Reports

Ozone and Temperature Trends Associated with the 11-Year Solar Cycle

Abstract. *Evidence is presented which suggests that trends in the ozone concentration and stratospheric temperature, reported between the early 1960's and 1976, are to a large extent due to solar ultraviolet flux variability associated with the 11-year solar cycle. Radiative-convective-photochemical simulations of ozone and temperature variations have been made with a solar ultraviolet flux variability model. Results for temperatures and ozone concentrations, when compared with published data, show good agreement.*

In 1971 Komhyr *et al.* (*1*), in a study designed to measure O_3 variations associated with planetary wave structure, determined that the total O_3 over selected North American stations increased at a rate of 4 to 8 percent per decade during the 1960's and noted increases at other stations around the globe. In a subsequent study, London and Kelley (*2*) concluded that for the same period the total O_3 increased by 7.5 percent per decade in the Northern Hemisphere and by 2.5 percent per decade in the Southern Hemisphere. Angell and Korshover (*3*) determined that slight decreases in the global O_3 had occurred after 1970. Angell and Korshover (*4*) and Quiroz (*5*) have analyzed stratospheric temperature trends determined with Western Hemisphere rocketsonde data for the years 1965 through 1976. They reported a warming in the middle and upper stratosphere prior to 1970 and a cooling thereafter.

As far as we know, no satisfactory explanation for the trends in global O_3 and stratospheric temperatures observed during the 1960's and early 1970's has appeared in the literature. The results we present here suggest that both the O_3 and temperature variations are due, in part, to ultraviolent (UV) flux variability, for wavelength $\lambda \leq 0.300$ μm, associated with the 11-year solar cycle. Studies of the correlation between O_3 variations and solar activity are controversial and have a long history. Investigations dating back to 1910 (*6*) have been conducted in an effort to establish a relationship between O_3 and sunspot number, 10.7-cm flux, or Lyman-α flux. These studies have been complicated by the natural variability of the O_3 layer, lack of sufficient long-term data, and poor geographical coverage. The question of a possible relationship between global O_3 and solar activity is both controversial and of importance. It is controversial because of the mixed conclusions that have been drawn about global O_3 (*6*) and because of the lack of agreement and the dearth of basic data on the nature of the variation of the solar output at $\lambda \leq 0.300$ μm. It is of importance since such a relationship could provide a significant, long-sought link between solar activity and climate-related phenomena (for example, changes in the surface temperature or the structure of planetary long waves) in both the stratosphere and the troposphere.

Recently, on the basis of satellite, rocket, and balloon measurements made between 1964 and 1972, Heath and Thekaekara (*7*) have reported variability in the solar UV flux (for $\lambda \leq 0.300$ μm) between solar minimum and solar maximum (Fig. 1a). It is difficult to measure the solar UV flux between 0.120 and 0.300 μm, and there are substantial uncertainties and discrepancies in the reported data. Recently, Simon (*8*) has critically reviewed measurements of the solar flux between 0.120 and 0.400 μm. He indicates that there is no conclusive evidence, either for or against, a solar variability, of the magnitude reported by Heath and Thekaekara, in this wavelength range.

However, solar irradiance measurements are not the only means by which the presence of solar flux variations have been inferred. In 1965, Rangarajan (*9*) examined 104 sets of Umkehr O_3 data (vertical O_3 profiles) taken at Marcus Island (24°N, 154°E) between the 1958 solar maximum and the subsequent solar minimum. Rangarajan suggested that to reconcile the behavior of the observed O_3 column sum above 36 km would require a 60 percent decrease in the UV flux (for $\lambda < 0.240$ μm) with decreasing solar activity. This is compatible with the flux changes suggested by Heath and Thekaekara (*7*). Rangarajan further determined that the variation of the critical frequency of the atmospheric E-layer at Ahmedabad (23°N) between 1958 and 1962 also supports a UV flux change (albeit at lower wavelengths) of this magnitude. In view of the uncertainties and discrepancies in the UV flux data and the observed variations in the atmospheric parameters (for example, stratospheric O_3 and temperature) that could be caused by UV variability, it is desirable therefore to determine theoretically the effects that may be associated with solar UV variability. Stratospheric O_3 and temperature structure are currently of particular interest.

