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Solar activity and the mean global temperature

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Abstract
The variation with time from 1956 to 2002 of the globally averaged rate of ionization produced by cosmic rays in the atmosphere is deduced and shown to have a cyclic component of period roughly twice the 11 year solar cycle period. Long term variations in the global average surface temperature as a function of time since 1956 are found to have a similar cyclic component. The cyclic variations are also observed in the solar irradiance and in the mean daily sun spot number. The cyclic variation in the cosmic ray rate is observed to be delayed by 2–4 years relative to the temperature, the solar irradiance and daily sun spot variations suggesting that the origin of the correlation is more likely to be direct solar activity than cosmic rays. Assuming that the correlation is caused by such solar activity, we deduce that the maximum recent increase in the mean surface temperature of the Earth which can be ascribed to this activity is $\lesssim$14% of the observed global warming.

Keywords: global warming, solar activity, cosmic rays

1. Introduction

Ionization of the air occurs due to cosmic rays (CR), from the decay of trace radioactive isotopes, ionization by solar ultra violet light and electrical effects such as lightning. At cloud forming altitude (>1000 m) over the land and at all altitudes over the sea CR are thought to dominate the production of ionization in the troposphere [1]. Recently, detailed computations of the total ionization rates produced by CR in the atmosphere have become available [2–5], including the time variation from 1951 to 2004 arising from the changing solar activity. In addition, long term data on the charged particle fluxes in the atmosphere are now available [6, 7].

It was suggested long ago that CR could be connected with the weather and the climate [8] and various mechanisms have been suggested [9–11] (for reviews see [12, 13]). Much publicity has been given to the observation that the reduction in the low cloud cover (LCC) observed during solar cycle 22 correlates well with the decrease in the cosmic ray (CR) rate as measured by neutron monitors [14–16]. This led the groups to hypothesize that the reduction was caused by the influence of ionization from CRs on cloud cover. Furthermore, it has been suggested [16, 17] that this is a significant contributor to global warming. The basis of the suggestion is that the cosmic ray rate has been observed to decrease over the last century [18]. This leads to less ionization in the atmosphere, reducing cloud cover according to the hypothesis, allowing more sunlight to warm the Earth. This suggestion has been questioned on the grounds of inconsistencies between different methods of measuring cloud cover [19] and on the grounds of imperfect data analyses [20]. Attempts have been made to look for local or regional correlations which find either nothing [21], the opposite correlation [22] or some correlation [11, 23]. We discount these in order to investigate the hypothesis further and on a global scale. We further discount the likelihood that CR effects would change mainly the depth of the clouds, rather than the cloud cover. The suggestion was also questioned in a study of the long term CR rate [24] where it was shown that this rate began to increase in 1985 yet global warming continued. In a previous publication [25] we showed that less than 23% of the observed reduction in cloud cover in solar cycle 22, at the 95% confidence level, can be ascribed to ionization from CR. Nevertheless, there may be some connection between clouds and ionization since it is well known that charged drops grow at smaller radii than uncharged drops, providing that the supersaturation is high enough [26].

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In this paper we report a search for such an effect by attempting to correlate directly changes in the cosmic ray rate of ionization with changes in the surface temperature of the Earth either through clouds or via some other mechanism. First a study is made of the variation in the long term rate of ionization produced by CR. We then study the variation of the global average surface temperature, the mean daily sun spot number and the solar irradiance with time and show a correlation with the variation of the cosmic ray signal since 1956. From this variation a limit on the overall temperature rise over the last half century that can be ascribed to variable solar activity is deduced.

2. Long term variation of the rate of ionization due to CR

Computer simulations of the production of ionization by CR in the atmosphere have been made using the CORSIKA [27] simulation programme [2–4] and the GEANT4 [28] simulation package [5]. These simulations agreed with the available fragmentary ionization data and with each other to 10% precision [3, 4]. Recently independent long term data on the CR flux in the atmosphere using balloon borne Geiger counter measurements have become available [6, 7]. Information is also available from the cosmogenic nuclei ^{10}Be and ^{14}C. However, there are many complications in using such nuclei as a proxy for the ionization in the atmosphere [29]. The ionization measurements and the simulations both show an 11 year modulation due to the effects of the changing solar wind on the CR primaries. The amplitude of this modulation varies with the magnetic latitude on the Earth due to the geomagnetic field (see [30] for a review of these effects). The geomagnetic field causes a cut off for low CR rigidities. The minimum vertical rigidity primary which can hit the Earth's surface defines the vertical rigidity cut off (VRCO) [31].

