

COSMIC RAYS AND EARTH'S CLIMATE

HENRIK SVENSMARK

Danish Space Research Institute, DK-2100 Copenhagen Ø, Denmark

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Abstract. During the last solar cycle the Earth's cloud cover underwent a modulation in phase with the cosmic ray flux. Assuming that there is a causal relationship between the two, it is expected and found that the Earth's temperature follows more closely decade variations in cosmic ray flux than other solar activity parameters. If the relationship is real the state of the Heliosphere affects the Earth's climate.

1. Introduction

The physical cause of climate variability is not known in detail. There are several physical factors that are believed to influence the Earth's climate. For example: (1) Orbital changes in the Earth's motion around the Sun is believed to cause ice-ages. (2) Internal variability in the climate system, e.g., changes in atmospheric and ocean circulation. (3) Large volcanic eruptions, which are known to cause a sudden cooling lasting 2–3 years. A period with high volcanic activity could potentially lead to a cooling of the Earth. (4) Changes in concentration of greenhouse gases. Due to burning of fossil fuel during the last 100 years there has been an increase in atmospheric CO₂ concentration from about 280 to 365 ppm. Because CO₂ is a greenhouse gas that traps outgoing long wave radiation, and that the surface temperature has increased by approximately 0.7 °C during the last 100 years, there is a worry that this increase is leading to a warmer climate. (5) Changes in solar activity, which will be discussed further in this paper. The relative importance of the above different influences is not known very well.

It is obvious from historical records that the Sun has played an important role in the climate of the Earth. For more than a hundred years there have been reports of an apparent connection between solar activity and the Earth's climate (e.g., Eddy, 1976; Herman and Goldberg, 1978). William Herschel, a well known scientist in London suggested in 1801 that the price of wheat was directly controlled by the number of sunspots, based on his observation that less rain fell when there was few sunspots. Since then many reports have indicated a link between solar activity and climate. Solar activity is known for a long time back in time through a history of atmospheric isotope levels produced by galactic cosmic rays (see also the article of J. Beer in this book). Such records reveal a striking qualitative agreement between cold and warm climatic periods and low and high solar activity during the last



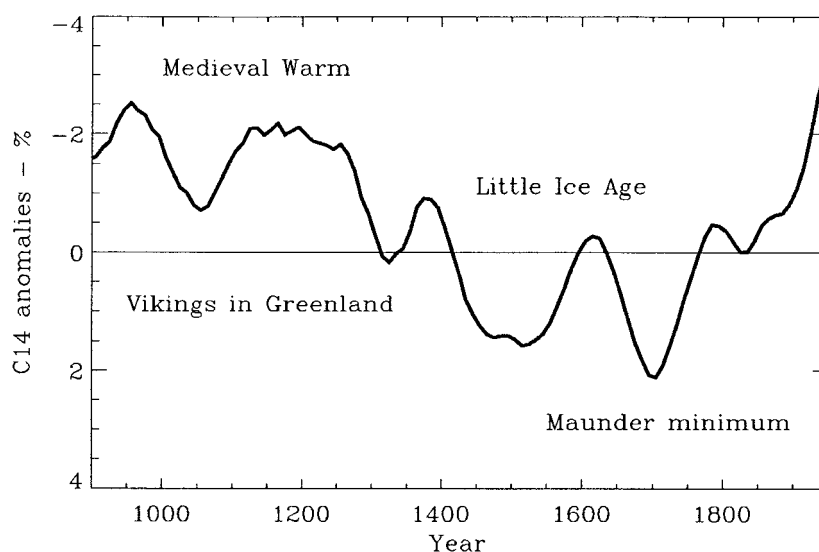


Figure 1. Change in ^{14}C concentration during the last 1000 years. The variation in the ^{14}C concentration is dominated by changes in solar activity. When solar activity is high the production of ^{14}C is low, due to the shielding effect of the solar wind against cosmic rays. Note that the axis for the ^{14}C concentration has been reversed. The Maunder minimum refers to the period 1645–1715 when very few sunspots were observed on the Sun. In this period the concentration of ^{14}C was higher in agreement with a low solar activity.

