Influence of Cosmic Rays on Earth's Climate

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During the last solar cycle Earth's cloud cover underwent a modulation more closely in phase with the galactic cosmic ray flux than with other solar activity parameters. Further it is found that Earth's temperature follows more closely decade variations in galactic cosmic ray flux and solar cycle length, than other solar activity parameters. The main conclusion is that the average state of the heliosphere affects Earth's climate. [S0031-9007(98)07774-6]

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For more than a hundred years there have been reports of an apparent connection between solar activity and Earth's climate [1,2]. A strong indication of a link between long term variations in solar activity and Earth's climate was found in 1991 by Friis-Christensen and Lassen [3,4] who showed that an empirically constructed measure of solar activity, the filtered solar cycle length, matched very closely variations in northern hemispheric temperature during the past 400 years. Another example is the 11 year variation of stratospheric pressure levels found to be in phase with solar activity [5]. In spite of these reports an accepted causal link between solar activity and effect in Earth's lower atmosphere has not been found. The initial speculations were directed towards the most obvious and direct way solar activity could affect Earth's climate, namely, via changes in the solar irradiance. But based on recent satellite measurements of the solar constant it is found that the variations are too small (0.1%) to explain the observed temperature changes [6].

Recently it was found that the Earth's cloud cover, observed by satellites, is strongly correlated with solar cycle variation of galactic cosmic ray flux (GCR) monitors [7]. Clouds are important in Earth's radiation budget, and a systematic variation will have climatic effects [7]. GCR consists of very energetic particles (mainly protons) that are produced in stellar processes in our Galaxy. Some of them enter Earth's atmosphere where nuclear processes take place and produce secondary particles which can penetrate still deeper into the atmosphere [8]. Ionization in the lower part of the atmosphere is almost exclusively produced by GCR and is the meteorological variable subject to the largest solar cycle modulation [9]. Previous and current speculations on the effect of the ionization have been mainly related to optical transparency, by either changes in aerosol chemistry or an influence on the transition between the different phases of water [7,9–13].

If there is a causal relation between cosmic ray flux and cloud cover it is expected that the long term variations in cosmic ray should reflect variations in Earth's temperature and should be important in an explanation of the high correlation between solar cycle length and global temperature.

This Letter is organized as follows. It will be shown that the Earth's cloud cover within the last solar cycle follows variations in GCR more closely than the 10.7 cm radio flux, the latter being indicative of other solar activity parameters. By assuming that there exists a causal relation between Earth's cloud cover and variations in GCR, it is argued and found that long term variations (1937–1996) in solar activity given by GCR reflect variations in Earth's temperature.

Figure 1 is a composite of satellite observations of Earth's total cloud cover. The cloud data comprise the NIMBUS-7 CMATRIX project [14] (triangles), the International Satellite Cloud Climatology Project (ISCCP) [15] (squares), and finally data from the Defense Satellite Meteorological Program (DMSP) Special Sensor Microwave/Imager (SSM/I) (diamonds) [16]. These data sets reflect different satellite coverage, instrumentation,

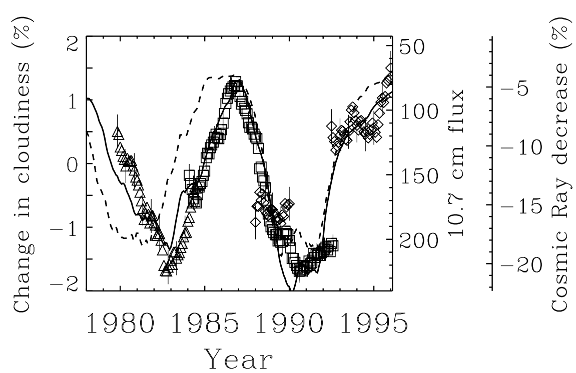

FIG. 1. Composite figure showing changes in Earth's cloud cover from four satellite cloud data sets together with cosmic ray fluxes from Climax (solid curve, normalized to May 1965) and 10.7 cm solar flux (dashed curve, in units of 10^{-22} $\mathrm{Wm^{-2}\,Hz^{-1}}$). Triangles are the Nimbus7 data, squares are the ISCCP_C2 and ISCCP_D2 data, diamonds are the DMSP data. All of the displayed data have been smoothed using a 12 month running mean. The Nimbus7 is for the southern hemisphere over oceans with the tropics excluded. The DMSP data are total cloud cover for the southern hemisphere over oceans, and finally the ISCCP data have been derived from geostationary satellites over oceans with the tropics excluded. Also shown are 2-standard-deviation error bars for the three data sets, one for each 6 months.

