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Modelling the Climatic Response to Solar Variability [and Discussion]

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Modelling the climatic response to solar variability

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The Sun, the primary energy source driving the climate system, is known to vary in time both in total irradiance and in spectral composition in the ultraviolet. According to solar interior evolution models, the solar luminosity has increased steadily by 25–30% over the past 4×10^9 years. Periodic variations are also suspected with characteristic timescales of 11 or 22 years, 80–90 years and possibly longer periods. The ultraviolet radiation below 300 nm also exhibits significant changes over the 27-day solar rotation period as well as the 11-year solar cycle.

Variations in the solar constant are expected to produce both direct and indirect (feedback) perturbations in the global surface temperature. A hierarchy of zero- to three-dimensional models have been used to study the complex couplings involved by such effects. The response of a zonally averaged model to possible total irradiance changes associated with the Gleissberg cycle is investigated and compared with measurements of the sea-surface temperature made since 1860.

Changes in the solar ultraviolet irradiance modulate the amount and distribution of atmospheric ozone, which is predicted to change by several percent in the stratosphere. These perturbations directly affect the middle atmospheric thermal structure, but may also generate indirect effects that could possibly account for some short-term geophysical signatures of solar activity. The cycle-modulated energetic particle interaction with the middle atmosphere is also a possible source of global climatic perturbations.

Introduction

The growing concern about climatic changes induced by anthropogenic perturbations of the energy balance of the planet has prompted a re-examination of the natural causes of climatic variability. The most extensively studied of the external varying forcings is the change in solar insolation due to the periodic changes in the orbital characteristics of the Earth's motion (Milankovitch theory). In addition to these effects, intrinsic variations of the solar output have also been observed and have become increasingly well documented through the use of space-borne instruments. Variations in the total solar irradiance and in the short-wavelength portion of the solar spectrum on timescales from seconds to years have been observed and modelled during the past 10 years. Longer-term variations are also suspected, but proxy data and/or solar physics modelling are the only means of investigating long-period modulations.

In this paper, I summarize the available evidence for intrinsic solar variability and describe the climatic consequences of such variations as predicted by current models. I present model calculations of the possible temperature signature of the Gleissberg solar cycle and climatic effects of ultraviolet irradiance variations and intense solar charged particle interaction with the Earth's atmosphere.

Variability of the total solar irradiance

One of the key questions in climate prediction and interpretation of palaeoclimates concerns the importance of the intrinsic solar luminosity changes in time and the response of the climate system to these variations of energy input.

Stellar evolution theories, based on firm theoretical physical grounds, predict a steady increase of the solar luminosity on a timescale of thousands of millions of years. This change in total solar irradiance is an unescapable consequence of the conversion of hydrogen into helium during the Sun's evolution on the main sequence. Sun interior models predict that the solar luminosity increased almost linearly by about 25–30% in 4.5×10^9 years. Climate models classically indicate that if the solar constant is decreased by a few percent, the ice-albedo feedback resulting from the temperature drop is strong enough to destabilize the system and produce a completely ice-covered Earth. This configuration with ice-caps extending to the Equator is fairly stable and solar luminosities well in excess of the present value would be required to unfreeze the planet. Various scenarios have been proposed to explain the long-term apparent stability of the past climate. One is based on the enhanced greenhouse effect due to larger atmospheric CO_2 concentrations at the early phases of the planet's history (cf. Gérard 1989). No numerical model of the CO_2 global cycle extending far enough in distant past has been developed so far. However, Marshall *et al.* (1988) showed that the reduced extent of the total continental area and the subsequent smaller silicate weathering rate could have resulted in a larger content of the atmospheric CO_2 reservoir than presently. The resulting positive heat increment would have maintained the globally averaged temperature at a sufficient value to prevent complete freezing.

The short-term variability of the solar output is increasingly better observed by sensitive space-borne instruments measuring total solar irradiances over periods of years with excellent stability (P. Foukal, this Symposium). These measurements indicate that, in addition to the blocking effect of sunspots and its compensation by facular energy release, a positive correlation is observed between the solar output and 11-year solar cycle (Willson & Hudson 1988). For solar cycle 22, a total variation of about 1 W m^{-2} was observed with the ACRIM instrument, corresponding to a peak to peak variation of about 0.09%. Because of the limited timespan of accurate solar radiometric data, a direct assessment of the presence and amplitude of longer periodicities is presently impossible.

