Indian Journal of Radio & Space Physics
Vol. 15, April 1986, pp. 79-84

Solar Cycle Modulation of Atmospheric Ozone

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Received 2 *April* 1986

Solar activity has both long term as well as short term influences on atmospheric ozone. A method has been developed here to distinguish between these influences in the observations of total ozone. Using this method, the relationships between the solar activity as represented by sunspot number and solar 2800 MHz radio flux ($F_{10.7}$) and the daily variation of total atmospheric ozone during the sunspot minimum (1976) and maximum year (1979) at 5 northern hemisphere stations, have been investigated. These studies reveal that the number of observations attributable to the short term effects are fewer in the sunspot minimum year than in the sunspot maximum year, irrespective of the solar activity index being considered. This has led to the conclusion that solar cycle modulation effects may not be observable in the ozone data. A possible explanation based on the variations in the intensities of short term events between sunspot minimum and maximum years has been given.

1 Introduction

The use of linear correlation analysis in solar activity —atmospheric ozone studies can be traced back to Fowle[1]. Since then a number of workers have used the correlation technique but with conflicting results[2-5]. This may be attributable to the fact that in the observation of ozone sudden departures from long term trends can occur. For example, Weeks *et al.*[6] observed a depletion in mesospheric ozone after the moderate solar proton event of 2 Nov 1969. In the large solar proton events[7] of Aug. 1972, Nimbus 4 observations of stratospheric ozone also showed a substantial decrease associated with the event. Similar observations have also been reported by Reagan *et al.*[8] and McPeters *et al.*[9] In a simple linear correlation analysis using sunspot numbers or $F_{10.7}$ there is no attempt to distinguish between such sudden and short term changes and the long term trend. In the present paper a method which takes care of such variations has been developed.

This method has been used to study the relationship between solar activity and the daily total atmospheric ozone at 5 stations, namely, Resolute, Churchill, Hohenpeissenberg, Wallops Island and New Delhi in the Northern hemisphere. The ozone data for the stations have been taken from the 'Ozone Data for the World' published by the Atmospheric Environment Services in Canada. The solar activity indices used are the daily relative sunspot number and solar 2800 MHz ($F_{10.7}$) flux, and the analysis has been carried out on data for 2 years, 1976 and 1979, the sunspot minimum and maximum years, respectively. These two years have been selected not only to establish a relationship between solar activity and the daily variation of total ozone but also to make a comparative study of the relationships existing between total atmospheric ozone (TOZ) and solar activity at the two extremes of a solar cycle. It may be mentioned here that ozone observations have not been made on all the days of the years under consideration. On the other hand, around 220-360 observations of total ozone have been made, with the exact number varying from station to station and year to year.

2. Method of Analysis

In this method, called the rank deviation technique, the total atmospheric ozone on any particular day is given a rank according to its magnitude with respect to the entire set of data. Thus the day on which the maximum total ozone occurs in the entire set is given a rank 1 and the day on which the next highest ozone occurs is given rank 2 and so on. This process is also repeated with the data set formed by the corresponding day-values of the solar activity index. Thus each day of observation of TOZ will have 2 ranks associated with it. The squared difference of these 2 ranks is then calculated for each day. If the number of observations is n, it has been found in most cases that observations showing squared deviations larger than $(n-1)^2/2$ can be considered to belong to days wherein significant departures from the long term trend have occurred. In effect, this method helps in dividing the observations of TOZ during the entire period of study into two groups. The group formed by observations with squared deviations less than $(n-1)^2/2$ has been termed the 'long term trend group' while the group formed by observations with squared deviations larger than $(n-1)^2/2$ has been termed the 'short term effects group'. This has been justified by an extensive in depth analysis of the data. These two groups of observations can now be analyzed separately. In the present paper, the two groups of ozone data for each station have been lag-correlated with the daily relative sunspot number over a lag period of 30 days from D −15 to D +14 around the day of observation (D) of the total ozone. This ensures that all periodicities within the 27-day solar rotation period would be taken into account.

