SOLAR INFLUENCE ON EARTH'S CLIMATE

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Abstract. An increasing number of studies indicate that variations in solar activity have had a significant influence on Earth's climate. However, the mechanisms responsible for a solar influence are still not known. One possibility is that atmospheric transparency is influenced by changing cloud properties via cosmic ray ionisation (the latter being modulated by solar activity). Support for this idea is found from satellite observations of cloud cover. Such data have revealed a striking correlation between the intensity of galactic cosmic rays (GCR) and low liquid clouds (<3.2 km). GCR are responsible for nearly all ionisation in the atmosphere below 35 km. One mechanism could involve ion-induced formation of aerosol particles (diameter range, $0.001-1.0$ μm) that can act as cloud condensation nuclei (CCN). A systematic variation in the properties of CCN will affect the cloud droplet distribution and thereby influence the radiative properties of clouds. If the GCR-Cloud link is confirmed variations in galactic cosmic ray flux, caused by changes in solar activity and the space environment, could influence Earth's radiation budget.

Key words: climate, GCR, sun

1. Introduction

In this paper we discuss the possibility that solar activity and the space environment can influence terrestrial climate. Outlined in the flow diagram of Figure 1 are the two major routes by which the sun can influence this region of the atmosphere. This involves both solar irradiance providing the energy driving terrestrial climate, and solar wind shielding of Galactic Cosmic Rays (GCR) which are responsible for ionisation in the lower 35 km of the atmosphere. Changes in Total Solar Irradiance (TSI) over the 11 year solar cycle is about 0.24 W m^2 at the top of Earth's atmosphere, which is currently believed to be too small to have had a significant influence on climate. However, indirect effects may be much larger, and there are two mechanisms which have recently gained considerable attention. The first involves the UV part of the solar spectrum which varies by up to $10-100\%$ over a solar cycle. The role of UV in stratospheric ozone production is thought to influence the temperature and circulation of the stratosphere. Through dynamic coupling with the troposphere these changes may influence surface climate, but the extent of the coupling is currently uncertain (Haigh, 1996; Shindell *et al.*, 1999). The second indirect effect, and the one that will be considered here, is the possible role of atmospheric ionisation, resulting from GCR, in the production of new aerosol. Aerosols acting as Cloud Condensation Nuclei (CCN) play an important role in

Space Science Reviews **107:** 317–325, 2003.

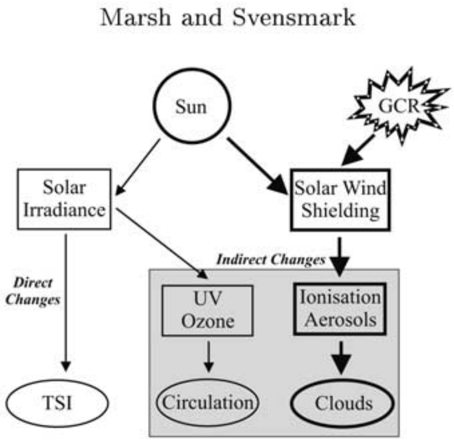

Figure 1. Possible routes for a solar influence on climate.

determining cloud properties. Clouds cover between 60−70% of the globe at any time, and influence the radiation budget by both reflecting incoming short wave radiation and trapping outgoing long wave radiation. A systematic change in the number of CCN will affect cloud properties, and thus would have an impact on Earth's climate.

2. GCR – Cloud Correlation

Using various satellite observations of cloud amount, a correlation has been found between total cloud cover averaged over the oceans and GCR (Svensmark and Friiss-Christensen, 1997; Svensmark, 1998). However, this result gave no indication as to the cloud type(s) affected, which is necessary for understanding the nature of any GCR-cloud mechanism and for estimating its potential radiative impact on climate. Marsh and Svensmark (2000b), have shown that the GCR-cloud correlation is limited to low cloud when using IR (at wavelength 10 μm) cloud observations provided by the International Satellite Cloud Climate Project (ISCCP version D2) between July 1983–September 1994 (Figure 2a). Recently, an extension to this data has been made available up to September 2001. From Figure 2a it can be seen that the correlation between low cloud and GCR breaks down after 1994. In addition a number of other ISCCP-D2 cloud parameters display a step function at around the same time. This is particularly apparent in the global average of high cloud amount shown in Figure 2b. Interestingly, between September 1994 and January 1995 ISCCP experienced a gap in available polar orbiting reference satellites required to inter-calibrate the five satellites used to provide global coverage of cloud observations (ISCCP homepage, 2002). An estimate of the effect of this calibration gap on ISCCP low cloud amount can be made by comparing it with independently observed cloud amounts obtained from the

