Influence of Solar Activity Cycles on Earth's Climate.

Task 1 – Literature Study

WP103 – Climate Variability Correlated with Solar Activity.

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9 February 2005

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1.0 Introduction

The observation that warm weather seems to coincide with high sunspot counts and cool weather with low sunspot counts was made as long ago as two hundred years by the astronomer William Herschel (Herschel, 1801;Hoyt and Schatten, 1992). Herschel noticed that the price of wheat in England was lower when there were many sunspots, and higher when there were few.
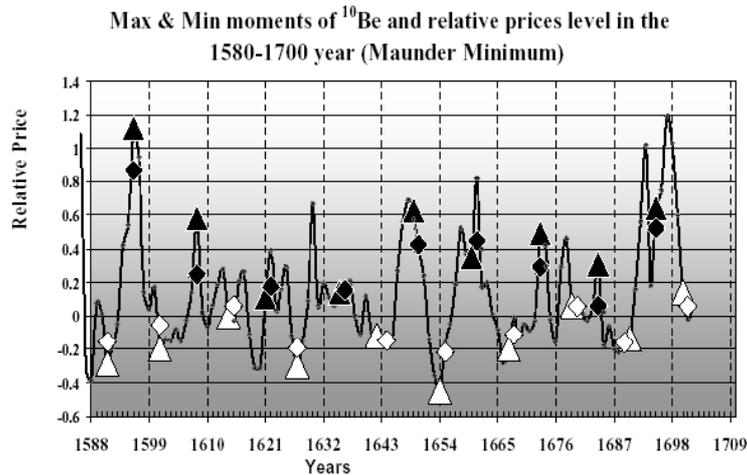
Figure 1: Wheat prices in England during the 17th century compared with solar activity. White (black) triangles are prices at maximum (minimum) sunspot number, and white (black) diamonds are 3-year averages centred at maximum (minimum) sunspot number. Figure adapted from *Pustilnik and Din* (2003).

The most well known example of this effect is the Maunder Minimum (Eddy, 1976) which occurred between 1645 and 1715, and was the coldest period of the Little Ice Age; ironically this almost exactly coincides with the reign of Louis XIV, *le Roi Soleil*, 1643–1715. During this period there was an almost complete absence of sunspots, and the River Thames in London regularly froze across and fairs complete with swings, sideshows and food stalls were a standard winter feature. Since the time of Herschel there have been numerous observations and non-observations of an apparent link between climate and the sunspot cycle, a large number of these have previously been recorded in various review articles and books on the subject (e.g., Dickinson, 1975;Herman and Goldberg, 1978;Hoyt and Schatten, 1997). In this literature study a review will be presented of some of the more robust observations indicating a solar influence on climate. A number of candidate solar mechanisms have been proposed and these will be briefly introduced together with a presentation of the supporting observational evidence.

2.0 Evidence for a solar influence on Earth's climate

A solar influence on Earth's climate has been found in many climate parameters from the surface up to the top of the atmosphere. However, it is often global temperature that is used as the key parameter for demonstrating variability in the average state of Earth's climate. In the following a summary is given of changes in observed temperature that coincide with variations in solar activity.

2.1 Ocean Temperatures

One example of a positive correlation is the apparent solar response of Sea Surface Temperatures (Reid, 1987;Reid, 1991;Reid, 2000). Sea Surface Temperatures (SSTs) have been obtained from ocean going ships since the middle of the 19th century. During the first part of the 20th century the observed SSTs increased, and then flattened out during the years 1940 and 1970, before continuing with the overall increasing trend. Figure 2 indicates that this long-term variability in SSTs is in phase with the 80-90 year envelope that modulates the approximately 11-year sunspot cycle.
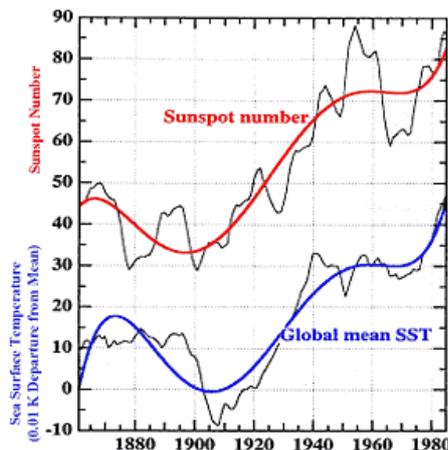
Figure 2: 11 year running mean of the annual sunspot numbers (upper thin curve), and the mean global sea-surface temperature anomaly (lower thin curve). The heavy curves represent a 7th degree polynomial least squares fit to the data. Units for the lower curves are 0.01K depatures from the 1951-1980 average.

White et al (1997) confirmed this finding with two independent SST datasets, i.e., surface marine weather observations (1900-1991) and upper-ocean bathythermograph temperature profiles (1955-1994). They band-passed basin average temperatures, and found each frequency component to be in phase with changes in solar activity across the Indian, Pacific and Atlantic Oceans. Global averages yielded maximum changes of 0.08±0.02 K on decadal (*ca*. 11-year period) scales and 0.14±0.02 K on interdecadal (*ca*. 22-year period) scales in reposnse to a 1 Wm^{-2} change in Total Solar Irradiance (TSI) at the top of the atmosphere. The highest correlations were obtained with ocean temperatures lagging solar activity by 1-2 years, as would be expected when accounting for the large heat capacity of the oceans. From simple energy balance arguments White et al (1997) estimated climate sensitivities due to changes in TSI at the ocean surface to be 0.2-0.4 $^{o}K/(Wm^{-2})$. This suggests that a 0.04-0.09 ^{o}K change in SSTs would be expected from a 1 Wm^{-2} change in TSI at the top of the atmosphere. While these estimates are of a similar order of magnitude to the observed changes in global SSTs, they are on the low side, suggesting a possible amplification of the solar signal exists within the atmosphere.

