AERONOMY AND PALEOCLIMATE

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Abstract. Solar-Terrestrial and aeronomic interactions with the Earth's global climate played a key role throughout the evolution of the planet. The evolving composition of the terrestrial atmosphere due to geochemical and biospheric interactions strongly controled the paleoclimate. An example is the apparent absence of glaciation in a period when the solar luminosity was substantially smaller than at the present time (young sun luminosity paradox). The most convincing explanation proposed so far assumes the existence of larger amounts of infrared radiatively actives gases (CO_2, CH_4) in the ancient atmosphere.

The vertical thermal structure of the atmosphere was notably different from the contemporary one, due to the lower abundance of oxygen and ozone before the development of green-plant photosynthesis. For O_2 mixing ratios less 10^{-4} time the present atmospheric level, the presence of 11-year and longer periodicities has been observed in precambrian and more recent varve formations. It has been interpreted as an indication of a stronger response of the ancient atmosphere to solar cycle activity. This increased sensitivity was possibly the consequence of a lower O_2 atmospheric mixing ratio and a less developed stratosphere.

Introduction

The evolution of the global climate system during the past 4.5 billion years was determined by both endogenic and exogenic forcings which are still controling today's climate. Amongst the external factors, the dominant one is the solar energy input and its temporal variations. The solar radiation reaching the planet's atmosphere is likely to have varied in time both in total power (solar luminosity) and in spectral composition (solar irradiance). Following the sun formation 4.6 Ga ago and the T-Tauri phase where both the solar luminosity and the ultraviolet radiation increased substantially during approximately 10 Ma, the solar luminosity increased steadily. It rose from a value about 25-30% less than the present one as the sun evolved on the main sequence of the Herzprung-Russel diagram. This nearly linear increase is an unescapable consequence of the progressive conversion of hydrogen into helium in classical theories of the stellar interiors. If the atmospheric composition was unchanged during this period, energy-balance models (North et al., 1981) and radiative-convective models (Wang and Stone, 1980; Gérard and François, 1988) predict that, as a consequence of the ice-albedo feedback, the Earth's climate would adopt a stable condition where the planet is totally ice-covered if the solar constant is decreased by only a few percent. However, geological evidence indicates that no world-wide glaciation occured until 2.3 Ga ago, at the time of the Huronian glaciation (Crowley, 1983). Moreover, models suggest that global glaciations of this type would be irreversible and luminosities higher than the present one would be required to unfreeze the system.

Changes in the continental mass and geographic distribution probably took place and possibly counteracted in part the lower solar luminosity (Endal and Schatten, 1982; Schatten and Endal, 1982). However, variations in the abundance of infrared-active gases has been suggested as the most likely mechanism to maintain the global temperature above the freezing point. It is now generally believed that carbon dioxide probably played the major role in the thermostatic control of the Earth's climate.

In the present atmosphere, ozone plays a dominant effect in the determination of the thermal structure of the stratosphere and a secondary role in the greenhouse heating of the mesosphere and the troposphere. The stratospheric rise in temperature is associated with the absorption of solar radiation shortward of 300 nm. In the primitive atmosphere, the only source of oxygen was the photodissociation of water vapor (Kasting et al., 1980). This mechanism was shown to yield only very small (10^{-8}) of the present atmospheric level or PAL) amounts of free oxygen and negligible quantities of ozone. Later, as photosynthetic activity began to develop at the ocean surface about 3.5 Ma ago. (Schopf, 1983), the oxidation of the reducing seawater probably acted as an efficient sink for atmospheric oxygen and prevented the accumulation of O_2 in the atmosphere. The simultaneous presence of ferrous and ferric iron observed in the banded iron formations (BIFs) is usually interpreted as an indication of the existence of small amounts ($< 10^{-6}$ PAL) of atmospheric O_2 during the precipitation of the oxidized iron (Holland, 1984, François and Gérard, 1986). Photooxidation of Fe $^{2+}$ ions may also have been a significant source of a abiotic formation of the BIFs (Braterman et al., 1983; François, 1987). More recently, oxidation of continental crust and formation of red rocks contributed to limit the level of oxygen in the atmosphere. Roughly 400 Ma ago, the oxygen reached approximately its present atmospheric mixing ratio (Cloud, 1983). Therefore, throughout most of its history, the Earth's atmosphere has varied continuously in composition and thermal structure. The abundance of other minor constituents (N_2O, NO_2, CH_4, NH_3) has probably also changed substantially during the Earth's history but they appear to have played a less crucial role in the climatic evolution of the planet.