Preliminary studies have been conducted of the effect on O_3 and thermal structure of the UV flux variability associated with the 27-day solar rotation and the 11-year solar cycle (*10, 11*). These studies indicate that the effect on the thermal structure is determined primarily by changes in the direct UV heating of the O_3 layer and to a lesser extent by changes in the O_3 concentrations. Changes in O_3 are due to both photochemical and thermal effects. Increases in the UV flux, for $\lambda < 0.300$ μm, lead to a net increase in the photochemical production and hence concentration of O_3. These increases are offset in part by the increased temperatures, which reduce the O_3 concentrations [see (*12*) for a discussion of this effect]. These interactions have been included in the present radiative-convective-photochemical (RCP) study of the effects of UV flux variability on the stratosphere.

The results of the study by Callis and Nealy (*11*), together with the investigations of temperature and O_3 data by Angell and Korshover (*3, 4*) and Quiroz (*5*), suggest that the O_3 increase in the 1960's and the decrease subsequent to 1970 may be due to the solar activity associated with the 11-year solar cycle. Our study differs from the work of Callis and Nealy (*11*) in the models used and the flux perturbations studied (*13*). In this work we used the UV flux variations shown in Fig. 1a, reported by Heath and Thekaekara (HT) (*7*), and a modification (MOD) of this variation (*14*) in a time-dependent, RCP model (*13*) to determine the stratospheric O_3 and temperature variations over an 11-year solar cycle. On the basis of the studies of Callis and Nealy (*11*), variations in the observed O_3 column sum and temperature above 32 km are

