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Long-Term Variations in the Stratosphere of the Northern Hemisphere During the Last Two Sunspot Cycles

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Stratospheric geopotential height and temperature data of three levels are examined for the period 1957–1979. By using a low-pass filter for each time series at a 10°-by-10° latitude-longitude grid, long-term variations over the northern hemisphere are obtained, whose amplitudes and phases depend on latitude and longitude as well as on the height level. Analyses of differences between sunspot maximum and minimum are made, looking for a possible solar relationship. It cannot be proved that convincing statistical evidence exists for such relationships because of the few degrees of freedom in the highly autocorrelated data series. However, these hemispheric analyses are presented in the hope that they may help lead to an understanding of relations, if they do exist, that can be supported on physical, rather than statistical, grounds.

INTRODUCTION

The stratospheric circulation varies considerably from year to year, especially in winter. There is no doubt, moreover, that detectable changes also occur on long time scales in summer. The question naturally arises whether variations in solar activity may influence the stratospheric circulation and be responsible, at least in part, for some of these changes.

An early study [*Kriester,* 1971] of the changes of monthly mean stratospheric geopotential heights of the 50-, 10-, and 5-mbar levels from 1957 to 1970 provided an in-phase relationship with the solar cycle at polar and middle latitudes but not in the tropics. For the same period, *Schwentek* [1971] found a strong connection between the sunspot numbers and stratospheric temperature over Berlin in winter but not in summer. *Zerefos and Crutzen* [1975] by using zonal averages of 10- to 30-mbar thicknesses, and *Buschner* [1977] by examining monthly anomalies of 30-mbar geopotential heights, argued that variations at polar and middle latitudes were apparently related to the solar cycle also in summer. All of these studies found no evidence of solar dependence in tropical latitudes. This was confirmed by *Fritz and Angell* [1976] who examined the temperature and wind variations in the tropical upper stratosphere and lower mesosphere. Recently, *Quiroz* [1979] calculated high correlations between sunspot numbers and summertime rocketsonde temperature data at several sites from 8°S to 64°N latitude for the upper stratosphere.

The present study considers the lower and middle stratosphere of the entire northern hemisphere during all seasons.

DATA

Monthly mean values of 50-, 30-, and 10-mbar geopotential heights and temperatures, calculated from the daily analyses of the Berlin Stratospheric Research Group, are available on a 10°-by-10° latitude-longitude grid for the whole of the northern hemisphere, covering the following periods:

	Geopotential Heights	Temperatures
50 and 30 mbar	July 1957 to June 1979	July 1964 to June 1979
10 mbar	July 1957 to March 1972	July 1964 to March 1972.

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In addition, the time series of the 30-mbar temperatures at the North Pole was determined from July 1955 to June 1964 with the aid of the daily maps from the Berlin Stratospheric Research Group and monthly mean charts published by *Muench and Borden* [1962]. Figure 1 shows the frequency distribution of these values for each month, illustrating the large variability in winter.

As the simplest index of solar activity the monthly mean sunspot numbers have been used which are regularly available from the Swiss Federal Observatory Zürich.

To eliminate the variations of higher frequency, low-pass filters constructed by *Bleck* [1965] have been used, whose frequency responses show an approximately steplike shape. The weights of these filters were determined by minimizing the deviations from the desired 'ideal' response function with no damping below and total extinction above a given frequency. The functions of the filters that were used are shown in Figure 2. The 13-point filter was used for smoothing the sunspot numbers and the 39-point filter to eliminate the annual cycle and the quasi-biennial oscillation from the stratospheric data. It must be taken into account that the time series are shortened by the filtering process according to the number of weights of the filter minus 1.