10 000 years (Eddy, 1976). Figure 1 shows the variation in ^{14}C concentration during the last millennium. From year 1000–1300 AD solar activity was very high, which coincided with the warm medieval period. It was during this period that the Vikings settled in Greenland. Solar activity decreased considerably after 1300 AD and a long cold period followed, called the little ice age. This climatic shift was a disaster for the Vikings. The Little Ice Age lasted until the middle of the last century. During this century solar activity has again increased and is at its highest level the past 600 years.

It is not only proxy data that show an apparent agreement with solar activity. An indication of a link between long term variations in solar activity and the Earth's temperature was found by Friis-Christensen and Lassen (1991) and Lassen and Friis-Christensen (1995). They showed that an empirically constructed measure of solar activity, the filtered solar cycle length, closely matched variations in northern hemispheric temperature during the last 400 years. Another interesting example of a solar influence was discovered by Labitzke and van Loon (1993). They showed that the height of the pressure surfaces in the lower stratosphere varies in phase with solar activity and has done so through the last four solar cycles.

The most obvious and direct way solar activity could affect the Earth's climate would be via changes in solar irradiance. But the steadiness of the Sun has been established by satellite measurements of solar irradiance during the last 20 years.

It is found that the variations are small ($0.1\% \approx 0.3 \text{ W m}^{-2}$ during a solar cycle), although this is not completely negligible, it is too small to explain the observed temperature changes (Lean *et al.*, 1995). Apart from a direct influence of solar irradiance variations, there have been speculations on how small changes in solar activity can be amplified in the Earth's atmosphere. One idea is related to the fact that during a solar cycle, changes in the UV radiation of the solar spectrum are of the order of 10%. Due to the importance of UV in the formation of ozone it has been suggested that the resulting heating in the stratosphere is dynamically transported down into the troposphere (Haigh, 1996; Shindell *et al.*, 1999).

Another suggestion involves galactic cosmic rays (GCR). GCR consist of very energetic particles (mainly protons) that are accelerated in stellar processes in our galaxy. Some of them enter the Earth's atmosphere where nuclear processes take place and produce secondary particles that can penetrate still deeper into the atmosphere (Lal and Peters, 1967). Ionisation in the atmosphere below 35 km is almost exclusively produced by GCR, except for the lowest 1 km over land where radioactive gases are the main cause of ionisation. Ionisation by GCR is the variable of the lower atmosphere subject to the largest solar cycle modulation (Ney, 1959). The ionisation variation could potentially influence optical transparency of the atmosphere, by either a change in aerosol formation or an influence on the transition between the different phases of water (Ney, 1959; Dickinson, 1975; Pudovkin and Raspopov, 1992; Pudovkin and Veretenenko, 1992; Tinsley, 1996; Svensmark and Friis-Christensen, 1997; Svensmark, 1998).

In the following it will be shown that the Earth's cloud cover, obtained from satellites, within the last solar cycle follows variations in GCR more closely than other solar activity parameters. Further it will be shown that long term variation in solar activities given by GCR reflects variations in the Earth's temperature during the period (1937–1994) based on direct measurement of cosmic ray flux. Finally an indication of a GCR influence on temperatures during the Maunder minimum is presented.