2.2 Land Temperatures

Another example of a positive observation is the correlation between solar activity and northern hemisphere land temperatures (FriisChristensen and Lassen, 1991). They used the sunspot cycle length as a measure of the Sun's activity. The cycle length averages 11 years but has varied from 7 to 17 years, with shorter cycle lengths corresponding to a more
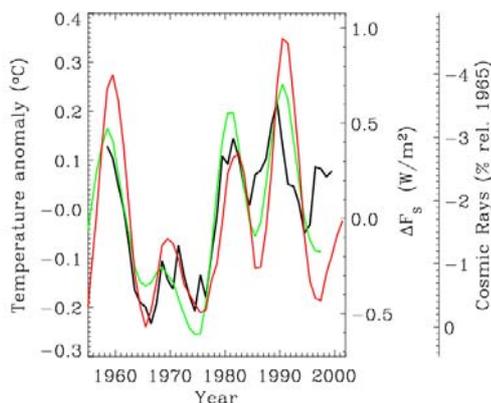
magnetically active Sun. A correlation was found between the sunspot cycle length and the change in land temperature of the northern hemisphere over the period 1861 to 1989 (latest update in figure 3). The land temperature of the northern hemisphere was used in order to avoid the lag by several years of air temperatures over the oceans, due to their large heat capacity. Of particular note is the dip between 1945 and 1970, which was also present in the Sea Surface Temperatures discussed above. This cannot easily be explained by the steadily rising greenhouse gas emissions but seems to coincide with a decrease in the Sun's activity. The data plotted in figure 2 has been extended to include the most recent solar cycle. Clearly the correlation breaks down after 1990 and it has been suggested that this is an indication of the increasingly dominant effect greenhouse gas emissions have had on global warming (Thejll and Lassen, 2000).
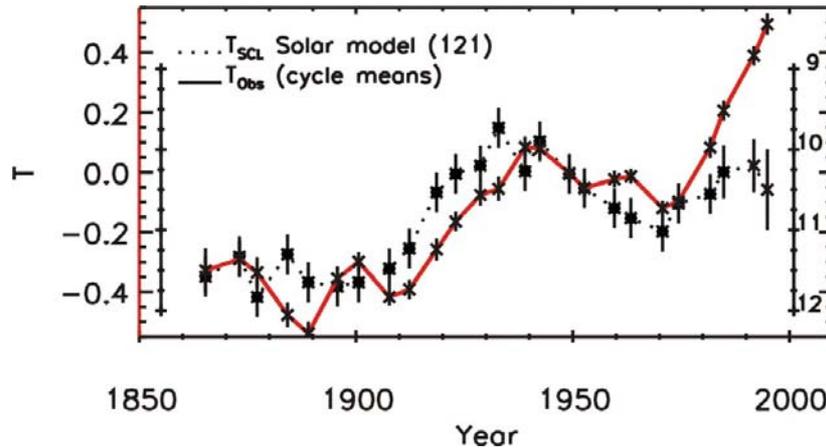
Figure 3 – Sunspot cycle length (black dotted curve) versus the northern hemisphere temperature anomaly over land (red solid curve).

However, the physical significance of the solar cycle length and whether it reflects changes in solar properties that in turn affect Earth's environment are currently uncertain. Attempts have been made to attribute the solar cycle length with secular variations in the Sun's large-scale magnetic field, which influences the interplanetary shielding of cosmic rays arriving at Earth (Solanki et al., 2000), but there are still a number of open questions.

2.3 Tropospheric Temperatures

Radiosonde observations of Tropospheric temperatures over the period 1958 - 2001 display significant variability at a number of different time-scales. From monthly data the effects of El Nino and volcanic eruptions are particularly evident. However, these features are largely removed when filtering with a three-year running mean, and the low pass Tropospheric temperatures show a remarkably good agreement with changes in reconstructed Total Solar Irradiance (TSI). Figure 4 indicates that an increase in reconstructed TSI of 1 Wm^{-2} coincides with an increase of ~0.4 ^{o}K in tropospheric temperatures.

Figure 4: Tropospheric temperatures (black), obtained from radiosondes, shown together with reconstructed TSI (green), ΔF_s, using re-scaled sunspot numbers as a proxy and cosmic rays (red). Both data sets have been low pass filtered with a three year running mean (adapted from Marsh and Svensmark, 2003b).

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An expected temperature response from the reconstructed changes in TSI can be estimated with a simple climate sensitivity analysis. Assuming a climate sensitivity of 0.6-0.8 K/(Wm^{-2}), estimated from the average response of climate models to a doubling of CO_2 (e.g., Appendix 9.1 - Houghton et al., 2001), predicts that a 1 Wm^{-2} change in TSI at the top of the atmosphere would result in only ~0.1 ^{o}K change in temperature. Clearly, changes in TSI alone are too small to explain the observed Tropospheric temperature variability and an amplification factor is required (Marsh and Svensmark, 2003b).

3.0 Observational Evidence for Indirect Mechanisms

Although a solar influence on climate is apparent, model studies have indicated that variations in the Total Solar Irradiance (TSI) are too small to explain the observed changes in recent climate. Stott et al. (2003) found that current climate models underestimate the observed climate response to solar forcing over the twentieth century as a whole, and concluded that the climate system has a greater sensitivity to solar forcing than models currently indicate. This is consistent with other studies that show models underestimate the response to solar forcing in Tropospheric temperatures by a factor of 2 to 3 (Hill et al., 2001), and near-surface temperatures by a factor 2 (North and Wu, 2001). These studies assumed the solar imprint on climate originated from direct changes in TSI at the top of Earth's atmosphere and did not include any possible indirect mechanism. Clearly an amplification of the solar signal, via some indirect mechanism(s), is required to explain the observed correlations with climate, and resolve the inconsistency with models.

There are three possible vectors between the Sun and the Earth that could lead to a solar imprint on climate; a) the electromagnetic radiation (Total Solar Irradiance) - or some component of it such as the ultra violet (UV), b) the direct influence of the solar wind, and c) the galactic cosmic radiation, which is modulated by the solar wind. Figure 5 shows the evolution of each of these parameters where observations are available. However, correlations reported between solar variability and climate cannot be uniquely ascribed to a single mechanism. This is because the observed long-term changes in various climate parameters correlate equally well with more than one solar-related index as indicated in figure 5. Additionally, such analyses are plagued by short time series and the influence of the major volcanic eruptions that occurred near two solar maxima, so uncertainties can be large.
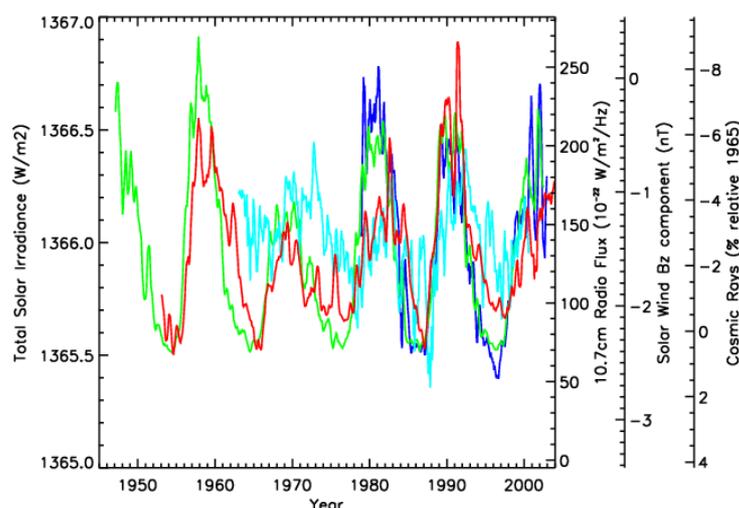
Figure 5: Monthly observations of TSI (blue) together with other solar parameters influencing Earth's environment: 10.7cm Radio Flux often used as a proxy for Solar UV (green), Solar Wind Bz component (light blue), and Cosmic Rays (red). All data have been smooth with a 5-month running window.

A number of solar amplification mechanisms have been proposed, involving each of these three parameters. The mechanisms are reviewed below, together with a summary of the evidence that currently exists for each one.