STRATOSPHERIC VARATIONS

Application of the 39-point filter to every grid point of the 50-, 30-, and 10-mbar geopotential heights and temperatures resulted in a complex variety of curves. The latitudinal means of the filtered 30-mbar heights (Figure 3) illustrate some of the results: The dominant feature at low latitudes is a trend of continuous decrease since 1957, which has been reported also by *Zerefos and Mantis* [1977]. This trend was found to be most pronounced at the 30-mbar level and to be present at all longitudes. Shorter time scale variations seem to be out of phase with similar variations at polar latitudes until 1967 but in phase during recent years. At middle latitudes the trend remains dominant (confirming the results of Zerefos and Mantis), and the shorter variations are smaller than at tropical latitudes but permanently out of phase to those at polar latitudes. In this latitude belt, however, considerable longitudinal differences occur as will be seen later. At polar latitudes a fluctuation with increasing amplitude as latitude increases becomes obvious, which might be related to the solar activity (plotted

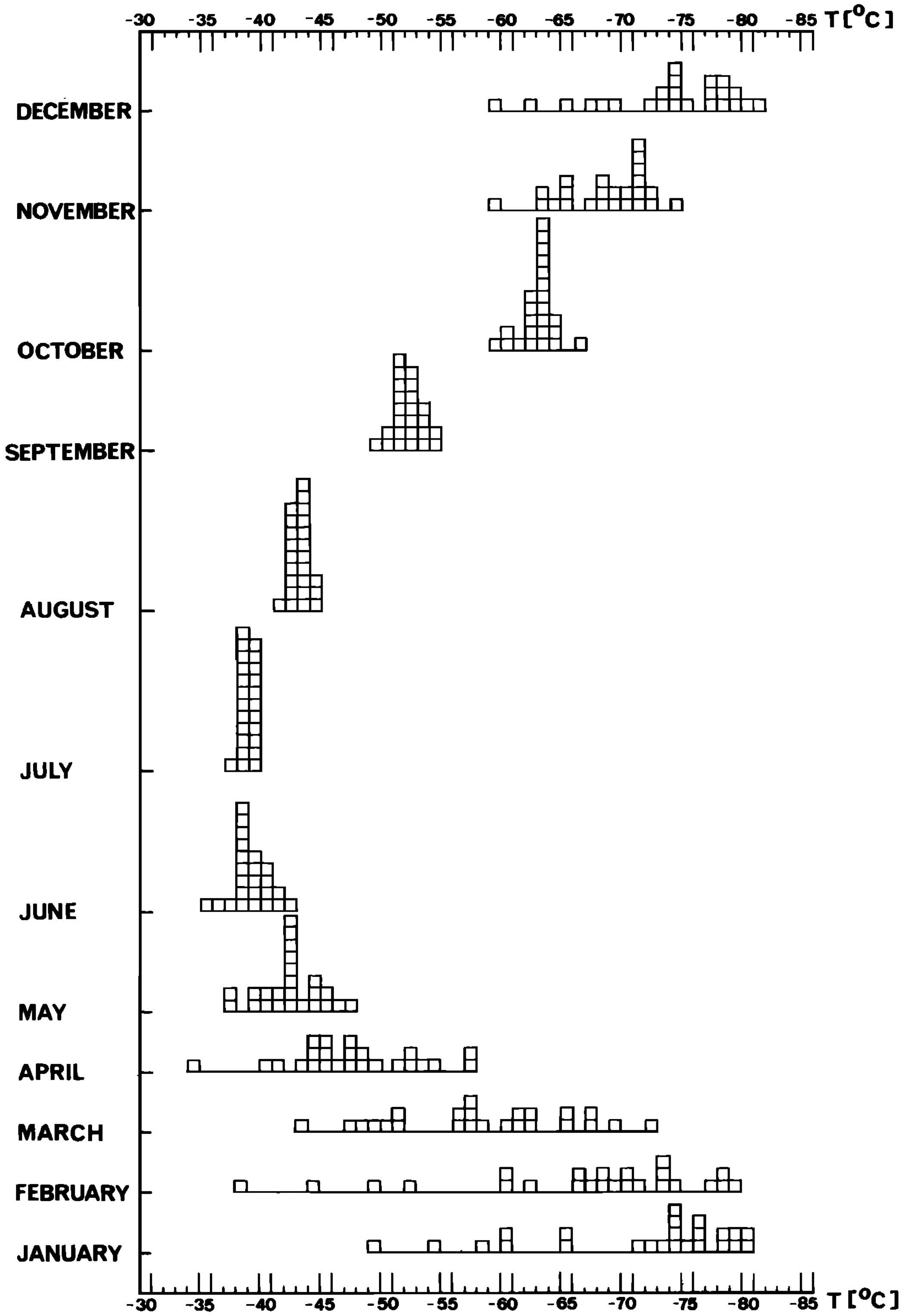

Fig. 1. Frequency distributions of monthly mean 30-mbar temperatures at the North Pole, 1956–1979.

