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Possible effects of galactic cosmic ray flux and low-cloud amounts on global surface temperature

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Abstract. The solar variations, solar–climate interactions, and the mechanisms controlling the response of Earth's climate system are important to understand the effect of solar variability on climate change. The solar magnetic field is directly/indirectly disturbing the interplanetary space, the ionosphere, the magnetosphere, and even the atmosphere. To investigate the contribution of varying galactic cosmic flux, the role of sunspot number (Rz), galactic cosmic ray (GCR) rates, cloud condensation nuclei (CCN), total solar irradiance (TSI), CO_2 concentration and the global surface temperature (GST) is examined. The variations of TSI can partially explain the global increase in temperature, and it accounts for about 0.5°C warming experienced from 1950 to 2016. Therefore, the future predictions of global warming should take into account the effects due to long-term changes in the galactic CRs, the low-level cloud condensation (LLC), etc. The concentrations of CO_2 increased in the upper atmosphere by 19% during the last 65 years. A strong correlation between LLC and GST suggests a linear relationship between these parameters. These observations are suggestive of the possible role of GCRs in global climate.

Keywords. Galactic cosmic rays; solar variability; atmospheric physics; climate change; geomagnetic activities; sun–climate interaction; total solar irradiance.

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1. Introduction

It is well known that the climate system of the Earth has shown irregularity and significant changes from the second half of the 20th century to now. As the climate system depends on many factors, the influence of each factor on this variation is not yet understood [1]. Several authors have long (and more recently) recommended that climate change could be affected by solar and geomagnetic activities (e.g., [2–5]). Le Mouël *et al* [6] analysed data from climatological stations using long homogeneous data sets of daily temperatures in the USA and Europe. Their results clearly illustrated that the mean temperatures, displayed in the IPCC report, were somewhat different from the corresponding curves. Moreover, some of the solar indices displayed similar secular-trends with variations of higher frequency temperature [7].

The global surface temperature (GST) of the Earth was increased by about 1.72°C between 1850 and 2015, while in recent years between 1970 and 2015, the GST was increased by ∼1.23°C. Also, during the period from 1850 to 1970, the GST was increased by ∼0.48°C. Is this increase due to natural variations or resulting from human behaviour and activities? That is the contention among researchers. Some believe that the increase happened in the post-industrial era and the main reason for global warming is the excessive increase in greenhouse gasses (GHGs). But, some scientists argue that the increase in the concentration of the GHGs is the main reason but not the only one, and solar variations have a great (or significant) role in the Earth's temperature. The main source of input energy to the terrestrial atmosphere is solar radiation, and it partially controls the Earth's radiation balance and in turn the climate [8]. It is so hard to understand the mechanism

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that governs climate change because there are many external factors like GHGs, solar variations, aerosols, etc. Some studies showed non-stationary forcing control [9–11]. Most natural factors such as volcanic and solar variations could explain the temperature variations during the last centuries until the beginning of the 20th century [12]. But the rapid increase in temperatures, during the last five decades, needs another source with the anthropogenic GHGs that played an important role in climate change [13]. It is well known that the aerosols (small fractions in the atmosphere) reduce the total solar irradiance (TSI) in two ways: by altering the properties of clouds and by scattering and absorbing solar irradiance [14].

The influence of solar variability on the Earth's climate requires the knowledge of short- and long-term solar variability and the mechanisms of reaction of these variables with the Earth–climate system [15]. The radiation from the Sun into the space is redistributed by the Earth's atmosphere and finally re-radiated to affect the climate, and may absorb radiation from space and different air constituents. The dynamics of each solar cycle (the general circulation pattern) is one of the most important solar factors, which plays a major role in solar variability and consequently influences the atmospheric response [16,17]. Haigh [18] mentioned that the variations in the composition and intensity of incident solar radiation hitting the Earth might produce changes in global and regional climate which are both different, in addition to those from man-made climate change. In addition, Sukhodolov *et al* [19] reported that the physical/chemical mechanisms responsible for solar irradiance changes on climate is of significant interest and currently it is an important scientific problem.

Some studies showed that the effect of variations of solar activity on climate is far from being correctly quantified, leading to difficulties in distinguishing between distinctive causes of global warming [15,20]. To find the relation between the role of sunspot number (Rz) and GST, El-Borie and Al-Thoyaib [21] indicated a close correlation between Rz and GST with correlation coefficient $\rho = +0.55$ throughout the period from 1868 to 2006. Valev [22] studied the relationship during the period from 1845 to 2000 between the global, hemispheric temperatures and solar-geomagnetic parameters. Correlations between the global, hemispheric temperatures, the sunspots, and the aa-index, have been shown. The geomagnetic activity predominates the solar activity on the global and hemispheric surface temperatures. Additionally, Souza Echer *et al* [23] studied the surface temperature anomalies and the Rz throughout the period 1880–2000 by the wavelet multiresolution analysis. For the 11-year solar cycle band, a weak correlation of 0.11 between GST and Rz was obtained, as well as a higher correlation of about 0.66 between them in the 22-year band with zero lag, reflecting the dominant role of global warming artificially induced in the last century over solar activity.