3.1 Solar UV

According to various modeling studies, a response in atmospheric circulation can amplify the terrestrial effect of solar irradiance changes, possibly via the influence of solar UV variability

on ozone concentrations and a corresponding response in stratospheric temperatures (Haigh, 1996;Haigh, 1999;Haigh, 2003). Model results further suggest that this amplified stratospheric response to solar variability has the potential to influence tropospheric circulation patterns (Matthes et al., 2004).

a)   b)
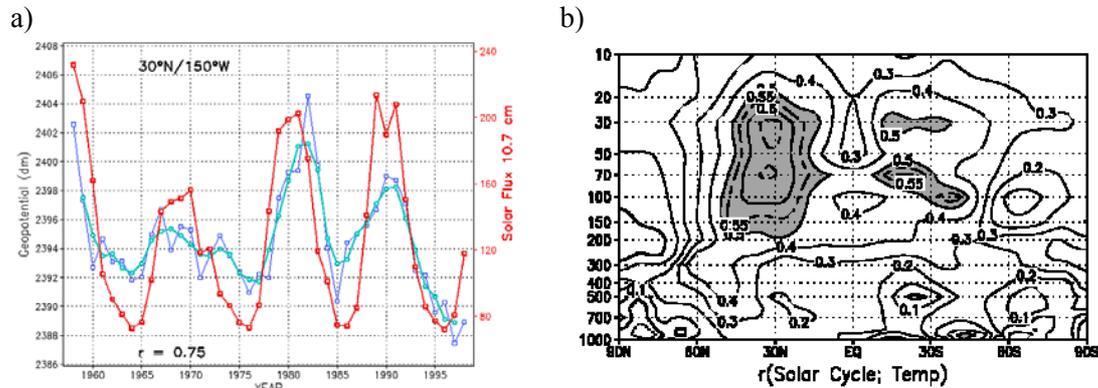
Figure 6: a) Geopotential heights at 30 hPa (blue curve) at 30N, 150W versus 10.7cm solar flux (red curve). **b)** Correlation between zonally averaged annual mean detrended temperatures and 10.7cm solar flux, shaded regions are for correlations >0.5 (adapted from *Labitzke and Matthes* (2003)).

Meteorological parameters in the stratosphere, e.g., temperature and geopotential height, are strongly correlated with the 11-year solar cycle (Labitzke, 1987;Labitzke and Matthes, 2003;Labitzke and Vanloon, 1988). In particular, the zonally averaged temperatures in the stratosphere are found to be significantly correlated with changes in UV flux, and the 30hPa geopotential height, which is a measure of the mean temperature of the atmosphere below about 24 km, is seen to vary in phase with solar activity, preferentially at mid-latitudes (Figure 6). A general picture has now emerged in which the low-to-mid-latitude upper stratosphere warms by ~1 ^{o}K at solar maximum with respect to solar minimum, the temperature signal is very small, or possibly negative near 50hPa and then larger, perhaps 0.5 ^{o}K in the lower stratosphere.   Although changes in TSI over a solar cycle are too small, ~0.1%, to explain this observed temperature response, solar UV variations are much larger, ~5%, at wavelengths between 200nm to 300nm (Lean et al., 1997). At these wavelengths solar UV has a direct effect on the photochemistry generating stratospheric ozone, which in turn influences the radiative heating and dynamics of the upper stratosphere (Hood et al., 1993).
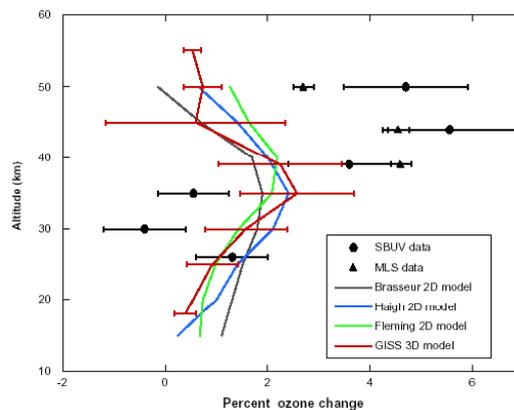
Figure 7: Annual average ozone differences between solar maximum and solar minimum between 60°S to 60°N in percent. Filled circles are from satellite observations covering 15 years for Solar Backscatter Ultraviolet (SBUV) data, and triangles are from 3 years for Microwave Limb Sounder (MLS) data . The coloured lines represent results obtained from various models of ozone photochemistry in the stratosphere (adapted from Shindell et al. (1999)).

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The ozone response to the 11-year solar cycle variability has been assessed from satellite datasets (e.g. SBUV/TOMS) and a similar picture emerges to that seen in the temperature structure with a mid-stratospheric minimum (Figure 7). That the same feature is also apparent from the influence of the 27-day solar rotation, for which statistically longer time series are available, suggests it is real (Williams et al., 2001).

Model studies have confirmed that solar UV will have an impact on the radiation, temperature, ozone budget, and dynamics of the stratosphere (Balachandran and Rind, 1995;Haigh, 1999;Shindell et al., 1999), but they have not been successful at reproducing the magnitude or structure of the response. However, very recent work has indicated that improvements are possible when correctly capturing the observed equatorial wind properties throughout the stratosphere, while taking into account the phase of the Quasi-Biennial Oscillation (Matthes et al., 2004).

Observations of various meteorological parameters in the Troposphere also demonstrate correlations with solar activity (Egorova et al., 2004;Gleisner and Thejll, 2003;Labitzke and Vanloon, 1997;Labitzke and Vanloon, 1995;Labitzke and Vanloon, 1988). However, coupling of the solar induced stratospheric signal with the troposphere is currently not well understood, and there is still uncertainty as to the physical mechanism responsible for a tropospheric response to solar variability. Model studies do hint at a tropospheric circulation response (Balachandran et al., 1999;Haigh, 1999;Shindell et al., 1999;Tourpali et al., 2003), which can be seen in figure 8 with a comparison between solar min and solar max differences of zonal wind speed obtained from observations and a Global Climate Model (GCM). While some of the general features revelaed in the observations are captured in the GCM response, namely that the mid-latitude jets weaken and broaden at solar maximum, there are still significant differences in structure and magnitude of the tropospheric response.
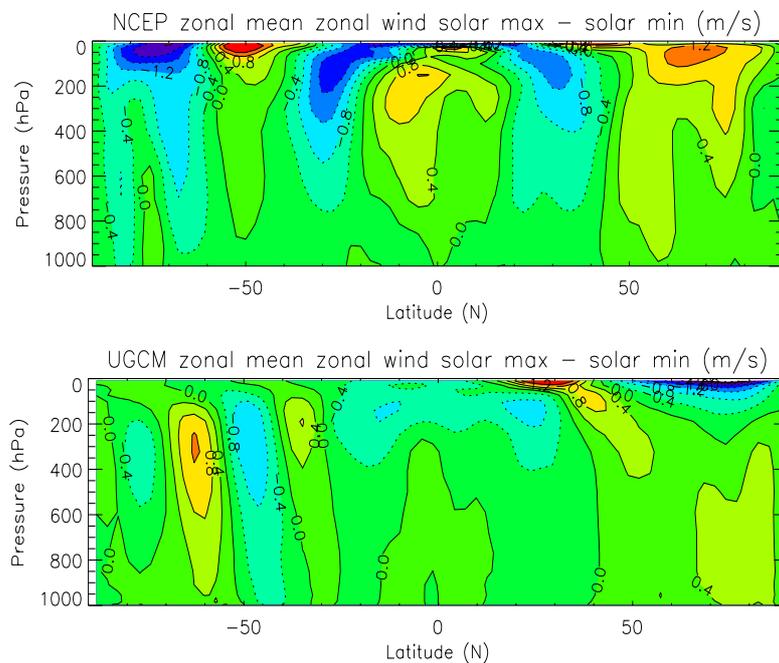
Figure 8: Differences in zonal wind speed between solar max and min from a) a multi regression analysis of NCEP reanalysis data between 1979-2002 and b) a GCM simulation (adapted from Haigh (1996) and Haigh et al. (2005)).