0036-8075/79/0622-1303$00.50/0

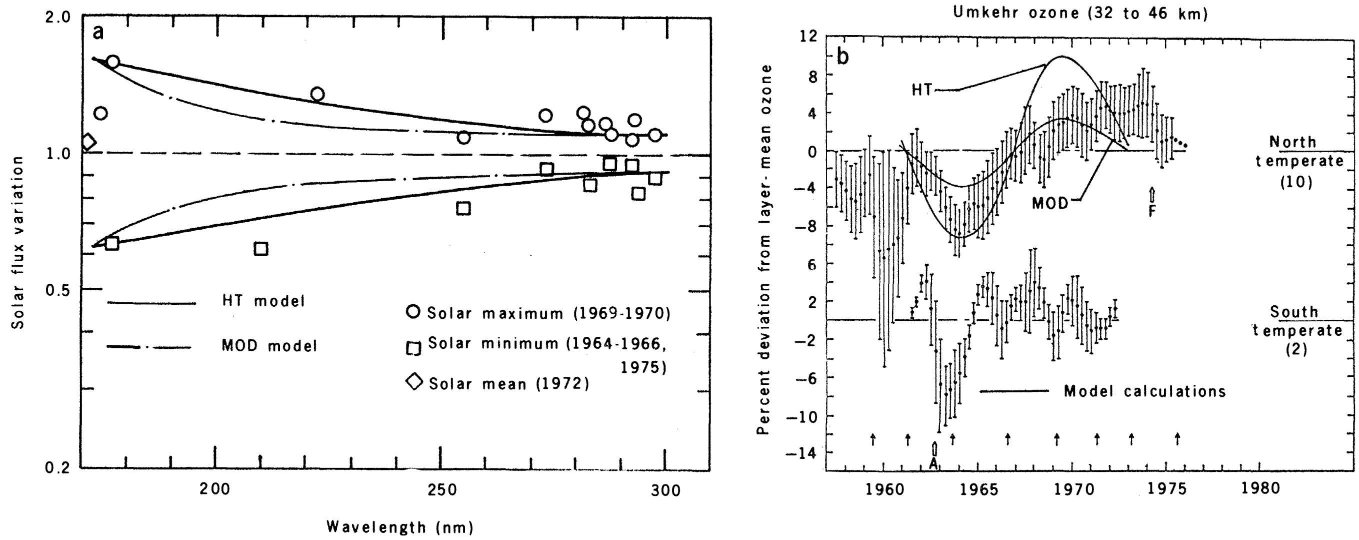

Fig. 1. (a) Solar flux perturbation factors, at solar maximum and solar minimum, as a function of wavelength. Open symbols represent data taken during balloon, rocket, and satellite flights (*7, 24, 25*). The solid curve is the solar variability model proposed by Heath and Thekaekara (*7*), and the broken curve is a modification of this model. These UV flux variations are assumed to occur sinusoidally with a period of 11 years. Ambient UV fluxes used in the model are taken to be those reported by Ackerman (*25*) as modified by Simon (*26*). (b) Comparison of calculated and observed O_3 variations between 32 and 46 km for the period 1962 to 1973. Small arrows (at the bottom) indicate the occurrence of the quasi-biennial oscillation; open arrows indicate the occurrence of volcanic eruptions [Agung (*A*) and Fuego (*F*)]. Data are from Angell and Korshover (*3*).

taken to be the most reliable indicators of solar UV activity for $\lambda < 0.300$ μm. Above these levels at the temperate and lower latitudes, O_3 and temperature are primarily in photochemical and radiative equilibrium and should more readily reflect any variations in the UV flux. Below 32 km, O_3 and temperature variations are subject to the complicating influences of transport in the lower stratosphere and upper troposphere.

Resultant RCP model calculations of stratospheric temperature and O_3 column sum variations between 32 and 46 km are shown in Fig. 1b and Fig. 2, a and b, for both UV variability models. Calculated O_3 values are superposed in Fig. 1b on Umkehr data reported and analyzed by Angell and Korshover (*3*). The O_3 comparisons are shown only for the north temperate zone since data from only two stations are available in the south temperate zone. The globally averaged model calculations simulate the O_3 variation, due to the reported (and assumed) UV flux variations (see Fig. 1a) occurring during the last 11-year solar cycle. The model-determined variations are representative of the temperate latitudes and the agreement with observations is generally good, especially for the modified UV flux variability model. Calculations indicate that minimum and maximum O_3 concentrations occur slightly after the solar minimum (1964) and maximum (1969), respectively. The data indicate a minimum in the O_3 in 1964 followed by a broad maximum beginning in 1970 which extends to 1974.

Figure 2a illustrates temperature differences (from solar minimum to solar maximum) determined with the model compared to data reported by Zlotnik and Rozwoda (*15*). The observed temperature variations were determined from Fort Greely (64°N, 145°W) rocketsonde data for the period 1964 to 1971. Despite the differences in the profiles, the similarities are noteworthy. The maximum temperature deviation for both the model calculations (using the HT data) and the observations is 14°K. For the modified flux perturbation, the maximum deviation is 10°K. The altitude of the maximum deviation is 46 km for calculations based on HT data, 43 km for MOD data, and 40 km for the observations. Trends above and below the maximum, for both the model results and the data, are the same. Differences may be attributed to the fact that a comparison is being made of globally averaged model results with data from a single rocketsonde station. Moreover, the rocketsonde data may include dynamical heating effects which cannot be removed with the information available. The O_3 distributions at these latitudes are due mainly to transport. However, any temperature variations due to UV flux variability would result primarily from variations in the UV heating of the O_3 layer. In the absence of increased UV heating, for example, the O_3 increases from solar minimum to solar maximum provide a maximum temperature increase of only 2° to 3°K compared with 14°K with the heating included. Both Zlotnik and Rozwoda (*15*) and Quiroz (*5*) include only summertime data in their analyses, thus minimizing the effect of dynamics in the observed temperature variations.

Figure 2, b through d, illustrates the time history of the temperature deviation from the mean averaged over two altitude bands and at the 35-km level. Comparisons are between model results and the data reported by Angell and Korshover (*4*) and by Quiroz (*5*). Results are in excellent agreement, in both phase and amplitude, with the data for the level from 26 to 35 km (Fig. 2c) and with the data for the 35-km level (Fig. 2d). For the level from 35 to 45 km (Fig. 2b) there is general agreement for model results based on the use of the HT data, once allowance is made for the temperature deviations due to the quasi-biennial oscillation. Calculations based on the MOD UV flux perturbation are in good agreement with the observations from 35 to 45 km. The model results, however, show larger temperature variations at 50 km than results reported by Quiroz (*5*) (not shown). The reason for this overprediction is not clear. It may be due to the fact that the upper boundary of the model is taken to be 55 km, which precludes the inclusion of effects due to Lyman-α flux variation at higher levels. The omission of this variation at levels above the model upper boundary could result in an overprediction of O_3 and thus temperature variations from 50 to 55 km. The overall temperature trends are remarkably well reproduced, especially by model results based on the use of the smaller UV flux perturbations (MOD data).