Special Sounder Microwave Instrument (SSMI) (Ferraro *et al.*, 1996). SSMI data is available over oceans from July 1987–present with an 18 month gap between June 1990–December 1991. Since the SSMI cloud data is at a much lower resolution than ISCCP data, it is important to determine regions where the two data sets are observing similar cloud properties. These regions are found where the correlation coefficient at each grid point is >0.5. Limiting the period over which the correlation coefficients are found to July 1987–June 1990 allows for an independent test between the ISCCP and SSMI long term trends after January 1992 (Marsh and Svensmark, 2003). Figure 2c displays the regional averages over the full period of available data. While initially there is a good agreement between the two curves, after 1994 the long term trends diverge while the month to month fluctuations are still correlated. A correction factor can be estimated from the difference between the long term trends. When adding this correction factor to the globally averaged ISCCP-D2 low cloud cover (Figure 2a, dashed curve), the correlation with GCR is then found to exist for all available data (Marsh and Svensmark, 2003).

3. Ionisation – CCN – Cloud Properties

Svensmark (1998) suggested that a physical mechanism to explain the GCR-cloud link could involve the effects of atmospheric ionisation on aerosol chemistry or the phase transition of water vapour. Previously, Ney (1959) had observed that atmospheric ionisation was 'the meteorological variable subject to the largest solar cycle modulation in denser layers of the atmosphere'. This lead Dickinson (1975) to speculate that ionisation might modulate sulphate aerosol formation which when activated as CCN would influence cloud radiative properties.

Low clouds generally consist of liquid water droplets which have formed where water vapour has condensed onto atmospheric aerosols acting as CCN. Artificial inputs of aerosol, e.g. ship exhaust or emissions from chimneys, into regions of low cloud formation tend to result in large increases of CCN locally, and it is possible to observe their influence on cloud radiative properties (King *et al.*, 1993). However, observing the impact of natural variations in CCN is not so straight forward. The fundamental physics of new particle formation is not understood and there are many complex processes involved in the growth from newly formed ultra fine aerosol $\sim 0.001\ \mu$m up to CCN $\sim 1.0\ \mu$m. Atmospheric ionisation has been suggested as potentially important for influencing any one of the stages in the production and growth phases of aerosol. Numerical simulations focusing on the role of ionisation in the production of new aerosol have been successful at reproducing observations of new particle formation over the Pacific where classical nucleation theories have failed (Clarke *et al.*, 1998; Yu and Turco, 2000). Further, these model results suggest that the production of new aerosol is sensitive to small changes in ionisation in regions of low cloud formation <3.2 km, while relatively insensitive at higher altitudes (Yu, 2002). Although it is currently uncertain whether