2. Cosmic Rays and the Earth's Climate

2.1. COSMIC RAYS AND CLOUDS

Recently it was found that the Earth's cloud cover, observed by satellites, is strongly correlated with GCR (Svensmark and Friis-Christensen, 1997). Clouds influence vertically integrated radiative properties of the atmosphere by both cooling through reflection of incoming shortwave radiation, and heating through trapping of outgoing longwave radiation. The net radiative impact of a particular cloud mainly depends upon its height above the surface and its optical thickness. High optically thin clouds tend to heat while low optically thick clouds tend to cool (Hartmann, 1993). With a current climatic estimate for the net forcing of the global cloud

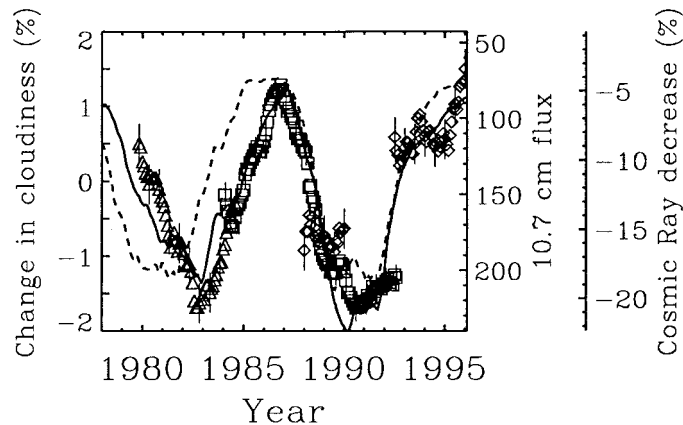


Figure 2. Composite figure showing changes in the Earth's cloud cover from four satellite cloud data sets together with cosmic rays fluxes from Climax (*solid curve*, normalized to May 1965), and 10.7 cm solar flux (*broken curve*, in units of $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$). Triangles are the Nimbus7 data, squares are the ISCCP_C2 and ISCCP_D2 data, diamonds are the DMSP data. All the displayed data have been smoothed using a 12 months running mean. The Nimbus7 and the DMSP data are total cloud cover for the Southern Hemisphere over oceans, and the ISCCP data have been derived from geostationary satellites over oceans with the tropics excluded.

cover as a $17\text{--}35 \text{ W m}^{-2}$ cooling, clouds play an important role in the Earth's radiation budget (Ohring and Clapp, 1980; Ramanathan *et al.*, 1989; Ardanuy *et al.*, 1991). Thus any significant solar influence on global cloud properties is potentially very important for the Earth's climate (Svensmark and Friis-Christensen, 1997; Svensmark, 1998).

Figure 2 is a composite of satellite observations of the Earth's total cloud cover adapted from Svensmark and Friis-Christensen (1997). The cloud data comprise the NIMBUS-7 CMATRIX project (Stowe *et al.*, 1988) (triangles), and secondly the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schif-fer, 1991) (squares). Finally data from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) (diamonds) (Weng and Grody, 1994; Ferraro *et al.*, 1996) are included. Since the cloud data are obtained from four different cloud satellite programs the data presented are not homogeneous. The reason is that the instrumentation, spatial and temporal coverage is different from one satellite system to another. Therefore only the relative variations in the data can be compared. Only the most reliable data common to all satellites were used in an attempt to improve inhomogeneities. For example the DMSP satellites only retrieve data from over the oceans, therefore only cloud coverage over oceans is used. Further, only ISCCP data retrieved from geo-stationary satellites was used due to their superior spatial and temporal coverage over the polar orbiting satellites. The tropics were excluded in the above Figure 2 for two reasons. Due to the shielding of the Earth's magnetic field there is a significant reduction of GCR flux close to the equator. Secondly, tropical cloud processes are