The present study aims to examine reliable roles for galactic cosmic rates (GCRs), low-level cloud (LLC), Rz, total solar irradiance (TSI), and the CO_2 concentrations on the GST. These measures may partially have a significant role on the GST changes throughout the last two centuries.

2. Datasets and resources

The following data have been examined throughout the present work. Types of data and their resources are listed in table 1:

(1) Annual GCR during the period 1800–2006 for climax neutron monitor rates. The rates from 1956 to 2006 are the direct measurements. The rates from 1936 to 1964 are the equivalent rates deduced from ion chamber measurements and those from 1801 to 1936 were derived from the ^{10}Be data from ice cores [24].

Table 1. Types of data and resources.

Data type	Location source	Via
Annual global surface temperature (GST)	Carbon Dioxide Information Analysis Center (CDIAC)	http://cdiac.esd.ornl.gov/ftp/trends/temp/jonescru/global.txt
Yearly mean total sunspot number (Rz)	SILSO	http://sidc.be/silso/datafiles#total
Galactic cosmic ray rates (GCRs)	Climax count rates (%)	[24]
Annual reconstructed total solar irradiance (TSI)	KNMI Climate Explorer	[25] http://climexp.knmi.nl/data/itsi_wls_ann.dat
Annual CO_2 concentrations	KNMI Climate Explorer	http://climexp.knmi.nl/selectannualindex.cgi?id=someone@somewhere
IR Low-level cloud amount (LLC)	International Satellite Cloud Climatology Project (ISCCP)	https://isccp.giss.nasa.gov/climanal7.html

(2) Annual means of Rz over the period 1800–2018, which were obtained from the sunspot index and long-term solar observations (SILSO).
(3) The reconstructed TSI for the period 1800–2008.
(4) Annual CO_2 concentrations for the period 1800–2016.
(5) IR LLC amount for the period 1983–2009, which was obtained from the International Satellite Cloud Climatology Project (ISCCP).
(6) Finally, we used the yearly data of GST, for the period 1850–2015, which were obtained from the Carbon Dioxide Information Analysis Center (CDIAC).

3. Results and discussion

Previous studies presented some factors/parameters that may have contributed to global climate change, which have not been fully taken into account. Primary GCR variation, which generates cloud condensation nuclei, may have a significant effect on global temperature. Svensmark and Friis-Christensen [26] first expected a significant role of primary GCR in generating LLC nuclei. The reduction of albedo radiation reflected the thermal radiation back into space, i.e. increases the temperature of the Earth. Till now, the exact effects of long-term changes of GCR flux on LLC formation and its role on global warming are not clearly understood due to the non-availability of a reliable estimate of GCR variations over a long period.

In order to examine the realistic contribution of long-term CR intensity changes to climate warming, we present recent results of galactic cosmic intensity changes since 1800, obtained using accurate measurements of ^{10}Be derived from deep ice core measurements as a proxy [24]. It is well known that the ^{10}Be nuclei, in deep polar ice, are considered a reliable proxy for measuring ∼2 GeV/nucleon of CR intensity impinging the Earth. The radioactive nuclide, ^{10}Be, is produced in the atmosphere due to CR-induced spallation of nitrogen and oxygen atoms. In the polar regions, atmospheric ^{10}Be is deposited in the ice sheets and snow directly and is used as a proxy for solar activity. It has been observed that during times of lower ^{10}Be concentration, i.e., greater solar activities, the surface temperatures were higher. Figure 1 shows the long-term changes (∼20 solar activity cycles (SACs)) of Rz (figure 1a) during 1800–2018 with the corresponding changes in GCRs (figure 1b) through the period 1801–2006. For GCR changes, the red circles represent direct climax NM counting rates (1956–2006), green line denotes the ionisation chamber measurements during the period 1933–1955, and black circles represent CR intensity derived from ^{10}Be (1801–1932). Using Sen's slope estimator method [27], the percentage of change for both Rz and GCR are calculated by using eq. (1) for each of them. The results show an increase in Rz of about 56% for the period 1800–2018 and a decrease of about 19% in GCR for the period 1801–2006 (figure 2).