Temperature variability in the stratosphere, associated with the 11-year solar cycle, has also been reported by Schwentek (*16*), but he found it to occur only during the wintertime. Ramakrishna and Seshamani (*17*) reported a strong positive correlation between temperature and the 10.7-cm flux in the lower mesosphere. Fritz and Angell (*18*) also investigated stratospheric temperature variations during the period 1964 to 1970 and found no simple relationship between UV variability and stratospheric temperatures. However, as they noted, the data showed anomalous behavior in the upper levels.

The results of the simulations, when compared with the O_3 and temperature data presented, suggest that the O_3 and temperature variations observed during the 1960's and the first half of 1970 are due to the mechanisms associated with the variation of the solar UV flux during the 11-year solar cycle as discussed by Callis and Nealy (*11*). The agreement between the calculated and observed amplitude and phase of the temperature variations is good, especially for the MOD UV flux model. For O_3 there is general agreement between 1962 and 1972, with the amplitude of the observations lying between the MOD and HT simulation results. There are significant differences between the calculated and observed O_3 concentrations prior to 1962 and after 1972, and the lack of agreement cannot be satisfactorily explained.

Not all solar cycles exhibit a uniform degree of activity as determined by sunspot number (or other indicators of solar activity) (*19*), and the relationship between solar activity and UV flux is not at all well established. Furthermore, there are many other natural phenomena that may induce either subtle or large O_3 variations during the course of a year. An example of such a phenomenon is the atmospheric absorption of galactic cosmic rays. Ruderman and Chamberlain (*20*) and Ruderman *et al.* (*21*) have discussed the modulation of global O_3 due to the variation of galactic cosmic rays during the solar cycle. They suggested, however, that this mechanism cannot quantitatively explain the 11-year O_3 variation because of the insufficient production of nitrogen atoms. Other phenomena which may modulate global O_3 are solar proton events and dynamic effects such as sudden stratospheric warmings, the quasi-biennial oscillation, and tropospheric synoptic effects (*1, 3, 22*). In addition, it has been suggested that trends derived from Umkehr O_3 measurements may be subject to error (especially between 1963 and 1965) as a result of variable amounts of stratospheric dust and aerosols (*23*).

All of these factors, which are difficult to take into account, will act to establish the phase and amplitude of the observed O_3 and temperature variations. They will also affect the extent to which the analysis of a single phenomenon, such as UV flux variability, yields results that are in agreement with observed and reported data. However, it is important to note that the significant atmospheric temperature variations discussed by Angell and Korshover (*4*), Quiroz (*5*), and other investigators (*15–18*) require not only significant O_3 changes (of the magnitude discussed here) but also significant changes in the solar UV flux, which provide the required stratospheric heating rates from 35 to 45 km. Thus the variation of solar UV flux, in phase with solar activity, appears to provide a mechanism that is able to reconcile trends observed since the middle 1960's in both the O_3 and the temperature data. Although comparisons with the data are consistent with this contention, more comprehensive and consistent data on the variation of stratospheric O_3, temperature, and the solar UV flux for $\lambda < 0.300$ μm are required before the question can be definitively resolved.