Finally, if evidence of a control of solar cycle activity over the climate has remained elusive in the comtemporary atmosphere, precambrian sedimentary rocks have revealed a clear signature of the ancient solar variations. It is therefore important to examine whether the different atmospheric composition which prevailed in the past may have favored a stronger response of the global climate to solar forcing.

Carbon Dioxide and Precambrian Climate

The response of the surface temperature to variations in solar luminosity was examined in details with one-dimensional energy balance models (North et al., 1981; Endal and Schatten, 1982). More recently, Gérard and François (1988) used a radiative-convective model to test the sensitivity of the climate response to decreases of the solar luminosity. In particular, they showed that, in agreement with energy-balance models, irreversible global glaciations would be predicted if the solar constant dropped by a few percent below its present value. The exact position of the discontinuity from the unfrozen to the totally frozen solution depends on several factors such as the global albedo-temperature function and the tropospheric lapse rate (figure 1). Sagan and Mullen (1972) initially suggested that large amounts of NH_3, an active greenhouse gas, would be able to elevate the surface temperature and compensate for the past lower solar luminosity. However, due to the short lifetime of ammonium (Kasting, 1982) in the primitive atmosphere, this molecule was abandoned and CO_2 appeared as the most likely infrared absorber. Hart (1978) calculated a scenario for the CO_2 atmospheric level which is compatible with the absence of global glaciation in the Precambrian. His work was based on a simplified global climatic model coupled to a geochemical approximation. This CO_2 history was frequently used in conjonction with radiative-convective models to test the validity of the thermostatic effect of this constituent (Owen et al., 1979; Kasting et al., 1984; Kuhn and Kasting, 1983; Kiehl and Dickinson, 1987). The results of Kasting et al. (1984) and Kiehl and Dickinson (1987)(figure 2) show that the combination of increasing solar luminosity and decreasing CO_2 mixing ratio is able to maintain the global temperature of the planet within $\pm$ 5 K. However, the treatment by Owen et al. (1979) yields an average surface temperature 3.5 Ga ago approximately 7 K warmer than Kiehl and Dickinson who found that the pressure scaling of the mean band halfwidth of the CO_2 bands at 961 and 1064 cm^{-1} accounts for most of the temperature difference with Owen et al.'s calculations.

Adopting the same scenario, we use the one-dimensional radiative- convective global model described by Gérard and François (1988) and François (1988) to calculate the evolution of the mean surface temperature. Briefly, this model solves the thermodynamic equation using a forward time-marching method. The absorption of solar radiation by CO_2, H_2O, O_3 and clouds is calculated using the Lacis and Hansen (1974) formulation, including the effects of Rayleigh scattering and surface albedo. The cloud cover is characterized by a single layer with fixed altitude and optical depth. Rossow et al. (1982) demonstrated the important potential role of cloud feedback on the stabilization of the Earth's climate during its evolution. In particular, they demonstrated that the strong negative cloud feedback present in their model is able to partly compensate the lower ancient sun luminosity. The greenhouse effect due to infrared absorption by O_3, N_2O and CH_4 is treated following the method by Ramanathan (1976) and Donner and Ramanathan (1980). The contribution of water vapor is calculated from the parameterization given by Sasamori (1968). The variation of the CO_2 absorptance with the CO_2 column given by Kasting et al. 1984) is adopted. This expression was