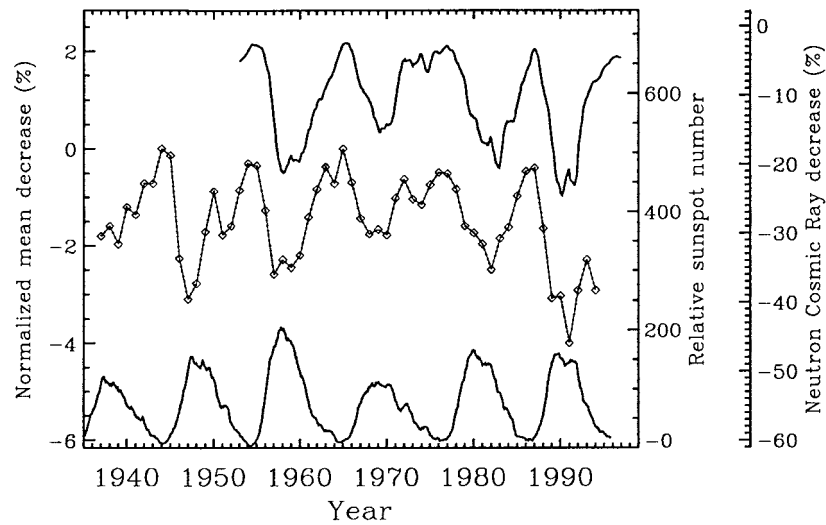


Figure 3. Top curve is cosmic ray flux from the neutron monitor in Climax, Colorado (1953–1996). Middle curve is annual mean variation in cosmic-ray flux as measured by ionisation chambers (1937–1994). The neutron data has been normalized to May 1965, and the ionisation chamber data has been normalized to 1965. Bottom curve is the relative sunspot number.

different from cloud processes at higher latitudes, e.g., the net radiative impact of clouds in the tropical regions is small compared to higher latitudes. For further details see Svensmark and Friis-Christensen (1997). The obtained results are not very sensitive to the selection mentioned above, and therefore the term the ‘Earth’s cloud cover’ is used in Figure 2.

In the figure the cloud data are compared with variations in GCR and the 10.7 cm radio flux from the Sun. One sees that there are clear differences between the variations of GCR and the radio flux. From 1987 to present the two follow each other. However, there is a lag between the two of almost two years prior to 1987. What is crucial in this context is that the Earth’s cloud cover follows the variation in GCR. This is important since it indicates that it is the ionisation in the atmosphere produced by GCR that is essential in the solar climate link, and not necessarily the variations in the 10.7 cm flux. This radio flux follows closely variations in total solar irradiance, soft X-rays, and in ultraviolet radiation.

2.2. INFLUENCE ON TEMPERATURE

Having established that variations in GCR are a good candidate for indirectly influencing the Earth’s climate based on data covering the last solar cycle, it is important to compare variations in solar activity over a longer time span. However, there is no reliable data of cloud cover outside the period already used. But if variations in GCR cause a climatic effect it should be reflected in variations in the Earth’s temperature. To investigate this a long data series of GCR flux is needed. In-