The simulations and the balloon data are used here to assess the long term variation of the ionization rate in the atmosphere due to CR. To average over the periodic variations due to the 11 year solar cycle the method adopted by Lockwood and Fröhlich [24] was used. In this method the average at a particular time, t, is taken as the average over the full solar cycle length starting one half a cycle earlier than t. The time dependent cycle lengths were taken from figures 3(b) and 4(b) in [24].

Figure 1 shows the count rates from the balloon measurements [6, 7] as a function of time at different altitudes over Moscow with the 11 year smoothing applied. There were also measurements over Murmansk which gave similar results to the Moscow data and from the Antarctic (Mirniy station) which were much more noisy and difficult to interpret. The figure also shows the results of the simulations from [2, 3] at the value of the VRCO of 2 GV (close to the value at Moscow).

The measurements and the simulation show a similar cyclic behaviour with a period of roughly twice the 11 year solar cycle and amplitudes in the fractional deviations from the mean varying from 3% at the lowest altitude to 5% at higher altitudes. The simulated values of the fractional deviation from the mean agree with the measurements to within a factor of two (see figure 1). This represents the uncertainty in the procedure to assess the long term variation of this quantity. Since the values from the simulation are less noisy and are uncontaminated by background they will be used in the following as the long term time variation of the rate of ionization in the atmosphere by CR.

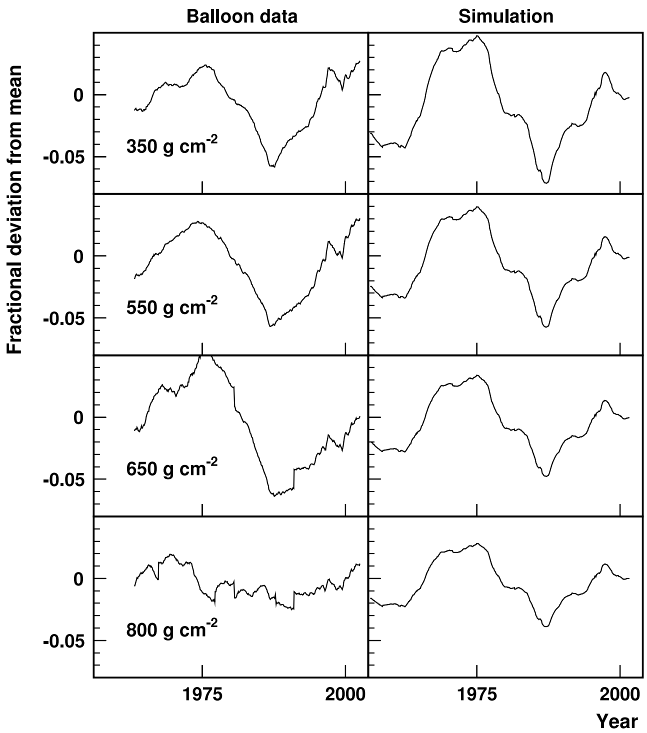

Figure 1. Long term variation of the rate of the flux of charged particles in the atmosphere as measured from the Moscow balloon data [6, 7] (the left-hand panels). The altitude for each set of data is indicated in the panels. The right-hand panels show the results of the simulation [3] of the ionization rate from CR at each altitude. The smoothing described in the text has been applied to each data set to eliminate the effects of the 11 year solar cycle.

The amplitude of the observed cyclic variation of the long term CR rate varies with VRCO. The value of the VRCO averaged over the Earth is 8 GV. In the remainder of this paper we use the simulation for a VRCO of 8 GV at an altitude of 825 g cm^{-2} (2000 m) to represent the change in the global mean ionization rate in the atmosphere at cloud forming height.

Figure 2 shows the variation of the simulated ionization rate due to CR at a VRCO of 8 GV and altitude of 825 g cm^{-2} as a function of time averaged over the 11 year solar cycle. Also shown in figure 2 is the mean daily sun spot number (SSN) [32] and the mean solar irradiance (SI) [33] similarly averaged over the 11 year solar cycle. Interestingly, there is a reasonable correspondence between the three curves, illustrating the connection between the three phenomena. However, the CR changes are delayed by 2–4 years relative to the SSN and SI changes. The delay is somewhat longer than those observed between the SSN and the CR changes due to the 11 year solar cycle [34]. This indicates that the long term and shorter term 11 year cycle in the CR variation may be influenced by different components of the solar wind.