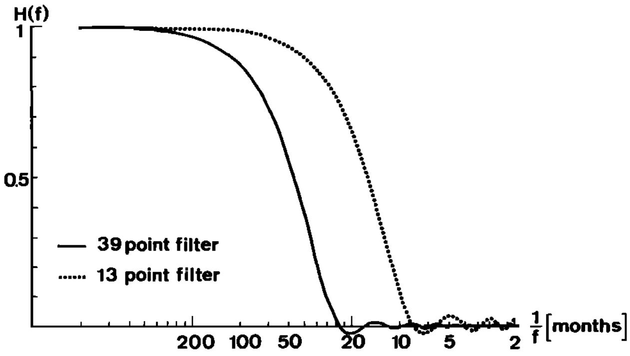

Fig. 2. Frequency response functions.

at the top of the figure). However, shorter variations of important magnitude occurred at these latitudes, too. The temperature time series are much shorter and do not cover the period from the sunspot maximum in 1957 to the minimum in 1964. For comparison with the geopotential heights, however, the 30-mbar values are shown in Figure 4. They appear inconsistent with the height values, which is mainly due to the fact that they only represent the situation at one single level. At polar latitudes, however, the march of temperatures mostly corresponds to that of the geopotential heights. At middle latitudes an overall cooling seems to exist as was noticeable in the height values. At all latitudes, especially at the lower ones, a pronounced minimum is found in the early 1970's. During this time a maximum of total ozone amount has been observed [*London and Oltmans,* 1978; *Angell and Korshover,* 1978] and an out-of-phase relation has been suggested by Angell and Korshover.

To demonstrate the longitudinal differences, the height changes during the last two sunspot cycles are shown on a hemispheric scale in Figure 5. From sunspot maximum to minimum (Figures 5*a* and 5*c*) the heights over high latitudes are reduced by more than 120 gpm in both cases, while from sunspot minimum to maximum (Figure 5*b*) they are increasing to the same amount. The region of these strong height changes coincides well with the area north of 60° geomagnetic latitude. In the mid-latitude belt, changes of opposite sign occur, centered mainly over Asia, whereas in the tropics an in-phase relation is weakly indicated. These changes have been observed at the 50- and 10-mbar level, too, with amplitude increasing as pressure decreases. Figure 6 summarizes this result by showing the latitudinal means of the height changes for all three levels.

STATISTICS

Correlation coefficients have been calculated between the smoothed sunspot numbers and each time series of the filtered