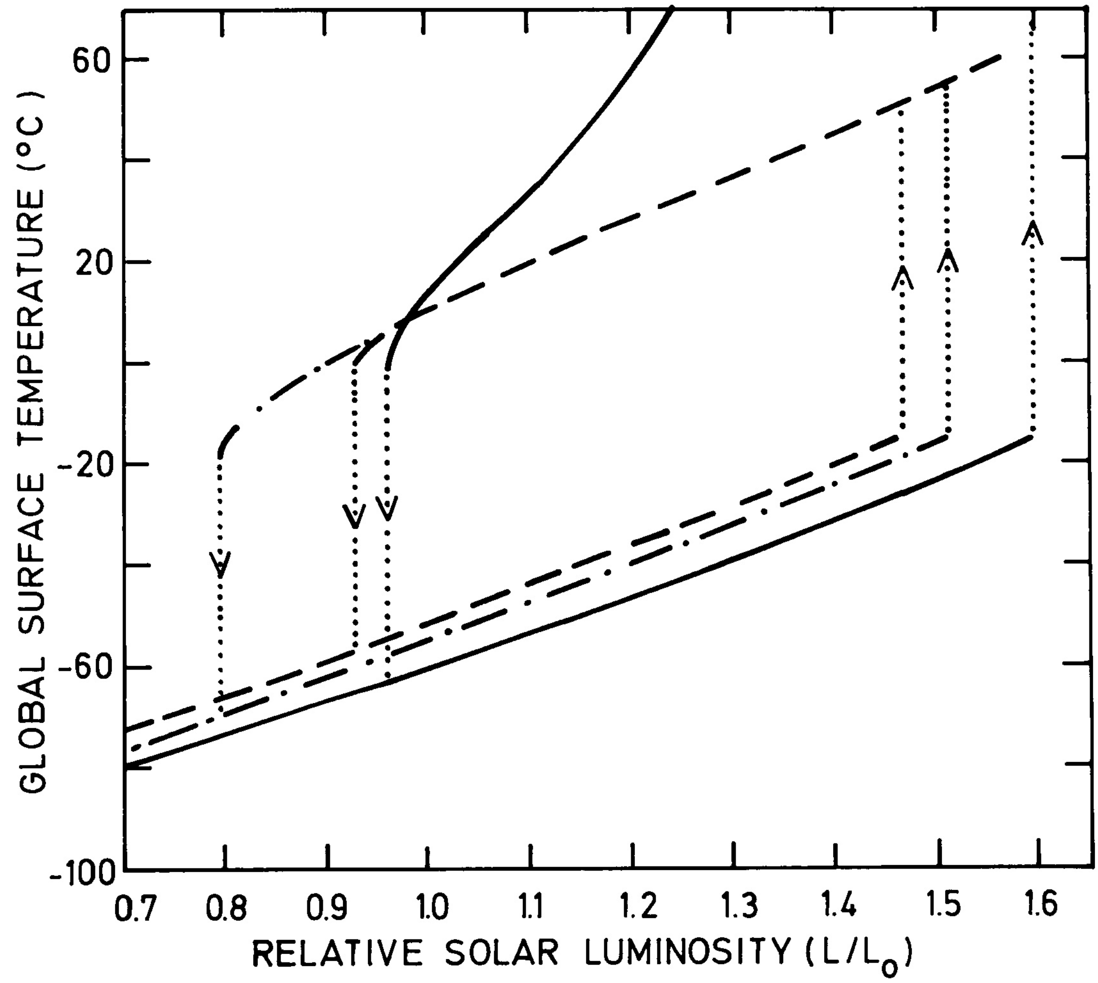


Fig. 1. Global mean surface temperature as a function of the luminosity relative to the present one for different cases. In the first case, the tropospheric temperature gradient is fixed to 6.5 K/km (full line), while in the second curve it is fixed to the moist adiabatic value (dashed line). For both curves, the temperature dependence of the surface albedo is adopted from Gérard and François (1988) and corresponds to an ice albedo of 0.5. In the third case (dash-dotted line), a moist adiabatic gradient is used and the albedo-temperature relation from Wang and Stone (1980) is adopted. The locations of the jumps to and from the frozen solutions are also indicated.

obtained by parameterizing results of laboratory absorption measurements. Whenever the temperature gradient tends to exceed the moist adiabatic lapse rate, a convective adjustement is applied to restore the convective profile. This convective adjustement is made following the method of Manabe and Wetherald (1967). Our calculated surface temperature T_s also remain within 5 K of the value calculated for present conditions, but the variations are slightly larger than those obtained in previous studies It is likely that differences in the radiative code, and in the convective adjustment scheme, amplified by the water vapor feedback, account for the differences in ΔT_s . Overall, all models lead to the conclusion that it is possible to find a plausible CO_2 scenario able to counteract the effect of the reduced past solar luminosity and thus to avoid global glaciation. Yet, it is important to stress that, at this point, the only detailed geochemical model extends back in time only 100 Ma ago (Lasaga et al., 1985). These global carbonate-silicate geochemical cycle calculations predict a significant increase in the past CO_2 atmospheric content and a parallel rise in the global surface temperature reaching 8 K, 100 Ma ago. Devel-