3 Results

3.1 Analysis with the Sunspot Number

The results of the correlation analysis carried out between the two groups of ozone data for each station and the sunspot number during the sunspot minimum year 1976 are presented in Table 1. Fig. 1 shows a plot of the variation in correlation coefficient with lag for the 'long term trend group'. From Table 1 it can be seen that a fairly large percentage of the days which form the 'long term trend group' show a significant positive correlation between total ozone and sunspot number at all the stations and around 15-30% of the days which form the 'short term effects group' show a negative correlation. From Table 1 a latitudinal trend in correlation coefficient can be observed with higher correlations being associated with the higher latitudes. Another feature of the observed correlations is that all the peaks occur on D-day irrespective of the group under consideration. Also from Fig. 1 it can be observed that the correlation coefficient (for the long term trend group) peaks on D-day at all stations and gradually drops off to zero with increasing lag or lead.

The results of the correlation analysis for the sunspot maximum year 1979 is presented in Table 2. Fig. 2 shows plots of variations of the correlation coefficient with lag for the 'long term trend group' at all the 5 stations.

A comparative study of Tables 1 and 2 reveals the contrasting influences of solar activity as represented by sunspot number on atmospheric ozone during the sunspot minimum and maximum years. While in the sunspot minimum year only a small percentage of the days corresponding to the 'short term effects group' showed a negative correlation, in the sunspot maximum year the number of days showing positive correlation was only marginally greater than the number of days showing negative correlation.

A feature of the results presented for the sunspot maximum year is the lack of any visible latitudinal trend in the influence of solar activity on atmospheric ozone. This lack of trend is observable not only in the 'short term effects group' but also in the 'long term trend group'.

A comparison of Figs 1 and 2 reveals that in 1976 the correlation coefficient gradually tapers off to zero with increasing lag but in 1979 there is a tendency for a negative peak to occur around a lag of 14 days (sunspot number preceding TOZ by 14 days). This negative

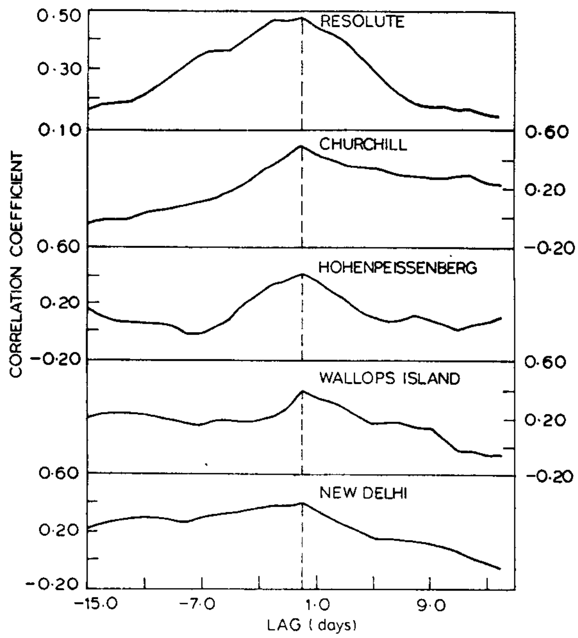

Fig. 1 — TOZ-sunspot correlations for the 'long term trend group in 1976

Table 1 — Correlations for Total Ozone and Sunspot Number in 1976

Station	No. of days of data	No. of days in 2 groups	Correlation coefficient (c.c)	Lag	Significance level of c.c.
Resolute	222	203	0.4765	0	0.00001
		19	−0.9299	0	0.00001
Churchill	360	267	0.4515	0	0.00001
		93	−0.7415	0	0.00001
Hohenpeissenberg	225	182	0.4229	0	0.00001
		43	−0.7983	0	0.00001
Wallops Island	297	225	0.4108	0	0.00001
		72	−0.6832	0	0.00001
New Delhi	332	292	0.4063	0	0.00001
		40	−0.8463	0	0.00001

Table 2 – Correlations for Total Ozone and Sunspot Number in 1979

Station	No. of days of data	No. of days in 2 groups	Correlation coefficient (c.c.)	Lag	Significance level of c.c.
Resolute	240	122	0.4522	0	0.00001
		118	−0.6651	3	0.00001
Churchill	349	166	0.5045	0	0.00001
		183	−0.6242	1	0.00001
Hohenpeissenberg	236	119	0.4177	0	0.00001
		117	−0.6830	0	0.00001
Wallops Island	280	158	0.3791	0	0.00001
		122	−0.7385	0	0.00001
New Delhi	342	172	0.5121	0	0.00001
		170	−0.7121	0	0.00001