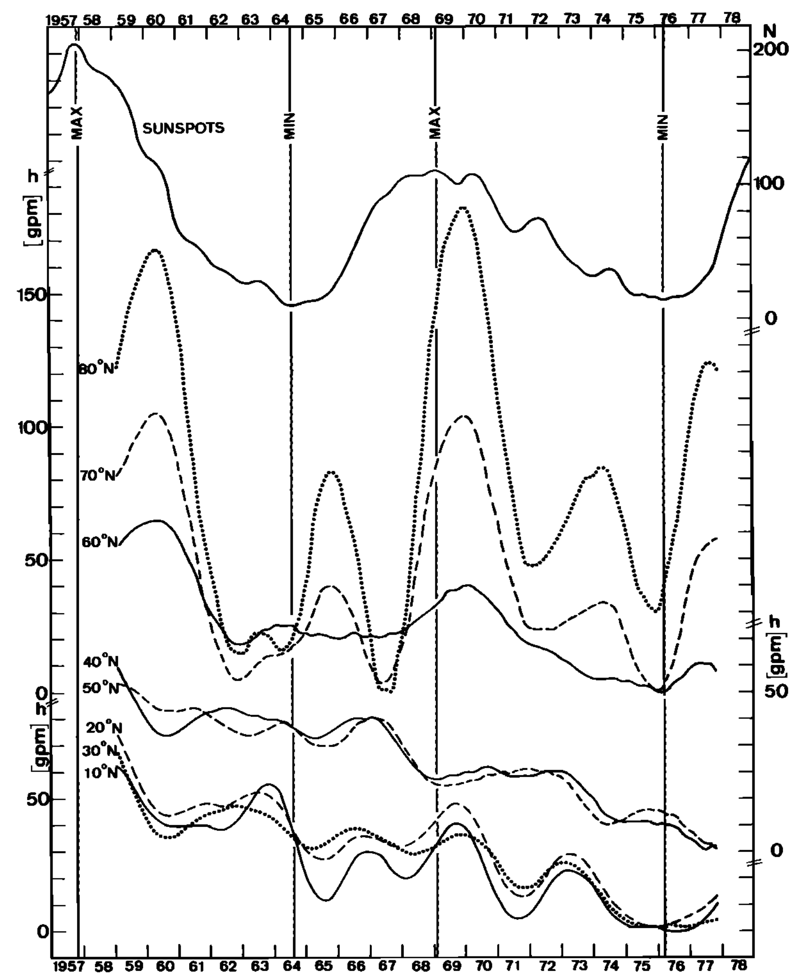

Fig. 3. Filtered monthly mean sunspot numbers and latitudinal means of filtered monthly mean 30-mbar geopotential heights (plotted are the differences to the minimum value of each latitude).

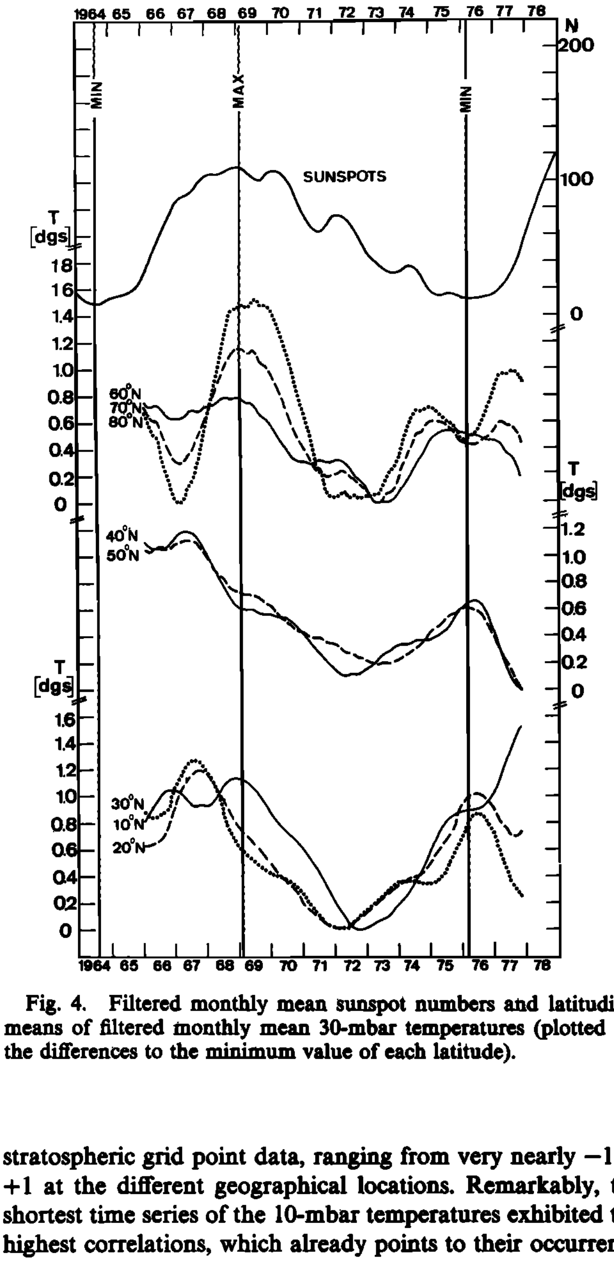

Fig. 4. Filtered monthly mean sunspot numbers and latitudinal means of filtered monthly mean 30-mbar temperatures (plotted are the differences to the minimum value of each latitude).

stratospheric grid point data, ranging from very nearly −1 to +1 at the different geographical locations. Remarkably, the shortest time series of the 10-mbar temperatures exhibited the highest correlations, which already points to their occurrence only by chance.