From figure 2b, it can be easily seen that CO_2 concentration increases from ∼281 to 311 ppm (∼0.2 ppm/yr) during the period 1800–1950, then it sharply increases by 1.41 ppm/yr through the period 1950–2016, recording an increase which is seven times more than the increase in the former period. Therefore, the concentrations of CO_2 increased in the upper atmosphere by 19% in the last six and half decades. This rising CO_2 is largely responsible for climate change, especially in recent years. Furthermore, the TSI shows an increase of 0.75 W/m^2 during the epoch 1800–2008. These results show that there is a 56% increase of solar activity, as well as the magnetic field, which reduces the GCR from reaching the atmosphere by 19% and as a result the GST increases.

$$\text{Percent change} = \frac{\text{Sen's slope} * \text{total no. of data points}}{\text{mean of data points}} * 100. \quad (1)$$

The descending phase of the SAC 23 from the maximum to minimum (from 2000 to 2009) is the longest and the weakest one compared to the previous eight SACs. The solar minimum of SAC 23 (2006–2009) has been unusually long and deep since 1911–1913, compared to the previous eight solar minima. Jian *et al* [28] showed that the solar minimum between solar cycles 23/24 has the smallest and slowest activity, least dense and coolest solar wind, as well as the weakest helio-magnetic field.

The change in GCR flux due to its modulation by IMF is a very well-established fact. The GCR incident on Earth is strongly 'modulated' by the heliospheric magnetic fields (HMF) dragged in the outward sweeping solar wind (e.g., [29,30]). As figure 1 shows, the GCR intensity is highest during the Schwabe cycle minima when the HMF strength is low, decreasing to low values near sunspot maximum when the HMF strengths are high. As a result of the theoretical work of Jokipii [29], there is now a good understanding of this process, as described by the CR modulation equation. In addition, enhancement in HMF activities increases the GCR modulation potential ψ, which is given by $\psi = V_{SW}/K(r)$, where V_{SW} is the velocity of solar wind and $K(r)$ is the diffusion coefficient of the cosmic ray [31] and a corresponding reduction occurred in CR flux impinging on the Earth. Therefore, the actual CR flux in interplanetary space derived from ^{10}Be observations during 1801–2006 has been used to calculate the average HMF,