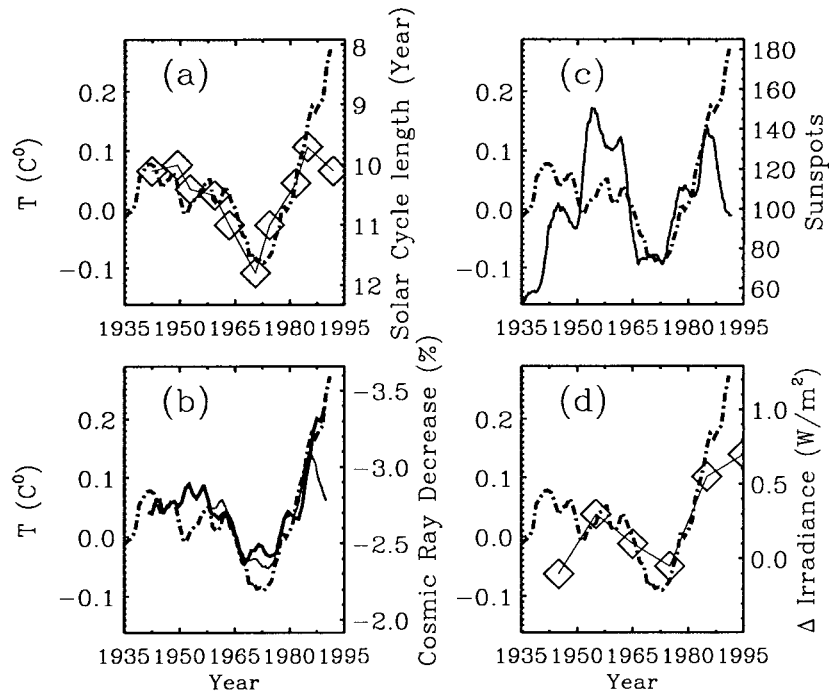


Figure 4. Eleven-year average of Northern Hemispheric marine and land air temperature anomalies (*broken line*) compared with, (a) unfiltered solar cycle length, (b) 11-year (box-car) average of cosmic-ray flux (from ion chambers 1937–1994, normalized to 1965, *thick solid line*), the thin solid line is cosmic ray flux from Climax, Colorado neutron monitor (arbitrarily scaled), (c) 11-year (box-car) average of relative sunspot number, (d) decade variation in reconstructed solar irradiance (zero level corresponds to 1367 W m^{-2}). (Adapted from Lean *et al.*, 1995.)

strumental recordings of cosmic rays started around 1935. The first measurements were performed primarily with ionisation chambers, which measure mainly the muon flux. Muons are responsible for most of the ionisation in the lower part of the troposphere (Lal and Peters, 1967). Ahluwalia has constructed a measure of cosmic ray flux, based on ion chambers, covering the period 1937 to 1994 (Ahluwalia, 1997), which is shown in Figure 3. This extended data string is made by combining annually mean hourly counting rates from Cheltenham/Fredericksburg (1937–1975) and Yakutsk (1953–1994). These data represent part of the high energy GCR spectrum, and is only modulated about 4% during a solar cycle. Also shown in Figure 3 are data from the Climax neutron monitor (1953–1995) in Colorado, which measures the low energy nucleonic part of the GCR spectrum. For comparison the relative sunspot number is plotted, which follows closely the solar 10.7 cm flux. Note that even though there is a clear solar cycle modulation of the cosmic ray flux, the minima in GCR intensity are not well correlated with the maxima in sunspot number (Ahluwalia and Wilson, 1996), which gives a possibility to make a distinction between long term trends in the two.

Figure 4 displays four different measures of long term solar activity together with the Earth's temperature. (The temperatures used here and in the following are all temperature anomalies). Eleven-year averages of the northern hemispheric land and marine temperatures (Jones, 1997a, b) are shown in all four panels. The northern hemispheric temperatures are chosen for two reasons, first the data are superior since there are far more recordings compared to the southern hemisphere. Secondly the southern hemisphere is mainly water and the thermal inertia of the ocean tends to mask a solar forcing in contrast to the northern hemisphere. Figure 4(a) shows in addition the unfiltered solar cycle length. Figure 4(b) displays the 11-year averaged (ion chamber 1937–1994) cosmic-ray flux (thick solid line). For comparison the Climax neutron monitor is also shown (thin solid line, scale not shown). Figure 4(c) shows the 11-years average of sunspot number, and finally Figure 4(d) is decade variations in reconstructed solar irradiance adapted from Lean *et al.* (1995). The most direct correspondence between solar activity and temperature seems to be between solar cycle length and variations in cosmic-ray flux. The variations in reconstructed solar irradiance, shown in Figure 4(d), follows more closely the variations in the sunspot number.

