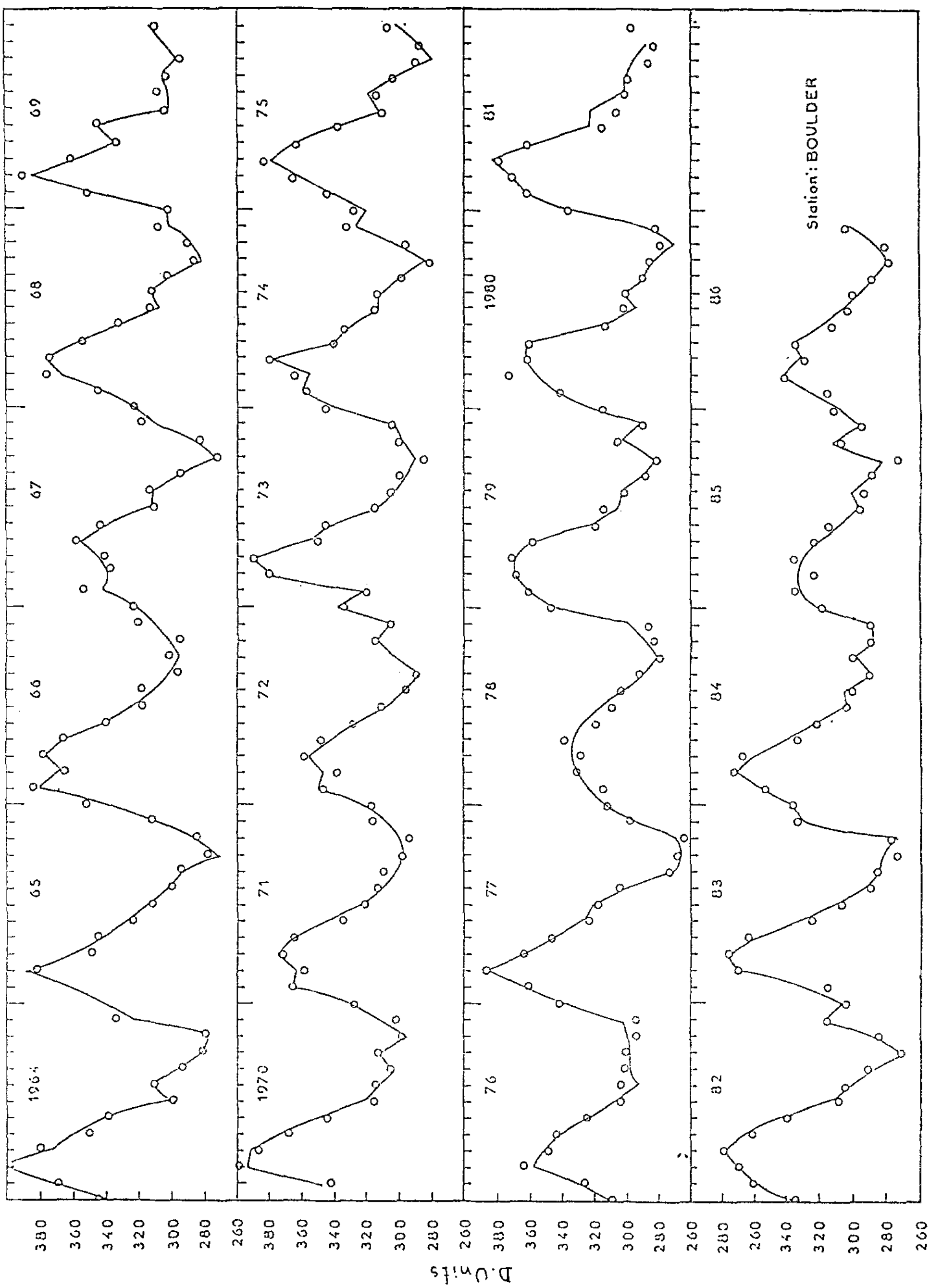

Fig. 14. The small circles represent the observed monthly values of total ozone for the station Boulder. The time interval covers the period 1964–1986. The continuous line represents the monthly values of total ozone computed with the aid of Equation (7). The accuracy is equal to 97%.