Proxy data and indirect evidence need to be used for longer periods and, consequently, lead to speculative and more qualitative results. The best-documented and probably most widely used indicator is the sunspot index time series, which dates back to 1700. This time series was extensively studied by using various analysis methods (cf. Berry 1987; A. Berger, J. L. Mélice and I. van der Mersch, this Symposium). Besides the ubiquitous 11-year periodicity, an amplitude modulation of this cycle by an 80–90-year component (the 'Gleissberg cycle') has been suggested by various studies of the sunspot index series. A 180-year period was also indicated by some analysis but the length of the record and the intrinsic noise do not allow an unambiguous identification of these long periods. Support for the existence of a Gleissberg cycle signature in proxy data mostly originates from indirect climate records, auroral activity and isotropic composition measurements of ice cores. Observations of 80–90 periodicities in the diameter of the Sun have been identified (Gilliland 1981). Ribes *et al.* (1987) indicate that the solar radius was larger and the rotation slower during the Little Ice Age associated with the

Maunder Minimum. The analysis of the thermoluminescent profile of a recent sedimentary core spanning a period of over 18 centuries shows the presence of four main periodicities. The sum of the two low-frequency signals may be considered (Cini Castagnoli *et al.* 1988) as a 82.6-year period component modulated by a second wave with a period of 206 years. The location of the last two maxima corresponds fairly well with the dates of past solar diameter maxima, suggesting a possible link between the two sets of observations.

In summary, converging evidence suggests the existence of a variability of the solar total irradiance with periods of *ca.* 11 years, 80–90 years and possibily longer characteristic times. The reality of claimed statistical Sun–climate correlations and the search for physical mechanisms linking the solar radiative and corpuscular 11- or 22-year cycle to climatic effects has been a subject of considerable debate and speculation (Pittock 1978, 1983). We now concentrate on the description of the global temperature variations induced by changes in the total solar energy input to the climate system.

Global climate sensitivity

The sensitivity of climate models to radiative perturbations (including changes in solar output) is frequently expressed as the sum of a direct radiative response and various indirect contributions (feedbacks). Major feedbacks include the effect of the surface-albedo response to changes in surface temperature (extent of the polar ice and snow cover and vegetation changes), water vapour content of the atmosphere, vertical temperature lapse rate, cloud temperature and optical depth. In the study of climate model sensitivity to solar constant variations, it is of common use to specify the sensitivity parameter β defined as

$$\beta = S\,\mathrm{d}\bar{T}_s/\mathrm{d}S,$$

where S denotes the total solar irradiance and $\bar{T}_s$ the globally averaged mean surface temperature. Another global feedback parameter λ (Dickinson 1985) was also introduced to characterize the relative importance of direct and indirect forcing factors on the global response. This parameter links the perturbations in the global surface temperature ΔT_s to an externally prescribed change in the net radiative flux across the tropopause ΔQ:

$$C\,\partial(\Delta T_s)/\partial t + \lambda \Delta T_s = \Delta Q,$$

where C denotes the system heat capacity. The total sensitivity factor λ may be considered as the summation of a blackbody sensitivity $\lambda_B (= 3.75\ \mathrm{W\,m^{-2}\,°C^{-1}})$ and other contributing feedback factors:

$$\lambda = \lambda_B + \sum_i \lambda_i.$$

The main components λ_i are the ice–albedo and the water–vapour feedback. Another potentially important contribution to λ is the cloud-albedo feedback. However, conflicting results have been obtained about the cancellation of the albedo and long-wave absorption effects resulting from perturbations of the physical characteristics of the clouds. A classical and useful test of a model sensitivity is to change the solar constant by 1% and calculate the resulting steady-state surface temperature perturbation $\Delta\bar{T}_s$.

A hierarchy of simple to very sophisticated models have been developed, mostly as a response to the growing concern about climate perturbations induced by the anthropogenic production of radiatively active trace gases. The simplest (zero-dimensional) model expresses radiative equilibrium between the global surface emitting as a blackbody and absorption of solar radiation,

$$4\pi R_E^2 \sigma T_e^4 = S(1-a)\,\pi R_E^2, \tag{1}$$

where R_E is the Earth radius, T_e the effective radiating temperature of the planet, a the global planetary albedo and σ the Stefan–Boltzman constant. In this approximation, the sensitivity parameter β is simply equal to $\frac{1}{4}T_e \approx 64$ °C, implying a temperature change of 0.6 °C for a 1 % variation of the solar irradiance. This value is generally used as a reference to quantify the importance of feedbacks.

One-dimensional models are classified as zonally averaged (ZA) energy-balance models (EBMS) if the spatial coordinate is latitude and radiative–convective (RC) models if variables depend explicitly on the vertical dimension (altitude or pressure). Two-dimensional models consider both altitude and latitude explicitly, whereas three-dimensional models (GCMS) solve the full coupled energy, momentum and mass conservation equations. The heat storage and spatial redistribution by the ocean is parametrized by using various degrees of complexity ranging from box models, which may include eddy mixing (BDOMS), advection and diffusive mixing (BADOMS) to three-dimensional representations.