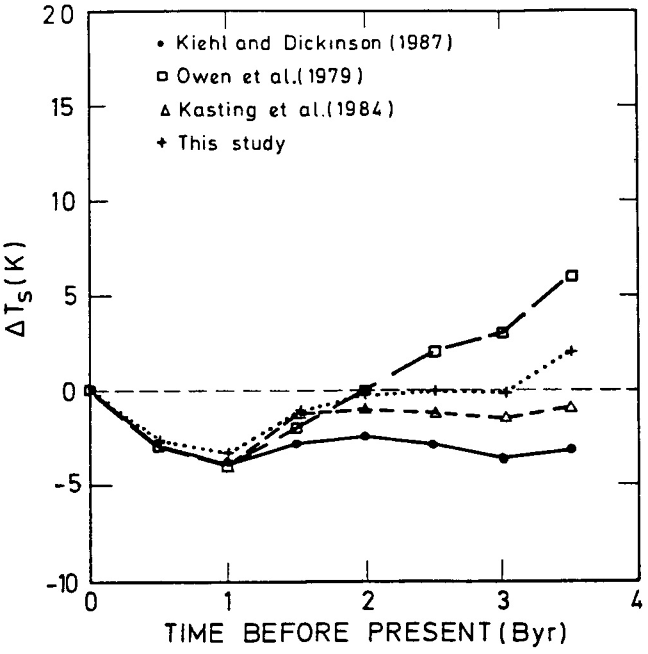


Fig. 2. Change in mean surface temperature from present conditions calculated with various models for the time period 0 to 3.5 Ma before present using the CO_2 and solar luminosity scenario from Hart (1978).

opment of such numerical geochemical models extending further back in time and linking CO_2, paleoclimate and tectonic activity is unfortunately limited by the lack of geochemical constrains.

The Climatology of the Oxygen-Poor Atmosphere

In the present atmosphere, ozone plays a dominant role in the determination of the thermal structure of the stratosphere and a secondary role in the mesosphere and troposphere. This peak in temperature is associated with the absorption of solar radiation shortward of 300 nm. Presently, the contribution of ozone to trapping of thermal infrared radiation amounts to 2.3 $W.m^{-2}$ out of a total of 148 Wm^{-2} (Dickinson and Cicerone, 1986). It is believed that, in the ancient atmosphere, containing no or trace amounts of oxygen, the thermal structure was significantly different from the contemporary one. The climatology of these phases of the Earth evolution when the O_2 level was substantially less than presently is discussed below.

The model used to investigate this question is a coupled radiative-convective model coupled to a diffusive-photochemical calculation. The first aspect was presented above and the diffusive-chemical model is similar to that described by Gérard and François (1987) and François and Gérard (1988). The continuity and turbulent flux equations are solved for O, O_2, $O(^1D)$, O_3, H, OH, HO_2, H_2O_2, N_2O, NO, NO_2, NO_3, N_2O_5, HNO_2, HNO_3, N_2O_4 , and CO. Short-lived species (H_2CO, CH_3, CH_3O_2, H_3 CO, CH_3OOH, HCO) are assumed to be in photochemical equilibrium. The vertical mixing ratio distributions of CO_2, CH_4 and H_2 observed in the present atmosphere are adopted. The H_2O profile is consistent with the calculated verticaltemperature distribution. To account for the feedback between the water vapor and ozone distributions and the thermal structure, numerical integration is alternated between radiative and photochemical calculations until convergence is achieved.

The effect of the O_2 rise during the Earth's evolution on the ozone column and on the average surface temperature is shown in figure 3, ignoring the variation of the solar luminosity. Our model calculations yield a surface temperature T_s slightly larger than the observed mean global temperature, due to the particular choice of the cloud cover characteristics. However, the absolute value of T_s is not essential here since we are only interested in the effect of O_2 variations on the mean surface temperature changes. When O_2 is decreased for 1 to 10^{-1} PAL, this model predicts a 3-4 K drop of T_s. This change is the result of two combined effects. First, as O_2 is decreased, the ozone distribution is reajusted vertically and the ozone column is slightly increased. Consequently, the efficiency of the greenhouse is larger and the surface temperature tends to increase. Simultaneously, the visible albedo decreases due to changes in the ozone and water vapor concentration. Another source of temperature changes amounting to about 5 K is due to the total pressure drop accompanying the O_2 decrease. This is the result of the reduction of the line broadening of H_2O and CO_2 infrared bands. The relative importance of these competing effects is dependent on the assumption concerning the tropospheric lapse rate. In this case, the use of a moist adiabatic lapse rate stabilizes the surface temperature and causes the T_s change to be smaller than in other studies (Levine and Boughner, 1979).