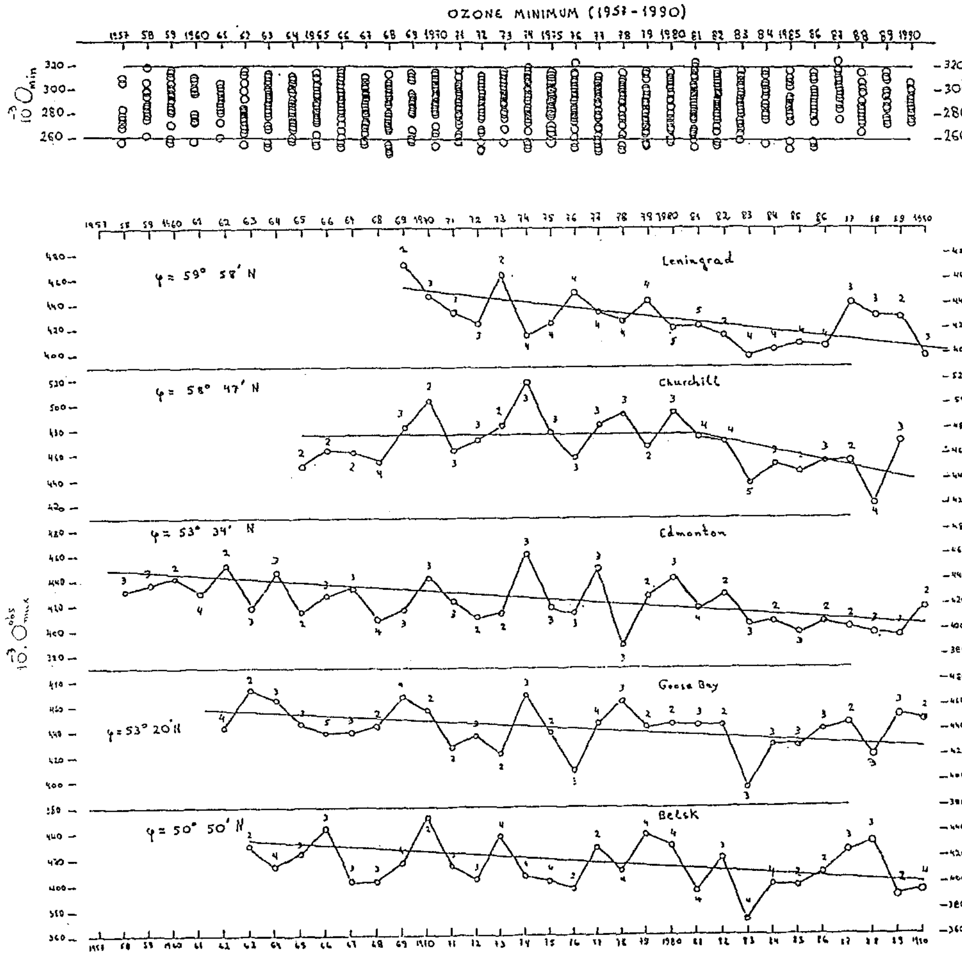

Fig. 15. (a) The small circles represent the monthly minima per year for the period 1957–1990. As it is seen the monthly minima of total ozone do not fall below the limit of 240 DU. (b) Inversely, the monthly maxima per year (a sample of 5 stations of the Northern Hemisphere) show a slight linear decrease with time.

$$10^{-3} \cdot O_{\text{mean}} = A + B[\sin(\pi/12)t + W],$$

which is valid for both hemispheres.

3. The parameters A, and B are very closely correlated with latitude φ and can be analytically expressed as a function of the latitude φ. This is for the first time revealed by the present investigation.

4. The spectrum analysis, applied to all available data, revealed short-term periodicities with period equal to 6, 4 and 3 months.

5. The method of the successive approximations applied to the residuals between the mean monthly values of total ozone and the corresponding computed

values illustrates for each station and for the whole period 1957–1990 the position and the amplitude of the revealed short-term periods.

6. The variation of the monthly values of the total ozone for each station and for the period 1957–1990 can be expressed with the help of a relation of the form

$$10^{-3} \cdot O = A + B[\sin(\pi/12)t + W] + a\sin(2\pi/3)t + \\ + b\sin(\pi/4)t + c\sin(2\pi/6)t\,,$$

the above equation describes the whole phenomenon of the total ozone, i.e. the fluctuation, the variability and the periodicity of the total ozone layer and represents the observational data with an accuracy equal to 97%.

7. The monthly minima per year for the period 1957–1990 do not fall below the value of 240 DU.

8. The monthly maxima per year for the period 1957–1990 show for some stations of the Northern Hemisphere (16 out of 28 stations) a slight linear decrease with time. The decrease in no case exceeds per decay the 2%.

Acknowledgments

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References

Angell, J. K.: 1990, 'Influence of Equatorial QBO and SST on Polar Total Ozone and the 1990 Antarctic Ozone Hole', *Geophys. Res. Lett.* **17**, 1569–1572.

Bowman, K. P.: 1989, 'Global Patterns of the Quasi-Biennial Oscillation in Total Ozone', *J. Atmos. Sci.* **46**, 3328–3343.

Dutch, H. U. and Ling, Ch.: 1973, 'Six Years of Regular Ozone Soundings over Switzerland', *Pure Appl. Geophys.* **106**, 1151–1168.

Funk, J. P. and Graham, G. L.: 1962, 'Australian Ozone Observations and a Suggested 24-Month Cycle', *Tellus* **14**, 378–382.

Hasebe, F.: 1983, 'Interannual Variations of Global Total Ozone Revealed from Nimbus-4 BUV and Ground-Based to Observations', *J. Geophys. Res.* **88**, 6819–6834.

Pittock, A. B.: 1978, 'A Critical Look at Long-Term Sun-Weather Relationships', *Rev. Geophys. Space Phys.* **16**, 400–420.

Willett, H. C.: 1962, 'The Relationship of Total Atmospheric Ozone to the Sunspot Cycle', *J. Geophys. Res.* **67**, 661–670.

Wilcox, R. W., Nastrom, G. D. and Belmont, A. D.: 1977, 'Periodic Variations of Total Ozone and its Vertical Distribution', *J. Appl. Meteor.* **16**, 290–298.

Zerefos, C. S.: 1983, 'On the Quasi-Biennial Oscillation in Equatorial Stratospheric Temperatures and Total Ozone', *Adv. Space Res.* **2**, 177–181.

Zerefos, C. S. and Crutzen, P. J.: 1975, 'Stratospheric Thickness Variations over the Northern Hemisphere and their Possible Relation to Solar Activity', *J. Geophys. Res.* **80**, 5041–5043.