TABLE 1. CLIMATE MODEL SENSITIVITY TO THE TOTAL SOLAR IRRADIANCE VARIATIONS

model type	authors	β parameter/°C
zero-dimensional		
black body		64
EMB[a]	North *et al.* (1981)	112
one dimensional		
EBM[b]	North *et al.* (1981)	160–400
RC	Manabe & Wetherald (1967)	128[a]
RC	Cess (1974)	125[a]–231[b]
RC	Ramanathan (1976)	121[a]–197[b]
RC	Wang & Stone (1980)	110[a]–188[b]
RC	Gérard & François (1988)	93[a]–233[b]
ZA	Thompson & Schneider (1979)	145[a]–230[b]
ZA	Harvey (1988)	168[b]
two dimensional		
	Peng *et al.* (1982)	155[a]
three dimensional		
GCM	Wetherald & Manabe (1975)	180[b]
GCM	Wetherald & Manabe (1980)	205[b]
GCM	Hansen *et al.* (1984)	205[b]

[a] No surface-albedo feedback.
[b] With surface-albedo feedback.

Table 1 lists the value of β obtained with various classical or recent models of each category. The predicted temperature increases for a 1 % change of the solar constant and no ice-albedo–temperature feedback is of the order of 1.1 ± 0.2 °C, a value nearly twice as large as the pure blackbody case. The difference stems mostly from the water–vapour feedback: increased contents of atmospheric H_2O are associated with higher tropospheric temperatures as expressed by the Clausius–Clapeyron law. Surface-albedo–temperature feedback results from the decrease in the extent of the polar cap associated with a temperature increase (positive ice albedo feedback). Another possible component is the vegetation feedback associated with the changes of radiative, sensible and latent heat fluxes stemming from various land-surface processes.

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Secular variation of the surface temperature

Climatic models indicate that a global temperature increase of a few tenths of a degree could have occurred in this century as a result of the CO_2 increase due to extensive use of fossil fuel and the resulting enhanced greenhouse. Attempts to detect this climatic signature are based on the reconstruction of the recent records of near-surface continental air temperature (CAT), marine air temperature (MAT) and sea-surface temperature (SST). Reconstruction of these time series are made difficult by changes in the instrumentation and observing methods, presence of spurious measurements (sampling errors) and the intrinsic variability of the climate system. CAT and MAT compilations since 1850 were discussed by Jones *et al.* (1986). Over 46 million SST data from the British Meteorological Office Main Marine Data Bank were used by Folland *et al.* (1984) to estimate the magnitude of the temperature fluctuations for the period 1856–1981. The measurements concentrate at low and middle latitudes and various corrections were applied to account for changes in the sampling technique and experimental method. They found a worldwide temperature fluctuation of *ca.* 0.6 °C, with the coldest period centred around 1905–10 and the warmest values occurring in the 1940s. A three-dimensional plot of the 10-year mean of the temperature anomaly suggests the presence of a 80–90-year modulation reminiscent of the solar Gleissberg cycle (figure 1). The possibility of a climatic signature of the Gleissberg cycle was discussed by Gilliland (1982) and Reid & Gage (1987) using ocean box models. It is further discussed below on the basis of numerical simulations obtained with a zonally averaged seasonal model.

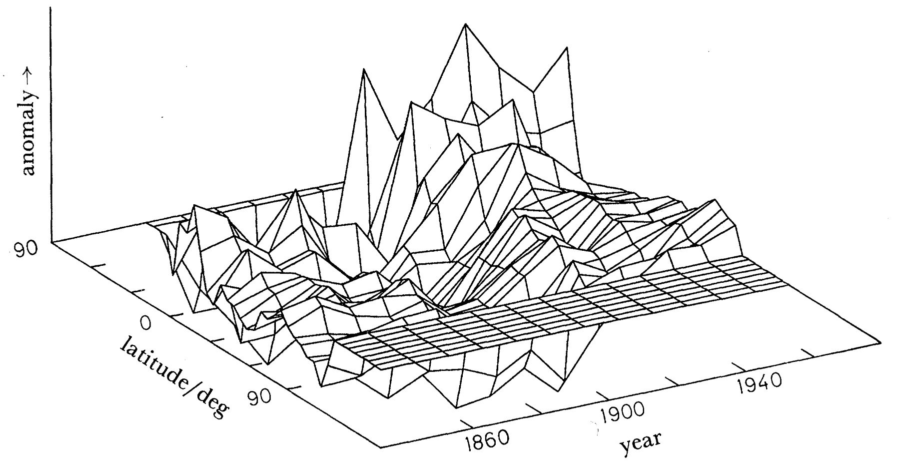

FIGURE 1. Three-dimensional plot of the 10-year average sea-surface anomaly from 1860 to 1980 determined by Folland *et al.* (1984). The empty high-latitude bins correspond to regions with insufficient data coverage.