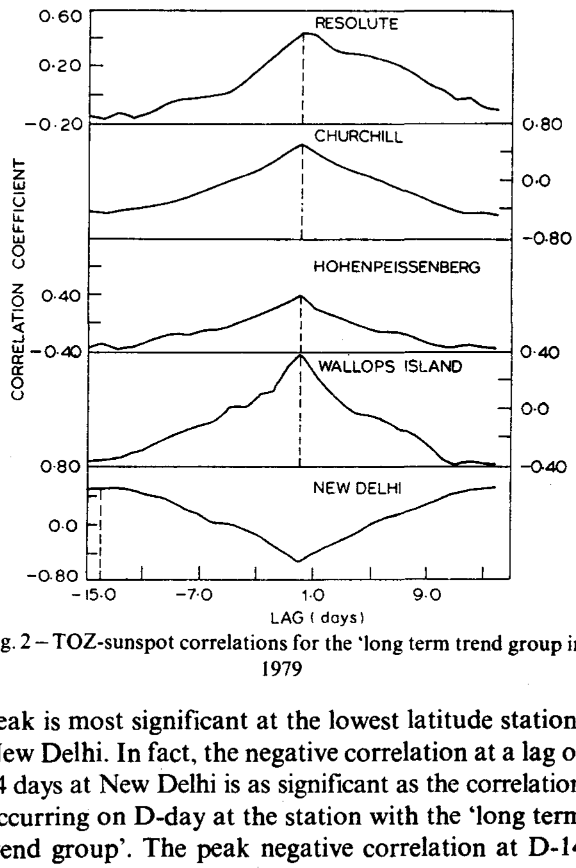

Fig. 2 – TOZ-sunspot correlations for the 'long term trend group in 1979

peak is most significant at the lowest latitude station, New Delhi. In fact, the negative correlation at a lag of 14 days at New Delhi is as significant as the correlation occurring on D-day at the station with the 'long term trend group'. The peak negative correlation at D-14 also decreases with increasing latitude.

3.2 Analysis with $F_{10.7}$

The analysis carried out with sunspot number has been repeated with the 10.7 cm solar radio flux data as the solar activity parameter. The results of the correlation analysis carried out between the two groups of ozone data for each station and $F_{10.7}$ during 1976 are presented in Table 3. The lag correlation analysis has also been carried out and the variation of correlation with lag for the 'long term trend group' during the year 1976 is shown in Fig. 3. From Table 3 it is clear that the correlations generally decrease with decreasing latitude except at the highest latitude station Resolute, where the corrělation is slightly less than that observed at Churchill. This latitudinal trend is similar to that observed with sunspot number. However, while the correlations are observed to be higher with $F_{10.7}$ in the higher latitudes, the correlations with sunspot number are higher in the lower latitudes.

Another similarity observed is that, as with sunspot number, only a small percentage of the total number of days for which ozone data are available falls into the 'short term effects group' and shows negative correlations at all stations in 1976. A comparison of Tables 1 and 3 shows that the number of days showing negative correlation with $F_{10.7}$ is slightly different from that showing negative correlation with sunspot number. However, it has been found that in Resolute the days showing negative correlation with either sunspot number or $F_{10.7}$ are the same. At the other stations around 60% of the days are common. A study of the plots of the variation of correlation with lag for $F_{10.7}$ as shown in Fig. 3 reveals a strong similarity to that for sunspot number in Fig. 1. Once again all peaks are seen to occur on D-day and the correlations tend to zero with increasing lag.

The results for the analysis with $F_{10.7}$ during the sunspot maximum year 1979 are presented in Table 4 and the plots of the variation of correlation coefficient with lag for the 'long term trend group' at the 5 stations under consideration are presented in Fig. 4.

It is found that the results obtained by the correlation analysis with $F_{10.7}$ are largely similar to those obtained with sunspot number in 1979. As with sunspots a fairly large percentage of days of ozone data form the 'short term effects group' and show significant negative correlations with $F_{10.7}$ in 1979 at all the 5 stations. Of the days showing negative correlation, more than 80% of the day are common to both $F_{10.7}$ and sunspot number in 1979.