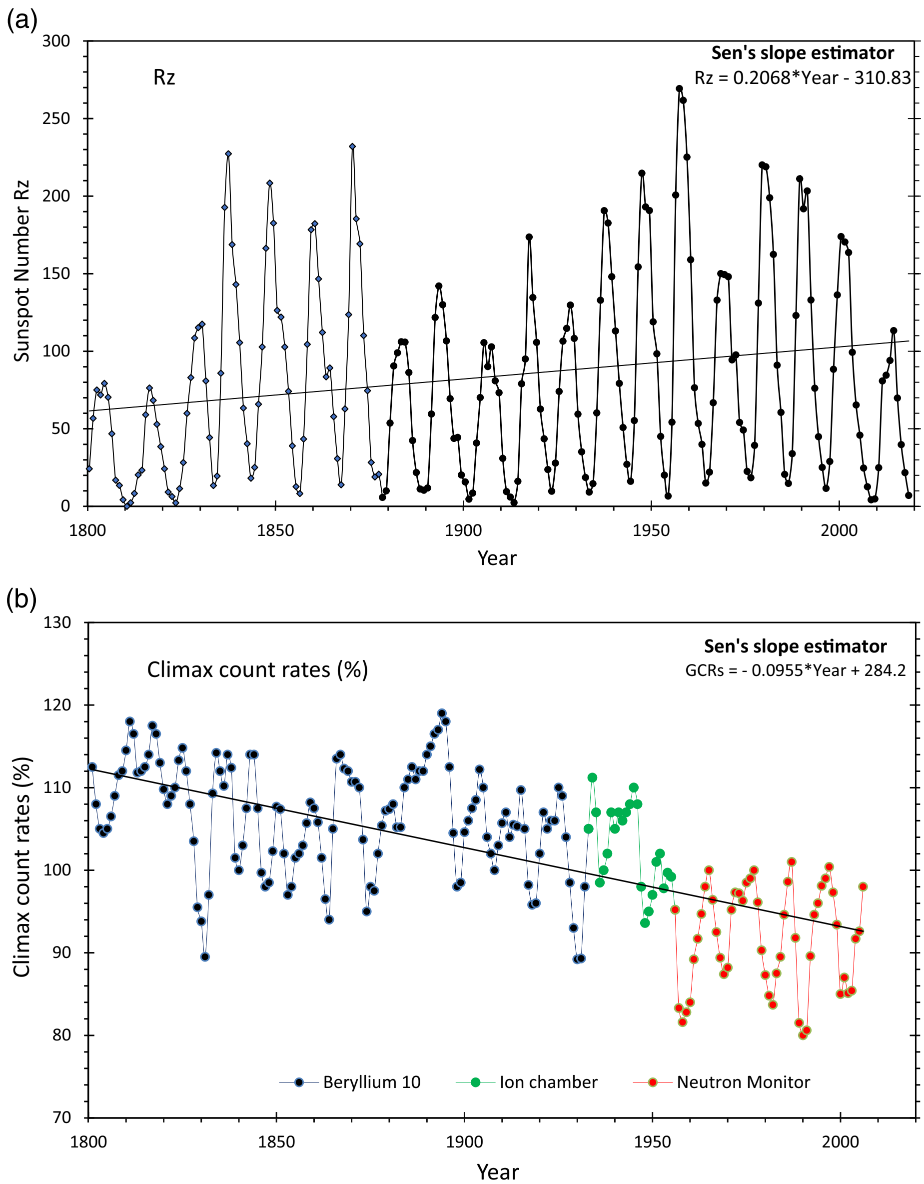

Figure 1. Long-term changes of Rz (**a**) during the period 1800–2018 with the corresponding changes in CR rates (**b**). Red circles represent direct climax NM counting rates (1956–2006), green circles denote ionisation chamber measurements (1933–1955), and black circles represent CR changes derived from ^{10}Be (1801–1932) [24].

which clearly shows that the 11-year averages of HMF increased from ∼2 to ∼7 nT, a factor of 3.5 larger. In addition, the small increases in dynamic pressure in the order of a nanopascal from the solar wind due to the expansion of the solar magnetic corona may be sufficient to increase solar radiation, causing an increase in the atmospheric and surface temperatures of the Earth [32].

To get a close look at how the GCR intensity variations and LLC can affect global temperature, we present figure 3a which shows the 11-year running averages of long-trend of GCR rates (blue curve), TSI (red curve), and GST (black curve). Such smoothing removes the effects of the solar cycle from data in order to illustrate their long trends. Figure 3b shows the amounts of IR LLC amount (%) throughout the period from 1983 to 2009. CRs, composed predominantly of high-energy protons, are the primary source of ionisation in the upper atmosphere, which acts as nuclei for cloud condensation. From the two plots, we noted the following:

(1) The modulation due to increased IMF resulting from increased solar activity reduces GCR intensity, which in turn reduces the low cloud amount (LLC %). Reduction in LLC due to the decrease in CR intensity results in reducing the albedo