The possible effect of the secular solar irradiance variability on the climate of the past 120 years is investigated using a two-layer zonally averaged model together with parametrized results from a radiative–convective model. The ocean model is composed of a variable-depth mixed layer overlying a deeper ocean layer with seasonal vertical heat exchange and latitudinal diffusion. This formalism was introduced by Thompson & Schneider (1979) and will only be briefly described here. The latitudinal grid extends from pole to pole in 5° latitude bins. The temperature of the top layer represents a composite between continental and oceanic surface temperatures. The bottom layer provides a thermal sink or source exchanging energy with the top layer over a prescribed annual cycle. It accounts for heat redistribution by vertical exchanges. The energy-balance equations of the two layers are written

$$\partial(RT)/\partial t = Q(1-a) - I - \operatorname{div}\phi + E \tag{2}$$

for the top layer, and

$$\partial(R_0\, T_0)/\partial_t = -E \tag{3}$$

for the bottom layer, where R and R_0 are the thermal inertias of the top and bottom layers respectively, T and T_0 the surface and bottom layer temperatures, Q the extraterrestrial insolation, a the planetary albedo, I the outgoing infrared radiation and ϕ the total meridional heat flux.

The expression of the last term E of equations (2) and (3) depends on the temporal variation of the effective thickness of the top layer:

$$E = T\partial R/\partial t \quad \text{if} \quad \partial R/\partial t < 0,$$

and

$$= T_0 \partial R/\partial t \quad \text{if} \quad \partial R/\partial t > 0.$$

The total thermal inertia in each bin R_t is constant in time and R is written as a sum of two time-dependent terms, which each correspond to one of the vertical layers:

$$R_t(\theta) = R(\theta, t) + R_0(\theta, t).$$

The values of the coefficients R_t and the R/R_t ratio are adjusted to best reproduce the observed seasonal variation of the zonally averaged surface temperatures. The amplitude of the seasonal exchange cycle between the two layers is derived from observations. In the context of the preceding section, the sensitivity parameter β of this model is equal to 145 °C.

I now discuss the parametrization of the secular variation of the total solar irradiance. Gilliland (1982) postulated a sinusoidal variation of the solar constant with a 76-year period shifted in phase by 19 years from the observed solar radius modulation. Reid & Gage (1987) assumed a linear relation between the sunspot index averaged over 11 years and the solar output. Schatten (1988) derived a linear expression between the value of S and the variation of the upper envelope of the sunspot number R_e. Figure 2 illustrates the percentage variation

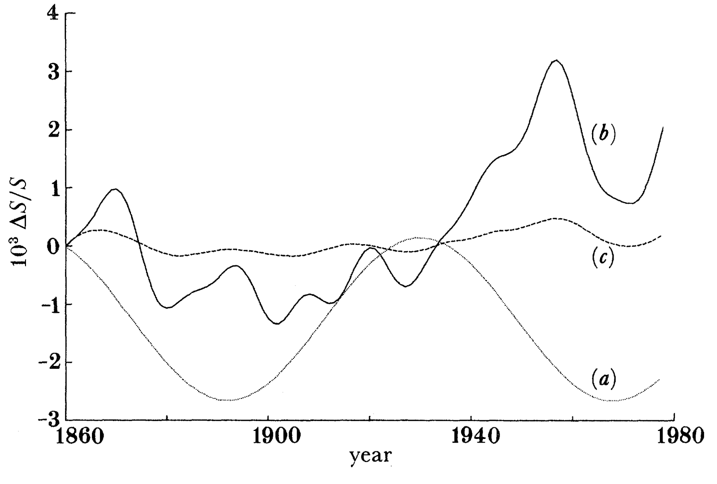

FIGURE 2. Example of assumed secular fractional variations of the solar constant $\Delta S/S$: (*a*) Gilliland (1982), (*b*) Reid & Gage (1987), (*c*) Schatten (1988). The three curves are normalized to a common value of the solar constant in 1860.

of the solar constant since 1860 proposed in these three studies. To test the plausibility of a solar modulation of the surface temperature, we adopt scenarios based on the last two assumptions:

$$S(t) = S_0 + \alpha S_0(\bar{R} - R_0) \tag{4}$$

and

$$S(t) = S_0 + \gamma(R_e - R_0), \tag{5}$$

where $\bar{R}$ is the 11-year mean sunspot number, R_0 and S_0 reference values for R and the total irradiance respectively. The coefficient α is a proportionality constant to be determined, whereas we use the value $\gamma = 7.5 \times 10^{-3}$ determined by Schatten.