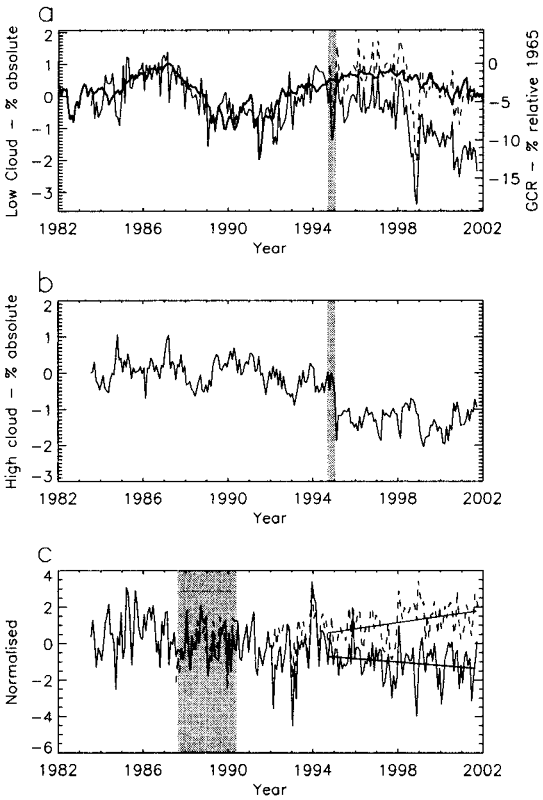

Figure 2. Monthly averages of cosmic rays (thick solid) and globally averaged anomalies (solid) of (a) ISCCP-D2 low cloud amounts, and (b) ISCCP-D2 high cloud amounts over the period of available ISCCP-D2 data. The dashed portion of the curve in (a) includes a drift term calculated by adding the difference between the linear trends seen in (c) to the ISCCP-D2 low cloud amount for each month. The anomalies are found by subtracting the climatic annual cycle for each month, averaged over the available period of ISCCP observations (July 1983–September 2001), before averaging over the globe. The shaded region in (a) and (b) denotes the gap in available ISCCP calibration satellites. (c) Spatial average of ISCCP low cloud amount (solid) and SSMI cloud amount (dashed) over regions of significant correlation ($r > 0.5$, $p > 99\%$). Both ISCCP low cloud amount and SSMI cloud amount have been normalised to their respective mean and variance over the highlighted period July 1987–June 1990. The thick lines represent the linear trends used in (a) for the respective curves starting July 1994.

this dependency on ionisation is maintained through the growth phase up to CCN sizes, it is consistent with the strong positive correlation found between low clouds and GCR.

The flow diagram in Figure 3 shows the link between ionisation and cloud radiative properties, assuming that a relationship between ionisation and CCN exists. An increase in CCN will lead to an increase in the number of cloud droplets and hence changes in liquid water content affecting the long wave properties (Han *et al.*, 2002). Increasing the droplet number will also lead to a decrease in droplet

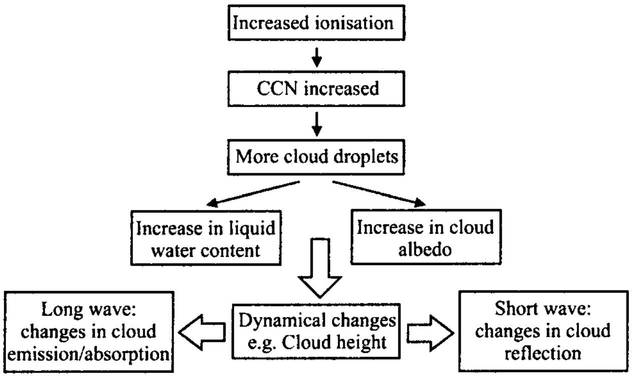

Figure 3. Possible route for an influence from atmospheric Ionisation on cloud radiative properties.

size which will affect a clouds albedo, and hence its short wave properties. Thus if there is a systematic change in atmospheric ionisation, such as over a solar cycle, a response is expected in both long wave and short wave cloud radiative properties.

Figure 4 shows a global map of the correlation coefficient found at each grid point between GCR and ISCCP-D2 low cloud top temperature (Marsh and Svensmark, 2000b). A region centered around the equator displays strong positive correlation coefficients. Figure 5 shows the global averages of ISCCP-D2 cloud optical depth for low and mid liquid stratus clouds. The optical depth observations are found using visible wavelengths (VIS) which are less certain then the IR observations and so the results are less robust. Despite these uncertainties Figure 5 indicates that a significant correlation is found between GCR and cloud optical depth. These results suggest that both long (IR) and short wave (VIS) properties of low clouds are responding to changes in atmospheric ionisation due to variations in solar activity.