and algorithms to derive the cloud cover, and as a result only variations in cloud cover will be compared. The error bars in the figure are purely statistical errors and do not include systematic drifts that could be in the data. For details, see Svensmark and Friis-Christensen [7]. In the figure the cloud data is compared with variations in GCR flux and the 10.7 cm radio flux from the sun. One sees that there are clearly differences between the variation of GCR and the radio flux. From 1987 to the 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 Earth's cloud cover follows the variation seen in GCR, and not necessarily the variations in the 10.7 cm radio flux which closely follows variations in total solar irradiance, soft x rays, and ultraviolet radiation [6].

Having established that variations in GCR are a good candidate for indirectly influencing Earth's climate, based on data covering the last solar cycle, it is important to compare with variations in solar activity over a longer time span. However, there are 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 Earth's temperature and hopefully better than variations in other solar activity parameters. To investigate this a long data series of GCR flux is needed. Instrumental recordings of cosmic rays started around 1935. The first measurements were done primarily with ionization chambers, which measure mainly the muon flux. The muons are responsible for most of the ionization in the lower part of the troposphere [8]. Ahluwalia has constructed a measure of cosmic ray flux, based on ion chambers, covering the period 1937 to 1994 [17], which is shown in Fig. 2. This extended data string is made by annually combining mean hourly counting rates from Cheltenham/Fredericksburg (1937–1975) and Yakutsk (1953–1994). These data represent part of the high energy GCR spectrum. Figure 2 also plots the 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 closely follows the solar 10.7 cm flux. Notice that the amplitudes of the solar activity cycle and the amplitudes of GCR are not closely related [18], which is fortunate since it gives a possibility to make a distinction between long term trends in the two.

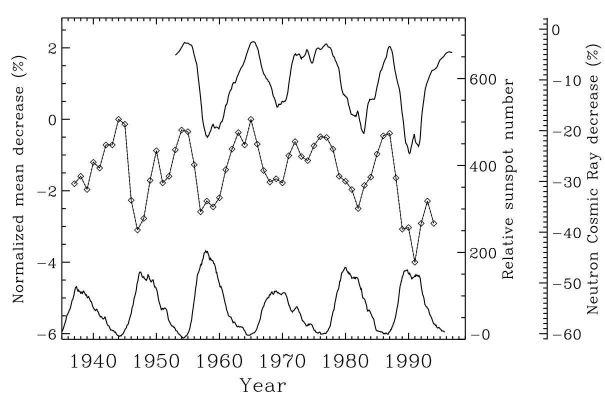

FIG. 2. Top curve is cosmic ray flux from the neutron monitor in Climax, Colorado (1953–1996). Middle curve is annual mean variation in cosmic ray flux as measured by ionization chambers (1937–1994). The neutron data have been normalized to May 1965, and the ionization chamber data have been normalized to 1965. Bottom curve is the relative sunspot number.

Figure 3 displays four different measures of long term solar activity together with Earth's temperature. In the figure, 11 year averages of the northern hemispheric land and marine temperatures [19,20] are shown in all four panels. The panel 3a shows in addition the unfiltered solar cycle length. Panel 3b 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). Note that the axis for the cosmic rays has been reversed, so that higher temperatures correspond to fewer cosmic rays which also means higher solar activity. Panel 3c shows the 11 year average of a sunspot number, and finally panel 3d shows decade variations in reconstructed solar irradiance adapted from Lean *et al.* [6]. 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 more closely follow the variations in the sunspot number panel 3d.