The increase of atmospheric CO_2 of anthropogenic origin generates a time-dependent enhanced greenhouse effect that also affects the long-term evolution of the surface temperature. We adopt the observed CO_2 variation as parametrized by Hoffert *et al.* (1980). The time-dependent CO_2 greenhouse warming is simulated by including a dependence on CO_2 in the coefficient B of the infrared radiation term $I = A + BT$ of equation (2). This dependence was calculated by running a full radiative–convective model (Gérard & François 1988) for various values of the tropospheric CO_2 mixing ratio. The possible contribution of high-altitude aerosols of volcanic origin is neglected in this simulation.

Figure 3*a* illustrates the global mean (area-weighted) decadal temperature anomaly (with respect to the 1945–75 average) derived from Folland *et al.*'s data and the calculated values by using equations (2)–(5). The general trend of the SST variations deduced from the 10-year average data is reasonably well reproduced by the model (figure 3*b*) with the total irradiance variation given by (4) for values of α of the order of $0.7–1.3 \times 10^{-4}$. The temperature minimum observed near 1910 is predicted by the model as a consequence of the minimum of solar activity at the beginning of the twentieth century. The peak-to-peak total irradiance variation during this period if the simple dependence of equation (4) is correct, would be on the order of 0.8%, on a timespan of about 50 years. This amplitude is significantly larger than the *ca.* 0.1% variation associated with the current 11-year solar cycle, but may not be unreasonable over the longer period discussed here. The fairly steady SST temperatures observed after 1960 are also

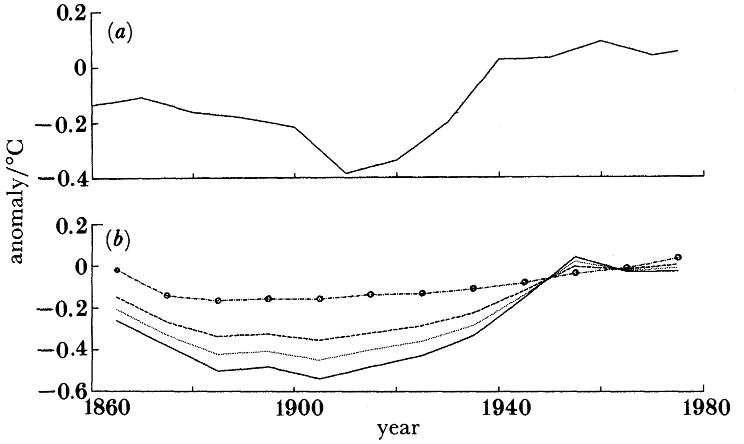

FIGURE 3. (*a*) Time-dependence of the globally averaged sea-surface temperature anomaly deduced from Folland *et al.*'s data. (*b*) Model calculation of the globally averaged anomaly evolution driven by the atmospheric CO_2 increase and assumed secular changes in the solar total irradiance. The four curves correspond to different solar forcing functions: ––––, equations (4), $\alpha = 7.5 \times 10^{-5}$; ······, idem, $\alpha = 1.1 \times 10^{-4}$; ——, idem, $\alpha = 1.4 \times 10^{-4}$; ○—·—○, equation (5), $\gamma = 7.5 \times 10^{-3}$.

well reproduced by the model with the functional dependence given by (4) for all three values of the parameter α represented in figure 3*b*. By contrast, the anomaly calculated by using (5) fails to exhibit the correct anomaly amplitude and the fairly constant value observed during the second part of the twentieth century. The amplitude of the solar constant variation in this case is less than 0.1 %, which explains the weak response of the average surface temperature calculated with this expression.

We thus conclude that, if the secular variation of SSTs observed since 1860 is of solar origin, a total solar irradiance of several tenths of a percent is needed to account for the *ca.* 0.6 °C observed temperature change. A similar conclusion was reached by Gilliland & Schneider (1984) using a seasonal 10-box energy-balance model with least-squares fitting of the amplitude and phase of various forcing functions. However, this observational data were based on hemispherically averaged air temperature over land instead of SSTs and involved several degrees of freedom.

The agreement obtained by using an expression such as (4) does however not imply any causal relation between the number of sunspots and the solar constant. It would merely suggest that a common physical mechanism modulates the amplitude of the 11-year sunspot cycle and the value of the total irradiance with a 80–90-year periodicity.