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3.2 Direct Influence of the Solar Wind

The solar wind is able to generate significant heating of the lower thermosphere at high latitudes by direct particle precipitation, as well as generating upper atmospheric ionisation that may influence the global electric circuit. Through coupling with the magnetosphere the solar wind also drives ionospheric currents at high latitudes that in turn accelerate the neutral atmosphere.

Recent studies (Boberg and Lundstedt, 2003;Boberg and Lundstedt, 2002) have shown a strong relationship between the electric field of the solar wind and a pressure phenomena in the north Atlantic termed the North Atlantic Oscillation (NAO) (Marshall et al., 2001). A substantial portion of the climate variability in the Atlantic sector is associated with the NAO with variations occurring on a wide range of scales.

Model studies (Arnold and Robinson, 2001;Arnold and Robinson, 1998) indicate that the influence of geomagnetic activity on the stratosphere is comparable to that of ultraviolet flux variation between solar minimum and solar maximum and that planetary wave activity is a key process in determining the extent to which the stratosphere is able to respond to changes in the lower thermosphere.

Bucha and Bucha (1998) observe an intensification of both thermospheric and tropospheric flows following strong geomagnetic activity. They suggest a mechanism where downward winds are generated in the polar cap of the thermosphere and penetrate to the stratosphere and troposphere.
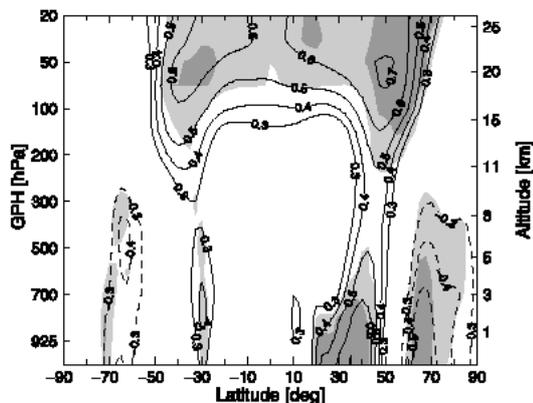
Figure 9: Linear correlations between the electric field of the solar wind and geopotential height variations as function of latitude at the zero meridian and geopotential height (adapted from Boberg and Lundstedt, 2003).

A possible scenario for the solar wind/NAO interaction could include an electromagnetic disturbance induced by the solar wind in the global electric circuit of the ionosphere. This global disturbance could then dynamically propagate downwards through the atmosphere, a scenario similar to the one proposed by Baldwin and Dunkerton (2001). This downward motion takes several weeks and during this time it would be affected by different atmospheric circulations from the equator toward the poles (Peixoto and Oort, 1984) resulting in a pressure pattern more concentrated at high latitudes (figure 6). Due to this slow, dynamic, propagation, one can make forecasts of the weather/climate in the Atlantic sector based on the solar wind state.

3.3 Galactic Cosmic Rays

Cosmic rays are the main source of ionization in the troposphere [*Bazilevskaya* (2000)], however, the energy they deposit into the Earth's atmosphere, $\sim 10^{-5}$ Wm^{-2}, is negligible compared to that from changes in solar irradiance over an 11-year solar cycle, ~ 0.34 Wm^{-2}. Clearly some form of amplification mechanism is required if cosmic rays are to play a role in climate variability.

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There is increasing evidence that the cosmic rays, which are modulated by the solar wind, can noticeably affect Earth's planetary albedo, and hence climate, via an influence on tropospheric cloud properties (Carslaw et al., 2002;Marsh and Svensmark, 2000b;Marsh and Svensmark, 2003a;Svensmark and FriisChristensen, 1997).

Based on five different satellite observations, a link was proposed between total cloud amount and the number of Galactic Cosmic Rays (GCR) received at Earth between 1979-1996 (Svensmark, 1998;Svensmark and FriisChristensen, 1997). Since clouds play an important role in the radiation budget of the atmosphere, by both reflecting solar radiation and trapping outgoing longwave radiation, the existence of a GCR-cloud link would introduce a previously unknown external forcing mechanism to the climate system. *Marsh and Svensmark* (2000b) found the correlation to be limited to low liquid water clouds below ~3.2km (rather than clouds at other altitudes) between 1983-1994 (figure 10). They suggested that this was consistent with a mechanism involving ionisation and aerosol nucleation, which in turn could influence the activation of cloud droplets in the lower troposphere, and hence cloud radiative properties (Marsh and Svensmark, 2000a). This basic result has subsequently been confirmed by other independent studies (Palle Bago and Butler, 2000;Yu, 2002a). More recently *Marsh and Svensmark* (2003a) found that the low cloud-cosmic ray correlation can be extended until 2001 (figure 10), but only after the globally averaged cloud data are re-calibrated (Marsh and Svensmark, 2004b).
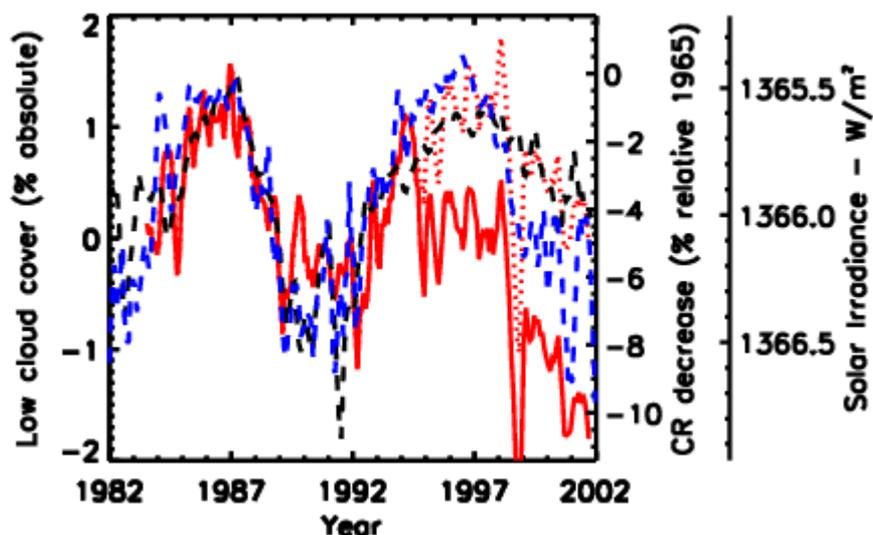

Figure 10: Monthly averages of ISCCP-D2 IR global Low Cloud Amount (red) shown together with cosmic rays (black dashed), and solar irradiance (blue dashed). The red dashed curve includes an offset after 1994 that has been added to Low Cloud Amount, this accounts for a possible inter-calibration problem at the end of 1994.