4. Past Cloud Radiative Impact on Climate

Tropospheric temperatures observed with radiosondes over the period 1958–2001 display significant variability at a number of different time-scales. From monthly data the effects of El Niño and volcanic eruptions are particularly evident. 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 solar activity (Figure 6) (Svensmark *et al.*, 2003). From Figure 6 an increase in reconstructed TSI of $\triangle F_s = 1$ W m^2, is seen to coincide with a 0.4 K increase in tropospheric temperature. To estimate whether the increase in TSI can explain the temperature change a simple sensitivity analysis can be performed where, $\triangle T = \lambda * \triangle F$. Here, $\triangle T$ is the response to a change in radiative forcing $\triangle F$ at top of the atmosphere. The climate sensitivity parameter $\lambda = 0.6$, is found from the average response of various climate models to a doubling of CO_2. Accounting

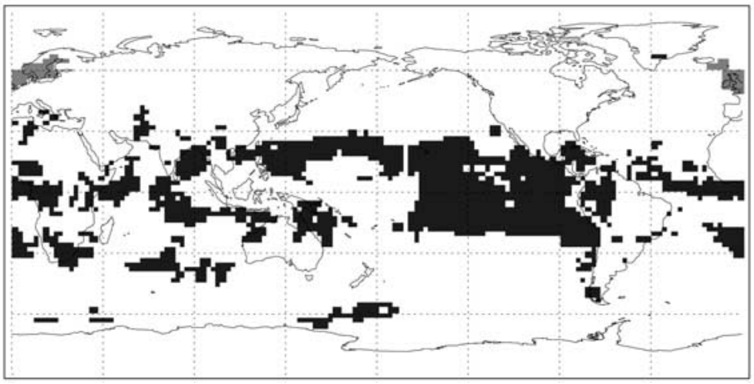

Figure 4. Point correlation maps for the period July 1983–August 1994 between GCR and ISCCP-D2 low cloud amounts. The correlation coefficient, r, is calculated from the 12 month running means at each grid box. The shading corresponds to regions where r $>$ 0.6 (dark grey) and r < -0.6 (light grey) with p $>$ 95% significance. White pixels indicate regions with either no data or an incomplete monthly time series.

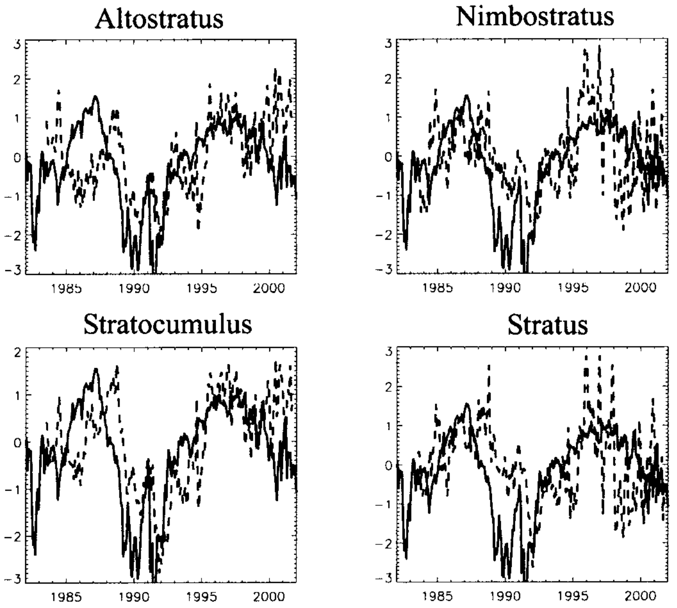

Figure 5. Monthly averages of cosmic rays (solid) and globally averaged anomalies (dashed) of ISCCP-D2 liquid stratus cloud optical depth. Anomalies are found as in Figure 1.

for Earth's average albedo, $\alpha = 0.3$, and the geometric effect, the TSI forcing at the top of the atmosphere is found to be $\triangle F = (1-\alpha)/4 * \triangle F_s = 0.2$ W m^2, which results in only a 0.1 K increase in temperature in contrast to the 0.4 K observed. Clearly, changes in TSI alone are too small to explain tropospheric temperatures and an amplification factor is required.