When the O_2 level is further decreased, the reduction of the ozone column and its vertical redistribution causes the temperature drop. This reduction is particularly efficient between 10^{-3} and 10^{-4} PAL. This is due to the localization of the ozone peak between 10 and 20 km for this O_2 level. Indeed, sensitivity studies (Wang et al., 1980; François, 1988) have shown that the sensitivity of the climate to ozone perturbations maximizes when the perturbations are located in this altitude range. A T_s

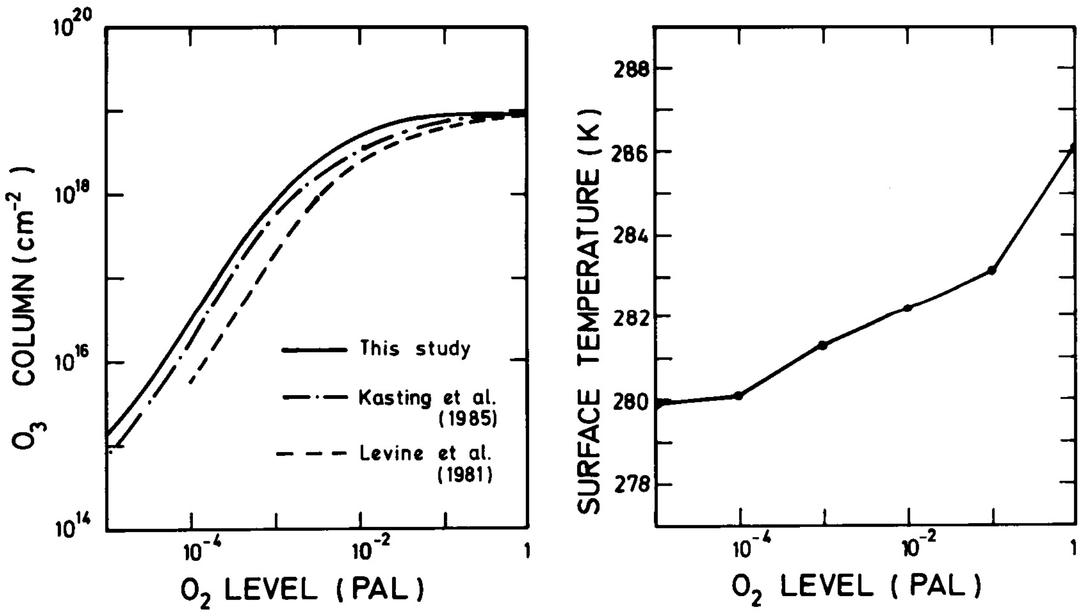


Fig. 3. Left : dependence of the ozone vertical column upon the oxygen level at the surface. Comparison is made with previous studies. Right : calculated variation of the global surface temperature with the O_2 atmospheric level.

drop by another 0.9 K is predicted when the O_2 level in the atmosphere is set to a vanishingly small value. Consequently, a global temperature decrease of 8.6 K is predicted if the oxygen was removed from the atmosphere, all other conditions being held constant.

The vertical distribution of the global mean temperature calculation with this model levels of O_2 from 10^{-4} to 1 PAL are shown in figure 4. The progressive development of the stratosphere is observed as the oxygen and the ozone abundances are increased. At 0.1 PAL, the stratospheric temperature peak is lower in magnitude and altitude. This change is due to the decrease of ozone in the upper stratosphere. By contrast, a small increase of the temperature is obtained in the region near 20 km as a result of the slightly enhanced ozone concentrations in the lower stratosphere. At 10^{-2} PAL of O_2, no stratospheric maximum is predicted by the model due to the low stratospheric ozone density. As the O_2 level is further decreased to 10^{-3} PAL, an inflexion in the temperature near 20 km is the only effect of vanishingly small O_3 concentrations. Finally, at 10^{-4} PAL, the role of ozone in the thermal structure of the atmosphere becomes negligible.

It is also noted that, in spite of the important changes in the vertical temperature distribution, the top of the convective region is located in each case between 10 and 14 km.

Response of the Precambrian Atmosphere to Solar Cycle Activity

Analysis of periodicities observed by Williams (1981) and Williams and Sonett (1985) in the annual deposits (varves) of a precambrian lake in South Australia strongly suggest a solar control of the mean annual temperature by solar activity. These 680 Ma old deposits were found on the Elatina formation in the Flinders Range, North of Adelaide. They were formed during the Marinoan glaciation, one of the series of glacial. episodes which characterize the end of the Precambrian era. The paleographic setting of the site indicates a marked seasonal, arid, periglacial climate. These circumstances imply a strong seasonal control of the glacier meltwater discharge into the periglacial lake. Laminae characteristic of distal clastic varves were obtained, avering a total period of 19, 000 va (varve years). Non-random cyclicities in the thickness of the annual varves were found in the sample showing characteristic periods of 8 to 16 va, with a mean period of 12 years. Recent re-analysis by Sonett and Williams (1987) indicate that the actual average period close to 11.7 va. Longer periods of 22 and a 314 years were also obtained in the Fourier analysis of the time series. Comparison with modern analogues indicates that the Elatina varve thickness may be interpreted as an in-