However, beyond the GCR-total cloud correlation there is currently no experimental confirmation to suggest that such processes has had a discernible effect on cloud properties (Marsh and Svensmark, 2003b). This has lead to suggestions that the correlation is fortuitous and might better be explained by internal climate processes, e.g., El-Nino Southern Oscillation (ENSO), such that any agreement with cosmic rays is purely coincidental. As a result a number of questions have been raised as to the validity of the GCR-cloud link.

Kernthaler et al (1999) found no clear relationship between individual cloud types and GCR, which became further degraded with the inclusion of polar-regions. However, their analysis relied on the individual cloud type derivations from the International Satellite Cloud

Climatology Project monthly C2 data (ISCCP-C2) (Rossow and Schiffer, 1991) using an algorithm which was abandoned by ISCCP in 1990 due to its poor performance (Klein and Hartmann, 1993). The reanalysed D2 data (ISCCP-D2) using an improved algorithm (Rossow et al., 1996), differs considerably from the ISCCP-C2 derivation of individual cloud types. The results of *Kernthaler et al* (1999) cannot be reproduced using the ISCCP-D2 data (Marsh and Svensmark, 2000b). *Kuang et al* (1998) confirmed the GCR - total cloud correlation using the ISCCP-C2 data, but were unable to distinguish between the effects of GCR and ENSO on the mean cloud optical thickness. *Jorgensen and Hansen* (2000) raised a number of criticisms but of a more general nature which have been addressed in a comment by *Svensmark and Friis-Christensen* (2000). *Farrar*(2000) argued that trends in the globally averaged total cloud amount were the result of a composite of expected regional cloud responses to ENSO, and found little evidence to suggest a role for GCR. However, *Marsh and Svensmark* (2003a) have shown that in low cloud properties the ENSO signal is limited to equatorial regions, while the GCR-low cloud correlation appears to dominate global properties. *Sun and Bradley* (2002;2004) expressed concern that the effects of high cloud would obscure the satellite view of low cloud. *Marsh and Svensmark* (2003a;2004a) show that the correlation between low cloud and cosmic rays is a robust feature in regions not obscured by overlaying high cloud.

However, variability in low cloud amount (LCA) correlates equally well with total solar irradiance (figure 10), and cannot be uniquely ascribed to a single mechanism when using globally averaged data. This has lead to suggestions that the cosmic ray-low cloud link is a result of a tropospheric circulation response to TSI or solar UV (Kristjansson et al., 2002). One way to distinguish between these two processes is to utilize the property that cosmic rays arriving at Earth are modulated by the geomagnetic field whereas solar irradiance is not. Recent observational evidence indicates that the solar cycle amplitude in LCA, over the period 1984–2000, increases polewards and possesses a similar latitudinal dependence to that found in cosmic ray induced ionization (CRII) of the troposphere (figure 11). This supports a physical mechanism involving cosmic rays rather than TSI or solar UV.
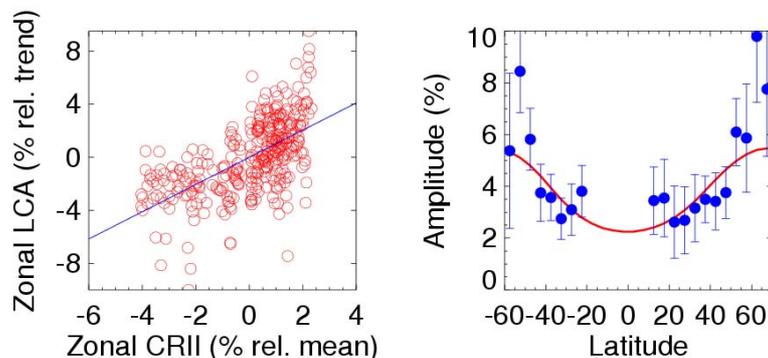
Figure 11: Latitudinal relation between relative variations of Low Cloud Amount (*LCA*) and Cosmic Ray Induced Ionisation (*CRII*) for the period 1984–2000 within the latitude range $55^o – 20^o$S and 10°-70^oN. **a)** Scatter plot of *LCA* vs. *CRII*, each dot representing an annual value within a 5° latitudinal bin. Solid blue line depicts the best linear. **b)** Latitudinal dependence of the amplitude of cyclic variations in *LCA* (blue dots) and *CRII* (red line). The amplitude is found by fitting a 10-year sinusoid to the respective time profiles. Adapted from Usoskin et al. (2004).

There is also evidence for the reduction of cloud coverage during strong Forbush decreases at time scales of a few days (Pudovkin and Veretenenko, 1996). This implies that the proposed cloud-cosmic ray relation may also be significant at short-time scales. Recently, *Kniveton and Todd* (Kniveton, 2004;2001) found a strong relationship between GCR and precipitation over southern oceans at mid to high latitudes. They suggest this is more consistent with

changes in the global atmospheric electric circuit according to *Tinsley* (1996a) rather than with tropospheric aerosols or ENSO.

The above evidence supports the suggestion that cosmic rays influence cloud properties, but a mechanism is required to physically link atmospheric ionization to clouds. Below two possible candidate mechanisms are briefly outlined.

3.3.1 Ion Induced Nucleation
Ions produced through the nucleonic cascade of cosmic rays in the troposphere rapidly interact with atmospheric molecules and are converted to complex cluster ions (aerosols) (Gringel et al., 1986;Hoppel et al., 1986). It is thought that these cluster ions grow through ion-ion recombination or ion-aerosol attachment and thus affect the number of aerosols acting as cloud condensation nuclei (CCN) at typical atmospheric super saturations of a few percent (Viggiano and Arnold, 1995). Recent atmospheric observations indicate a role for ion induced nucleation (IIN) in ultra-fine aerosol formation (sizes < 10 nm - Eichkorn et al., 2002;Lee et al., 2003). But it remains an open question as to whether aerosol concentrations at CCN sizes (~100 nm) are sensitive to a perturbation in ionisation and capable of significantly influencing cloud properties. Nucleation modelling studies suggest that it is the lower troposphere below 5 km that is most sensitive to changes in IIN (Yu, 2002b). Under such conditions, an increase in GCR would lead to an increase in aerosol and hence a decrease in cloud droplet sizes. Ferek et al. (2000) have shown that an increase in aerosol due to ship exhaust can lead to drizzle suppression which has implications for cloud lifetimes. If ionization from GCR can be shown to have a similar affect on the lower tropospheric aerosol distribution, and subsequently prolong a clouds lifetime, it would be consistent with the cosmic ray - low cloud correlation outlined above. However, ship tracks are a large perturbation locally, whereas a possible GCR - CCN mechanism will be a small perturbation globally. The possible link between atmospheric ionization and aerosols acting as CCN requires confirmation by experiment to determine it's potential implications for climate. Currently two such experimental efforts are underway at DNSC (http://www.dsri.dk/sun-climate/) and at CERN, Geneva (http://cloud.web.cern.ch/cloud/).