LINWOOD B. CALLIS

NASA Langley Research Center, Hampton, Virginia 23665

MURALI NATARAJAN

George Washington University at NASA Langley Research Center

JOHN E. NEALY

NASA Langley Research Center

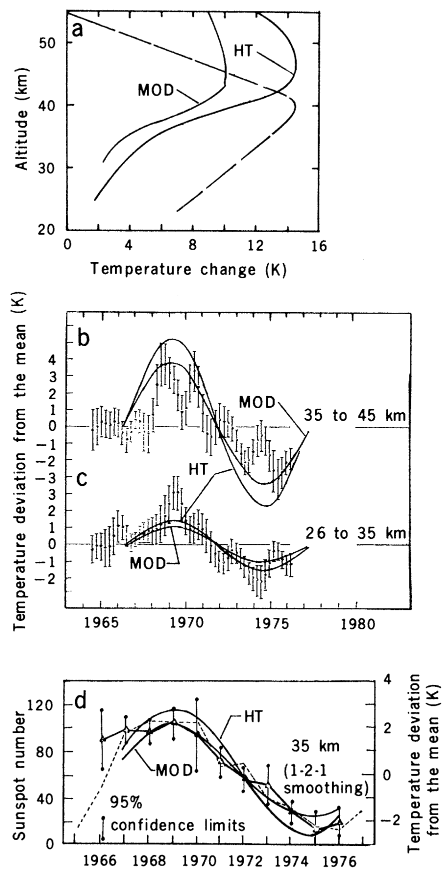

Fig. 2. (a) The temperature increase from solar minimum to solar maximum (1964 to 1969) as a function of altitude for model calculations (solid lines) and rocketsonde data from Fort Greely (dashed line) reported by Zlotnik and Rozwoda (*15*). Rocketsonde data used in the analysis were taken from 1964 to 1970 at the same time of day. Data from winter months were excluded. (b and c) Time histories of the average temperature deviation for the altitude bands 35 to 45 km and 26 to 35 km, respectively. Comparisons are with model results based on the two UV flux variation models. Short-term (2 to 3 years) fluctuations are due to the quasi-biennial oscillation. Temperature data are taken from Angell and Korshover (*4*). (d) Time history of sunspot number and the temperature deviation from the mean. Comparisons are with model results based on the two UV flux variation models. Both model results and data have been smoothed with a 3-year running average (with 1-2-1 weighting). Data are from Quiroz (*5*).

References and Notes

1. W. D. Komhyr, E. W. Barrett, G. Slocom, H. K. Weickmann, *Nature (London)* **232**, 390 (1971).
2. J. London and J. Kelley, *Science* **184**, 987 (1974).
3. J. K. Angell and J. Korshover, *Mon. Weather Rev.* **106**, 725 (1978).
4. ——, *J. Atmos. Sci.* **35**, 1758 (1978).
5. R. S. Quiroz, *J. Geophys. Res.*, in press.
6. W. J. Humphreys, *Astrophys. J.* **32** (No. 2), 97 (1910); H. C. Willett, *J. Geophys. Res.* **67**, 661 (1962); J. London and S. Oltmans, *Pure Appl. Geophys.* **106–108**, 1302 (1973); J. London and M. Haurwitz, *J. Geophys. Res.* **68**, 795 (1963); G. M. B. Dobson and D. N. Harrison, *Proc. R. Soc. London* **110**, 660 (1926); R. S. Steblova, *Geomagn. Aeron.* **8** (No. 2), 299 (1968); H. U. Dutsch, in *World Survey of Climatology*, D. F. Rex, Ed. (Elsevier, Amsterdam, 1969), vol. 4, p. 383; J. K. Angell and J. Korshover, *Mon. Weather Rev.* **104**, 63 (1976).
7. D. Heath and M. Thekaekara, *NASA Tech. Mem. X-71172* (1976).
8. P. C. Simon, *Planet. Space Sci.* **26**, 355 (1978).
9. S. Rangarajan, *Nature (London)* **206**, 497 (1965).
10. J. E. Frederick, *Planet. Space Sci.* **25**, 1 (1977); J. E. Nealy, L. B. Callis, M. Natarajan, *Eos (Trans. Am. Geophys. Union)* **58**, 1200 (1977); J. E. Penner and J. Chang, *Geophys. Res. Lett.* **5**, 817 (1978).
11. L. B. Callis and J. E. Nealy, *Geophys. Res. Lett.* **5**, 249 (1978); paper presented at the 18th meeting of the Committee on Space Research, Tel Aviv, June 1977.
12. J. J. Barnett, J. T. Houghton, J. A. Pyle, *Q. J. R. Meteorol. Soc.* **101**, 245 (1975).
13. The present work was carried out with a time-dependent, radiative-convective-photochemical model allowing self-consistent calculations of members of the O_x-NO_x-HO_x-Cl_x families and temperature structure. The RCP model is a result of combining the time-dependent model reported by M. Natarajan [thesis, State University of New York, Stony Brook (1976)] and the radiative code described by V. Ramanathan [*J. Atmos. Sci.* **33**, 1330 (1976)]. We assumed in the calculations that equilibrium exists between the CO_2, H_2O, and O_3 distributions and the stratospheric temperatures. The model includes 84 kinetic and 25 photochemical reactions. Profiles of CH_4 and H_2O are held fixed. Rate constants are those recommended by R. D. Hudson [*NASA Ref. Publ. 1010* (1977)]. The eddy diffusion coefficient is a modified version of that reported by D. M. Hunten, as shown by H. S. Johnston, D. Kattenhorn, G. Whitten [*J. Geophys. Res.* **81**, 368 (1976)]. In the radiative code, the CO_2 mixing ratio is specified to be constant at 320 parts per million (by volume). The stratospheric H_2O vapor content is also held constant, with values used typical of those observed in the stratosphere. In addition to the present calculations, the RCP model has been used in the steady-state mode to determine the effect of UV flux changes on surface temperature. Although a discussion of this effect is beyond the scope of this report,