From Figure 4 it is seen that the temperature in the period 1970–1990 rose by approximately 0.3 °C. It is possible to compare the variation in cosmic ray flux and this temperature change via some simple assumptions. From cloud satellite observations and numerical cloud modeling it is found that a 1% change in the total composition of the Earth's cloud cover corresponds to 0.5 W m⁻² change in net radiative forcing (Rossow and Cairns, 1995). From Svensmark and Friis-Christensen (1997) it is known that from 1987 to 1990 global cloudiness changed approximately 3.0% which can be estimated to 1.50 W m⁻². In the same period cosmic rays from the ion chamber changed 3.5% as seen in Figure 3. We can now calculate the approximate radiative forcing by noting that the running mean 11-years average increase of cosmic rays in Figure 4 from 1975 to 1989 is between 0.6–1.2% which then corresponds to a potential 0.3–0.5 W m⁻² change in cloud forcing. This is a fairly large forcing, about 2–4 times the estimated change in solar irradiance. Studies obtained from a general circulation model gave a sensitivity (0.7 to 1°C Wm⁻² for $\Delta S = 0.25\%$, where S is the solar constant) (Rind and Overpeck, 1993). The direct influence of changes in solar irradiance is estimated to be only 0.1 °C (Lean *et al.*, 1995). The cloud forcing, however, gives for the above sensitivity 0.2–0.5 °C. The basic assumption in the above simple calculation is that the whole cloud volume is affected by solar activity. This is consistent with the result from Figure 4 that shows that an increase in cloud cover results in lower temperatures. Solar forcing therefore has the potential to explain a significant part of the temperature changes over the period studied.

2.3. MAUNDER MINIMUM

The Maunder minimum (MM) (1645–1715) is a famous period in the Sun's history. It is a period where very few sunspots were observed. In 1976 Eddy suggested that during this period the solar output was lower, and that this reduction could explain the extreme climatic conditions at the time (Eddy, 1976). Since then various efforts have gone into reconstructing solar irradiance back in time. One of the better measures of solar activity is the sunspot number, which is known over the last 400 years. Therefore it is tempting to look for a relation between sunspot number and changes in solar irradiance observed by satellites during the last 20 years, since such a relation can be used in an attempt to reconstruct solar irradiance back in time. Figure 5(a) shows part of a reconstructed solar irradiance curve constructed by Lean *et al.* (1995), centered around the MM. Assuming that the Sun is in a non-cyclic state during the MM, the irradiance is found to be 0.24% ($\approx 0.82 \text{ W m}^{-2}$ when averaged over the Earth's surface) lower than the present day value (Lean *et al.*, 1992). As a result, the reconstructed solar irradiance shown in Figure 5(a) is nearly constant during the whole period of the MM. Figure 5(b) shows the variations in ^{10}Be , and is a signature of changes in cosmic-ray flux during the MM (Beer *et al.*, 1991). The ^{10}Be data thereby contain information on variations in the solar wind magnetic activity. It is seen that there seems to be a cyclic magnetic behavior through the MM (Beer *et al.*, 1985), and that the very low solar magnetic activity is occurring at the end of the MM, i.e., 1690–1715. It is interesting to compare the above curves for solar irradiance and the ^{10}Be data, i.e., Figures 5(a) and 5(b) with a recently reconstructed temperature curve, Figure 5(c), for the northern hemisphere (Jones *et al.*, 1998). A striking similarity between the ^{10}Be curve and the temperature is seen. In fact the decade 1690–1700 is the coldest during the last 1000 years, at the same time as the ^{10}Be concentration has the largest peak. Assuming there is a solar impact on climate during this period, it seems less likely climate was affected by the Sun in a non-cyclic state, which gives the nearly constant solar irradiance, according to the model of Lean *et al.* Rather, the good agreement between temperature and ^{10}Be concentration could suggest that cosmic rays are important in a Sun/climate link. Alternatively it could be that the origin of the irradiance changes during the MM are not understood. Of course the above conclusions hinge on how accurate the data are. The peak in the ^{10}Be curve might in fact be broader (Beer, 2000, personal communication), and the true shape of the minimum in the temperature curve could be different. However reconstructed temperatures of the northern hemisphere by Mann *et al.* (1998) also show that the coldest decade is 1690–1700.