Once again the 'long term trend group' does not

Table 3 – Correlations for Total Ozone and $F_{10.7}$ in 1976

Station	No. of days of data	No. of days in 2 groups	Correlation coefficient (c.c.)	Lag	Significance level of c.c.
Resolute	222	203	0.4489	4	0.00001
		19	−0.6582	0	0.00001
Churchill	360	260	0.5479	0	0.00001
		100	−0.6755	0	0.00001
Hohenpeissenberg	225	176	0.3529	0	0.00001
		49	−0.6649	0	0.00001
Wallops Island	297	230	0.3244	0	0.00001
		67	−0.6692	0	0.00001
New Delhi	332	268	0.2912	0	0.00001
		64	−0.7626	0	0.00001

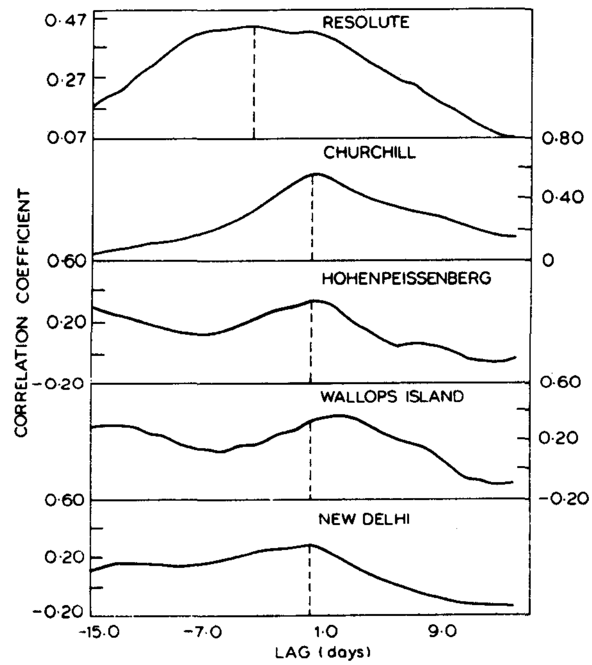

Fig. 3 – TOZ-$F_{10.7}$ correlations for the 'long term trend group' in 1976

show any latitudinal trend in the decrease or increase of correlation. With the 'long term trend group' it can also be seen from Fig. 4 that the positive peaks occur on D-day at all stations. At the lower latitude stations of New Delhi, Wallops Island and Hohenpeissenberg, a significant negative peak occurs at a lag of 15 days. This result is similar to the 14-day lag negative peak observed in the total ozone-sunspot number lag correlation analysis. Of the higher latitude stations, a negative peak at a lag of 12 days is observed at Churchill; but no such peak is observed at Resolute.

Thus the observations of correlations between total ozone and $F_{10.7}$ in comparison with those observed between total ozone and sunspot are largely similar. The differences that have been observed may be attributable to a lack of coherency between the sunspot number and $F_{10.7}$ at periodicities below 10 days[10].

Based on these studies certain specific observations can be made on the relationships between solar activity and atmospheric ozone. These are as follows:

(i) While a clear latitudinal trend in the variation of correlation exists in the sunspot minimum year 1976, no such trend can be observed in the sunspot maximum year 1979.

(ii) Only a small percentage of days seem to form the 'short term effects group' in 1976, but nearly 50% of the days fall into this category in 1979.

(iii) Most of the peak correlations irrespective of the group or the year under consideration seem to occur on D-day itself.

(iv) The correlation for the 'long term trend group' in 1976 gradually tapers off with increasing lag or lead. In 1979 a secondary negative peak is observed at a lag of 12-15 days. There is a tendency for this peak negative correlation to decrease with increasing latitude.

4 Discussion

One of the important contributions to an expected positive correlation between atmospheric ozone and sunspot numbers is the 27-day recurrence pattern in the latter. Herman and Goldberg[11] while reviewing various investigations of recurring magnetic storms and ionospheric events for the 27-day recurrence pattern concluded that such tendencies were more easily observable in the sunspot minimum years than in the sunspot maximum years. This was attributed to the fact that in the sunspot minimum years there are fewer active regions on the sun and those present existed for a number of solar rotations. In the sunspot maximum years, new active regions are continually forming at different solar longitudes and these have a tendency to die after 1 or 2 rotations. These active regions would be superimposed on any existing long-lived active regions and tend to obscure any 27-day recurrence pattern. Therefore, a regular 27-day recurrence pattern coupled with fewer SPEs and REPs