the result may be of interest. The surface temperature was found to decrease by 0.11°K, from solar minimum to solar maximum, with flux changes described by the HT UV flux model. These results will be discussed elsewhere (L. B. Callis, M. Natarajan, J. E. Nealy, in preparation). Callis and Nealy (*11*) used a much simpler photochemical scheme (19 species, 41 reactions) than that used here and examined the effects of stepwise constant perturbations in the spectral solar UV flux of varying size rather than the continuous distributions shown in Fig. 1. Differences in results are attributed to a combination of these effects. Qualitatively, the results are the same.

14. Because of the difficulty in making the UV flux measurements and the lack of consistent coverage in time during the solar cycle, the error bars associated with the UV flux variability model postulated by Heath and Thekaekara (*7*) must necessarily be large. Therefore, two variations (see Fig. 1a) of the UV flux were used for the present analysis, that reported by Heath and Thekaekara and a modification of of this variation. The use of two flux perturbation distributions provides a comparison which illustrates the sensitivity of O_3 and temperature results (as a function of time and altitude) to such variations.

15. B. Zlotnik and W. Rozwoda, *Artificial Satellites* (Polac Kulturyi Nauki, Warsaw, 1976), vol. 11, p. 55.
16. H. Schwentek, *J. Atmos. Terr. Phys.* **33**, 1839 (1971).
17. S. Ramakrishna and R. Seshamani, *ibid.* **35**, 1631 (1973).
18. S. Fritz and J. K. Angell, *J. Geophys. Res.* **81**, 1051 (1976).
19. J. A. Eddy, *Science* **192**, 1189 (1976).
20. M. A. Ruderman and J. W. Chamberlain, *Planet. Space Sci.* **23**, 247 (1975).
21. M. A. Ruderman, H. M. Foley, J. W. Chamberlain, *Science* **192**, 555 (1976).
22. J. W. Chamberlain, *J. Atmos. Sci.* **34**, 737 (1977); G. C. Reid, I. S. A. Isaksen, T. E. Holzer, P. J. Crutzen, *Nature (London)* **259**, 177 (1976).
23. J. J. Deluisi, *J. Geophys. Res.*, in press.
24. D. Heath, *ibid.* **78**, 2779 (1973).
25. M. Ackerman, *Mesospheric Models and Related Experiments* (Reidel, Dordrecht, Netherlands, 1971), p. 149.
26. P. C. Simon, personal communication.

27. We thank J. K. Angell, J. Korshover, and R. S. Quiroz for making available the temperature and O_3 data prior to publication.