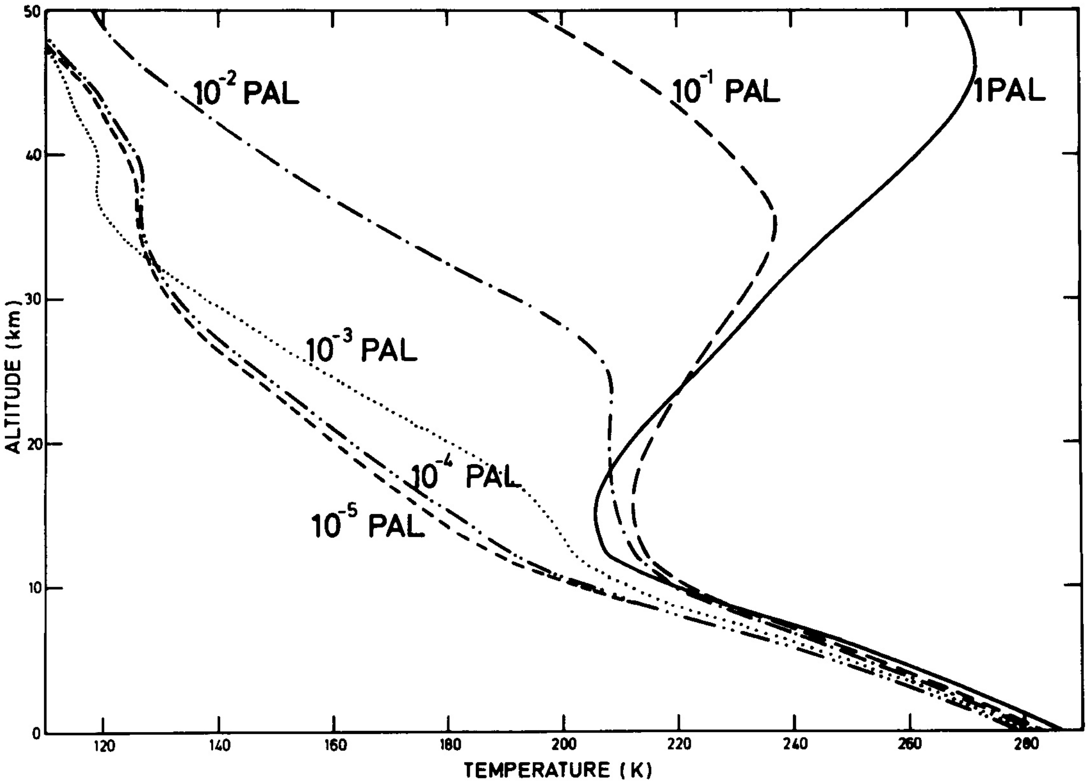


Fig. 4. Mean vertical atmospheric temperature distribution calculated with the coupled radiative-convective photochemical model for different mixing ratios of O_2 at the Earth's surface.

dicator of the mean annual temperature. Therefore, the Elatina series can be considered as a proxy of the time-variation of the mean annual temperature.

A weak solar influence on glacial climate was also discovered in the analysis of a 236-year varve sequence from Skilak Lake, Alaska (Sonett and Williams, 1985) . The geographic location of the lake, the climatic environment and seasonality of meltwaters make it a good analogy with what appear to have been the conditions prevailing at the time of the Elatina deposition. However, the Elatina periglacial environment was dryer and probably free of glacial ice whereas Skilak Lake is in a relatively humid periglacial climate with permanent glaciers as a source of meltwater. A correlation study between the varve sequence thickness and the sunspot indices between years 1700 to 1930 reveals a good correlation between the two series with common periods of 11 and 22 years. By contrast, analysis of three time series of varves from the Eocene Green River formation (Crowley et al., 1986) showed only a weak 11-year signal during a restricted portion of the 7496-year sample core deposited approximately 50 million years ago.