Solar ultraviolet cycles

Solar observations

The two dominant periodicities observed so far in the ultraviolet (UV) solar irradiance below 300 nm correspond to the 27-day solar rotation period and the 11-year solar cycle. The 27-day variability and its spectral dependence are increasingly well known (Lean 1987; Simon 1990). An analysis of the 27-day variations observed with the *Solar–Mesosphere Explorer* (*SME*) satellite and their dependence on the solar cycle using Fourier spectral methods was recently obtained by Simon *et al.* (1987). It shows that the amplitude of the 27-day modulation strongly depends on the phase of the solar cycle.

The wavelength dependence of the modulation of the solar UV irradiance over a solar cycle is much more uncertain. Satellite observations require a very good intrumental stability over several years of observations and corrections for sensitivity changes due to drift in surface reflections, transmission of optical elements, detector sensitivity, etc. Rocket observations carried out with similar instruments at different phases of the solar cycle do not guarantee identical observing conditions and calibrations. Nevertheless, a general view of the amplitude of the 11-year solar cycle may be obtained by synthesizing available observations obtained over the past 15 years or so (figure 4).

Below 102.5 nm, the *Atmosphere Explorer* database has been and is still the most widely used source of information for aeronomical modelling of the neutral and ionized upper atmosphere. The curve labelled AE-E refers to the corrected reference solar maximum and minimum spectra (21 REFW and F79050N) (Torr & Torr 1985). The variability in the wavelength region of the Schumann–Runge continuum deduced from the *AE* data by Torr *et al.* (1980) is also indicated. The LASP rocket observations were made between 1972 and 1977 (minimum) by Rottman (1981) and in 1979–80 (maximum) by Mount & Rottman (1981) using similar instruments and calibration techniques. The SBUV curve was deduced from an empirical relation based on the temporal variation of the ratio between core and wing

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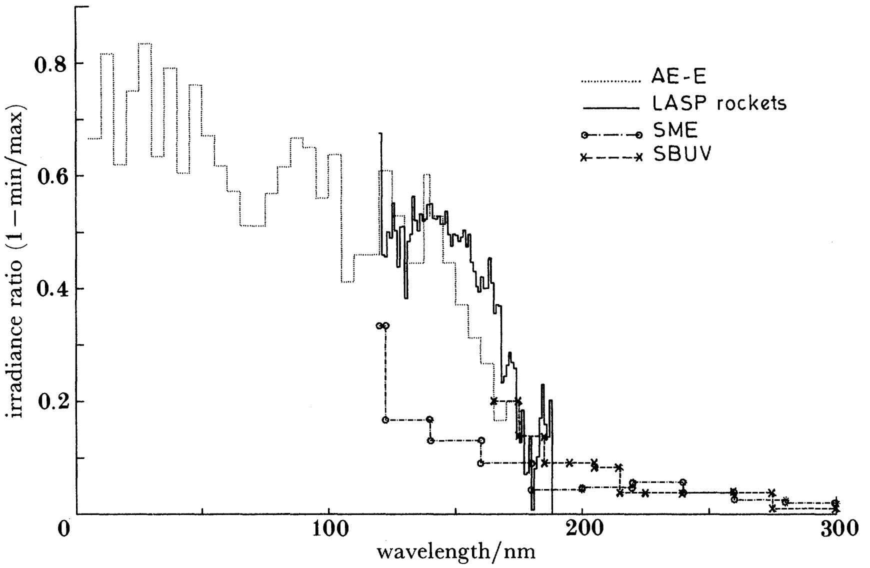

FIGURE 4. Wavelength dependence of the variability of the UV solar irradiance compiled from various satellite and rocket experiments.

irradiances of the MgII doublet at 280 nm and is thus not a direct measurement. This method was used because ageing problems of the instrument prevented the long-term observations to be used directly for solar sycle studies. The amplitude of the variability deduced from these observations is substantially larger than that derived from the *SME* mission. The UV solar spectrometer on board the *SME* satellite obtained solar spectra from 1982 to 1988 that exhibit a maximum: minimum ratio not exceeding 5% at 200 nm. The general behaviour of the UV solar spectrum during a solar cycle is a decreasing amplitude of variability from the X-rays to the visible. However, the exact quantitative wavelength dependence of this solar cycle variation is still debated in spite of major instrumental and calibration improvements. Virtually nothing is known concerning possible differences between individual solar cycles and the secular variability of the UV solar output.

The atmospheric response

The climate response of the middle atmosphere to UV solar variations has been observed with satellites and numerically simulated with various techniques. I briefly review its major characteristics.

The response of the middle atmosphere climatology to the 11-year solar cycle was studied in details by Brasseur & Simon (1981), Garcia *et al.* (1984) and more recently by Brasseur *et al.* (1988) using two-dimensional chemical–dynamical models. They calculate a maximum variation ranging between 2 and 3 °C near 50 km. The predicted variation depends on latitude (and season), the highest temperature changes being associated with the high-latitude summer regions.