Since the sunspot numbers are already highly autocorrelated by nature, and the filtering process introduces nearly the same high autocorrelation into the stratospheric data, the number of degrees of freedom for testing the significance of the correlation coefficients is small. Therefore, the effective numbers of independent values after *Bartels* [1935] for each data series were calculated:

$$N_{\mathrm{eff}} = \frac{N}{\varepsilon(N)}$$

where $\varepsilon(N)$, the equivalent length of sequences is defined by

$$\varepsilon(N) = 1 + 2 \sum_{t=1}^{N-1} \frac{N-t}{N} K_t$$

and K_t are the autocorrections for $t = 1, 2, \cdots, m$ with a maximum lag of $m = N/10$.

By using these effective numbers of independent values in a Students test it turned out that the correlation coefficients mostly did not reach the 95% confidence level.

Regarding the longest period available, the 30-mbar temperature values at the North Pole, the 250 pairs of filtered values were reduced to only 9 independent pairs, and the calculated correlation coefficient of +0.54 was not significant at the 95% confidence level. In addition, for these approximately 21 years, correlation coefficients have been calculated over moving 11-year intervals, showing a remarkable decrease and becoming insignificant since the 11-year interval, which begins with the sunspot minimum in 1964 (Figure 7).

DISCUSSION

Although the statistical significance is doubtful, a relationship between solar activity and the observed changes in the middle stratosphere possibly exists, but the mechanism by which solar variations may affect the structure of the stratosphere needs further clarification. The results presented in this paper point to the possibility that at high latitudes these effects play a more important role than at lower latitudes.

Going back to the initial monthly mean data, for instance the 30-mbar temperature at the North Pole (Figure 8), it is obvious that the long-term variations at high latitudes appearing in the filtered data for the most part originate in the wintertime variability. Although the quasi-biennial oscillation is also present at these latitudes at least during the last 10 years of the record (which will be the subject of a separate study), it seems that disturbed winters with exceptional high temperatures over polar latitudes in December, January, or February have more frequently occurred during the years around sunspot maximum. Inspection of the daily stratospheric charts has revealed that major warming events as well as Canadian warmings are responsible for these deviations. Two exceptions must be mentioned: in 1958/1959, 1 year after the sunspot maximum, a Canadian warming occurred as early as November, and in 1979/1980, during the last sunspot maximum, a major warming did not start before mid-February and did not affect the monthly mean value of the 30-mbar level before March. In spite of the different dynamics of the major warmings and the Canadian warmings, they both are leading to a reversal of the temperature gradient at high latitudes, whereas the cold undisturbed winters are characterized by a persistent cold trough over northeastern Canada reaching from the troposphere into the stratosphere, as *Labitzke* [1977] has shown. This might be responsible for the geopotential height changes over this area demonstrated in Figure 5 indicating changes of the structure of the planetary waves.

As the observed large variations are confined to high latitudes at the altitudes investigated, it could be suspected that the solar influence, if there is any, is exerted by charge particle effects. *Fritz and Angell* [1976] suggested that radiatively downward propagating heating from the ionosphere caused by enhanced particle emission could reduce or even reverse the north-south temperature gradient at stratospheric levels. Furthermore, studies on the August 1972 solar particle events [*Reagan et al.*, 1978] have shown that the particle ionization produced enhanced concentrations of the various oxides of nitrogen that resulted in a destruction of stratospheric ozone down to 30 km altitude. They calculated changes of daily ozone heating rates and found a reduction in heating at the higher altitudes but a compensating increase at levels below 40 km due to the increased incoming of radiation.