### 3.3.2 Global Atmospheric Electric Circuit
A further suggestion is that the amplification of cosmic rays on climate could be through changes in the global atmospheric electric circuit. Current flowing in the global atmospheric electrical circuit substantially decreased during the twentieth century, which has been quantitatively explained by a decrease in cosmic rays (CR) reducing the ionispheric potential as solar activity increased (Harrison, 2002). This potentially affects aerosol-cloud interactions at the edges of clouds, e.g., *Tinsley* (2000), (or a review of possible mechanisms in *Harrison and Carslaw* (2003)). Highly charged droplets are generated at cloud boundaries in the troposphere due to the weak vertical currents of the global electric circuit. Once these droplets have evaporated, highly charged CCN's remain, and the presence of this charge enhances collision efficiencies when interacting with other liquid droplets. The process of nucleation and evaporation repeats itself continuously and is thought to aid in the formation of ice particles in supercooled liquid water clouds, as a result it is referred to as 'Electroscavaging'(Tinsley, 1996b;Tinsley, 2000;Tinsley and Deen, 1991). There is some limited observational evidence to suggest that this process can have an additional influence on atmospheric dynamics (Roldugin and Tinsley, 2004;Tinsley, 1996b).

4.0 Paleoclimatic Evidence

From historical and geological records there are strong indications that the sun has played an important role in the past climate of the Earth, but the physical mechanisms are currently unknown. Whatever mechanism caused earlier changes would most likely also be operating today and may have been active throughout the history of our planet. It is therefore useful to be aware of solar related changes in climate on geological time scales as they may provide circumstantial evidence that is consistent with a particular mechanism.

4.1 Millennial Climate

A history of solar activity is known back in time from the production of cosmogenic nuclides in the atmosphere, e.g. ^{14}C and ^{10}Be, by galactic cosmic rays, the latter being influenced by solar activity. The historical flux of cosmogenic nuclides has been obtained from ice cores and tree-rings, and demonstrates that solar activity has varied considerably over the past 10000 years on 100–1000 year timescales. Variations in solar activity for the last millennium together with major climate epochs can be seen in figure 12.
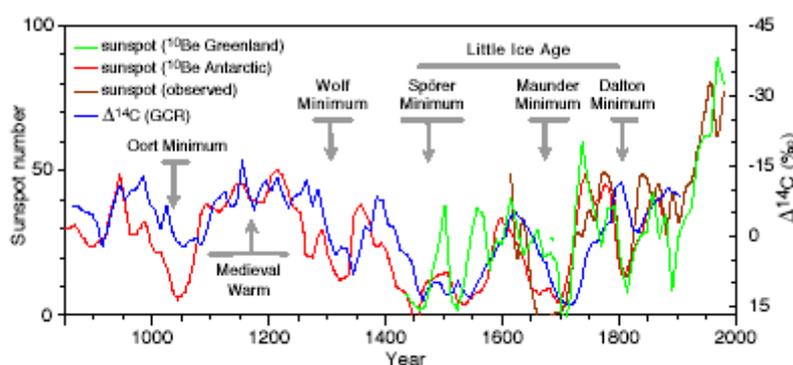

Figure 12: Changes in ^{14}C production relative to 1950 (blue) and reconstructed sunspot number from ^{10}Be for the past 1150 years. ^{14}C and ^{10}Be are produced through nuclear interactions of cosmic ray particles in the atmosphere. Cosmic rays are modulated by the solar wind; thus, variability in ^{14}C and ^{10}Be production is mainly a result of changes in solar activity. High solar activity leads to stronger shielding from the solar wind and thus a reduction in the production rate. Note the inverted axis for ^{14}C anomalies. The grey bars indicate major climate epochs. (adapted from Usoskin et al. (2003)).

Although a reliable estimate of the absolute global temperature record covering this period does not exist, some of the major changes in solar activity appear to coincide with significant climate shifts. There is a striking qualitative agreement between cold and warm climatic periods and low and high solar activity. For example, solar activity was particularly high from 1000 - 1300 AC, and coincided with the medieval warm period when wine was made from grapes grown in England, and the Vikings colonised Greenland. Solar activity decreased considerably after 1300 AC, a disaster for the Viking settlements in Greenland, and a long cold period followed, often referred to as the Little Ice Age, which lasted until the middle of the 19th century. This period was punctuated by some particularly significant climate shifts that coincided with major changes in solar activity (grey bars in figure 12), and are captured in various paleoclimatic proxies from around the world, e.g., lake sediments (Agnihotri et al., 2002;Hodell et al., 2001;Verschuren et al., 2000). Over the last 100 years solar activity has again increased and is at its highest level for possibly the past 8000 years (Solanki et al., 2004).

4.1 Holocene Climate

The Medieval Warming/Little Ice Age of the past 1000 years was not an isolated climate event associated with solar acitivity, and appears to be one of a number of warm/cold events that occurred during the Holocene. Examination of ocean sediment cores containing ice-rafted debris (see figure 13) suggest that the North Atlantic Ocean surface temperatures regularly fell by around 2^oC, coincident with periods of high solar activity (Bond et al., 2001).
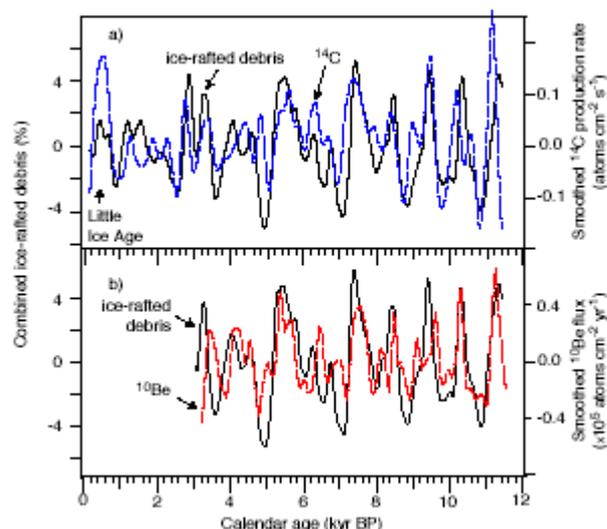
Figure 13: Correlation of ice-rafted debris from North Atlantic Ocean cores and solar activity indicated by a) ^{14}C and b) ^{10}Be (adapted from Bond et al. (2001)).

Recent evidence of solar activity influencing past precipitation rates have been obtain from the properties of stalagmites around the world (Burns et al., 2002;Fleitmann et al., 2003;Neff et al., 2001;Paulsen et al., 2003). Figure 14 indicates that variations of past monsoon rains in Oman, indicated by δ^{18}O changes in a U-Th-dated stalagmite from Hoti cave, Oman, over the period 6.2–9.6 kyr BP coincided with variations in solar activity. Water availability in this region requires a warm climate and monsoon rains brought by a northward shift of the Inter Tropical Convergence Zone (ITCZ) in summer. During a period of exceptionally rapid stalagmite growth, around 8000 years BP, decadal variability in Oman rainfall possesses an incredibly strong correlation with solar activity. This is one of the best examples of solar activity influencing past paleoclimates at time scales relevant for understanding present day climate change.
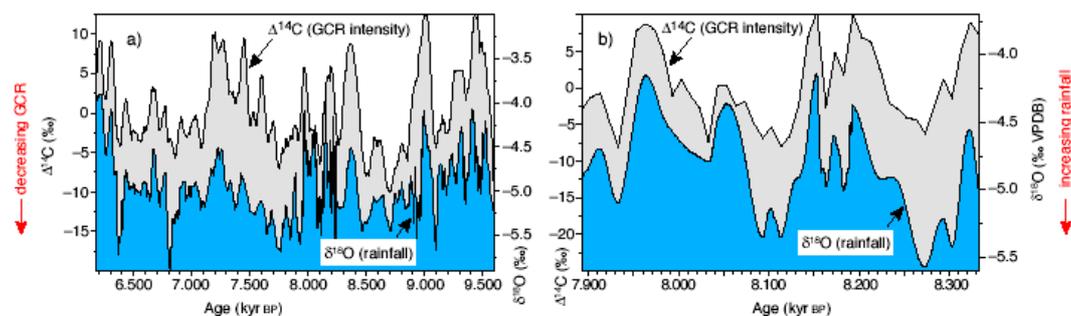

Figure 14: Profiles of δ^{18}O from a stalagmite in Hoti cave, Oman, which is a proxy for monsoon rainfall, together with atmospheric ^{14}C obtained from Californian tree rings, which is a proxy for solar

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activity. **a)** for the period 6200-9600 years BP and **b)** a period of high resolution 8330-7900 years BP (adapted from Neff et al. (2001)).