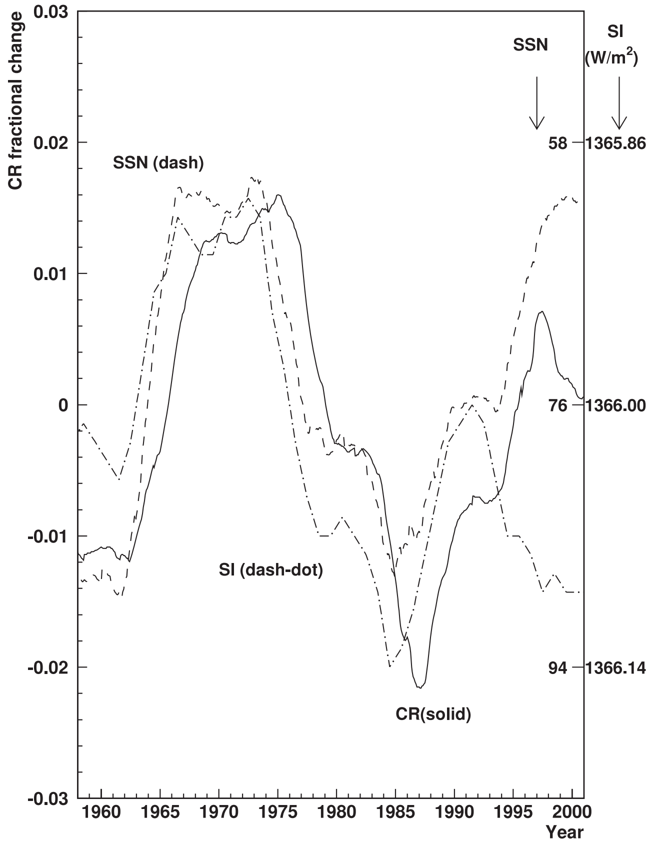

Figure 2. The solid curve shows the fractional change in the CR ionization rate from the simulation with time, at VRCO = 8 GV and altitude 2000 m, after the 11 year smoothing described in the text. The dashed and dash-dot curves show the mean daily SSN and the SI data from [36] each with the 11 year smoothing applied. The scales for the SSN and SI are shown on the right-hand axes, NB these two scales are inverted to illustrate the correlation i.e. they increase vertically downwards.

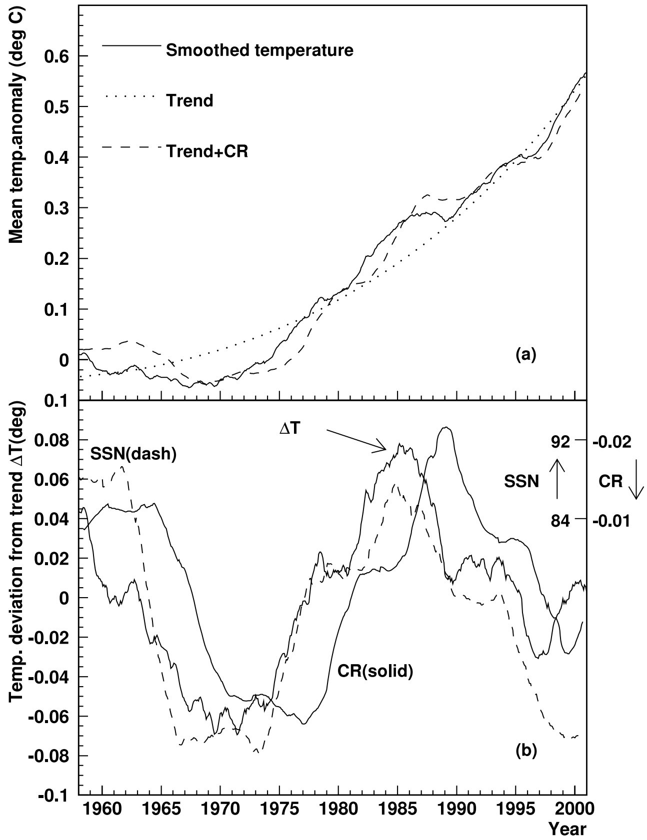

Figure 3. (a) The global surface temperature anomaly (solid curve) [37] with the 11 year smoothing described in the text. The dotted curve shows the smooth trend obtained by fitting an empirical function (see text). The dashed line shows the long term CR rate from figure 2 (inverted and normalized) added to the smooth trend curve. (b) The deviations from the trend line in the upper panel for the temperature (solid curve labelled ΔT), for the CR—labelled CR (solid)—and for the SSN—labelled SSN (dash). The scales for the latter two are given on the right-hand axis. NB the scale for the CR rate is inverted to illustrate the correlation i.e. it increases vertically downwards.