Table 4 – Correlation for Total Ozone and $F_{10.7}$ in 1979

Station	No. of days of data	No. of days in 2 groups	Correlation coefficient (c.c.)	Lag	Significance level of c.c.
Resolute	240	149	0.4833	0	0.00001
		92	−0.5282	2	0.00001
Churchill	349	176	0.4930	0	0.00001
		173	−0.4479	0	0.00001
Hohenpeissenberg	236	122	0.4734	0	0.00001
		114	−0.5591	0	0.00001
Wallops Island	280	162	0.4041	0	0.00001
		118	−0.6877	0	0.00001
New Delhi	342	194	0.5271	0	0.00001
		148	−0.6679	0	0.00001

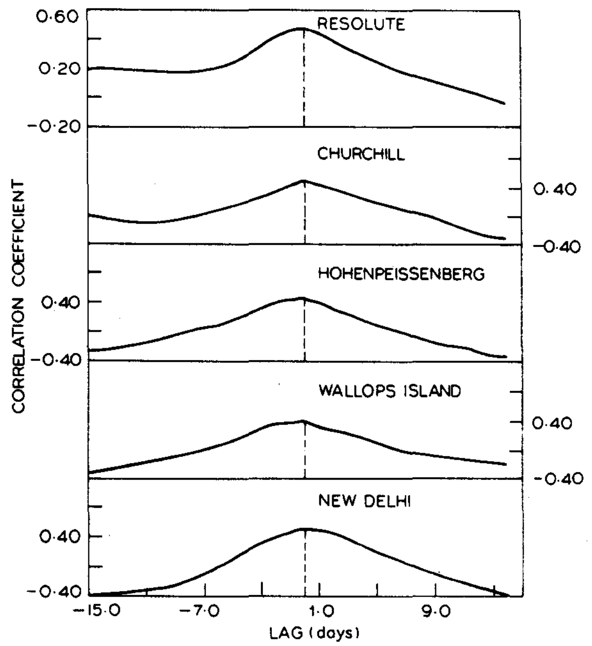

Fig. 4 – TOZ-$F_{10.7}$ correlations for the 'long term trend group' in 1979

in sunspot minimum years[12] might lead to a definite positive correlation between ozone and sunspot number during sunspot minimum year. A small percentage of days corresponding to the 'short term effects group' show a negative correlation even in this period because solar proton events and relativistic electron precipitations are not completely absent. This fairly regular behaviour of solar activity may also explain the latitudinal trend observed in correlation in 1976.

However, in the sunspot maximum year solar proton events and relativistic electron precipitations which cause depletions in ozone are more frequent[13]. Hence more number of days can be expected to form the 'short term effects group' and show a negative correlation. Such a behaviour is, in fact, observed in the sunspot maximum year 1979. An irregular variation in solar activity, for instance the obscuring of the 27-day recurrence pattern, could also explain the lack of a latitudinal trend in the observed correlation in 1979. Thus the more frequent occurrence of SPEs and REPs seems to clearly explain the lack of latitudinal trend as well as larger percentage of days showing negative correlations in 1979.

The reasons for the negative peak at a lag of 14 days are not so obvious. However, this highly significant negative peak at the lower latitudes may probably be due to an influence of solar activity on stratospheric circulation which might then lead to the redistribution of the ozone in the atmosphere by its transportation from the equator to the poles. In this connection it may be noted that Ebel and Batz[14] have found a very pronounced correlation between solar activity and mean zonal wind changes at 10 mbar (30 km) for oscillations with periods near 13.6 days. Thus the observation of a negative peak at a lag of 14 days supports this view and also suggests that the influence of solar activity on stratospheric circulation is stronger during the sunspot maximum years.

5 Conclusions

To determine different periodicites in a given data set, the classical approach is to apply the discrete Fourier transform technique. However, this technique cannot be easily adapted to the ozone analysis carried out in this paper since the ozone data are not available on all days of the year considered. In a simple linear correlation analysis, no attempt is made to distinguish between short term effects and the long term trend in ozone data. The rank deviation technique employed in the present paper overcomes the above drawbacks and gives a better picture of the relationships between atmospheric ozone and solar activity.

One of the proposed mechanisms for sun-weather relationships has been the solar cycle modulation of stratospheric ozone[11]. However, the studies in the present paper reveal dissimilarities in the relationships between solar activity and atmospheric ozone between the two extremes of a solar cycle. This has led to the conclusion that the solar cycle modulation effects may not be observable in ozone data. This is attributed to the variation in the intensities of short term solar events between the sunspot minimum and maximum years.

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