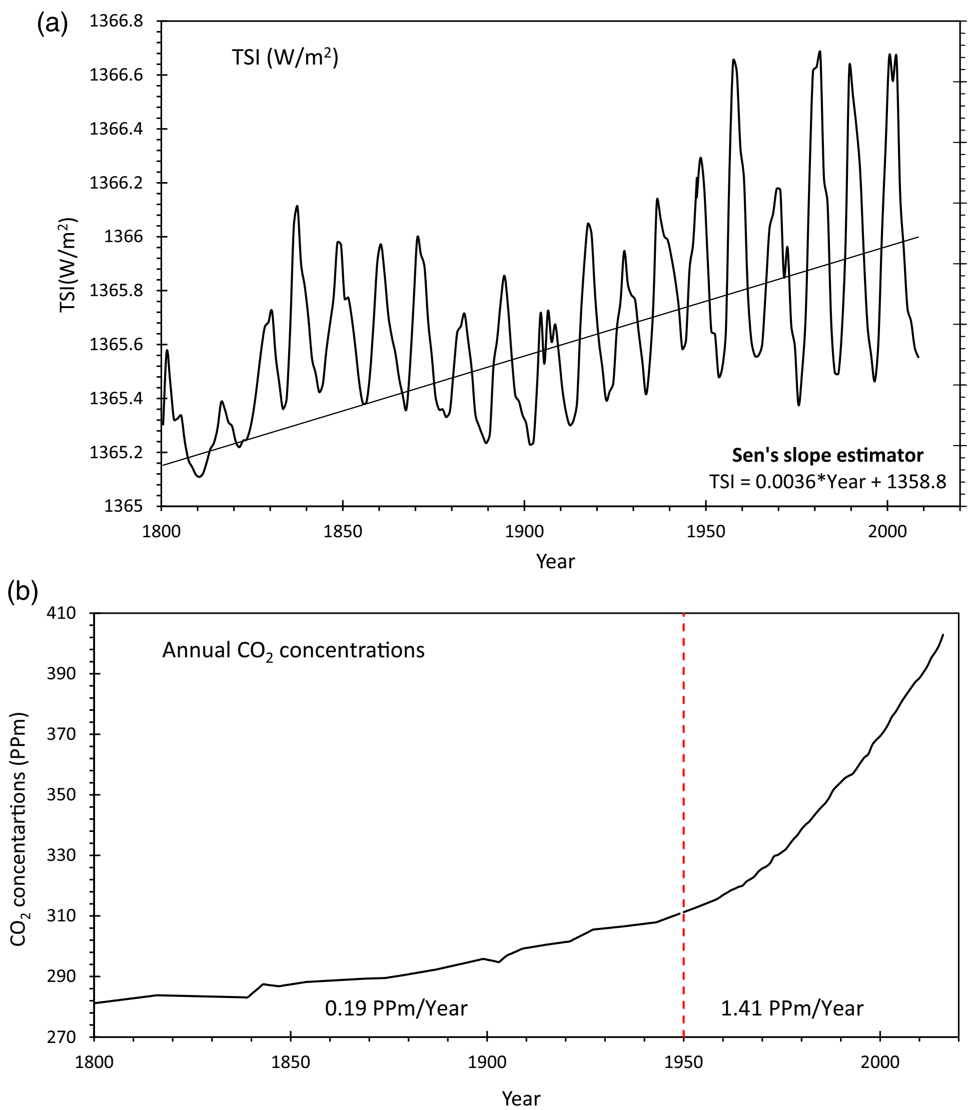

Figure 2. (**a**) Annual reconstructed data of the TSI [25] for the period 1800–2008 and (**b**) the variation in CO_2 concentrations during the period 1800–2016.

radiation (i.e., the ratio of the reflected to the incident radiation) and act as feedback mechanism reflected back into space which leads to an increase in TSI on the Earth and warms the lower atmospheric layer, causing a partial rise in the Earth's temperature. Therefore, the state of the Sun's activity modulates irradiance because it produces dark sunspots and bright faculae that respectively deplete and enhance solar radiation locally.

(2) Some impressive correlations have been shown between temperature proxies and CR proxies on long time-scales. The correlations could be returned to the possible strong connection between the surface temperature and GCR. In contrast, several other processes were happening on these time-scales, many of which were correlated [21, 33,34].

(3) The ISCCP IR measures of global cloud condensation cover at low level displayed a strong correlation with the observed variation of CR as follows:

(a) Through the years from 1999 to 2009, the data do show nearly a steady decreasing LLC, which is matched by an increase in middle-level cloud cover, as reported before [32,35]. This could be caused by a small shift in cloud height, which could generate an apparent correlation between the LLC and GCRs.

(b) During the period 1983–2009, the increase in solar activity reflected a decrease in GCR intensity which may cause a decrease of ∼4.3 LLC.

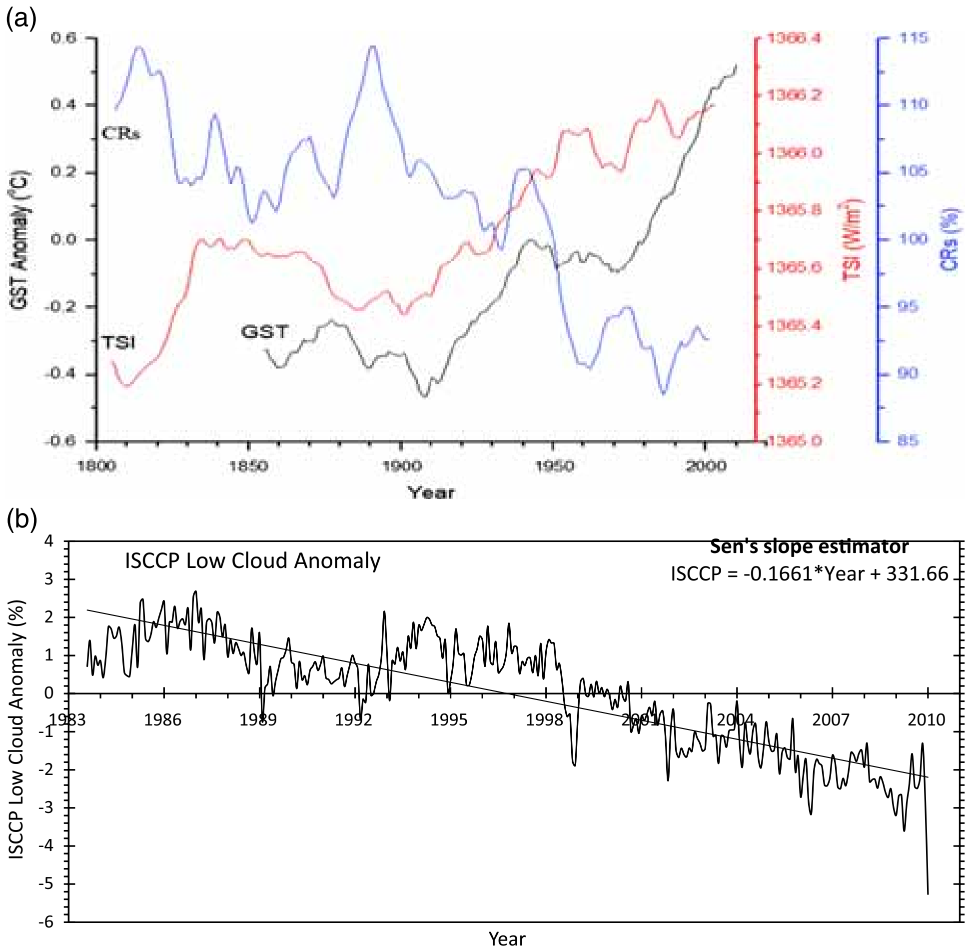

Figure 3. (**a**) Running 11-year averages for the GCR rates (blue), solar irradiance (red), and the global mean temperature (black) and (**b**) the IR LLC amount (1983–2009).