3. Solar modulation of the mean Earth's surface temperature

The data on the global surface temperature are now examined to see if a correlation can be found with the changes in solar activity shown in figure 2. Such changes could be expected since it is thought that the modulation of the global surface temperature due to the 11 year solar cycle is approximately 0.1 °C peak to peak [35, 36].

Figure 3(a) shows the global surface temperature [37], as a function of time with the same 11 year smoothing as that described above. The data show an oscillatory behaviour about a smooth upward trend. The smooth trend can be represented empirically by a function of the form $T = a\exp(bt + ct^2)$, where T is the global surface temperature and t is the time, with a, b and c free parameters. This is shown by the dotted curve in figure 3. The dash-dotted curve shows this smooth trend with the long term CR ionization rate from figure 2 added (inverted and arbitrarily normalized to give the best visual representation of the temperature data). The similarity between the deviations from the trend of the CR and temperature data is illustrated in more detail in figure 3(b) where the differences from the smooth trend are plotted against time.

The similarity between the solar activity measured by the SSN and CR and the temperature deviations is striking. The temperature deviations seem to be in time with the SSN variations rather than delayed by 2–4 years as observed for the CR deviations. Hence, assuming that this is a real correlation between global surface temperature and solar activity, it is more probable that the deviations arise from the effects of a phenomenon, such as SI, rather than the effects of CR which are known to lag behind the SSN changes.

Although the results of the simulations are only available for dates after 1951, it is instructive to examine the period before this using such data as are available. Figure 4 shows the temperature anomaly compared to the SSN and ^{10}Be data [38, 39], applying the same 11 year smoothing to each. Here we use the ^{10}Be data as a rough proxy for the CR ionization rate. It is apparent that the good correlation seen after 1956 shown in figure 3 does not continue before this date. However, the ^{10}Be data may not be a good proxy for the ionization rate in the troposphere since they show a different modulation due to the 11 year solar cycle than other CR measurements [29]. In addition, they produce a

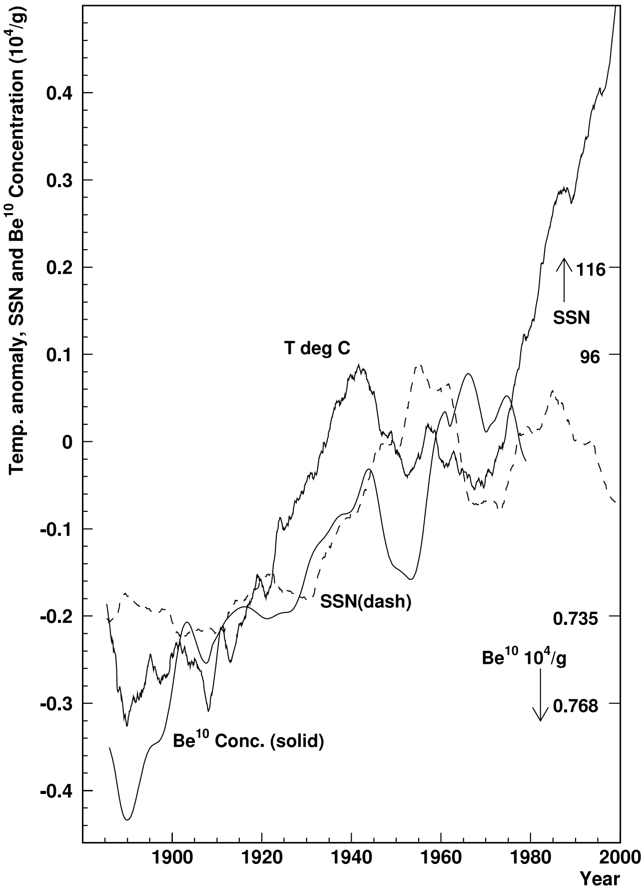

Figure 4. The global surface temperature anomaly, the SSN (dashed curve) and the ^{10}Be data from the Greenland ice core [38, 39] all with the 11 year smoothing. The scales for the SSN and ^{10}Be concentration are shown on the right-hand axes. Note that the ^{10}Be scale is inverted for illustration i.e. it increases vertically downwards.