4.3 Galactic Influences on Climate

Although cosmogenic nuclides are used as an indicator for past solar activity to be compared with paleoclimatic data, it is often assumed that the physical link with climate is via solar irradiance changes. This ignores the possibility that the cosmic rays themselves have played a role. Moreover, there is beginning to emerge evidence from geological indicators that climate, on time scales of Millions of years and longer, is correlated with long term variations in cosmic ray production. At these time scales the flux of cosmic rays entering Earth's atmosphere vary due to processes external to our solar system, through the traversing of the galactic spiral arms or changes in our galaxy's star formation rate (Shaviv, 2003a;Shaviv, 2003b). These processes are independent of solar activity and therefore provide an independent argument for the role of ions in climate change. Shaviv (2003a) estimates the timing of Earth crossing the galactic spiral arms from models of the Milky Way and finds coincidence with ice age epochs on Earth together with evidence from iron meteorite exposure ages for enhanced cosmic ray flux during the crossing of the galactic arms (Figure 15).
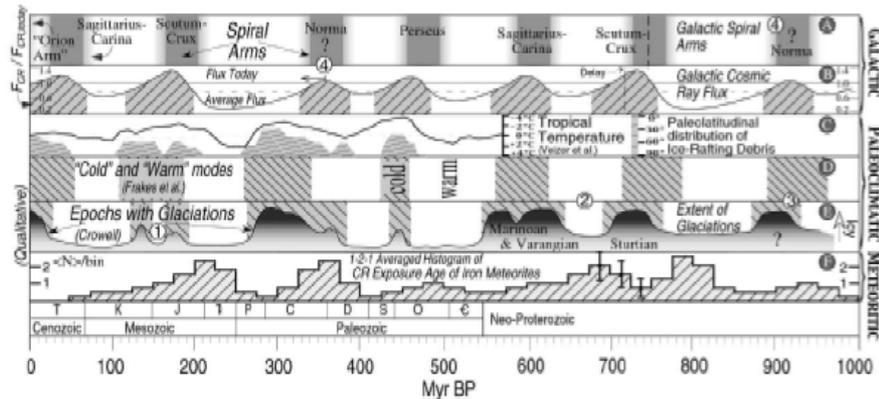

Figure 15: Crossing of galactic spiral arms with estimated external cosmic ray flux correlated with glaciation epochs. The estimated cosmic ray flux is substantiated be the iron meteorite exposure age histogram (adapted from Shaviv (2003a)).

Following this, *Shaviv and Veizer* (2003) reported a related correlation between reconstructed cosmic ray fluxes and ocean temperatures during the Phanerozoic (past 550 Myrs), with a periodicity of 140 Myr (Figure 16), finding that at least 66% of the variance in the paleotemperature trend could be attributed to galactic cosmic ray variations. Independently of the methods employed by *Shaviv* in the above work, *de la Fuente Marcos and de la Fuente Marcos* (2004) estimated periods of excess galactic cosmic ray flux from enhanced star formation rate in the Solar Neighborhood using a volume limited open cluster sample and found a strong correlation with ice age epochs (Figure 17). It is an open question whether the physical processes operating at geological time scales are equivalent to those responsible for the more recent decadal changes in climate. This work is at an early stage but the initial evidence hints at some intriguing possibilities.
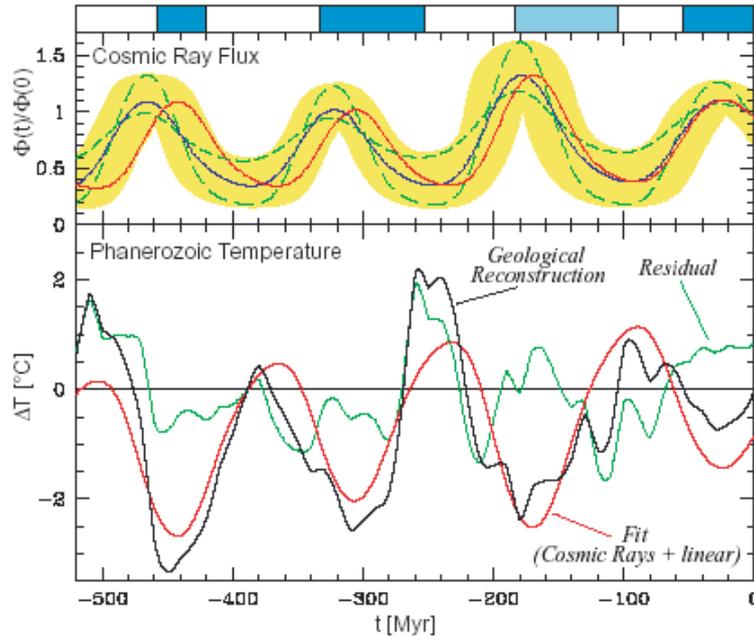
Figure 16: Cosmic ray flux and tropical temperature anomaly variations over the Phanerozoic. The upper curves show the cosmic ray flux reconstructed from iron meteorite exposure ages. The lower curves show the geologically reconstructed temperature anomaly (black) with that estimated from a model of cosmic ray influence on climate (red) and the residual.66% of the temperature anomaly can be attributed to the variation of cosmic ray flux (adapted from Shaviv and Veizer (2003)).
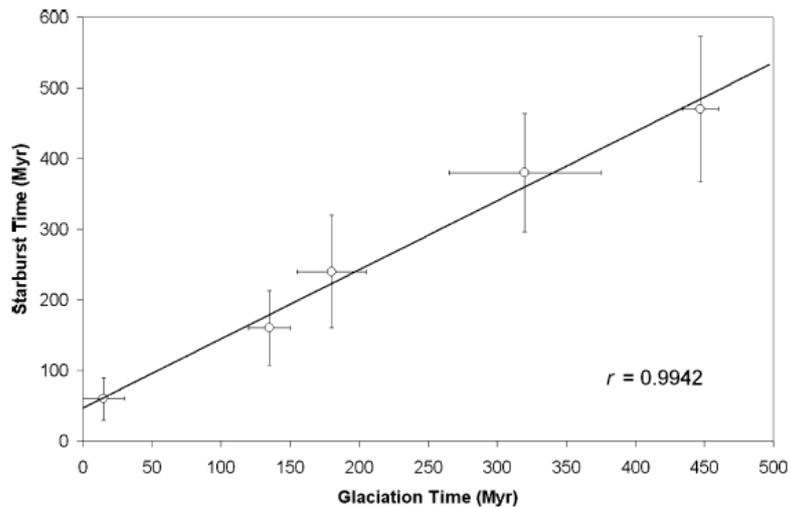
Figure 17: Enhanced star formation episodes as a function of the time-coincident glaciation events. A complete positive correlation is found within the error limits (adapted from de la Fuente Marcos and de la Fuente Marcos (2004)).