On the other hand, *Quiroz* [1979] has shown that upper stratospheric temperature variations of the magnitude re-

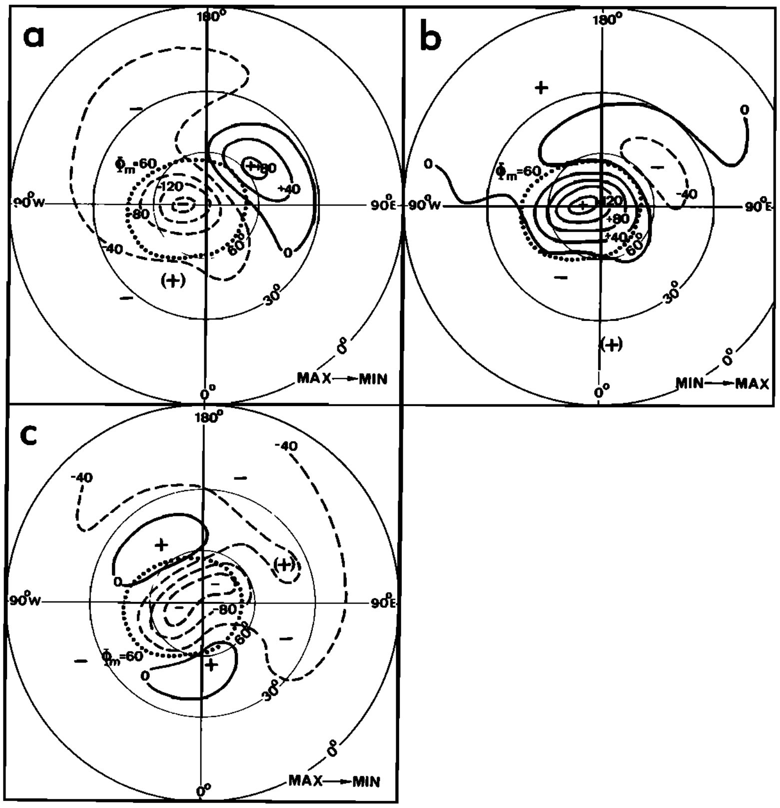

Fig. 5. Changes of filtered monthly mean 30-mbar geopotential heights (gpm) in relation to sunspot maxima and minima (*a*) from February 1959 to August 1964 (*b*) from August 1964 to February 1969, and (*c*) from February 1969 to March 1976.

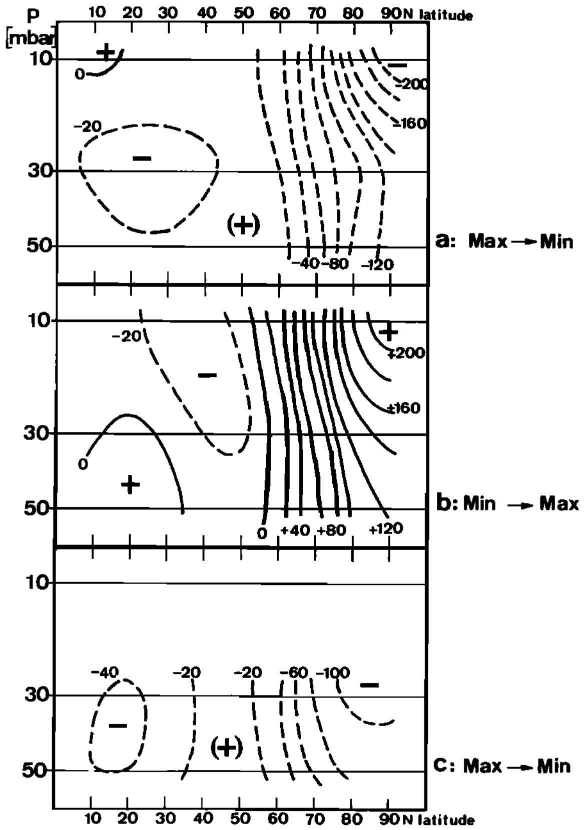

Fig. 6. Changes of latitudinal means of filtered geopotential heights (gpm) of the 50-, 30-, and 10-mbar level in relation to the sunspot cycle (periods as in Figure 5).