23 August 1978; revised 6 February 1979

Solar Constant: Constraints on Possible Variations Derived from Solar Diameter Measurements

Abstract. *Climatically significant variation of the solar constant (the energy output of the sun) implies measurable change in the solar radius. The available data limit variations of the solar radius between 1850 and 1937 to about 0.25 arc second; modeling of the sun indicates that the solar constant did not vary by more than 0.3 percent during that time.*

The sun is the predominant energy source for the terrestrial climate. It follows that an important step in an analysis of climatic change is a study of the changes, if any, in the sun's radiant energy output (the solar constant, S). Numerical models of the terrestrial climate indicate that the climate is, indeed, very sensitive to changes in S. However, reliable climatic simulations are difficult to construct because of the complicated feedback mechanisms involved in climatic change, and the present state of the art requires that the model predictions be treated with some caution (*1*). For this reason, historical data on possible variations in S, coupled with data on the climate for the corresponding periods, would be valuable in testing the climate models.

Direct measurements of S from within the atmosphere are difficult to make because of the large and variable absorption by the atmosphere. Two well-known studies have concluded that S has varied at about the 1 to 2 percent level within this century (*2, 3*), but these studies have been questioned because of the problems of atmospheric absorption and long-term calibration. Furthermore, variability at this level would indicate that the climate models are substantially in error since these models predict that such changes in S would cause climatic variations much greater than any that have, in fact, been observed (*4*). Space observations carried out in the last two decades have not detected significant variations in S (*5*). However, because of their limited accuracy (approximately 0.5 percent) and the short time span covered, these measurements cannot exclude the possible existence of long-term trends. Thus, long-term variations in S at the 1 to 2 percent level cannot be ruled out, and an independent check is highly desirable. Such an independent check can be provided by historical and recent measurements of the sun's diameter. We will show that historical diameter measurements constrain possible S variations to $\Delta S/S < 0.3$ percent for the period 1850 to 1937, and that current astrometric instrumentation could determine diameter changes corresponding to S variations as small as $\Delta S/S = 0.01$ percent.

In the outer layers of the sun, energy is transported from the interior to the surface by repeated emission and absorption of photons. The rate of this radiative diffusion of energy is governed by the temperature gradient. If S (and hence the diffusion rate) increases, the temperature gradient in the outer layers must also increase. This latter increase will be accompanied by other structural changes since the sun must maintain global hydrostatic equilibrium on time scales significantly longer than 1 hour (*6*). In general, a short-term increase in S will result in an increase in the solar radius, as will be discussed below. The magnitude of the change in radius corresponding to a given change in S must be determined by numerical solutions of the time-dependent equations of energy transport and hydrostatic equilibrium.

We define W as the ratio of fractional change in radius to fractional change in S

$$W = \frac{\Delta R/R}{\Delta S/S}$$

The value of W will, in general, depend on the nature of the change in the sun's structure that gives rise to a change in S; so, ideally, the physical mechanism responsible for the change should be specified and explicitly modeled. In practice, this is not possible since the mechanism is not known. Instead, we adopt the procedure of specifying (on physical grounds) the depth in the sun at which the perturbation arises and the time scale on which it occurs. We emphasize that these two parameters are not independent and, furthermore, that the time scale is constrained by the time period over which changes in S (or lack thereof) are observed.

The changes in S implied by the studies of (*2, 3*) apparently occur over periods shorter than 10^2 years and we adopt this as the relevant time scale. This immediately rules out any possible changes in the core of the sun since such changes require approximately 10^6 years (the photon diffusion time) to propagate to the surface and the change in S would be spread out over a similar time scale. This forces us to look closer to the surface.

The outer layers of the sun are unstable to convective motions, with the convective region extending from the surface to about 12 percent of the distance to the center. The thermal time scales (*6*) in the convective region range from about 2×10^4 years at the bottom to essentially zero near the surface. Over most of this region, convection is very efficient and carries essentially 100 percent of the thermal flux. Since the temperature gradient is nearly adiabatic (and will remain so for any reasonable changes in the convective flows), it is difficult to imagine a perturbation in this region that would lead to a substantial change in S. Near the surface (at a depth of less than 1 percent of a solar radius), the convection becomes less efficient because of the decreasing density, and radiative transport becomes increasingly important. A change in the efficiency of convection here would change the flux of energy carried by radiative diffusion, and