At lower altitudes, the atmospheric temperature response decreases drastically, reaching less than 0.5 °C at 20 km. The ozone column variation between 1986 and 1979 is about 2% in

Brasseur *et al.*'s simulation (including also changes in trace gas concentrations) and reaches about 3.5% between solar maximum and minimum conditions in Garcia *et al.*'s model.

A part of the atmospheric response in Garcia *et al.*'s model is a result of the 11-year modulation of the ionization caused by the interaction of energetic particles with the high-latitude upper and middle atmosphere. The exact magnitude and the details of the changes in the contribution of the particle flux and energy spectrum of the precipitated particles are not well established. Of particular importance is the change over a solar cycle of the nitric oxide density in the lower thermosphere and in the mesosphere resulting from the N_2 impact dissociation by magnetospheric particles and the subsequent formation of NO molecules. These molecules flow downward with a higher efficiency in the polar night region and partly reach the stratosphere. Once in this region, they contribute to the catalytic recombination of ozone. The variability of the upper atmospheric NO source is predicted by two-dimensional studies of the distribution and downward flow of nitric oxide at solar minimum and maximum conditions (Gérard & Roble 1988). The results exhibit larger NO concentrations associated with high solar activity, in agreement with the *AE* and *SME* satellite observations. This thermospheric–stratospheric coupling may contribute to the seeked solar–climatic link.

As altitude decreases, the temperature structure becomes less and less sensitive to the direct effect of solar UV variations for two reasons. First, the increasing air mass density decreases the temperature variations associated with a given change of energy per unit volume. Secondly, only radiation above *ca.* 320 nm reaches the troposphere. This wavelength region exhibits unmeasurably small (less than 10^{-3}) fractional spectral variation. As described before, the total irradiance variations observed in the visible and near infrared (IR) affect the energy balance of the troposphere and the surface rather than the photochemistry. Therefore, only indirect mechanisms may influence the tropospheric climate. A wealth of such processes have been proposed to explain the claimed correlation between climatic or meteorological effects and the solar output. The reader is referred to the excellent reviews by Pittock (1978, 1983) on this subject. Taylor (1986) discussed possible links between solar wind and climatic short-term processes.

Reductions of the amount of atmospheric ozone produces competing effects on the thermal structure. More solar (visible and UV) radiation reaches the troposphere and the surface temperature tends to increase. However, this effect is counteracted by a cooling of the stratosphere and a subsequent drop of the downward flux of infrared radiation to the surface. This downward flux is further decreased by the reduction of the greenhouse efficiency in the 9.6 μm band. Numerical experiments have shown that the IR cooling effect dominates the surface solar warming by about an order of magnitude.

The climatological influence of ozone perturbations on the global surface temperature was analysed quantitatively by using radiative–convective models (Reck 1975; Wang *et al.* 1980; François 1988). A general conclusion of these studies is that a decrease of ozone in the troposphere and lower stratosphere cools the surface as a consequence of the reduced greenhouse efficiency. The predicted response of the higher-altitude perturbations is more complex and strongly depends on climatic (warm or cold) conditions themselves. However, the magnitude of the calculated induced temperature perturbation remains fairly small. The peak value is 0.08 °C/(percent O_3 perturbation) (or 1.82 °C/(O_3 mm atm† change)). These studies also demonstrate that perturbations in the O_3 vertical distribution may induce climatic

† 1 atm ≈ 10^5 Pa.

effects, even in the absence of any total column change. More important indirect effects may result from the changes in stratospheric temperatures and subsequent perturbations in dynamical processes.

The atmospheric response to past solar events

The global response of the ancient oxygen-poor atmosphere to solar cycle effects was studied by Gérard & François (1987) with a one-dimensional photochemical–radiative–convective model. The aim of this study was to test quantitatively the atmospheric and surface temperature modulation as a response to the 11-year cycle in an atmosphere whose O_2 content was significantly lower than the present one. The model study indicated that the maximum temperature response is predicted for an O_2 mixing ratio of *ca.* 3×10^{-3} times the present level. The calculated temperature variation at the time of the Elatina Precambrian varves (640 Ma ago), where periodicities ascribed to the solar cycle have been observed. The recent re-examination of the Elatina deposits and analysis of other Precambrian varves (G. E. Williams, this Symposium) leads to the conclusion that the periodicities observed in the lake sediments are most likely of tidal origin. This conclusion would be in good agreement with the results of the model study indicating a weak direct solar-induced temperature effect.