Finally, 2 Ga-old varve records from the BIFs found in the Harmersley basin in Australia, show clear evidence of a 23.3 yr cycle which may be associated with the Hale (22-year) solar cycle. However, Walker and Zahnle (1986) interpreted this periodicity as reflecting the climatic influence of the lunar nodal tide, which is weakly present in modern climate records with a period of 18.6 years. In this theory, it would arise from the precession of the Moon's orbital plane occuring with a longer period at the Precambrian as a result of the smaller Moon-Earth distance in the past.

The clarity of the solar-cycle signature in the Elatina Formation and the remarkable length of the record make this set of data unique at the present time. Compared to the general absence of solar signal in published varve series, it is legitimate to wonder whether specific environmental conditions prevailed near the end of the Precambrian era which could explain the specificity of the Elatina response to the solar cycle forcing.

It is striking that the Elatina varves were formed during a period characterized by a series of glacial ages occurring between 0.9 and 0.6 Ma ago: a most unusual climatic event. The distribution of continental masses is difficult to reconstruct for this remote period. However, paleomagnetic studies indicate that the three major phases of extensive glaciations occured at low latitudes. Indeed, most regions of the Earth, with the possible exception of Antarctica, containing Precambrian rocks show evidence for glaciation during this phase of the Earth's history (Crowley, 1983, Christie-Blick, 1982). More specifically, a recent study of paleomagnetic measurements of the remanent magnetization of the Elatina Formation was made by Embleton and Williams (1986). The results clearly demonstrate that the deposition was made at a paleomagnetic latitude of 5 degrees, in agreement with previous determinations from other paleomagnetic Australian late Precambrian rocks (Huimin and Wenzhi, 1985). Thus, the occurence of ice sheets and periglacial climate near sea level at low latitudes, considered together with the apparent absence of glaciation during the late Precambrian is in itself, as a major enigma. The climatic seasonality responsible for the deposition of varves is also difficult to explain if the region was located at low latitudes at this period.

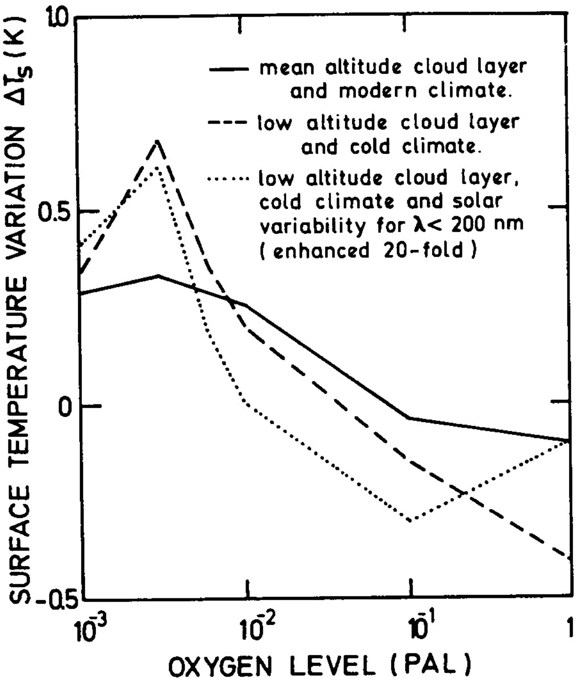
The periodicities associated with the Elatina varves have been interpreted as being of solar origin since the 11-yr and longer periods known to occur in the modern sun were found in the sediments. Could the different atmospheric conditions at the late Precambrian be responsible for the larger climatic response to the solar forcing? A possible mechanism linking the global climate and the solar activity cycle was analyzed by Gérard and François (1987). In this scenario, the lower ozone level in the atmosphere 680 Ma ago and its different vertical distribution could possibly have made the troposphere more responsive to the 11-yr modulation of the UV solar irradiance. Indeed, fluctuations of the temperatures associated with the 27-day and 11-yr cycles are observed today in the stratosphere. (Keating et al. 1986; Chandra, 1984). It may be expected that in an atmosphere poorer in ozone and with an ozone peak closer to the ground, the response of the surface temperature would be amplified compared to the modern atmosphere. This idea was quantitalively examined using the coupled chemical-R-C model described above. Since the Elatina varves were deposited during a periglacial period, the model cloud layer is fixed at low altitude with an optical thickness $\tau = 10$ to produce surface temperatures in the range 268-275 K, about 15 to 20 K lower than for the present atmosphere.