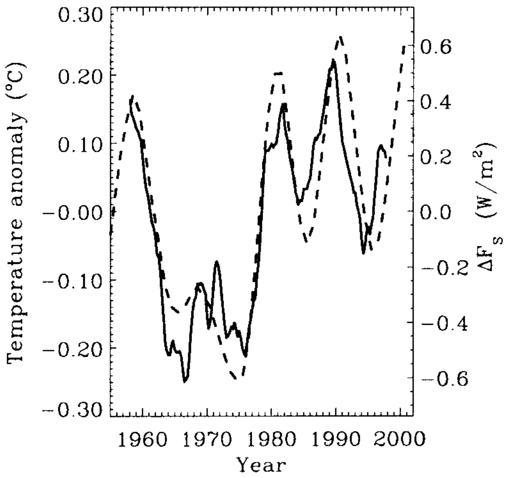

Figure 6. Tropospheric temperatures (solid) obtained from radiosondes (Parker *et al.*, 1997), together with reconstructed TSI (dashed), $\triangle F_S$, using re-scaled sunspot numbers as a proxy (Lean *et al.*, 1995). Both data sets have been low pass filtered with a three year running mean.

Using GCR as a proxy for low cloud changes, Marsh and Svensmark (2000a) estimated the changes in cloud radiative forcing over this period to be ~0.5 W m^2. If this forcing factor is included in the above calculation then $\triangle T$ is estimated to be ~0.4 K as observed. Although this is rather speculative, it does indicate that the contribution to climate change from an indirect response to changes in solar activity are potentially important.

An estimate of cloud radiative forcing for the past 100 years was found to be 1.5 W m^2 (Marsh and Svensmark, 2000a) by observing that the solar magnetic flux has more than doubled over the past century (Lockwood *et al.*, 1999). Over the same period global surface temperature has been observed to increase by ~0.6 K. Other indications suggesting that the sun has played a role in past terrestrial climate variability is reflected in the close agreement between cosmogenic isotopes and various paleoclimate proxies. Bond *et al.* (2001) showed that Ice Rafted Debris (IRD) from north atlantic marine cores closely followed changes in solar activity for the past 12 000 yrs. IRD deposits are the result of melting icebergs which have originated from the ice margins and traveled under the influence of surface winds and currents out over the north Atlantic. Fluctuations in IRD reflect changes in north Atlantic climate and the close agreement with cosmogenic isotopes ^{14}C and ^{10}Be suggests a solar influence. Another example can be found from studies of δ^{18}O obtained from stalagmites by Neff *et al.* (2001) in the caves of Northern Oman. Here δ^{18}O reflects changes in monsoon precipitation and the position of the Inter-Tropical Convergence Zone (ITCZ). δ^{18}O measurements between 6000 and 9500 BP show a close agreement with ^{14}C again implicating the sun in long term climate variability.

Finally, evidence exists to suggest that solar activity influences the atmospheric properties of other planets in the solar system. Observations in the brightness changes of Neptune reveal a 10% increasing trend between 1970–2000. The residual after removing this trend is $\sim$2% and shows a remarkable agreement with changes in solar activity (Lockwood and Thompson, 1991). One possible explanation is that ion mediated nucleation, modulated by GCRs, is affecting the albedo of methane clouds forming in Neptune's atmosphere (Moses *et al.*, 1989). This suggests that IMN modulated by the average state of the heliosphere could be a general feature of our solar system.

5. Conclusions

Inter-annual trends in ISCCP-D2 IR cloud data reveal a positive correlation between cosmic ray intensity and two parameters: (1) low cloud amount and, (2) low cloud top temperature. ISCCP-D2 VIS cloud data suggests that cloud optical thickness in liquid stratus clouds is also positively correlated with GCR. If confirmed, this would provide considerable support for a GCR-cloud mechanism. Numerical simulations of new aerosol production, suggest that production is most sensitive to changes in ionisation from GCR in the lower troposphere. Assuming that this is reflected in the final CCN distributions, this is consistent with the observations of a GCR-low cloud correlation.

Estimates of changes in cloud radiative forcing indicate that if a GCR-cloud mechanism exists it could have a significant impact on the global radiation budget. Past observations of climate change appear to follow changes in the cosmic ray flux lending support to the suggestion that solar activity and the space environment have influenced terrestrial climate.

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