(4) According to whether the long-term variation of primary CR intensities shows an increasing or a decreasing trend, the effect of GCRs over long periods could add or subtract to global warming. The contribution of GCR variations to climate change is significant and has a reasonable role and needs to be factored into the prediction of global warming.

(5) In recent years, the average growth rate of CO_2 ($\sim$1.41 ppm/year) is the largest compared to other GHGs. An increase in the growth rates of CO_2 is expected in the atmosphere, according to the growing global demand for energy. Therefore, a realistic assessment is necessary for the actual contribution of CO_2 to global warming, and it is essential to accurately predict the increase in temperature and its results on climate.

The present work shows the possible role of changing galactic cosmic flux to global warming. It implies that GCR provides a significant effect in the condensation of nuclei to form clouds. The changing GCRs can influence the amount of LLC and hence the climatic change. Good correlation between IR low cloud and primary CR intensity, which act as nuclei for cloud condensation, clearly shows that a decrease in primary CR flux results in lesser low cloud. The reduction of albedo radiation that reflected back into space, due to lesser LLC, results in an increase in the surface temperature on the Earth. The radiative forcing component due to the decrease in primary CR intensity during the last 56 years (1950–2006) was about 30% of that due to CO_2 increase. Solar variability influences the climate of the Earth, to varying degrees. Climate changes have shown that variations in TSI can explain the increase in temperature and it accounts for 0.5°C warming experienced from 1950 to 2016. It signifies that other factors (most probably anthropogenic emission of GHGs) are responsible for the rapid increase in surface temperature observed during the last century. We think that the effects due to the long-term changes in the GCR

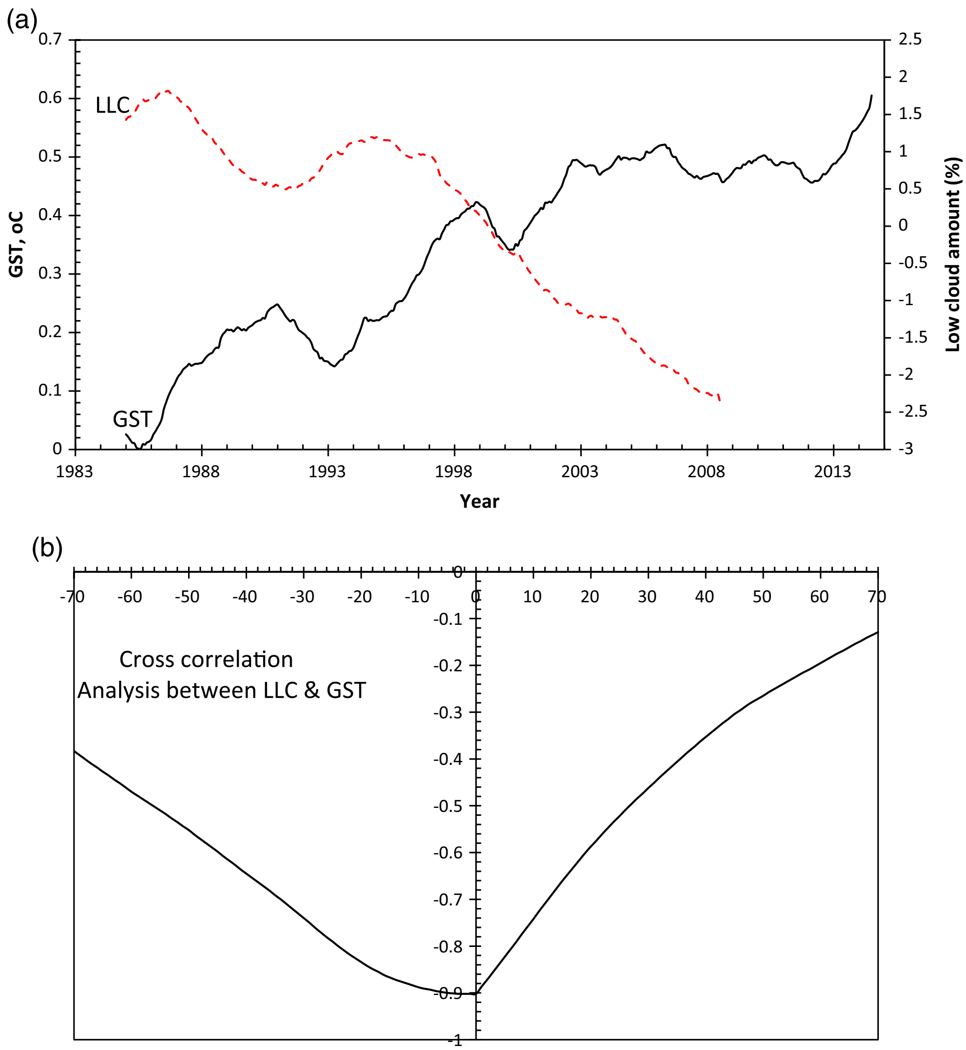

Figure 4. (**a**) The 36-month moving averages for the global temperature and LLC amount throughout the epoch from 1984 to 2015 and (**b**) the cross-correlation between LLC and GST with $\tau = \pm 70$ months.

flux and LLC condensations together should be totally considered in the future prediction of GSTs.