3. Conclusions

Climate has been varying during all time. The origin of these variations has previously, and almost exclusively, been attributed to internal causes. For example

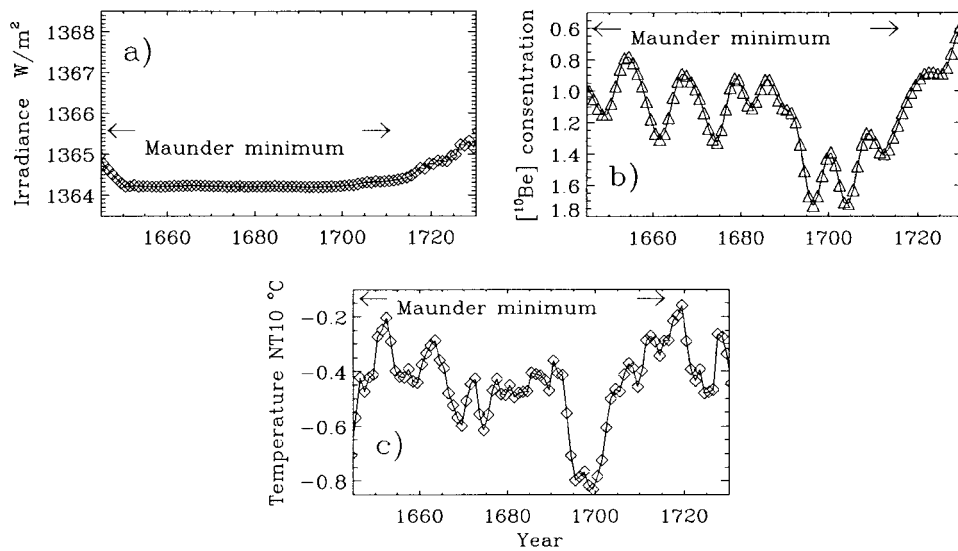


Figure 5. (a) Variation in reconstructed solar irradiance during the Maunder minimum (MM), from Lean *et al.* (1995). (b) Variation in ^{10}Be concentration during the MM (note that the ^{10}Be axis is reversed). (c) Reconstructed temperature anomalies of the northern hemisphere during the MM.

volcanic dust in the stratosphere can cause cooling of the order $0.5^{\circ}C$ for a year or more. The same goes for the atmospheric/ocean oscillation in the Pacific called El Niño Southern Oscillation. So it is expected that the annual variations in temperature will be a composite of several causes, of which only one is a solar influence. However, at time scales greater than 10 years it looks like the Sun has a significant influence on climate variations. This statement is based on the qualitative agreement between isotopes and proxy data for the Earth's temperature over the last 1000 years.

A remarkable correlation between cosmic ray flux and variations in the Earth's cloud cover has been demonstrated. Since clouds are important for the Earth's energy balance, a solar influence on clouds could be the main cause for the observed correlations between the Sun and the Earth's climate. However, as is well known a good correlation does not guarantee a physical cause and effect. It is therefore necessary to get an understanding of the microphysical mechanism that connects solar activity with the Earth's cloud cover. If the influence of cosmic rays on clouds is real, then it is thought that ionisation produced by GCR affects the microphysics in cloud formation. There is currently an initiative to do an experiment at CERN, in Geneva, to test this hypothesis. The idea is to study the effect of ionisation caused by cosmic rays on droplet formation. This will be done in a cloud chamber with a high degree of control of all relevant parameters. However, future efforts to understand the importance of solar activity must also involve observations. In particular it is important to find what type of clouds are affected. This can be done on the one hand from further studies by satellite observation, but also by regional observations

of cloud/aerosol formation, e.g., by LIDAR. It is hoped that the present study might increase the interest in finding a physical mechanism.

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Address for Offprints: Henrik Svensmark, Danish Space Research Institute, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark; hsv@dsri.dk