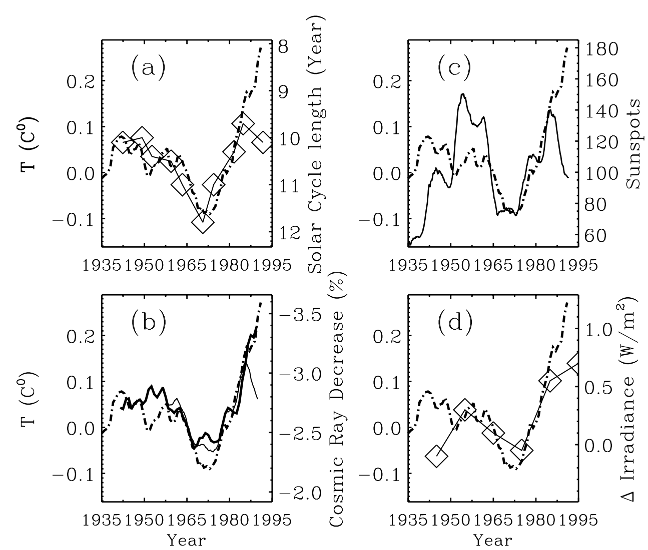

FIG. 3. 11 year average of northern hemispheric marine and land temperatures (dash-dotted line) compared with (a) unfiltered solar cycle length; (b) 11 year average of cosmic ray flux (from ion chambers 1937–1994, normalized to 1965), thick solid line; the thin solid line is cosmic ray flux from Climax, Colorado neutron monitor (arbitrarily scale); (c) 11 year 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.* [6]). Note the 11 year average has removed the solar cycle in (b) and (c).

Clouds reflect more energy than they trap and this leads to a cooling in the range of 17 to 35 $\mathrm{W\,m^{-2}}$ [21–23]. It is not easy to estimate the net change in radiative forcing from a solar modulation of the cloud cover. The main problem is that it is not known which part of the cloud volume is affected. This is important because different cloud types have different radiative properties. Although the net effect of clouds is to cool the planet, high thin clouds tend to warm the Earth's surface, and therefore one could imagine that an increase in cosmic ray flux could lead to a warming. However, high thin clouds which tend to warm the Earth's surface occur in association with high thick cooling clouds, and together the two cloud types tend to mitigate their effect on the energy balance [24]. The results of Fig. 3b seem to suggest that an increase in cloud cover results in a cooling, which again suggest that a larger part of the cloud volume is affected.

From Fig. 3 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 (assuming it is directly correlated with cloud cover) 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 Earth's cloud cover corresponds to 0.5 $\mathrm{W/m^2}$ change in net radiative forcing [25]. From Svensmark and Friis-Christensen [7] it is known that from 1987 to 1990 global cloudiness changed approximately 3.0% which can be estimated to be 1.50 $\mathrm{W/m^2}$ [7]. In the same period cosmic rays from the ion chamber changed 3.5% as seen in Fig. 2. We can now calculate the approximate radiative forcing by noting that the mean 11 year average increase of cosmic rays in Fig. 3 from 1975 to 1989 is 1.2% which then corresponds to a possible 0.5 $\mathrm{W/m^2}$ change in cloud forcing. This is a fairly large forcing, about 4 times the estimated change in solar irradiance. The resulting temperature change is difficult to estimate exactly. Studies obtained from a general circulation model gave a sensitivity (0.7 to 1 $\mathrm{°C/W\,m^{-2}}$ for $\Delta S = 0.25\%$, where S is the solar constant) [26]. The direct influence of changes in solar irradiance is estimated to be only 0.1 °C [6]. The cloud forcing, however, gives, for the above sensitivity, 0.3–0.5 °C, and has therefore the potential of explaining nearly all of the temperature changes in the period studied.

The solar cycle length has been shown to be an important parameter due to its close connection with temperature variations of the Earth. This parameter is determined empirically and it has not been straightforward to interpret. The present work gives a hint on why it is relevant to Earth's climate. The physical interpretation is based on the close agreement between variations in solar cycle length, GCR flux, and temperature as seen in Fig. 3. The solar cycle length is therefore a measure of the processes occurring within the sun of unknown dynamical origin which manifest themselves in the solar activity within the heliosphere that modulates the GCR, averaged over the solar cycle.

This does not imply that other factors cannot affect clouds or climate. However, a cloud cover that is modulated by solar activity in this way will have an influence on climate and could be important in explaining the observed agreement between climate proxies and solar activity [1,3,4]. There is at present no detailed understanding of the microphysical mechanism that connects solar activity and Earth's cloud cover. It is necessary to identify a microphysical mechanism, which might not be an easy task. The present study hopes to increase not just the interest in finding a physical mechanism but to point at where and how to locate it in the atmosphere.

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