different long term behaviour after 1956 than that shown in figure 1 as can be seen from the overlap region in time in figures 2 and 4. This cosmogenic isotope is thought to be produced in the stratosphere by somewhat lower energy primaries than those responsible for the bulk of the ionization in the troposphere [40]. Hence it could be expected to have different properties from the ionization in the troposphere. Thus, there is some possibility that the correlation seen after 1956 is real.

4. The effects of CR and SI on the global surface temperature

4.1. Cosmic rays

The data in figure 2 show that between the years 1956 and 2001 the global average CR rate has oscillated with the final value being roughly 1% higher than the starting value with an averaged fractional change of $0 \pm 0.2\%$. If global warming were being influenced by changes in ionization producing changes in low level cloud cover, as hypothesized in [16, 17], then the increase in the CR rate would be expected to produce a lowering of the globally averaged temperature of the Earth during this period rather than the increase shown in figure 3(a). This already is evidence against CR being a large contributor to global warming, as pointed out by Lockwood and Fröhlich [24].

In order to derive an upper limit on the global temperature rise which can be ascribed to changes in ionization from CR we adopt the hypothesis of [16, 17] and assume that the oscillation in temperature shown in figure 3 results from the oscillation in the ionization rate shown in figure 2. We observe in figure 2 that the CR ionization rate oscillation is $\pm 1.5\%$ which is anticorrelated with the temperature oscillation in figure 3 of amplitude $\mp 0.07\,^{\circ}$C. Any long term decrease in the CR ionization rate since 1956 is less than the amplitude of the cyclic variation. Hence, any long term change in the global temperature must be less than the amplitude of cyclic variation in the temperature i.e. less than $0.07\,^{\circ}$C. This is to be compared with an observed rise of $0.5\,^{\circ}$C (see figure 3). Thus, within our assumptions, less than 14% of the observed global warming since 1956 is attributable to the changing CR rate.

4.2. Solar irradiance

A similar argument can be applied to the case of SI. The data in figure 2 show that between the years 1956 and 2001 the SI rate has oscillated about the mean with an amplitude of $\sim$0.1 W m^{-2}. The final value is 0.09 W m^{-2} higher than the starting value. From this it can be seen that the SI could have increased since 1956 by an amount which is less than the amplitude of the observed cyclic variation. If we attribute the oscillation in temperature to the cyclic change in SI, a change in SI of 0.1 W m^{-2} causes a change in the global temperature of $0.07\,^{\circ}$C. Since the change in total SI since 1956 is less than 0.1 W m^{-2}, it follows that the total change in mean global temperature due to SI must be less than $0.07\,^{\circ}$C.

Hence, within our assumptions, less than 14% of the observed global warming since 1956 is attributable to changes in SI.

5. Conclusions

The long term variation of the cosmic ray ionization rate has been studied. This rate shows a cyclic variation with a period of roughly twice the 11 year cycle for the data available since the 1950s. The structures seen in the variation of the long term cosmic ray ionization rate with time are shown to be present in the variation of the mean daily sun spot number, solar irradiance and in the variation of the mean global surface temperature. Hence we report a possible observation of a cyclical variation in each of these quantities of a similar period. The cyclic variation of the global temperature is found to be in phase with the solar cycle as measured from the sun spot numbers and the solar irradiance and in antiphase with the cosmic ray variation. However, the cyclic variation of the CR cycle is delayed by 2–4 years. This indicates that, if it is real, the correlation is most likely caused by direct solar activity rather than by cosmic rays.

The long term variations of each of the cosmic ray rate and the solar irradiance are observed to be less than their cyclic variations. Therefore, assuming that there is a causal link between either of them with the mean global surface temperature, the long term variation of the temperature must be less than the amplitude of its cyclic variation of 0.07 °C. Hence within our assumptions, the effect of varying solar activity, either by direct solar irradiance or by varying cosmic ray rates, must be less than 0.07 °C since 1956 i.e. less than 14% of the observed global warming.

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