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On even longer timescales covering the 4.6 billion year history a remarkably correlation between Earths climate and GCR flux is found. In this case the GCR flux at Earth is reconstructed by considering variations in star formation (the galactic source of GCR) and the evolution of solar activity during the last 4.6 billion year. Figure 18 (Svensmark, 2003) shows a reconstruction of the GCR flux and variations in Earths climate. It is seen that in the early period most of the GCR flux is very low as a result of the highly magnetic active young sun. Later when the sun is less active the variations in the source of GCR flux, i.e. star formation rate, are clearly seen. In particular the minimum between one and two billion years ago fits very well with the lack of glaciations on Earth during this period. If the relation is real, it suggests that the whole history of the Milky Way influences the evolution of climate. In addition such a relation could be a significant contribution in the solution of the paradox of the young faint sun, i.e. the contrast of a weak young sun and warm early Earth.
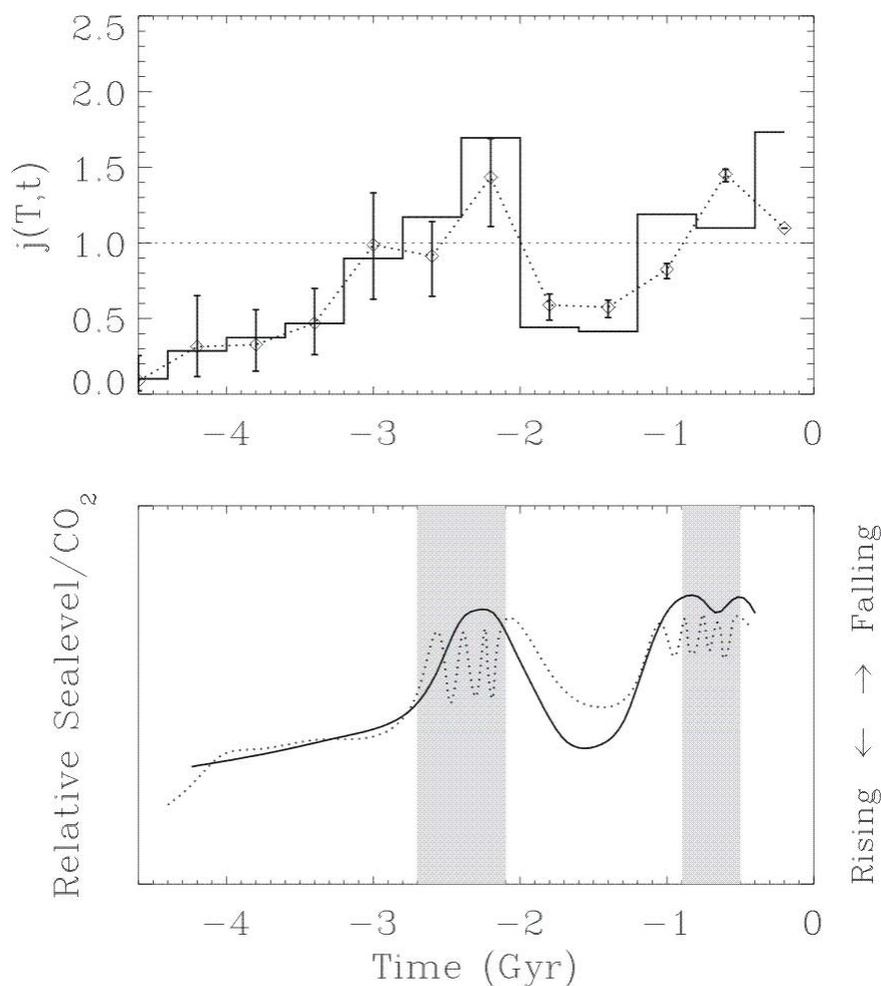
Figure 18. Top panel: Variation of Galactic Cosmic Ray (GCR) particles with energy 10 GeV at 1 AU over the entire history of the solar system. The error bars indicate the modulation for particles of 5 GeV (lower bound) or 20 GeV, respectively (upper bound). Lower panel: Generalized evolution of Earth's climate represented by relative sea level changes (solid curve) and relative changes of atmospheric content of CO_2 (dashed curve). The extremes indicate either a Greenhouse climate (Warm) or an Icehouse (Cold), corresponding to high sealevel/CO_2 level or low sealevel/CO_2 level respectively. The gray areas are known periods of glaciations.

5.0 Other Planets

The Earth's atmosphere is not alone in displaying variable properties related to the solar cycle. *Lockwood and Thompson* (1979) have shown that the albedo of other planets may also be linked to solar activity. Observations since 1973 indicate that the de-trended brightness of Neptune is varying by 3-4% and is in phase with the solar cycle as shown in Figure 19 (Lockwood and Thompson, 1991;Lockwood and Thompson, 1986;Lockwood and Thompson, 2002). Saturn's moon, Titan, has also displayed an 8% variation in brightness that is anti-correlated with solar activity (Lockwood and Thompson, 1986). One possible explanation for the changes in Neptune's albedo is a modulation in the rate of GCR ion-induced nucleation of methane clouds (Moses et al., 1989;Moses et al., 1992). This opens up the possibility that a link between GCR modulated by solar activity and the transparency of planetary atmospheres is a general feature of our solar system. If this is confirmed, then the magnetic fields that modulate GCR will have a new relevance. This would not be restricted to the solar wind's magnetic field alone, but would also include the influence from a planets own magnetic field. Another explanation for Neptune's albedo change is a darkening of stratospheric aerosols induced by changes in Solar UV (Baines and Smith, 1990).
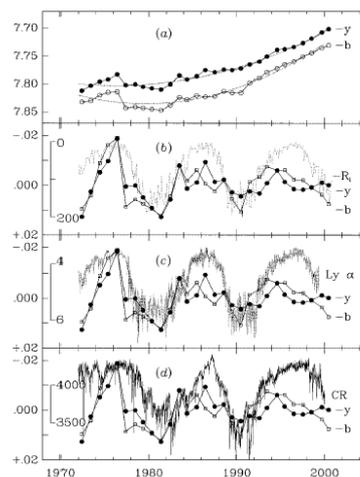
Figure 19: Neptune's brightness observed in band *b* (472-nm open dots) and band *y* (551-nm filled dots), correlated with solar activity. a) Neptune's brightness curve is fitted with a quadratic long-term trend, which is removed in the three remaining panels. Neptune's brightness anomalies (symbols) together with b) sunspot number, c) Lyman-a flux (a proxy for solar UV), and d) cosmic rays observed with the Climax neutron monitor (adapted from Lockwood and Thompson (2002)).

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