The importance of the solar energetic particle interaction with the middle atmosphere was described in details by Thorne (1980). He showed that the galactic cosmic ray and the relativistic electron inputs to the atmosphere are modulated by the 11-year solar cycle. The interaction of these particles with atmospheric N_2 produces NO molecules that participate in the ozone photochemistry and NO_2 that absorbs a fraction of the solar radiation. Consequently, climatic effects may possibly accompany solar periodic activity cycles. Similarly, large solar flares responsible for major solar proton events tend to concentrate near solar maximum activity peaks.

The largest such event during the space era was observed in August 1972 and followed by a strong stratospheric ozone depletion with a lifetime of several weeks. It is possible that, during the Earth's history, much larger and more frequent proton events accumulated during high solar activity periods. The efficiency of such events would be enhanced during periods of geomagnetic field reversals when a larger fraction of the Earth's atmosphere would be in contact with solar wind particles (Reid *et al.* 1978). The potential photochemical and climate impact of such events was examined recently by Hauglustaine & Gérard (1990) using a coupled photochemical–radiative–convective model. An upper limit on the effects generated by the accumulation of strong solar proton events was simulated by calculating the steady-state perturbations induced by the August 1972 proton flux. A large increase of NO_2 is predicted, together with a substantial ozone depletion near the altitude of the peak of the proton energy deposition. The solar radiation spectrum at the surface exhibits a depletion in the visible region as a consequence of the enhanced NO_2 absorption. The perturbation to the thermal structure is important (figure 5), especially in the stratosphere where NO_2 becomes the major source of heating. The surface temperature drops by about 6 K and the top of the convective region moves from 20 to 16 km. The total planetary albedo increases by 6.5% as a result of the increase of the atmospheric component. As mentioned before, the calculated temperature perturbation is an upper limit that would be obtained rapidly in the stratosphere whereas the time-constant of the surface thermal inertia would add considerable delay until equilibrium is

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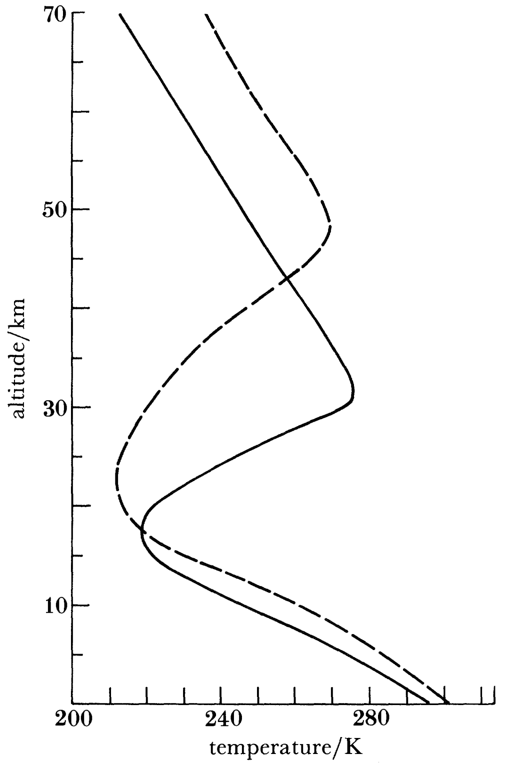

FIGURE 5. Vertical distribution of the atmospheric temperature (kelvins) calculated for solar–proton event conditions of August 1972 with a coupled chemical–radiative–convective model ran to steady state (solid line). The profile calculated for unperturbed conditions is also shown for comparison (dashed line).

obtained. This simulation, however, demonstrates the potential effect of the variability of the solar corpuscular output on the planet's climate.

CONCLUSIONS

Solar constant variations on timescales of minutes to years have been shown to exist with amplitudes less than 0.1 %. The associated predicted global temperature variations would be of the order of 0.1–0.3 °C, with the main uncertainty stemming from the difficulty to determine accurately the importance of the surface feedbacks and the role of heat exchanges inside the oceans. These temperature variations are small and probably insignificant to human activity. However, in this period of growing concern about the future of the climate, it is crucial to understand the details of the natural variability and its past and present response to external forcing. If surface warming due to the enhanced CO_2 and other trace gas concentrations is to be detected without ambiguity, it is necessary to properly account for even small natural causes of climate variability.

The spectral variations of the UV solar spectrum are increasingly better known. Their direct climate impact seems small but various indirect mechanisms may link for example the ozone solar cycle variation and global or regional climate. The interaction of energetic solar particles with the atmosphere may also have triggered climatic changes of fairly large magnitude.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Discussion

J.-C. Pecker (*Collège de France, Paris, France*). In the study of effects of solar UV irradiance, Dr Gérard has shown a diagram displaying the effects, at all altitudes and latitudes on Earth, of the cyclic variations of solar UV. I have noted in this diagram a clear N–S asymmetry. What is its origin?

J.-C. Gérard. The diagrams concern the solstice, not the equinox!

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