ported in his paper are possible with sufficient solar ultraviolet variations and are consistent with model calculations by *Callis and Nealy* [1978]. Significant variations of ultraviolet solar flux have been found on time scales of the order of the 11-year

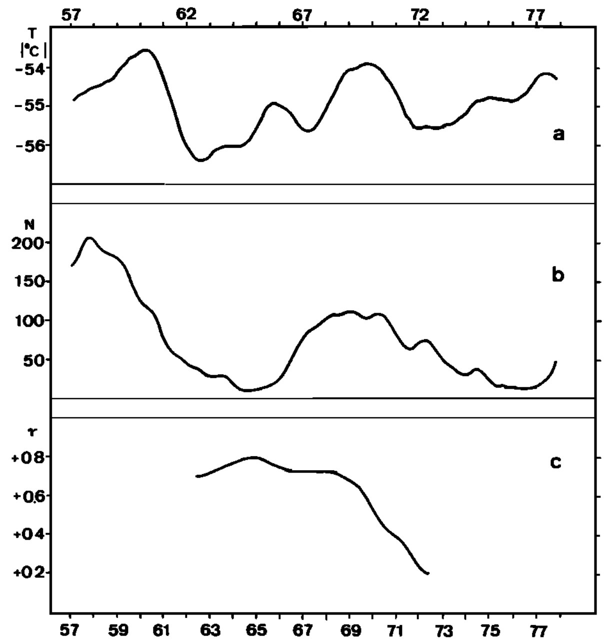

Fig. 7. (*a*) Filtered monthly mean 30-mbar temperature, North Pole, (*b*) filtered monthly mean sunspot numbers, and (*c*) correlation coefficients between these both for moving 132-month intervals (plotted in the middle of each interval).

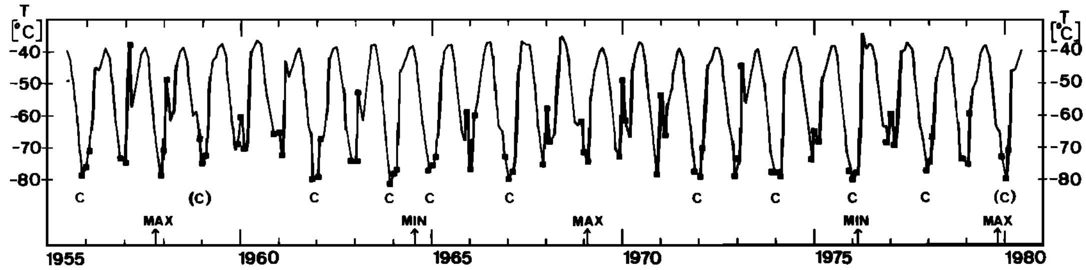

Fig. 8. Monthly mean 30-mbar temperatures at the North Pole from July 1955 to June 1980 (December, January, February are marked by squares, C indicating 'cold' winters; arrows at the bottom indicate solar maxima and minima).

sunspot cycle, which may not be inconsistent with the observations described in this paper (D. F. Heath, private communication, 1980).

The observed stratospheric changes at middle and low latitudes also point to other than solar related possibilities of influencing the stratospheric circulation on a long time scale. By using a radiative transfer model with a uniform reduction of stratospheric ozone density of 30%, *Ramanathan and Dickinson* [1979] calculated a strong cooling of the stratosphere at low latitudes with the maximum near 30 mbar. Vertical redistribution (with a constant total amount), such as reduction in the upper stratosphere and increase in the lower part, would yield a temperature increase in the lower stratosphere. It should be kept in mind, moreover, that *Manabe and Wetherald* [1975] found a considerable lowering of the stratospheric temperature at all latitudes by doubling the carbon dioxide concentration in a general circulation model. However, the observed hemispheric and global changes of ozone and carbon dioxide are at present far from such a magnitude [e.g., *Hudson and Reed,* 1979].

It should be emphasized that the available time series are far too short for obtaining conclusive results, either on such trends or on a solar cycle relationship. A clarification of the results presented in this paper will probably come from future analyses of temperature and ozone observations over extended periods.

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