To address the specific issue of the relationship between global temperature and LLC, we examine the close cross-correlation between GCR flux, LCC, and GST. Figure 4a shows the 36-month moving averages for the global temperature and LLC. It would be interesting to re-analyse the correlation of both GST and LCC. Results of the correlation magnitudes of the 36-month running means of GST and LCC, for the period 1983–2013 have been displayed. Figure 4b shows the cross-correlation between LCC and GST for time lag $\tau = \pm 70$ months. For this correlation, τ is usually recommended to be less than 30% of the data length. $\tau = 0$ means that there is no time shift between them (zero lag). The important findings from figure 4 are the following:

(1) The correlation between GCR and LLC is valid for the considered period 1984–2009. The role of GCR flux changes and LLC on climate overlooked some of the important conditions of validity.

(2) A strong correlation between LLC and GST, which comes out to be -0.9. Reduction in cloud cover is significant, a decrease of 4.3 LLC from 1984 to 2009, which would result in global warming. At zero lag, a strong correlation ($\sim -0.9 \pm 0.03$) has been obtained.

(3) The most important point is that figure 4b clearly shows a linear relationship between LLC and GST at opposite/different time lags. The anticorrelation between LLC and GST shows that even at late or earlier months the correlation between them still exists which confirms that any observed

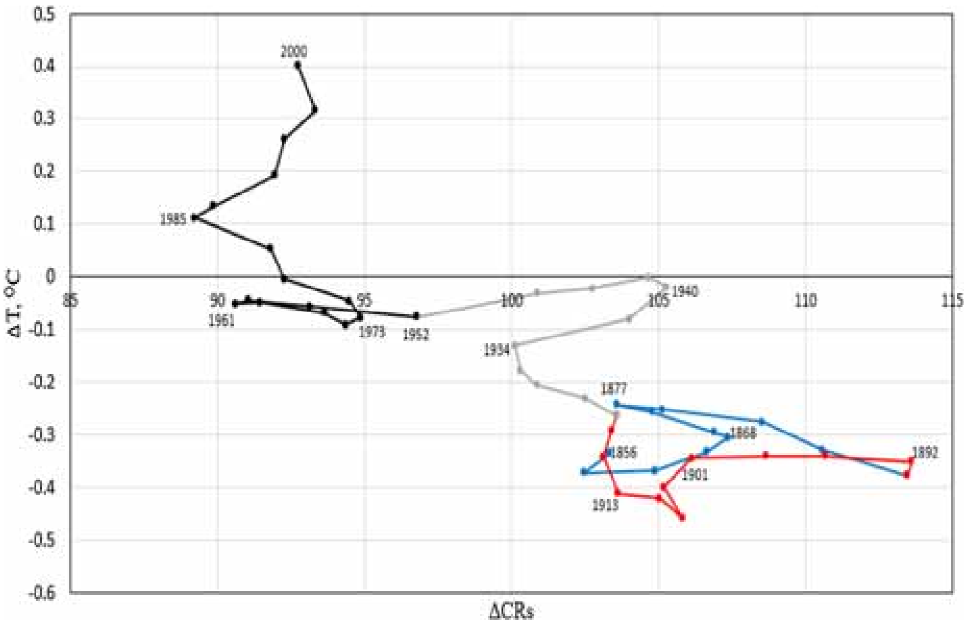

Figure 5. Variation of temperature anomaly ΔT against ΔCR throughout the period from 1856 to 2000. The period from 1856 to 2000 is displayed by different colours (blue line for period 1856–1889, red line for 1889–1922, grey line for 1922–1952, and black line for 1952–2000).

reduction in the LLC, as a result of a reduction in GCRs, will be reflected as an increase in the observed GST.