The response of the global surface temperature to an imposed variation of the solar UV irradiance associated with the 11-yr solar cycle is strongly dependent on the spectral distribution of the modulation. Therefore, two models of UV solar cycle modulation were tested. The first one (case A), assumed no variability above 200 nm and a max/min irradiance ratio varying linearly from 2.6 at 120 nm to 1 at 200 nm. The mean solar irradiance distribution reported by Brasseur and Simon (1981) was adopted. In this case, the calculated surface temperature variation remains negligibly small (0.03 K). In the second model, the solar cycle modulation extends to 300 nm. In this case (case B) the surface temperature response is much larger and exceeds 0.5 K at 3 x 10^{-3} PAL of O_2. A significant response is only obtained in case A if the variability ratio max/min is substantially increased.

Figure 5 illustrates the dependence of T_s and the ozone vertical column on the O_2 level for both cases. At low O_2 levels, the peak of ozone is located near 10 km, independently of the oxygen concentration. The magnitude of the temperature increases in parallel to the ozone column since the "greenhouse" fluctuation is progressively enhanced. However, for $O_2 > 10^{-3}$ PAL, the ozone maximum and the altitude of the maximum ozone variation shift toward higher altitudes. This altitude change of the solar cycle response tends to reduce the amplitude of the surface temperature response until, at still higher levels, the sign of the T_s modulation itself is inverted. This dependence on O_2 is complex and depends on the thermal structure as well as the altitude of the ultraviolet energy deposition. Numerical tests also indicate that these results are nearly unaffected by an increase of the CO_2 partial pressure. By contrast, it is found that during cold climatic conditions, corresponding to a dryer troposphere and to a larger ozone tropospheric content, the solar ultraviolet radiation penetrates less deep in the atmosphere. Both effects contribute to increase the variation of the ozone column during a solar cycle. The model indicates that the temperature variation response increases by a factor of 3.5 when the mean surface temperature drops from 18° C to 0° C. This factor may explain, in part, the specificity of the Elatina periglacial environment to the solar cycle activity.

Summary

Energy-balance and radiative-convective models show that the past reduced solar luminosity should have generated global irreversible glaciations as a result of the ice-albedo feedback. Geologic and paleontologic evidence indicates the absence of a totally frozen Earth at any stage of the planet's evolution. Increased levels of active greenhouse gases such as CO_2 appear as the most plausible compensating factor to maintain the global climate within the limited range by paleoclimates. Numerical models



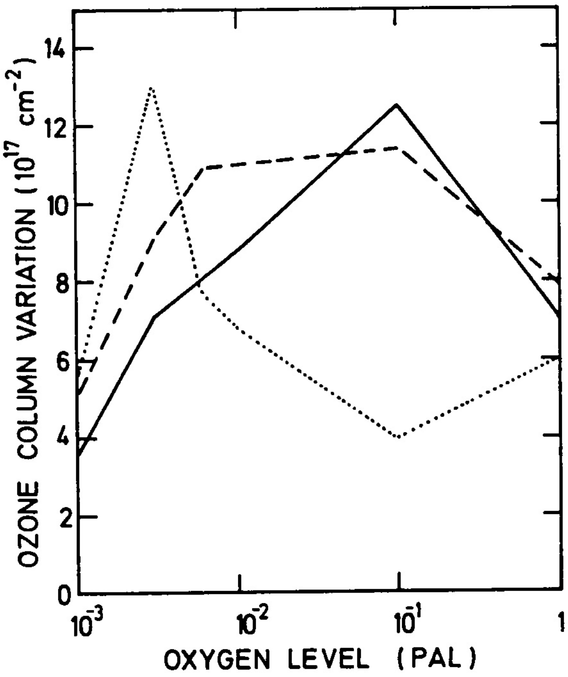


Fig. 5. Variations in surface temperature (left) and vertical ozone column (right) as a function of the oxygen level in the atmosphere from 10^{-3} to 1 PAL. The dashed line is obtained for a single cloud layer located at 750 mbar and a mean surface temperature between - 5 and + 2°*C*. The second curve (dotted line) is for a solar UV variability confined to wavelengths below 200 nm (see text).

show that it is possible to find atmospheric carbon dioxide evolution able to keep the global surface temperature within a few degrees of its contemporary value. The accumulation of photosynthetic oxygen in the atmosphere was another important source of climatic forcing. Its presence and the formation of the ozone layer significantly perturbed the thermal structure of the atmosphere and contributed to rise the surface temperature. The lower ozone abundance of the Precambrian atmosphere may have been an important factor to increase the climate response to solar cycle activity observed in the varves of the Elatina Formation. Numerical simulations indicate that the difference in solar irradiance between solar maximum and minimum conditions could have generated surface temperature variations substantially larger than in the present atmosphere.

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