It is important to note that there are some periods, in figure 3a, which display the shape of the change in CR that does not match with the changing temperature. It can be seen that from 1890 to 1920 and from 1940 to 1970 the CR rate changed rapidly, whereas the temperature changed rather slowly. In contrast, the temperature changed rapidly from 1973 to 2000, whereas the CR rate hardly changed. Therefore, during the considered periods, the behaviour of long-term CR variation does not match with the temperature variation. Therefore, in the long term, it may be hard to determine the connections between CR and the global mean surface temperature. In order to show good correlations, on short periods, between CR and GST, we plotted figure 5. It shows the variations ΔT of GST to the corresponding variations of the CR rate (ΔCR). The period from 1856 to 2000 is displayed by different colours (blue line for period 1856–1889, red line for 1889-1922, grey line for 1922–1952, and black line for 1952–2000). We derive the following results:

(1) It can be seen that from 1892 to 1901 (red points) the CR rate decreased rapidly (8.4%), whereas the temperature is not changed at all. In contrast, a rapid increase in CRs rate (10%) has been observed during the period 1877–1889, whereas the temperature decreases slowly with a sensitivity of $\mathrm{d}T/\mathrm{dCR} = -0.014°\mathrm{C}/\%$.
(2) During the period from 1922 to 1940 (grey circles), ΔT displayed an increase of $\sim$0.24°C in different directions with ΔCR, as $\mathrm{d}T/\mathrm{dCR} = -0.037°\mathrm{C}/\%$ for the period 1922–1934 and $\mathrm{d}T/\mathrm{dCR} = 0.022°\mathrm{C}/\%$ for the period 1934–1940.
(3) A rapid decrease in CRs rate (14%) has been observed throughout the epoch from 1940 to 1961 (grey-black line), whereas ΔT is hardly changed with a sensitivity of $\mathrm{d}T/\mathrm{dCR} = 0.0035°\mathrm{C}/\%$. The data appear to follow a linear relationship from 1940 to 1961.
(4) The recent two periods 1973–1985 and 1985–2000 displayed good correlations between CRs and GST, in opposite directions. The first period (1973–1985) reflected a negative correlation of $\mathrm{d}T/\mathrm{dCR} = -0.033°\mathrm{C}/\%$, whereas the CRs are decreased by 5.5% compared to a rapid increase of 0.2°C in GST during the period between 1973 and 1985. During the second period from 1985 to 2000, only 4% increase in CRs matched a great increase of 0.28°C. The considered period displayed a good correlation with a great sensitivity of $\mathrm{d}T/\mathrm{dCR}$.
(5) The change in temperature due to CR after 1973 is $\sim$0.44°C compared to an observed change in temperature of the order of 0.7°C, i.e., a fraction up to $0.44/0.7 = 62\%$ of the global warming after 1973 could have come from CR. Therefore, the warming effect of CR can be large, and the

radiative forcing due to CRs and LLC is well established.

(6) The variation of temperature anomaly ΔT with the CR rate showed a quasirelationship (cyclic) every 18–21 years. The two data which have shown two opposite directions/correlations in a cyclic extend 18–21 years as follows; 1859–1877 (18 years, blue circles), 1877–1901 (24 years, blue–red circles), 1922–1940 (18 years, grey line), 1934–1952 (18 years, grey line), 1952–1970 (18 years, black points) and 1976–1997 (21 years, black line).

(7) The figure clearly displayed that nearly every solar activity cycle had different behaviour to the sensitivity of GST according to the change in CRs rate. This is due to the different modulations of CRs by solar wind/magnetic parameters in every solar cycle.

(8) It is important to note that the absence of an appreciable 11-year wave on the global temperature indicates that the effect of CRs on the global mean surface temperature may be small or/and insignificant, but both GCRs and GST correlate well in a longer period (18–21 years). Each period indicated that the fractional increase or decrease of the temperature observed in the last century is due to the change in CR rates. This shows that the effects of CR on cloud formation must be important in comparison to those from known standard processes, and the effect of CR on the global temperatures during the last century is significant. Therefore, the change in solar emission had a significant contribution to the Earth's climate variability.

4. Conclusions

We have shown that during the last century the GCR flux was decreased by 19% and the TSI was increased by 0.75 W/m^2, due to the proceeding increment in the solar activity. Furthermore, the concentrations of CO_2 was increased in the lower environment by 19% during the last 65 years, causing a sizable impact on climate change. The decrease in LLC due to the reduction in CR rates comes about in decreasing the albedo radiation, reflected back into space which leads to an expansion of TSI on Earth and warms the lower atmospheric layer, causing a fractional rise in the Earth's temperature. The contribution of GCR variations to global warming implies that CR plays a significant role in helping such condensation nuclei to form. In this way changing CR can influence cloud cover and hence the climate. Also, we found a strong correlation between LCC and GST, which is about -0.9 ± 0.03. Our results clearly showed that there is a linear relationship between LLC and GST at opposite/different time lags. The anticorrelation between LLC and GST displayed that even at late or earlier months the correlation between them still exists confirming that any observed reduction in the LLC, as a result of a reduction in GCRs, will be reflected in an increase in the observed GST. Finally, the variation of temperature anomaly ΔT with the CR rate showed a quasirelationship every 18–21 years. The results of both measurements confirmed that there exist two opposite directions/correlations in a cycle extending from 18 to 21 years.

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