Galactic cosmic rays, total solar irradiance, sunspots, Earth surface air temperature: Correlations

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The variation in the annual mean Earth surface air temperature is a key indicator of the climate change. An empirical search explores the connection among the long-term surface air temperature change (ΔT), the ionization caused by the galactic cosmic rays (GCRs) in the upper atmosphere, the interplanetary magnetic field (IMF) intensity (B) at the Earth orbit, the total solar irradiance (TSI) and the sunspot numbers (SSNs). Several scenarios are investigated with the world's longest and robust GCR data string for the instrumental era (1937-2013) covering eight SSN cycles (17-24). The data are further extended to 1900 to include three additional cycles (14-16). For ΔT comparisons, three datasets used are: the US surface air temperature (UST), the global surface air temperature (GST), and the land ocean temperature (LOT). For 1900-1955 and 1968-1987, an inverse correlation between GCR and GST is obtained. For 1956-1967, GCR intensity changes significantly (~18%) with little change in GST. A positive correlation is obtained between GCR and GST for 1988-2008, implying that GCRs contribute to global warming. These results lead to infer that there is no sustained GCR - GST relationship, i.e. changes in GCR flux does not affect GST. Recent results from the CLOUD experiment are consistent with this inference. A comparison between the amplitude of the solar wind electric field and GST leads to an inconclusive result as well. It is also noted that TSI does not contribute to ΔT either. The historic evidence and the predicted trend for peak activity [Ahluwalia H S & Jackiewicz J, Sunspot cycle 23 descent to an unusual minimum and forecasts for cycle 24 activity, Adv Space Res (UK), 50 (2012) pp 662-668, doi:10.1016/j.asr.2011.04.023, 2012] for future cycles (25 and 26) suggests that Earth may cool in the next three decades, in contrast to IPCC [IPCC, Climate change 2007: The physical basis, Eds: S Solomon *et al*. (Cambridge Press, New York), 2007] consensus that GST will rise 4°C ± 2°C in the year 2100.

Keywords: Cosmic rays, Total solar irradiance, Sunspots, Surface air temperature.

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1 Introduction

The subject of sun-weather connection is complex[3,4]. To add to the complexity, the Earth climate system is occasionally chaotic, dominated by abrupt changes and driven by competing feedbacks with largely unknown thresholds[5]. No single physical process has been identified whereby a small change in solar output influences large energy stored in Earth weather system. Due to non-linearity of response, accurate measurements of all solar outputs to Earth environment have to be carried out with precise instruments for an extended time period. The data collection from the space has barely begun. Progress is very slow in understanding correlations of the winter cyclone intensity, storm track latitude shifts, volcanic activity, sulphuric acid (H_2SO_4) and soot with the long-term changes in the galactic cosmic ray (GCR) flux[6]. For an illustration of the volcanic activity caused (transient) global anomalies in Earth climate leading to very serious socioeconomic consequences, one recalls Mt Tambora eruption of 10 April 1815 on Sumbawa Island (8.25°S, 118°E) in Indonesia. The eruption caused global climate anomalies including the phenomenon known as volcanic winter; the year 1816 became known as the "year without summer" because of the effect on North American and European weather. Agricultural crops failed and livestock died in much of the northern hemisphere leading to the worst famine of the nineteenth century (http://en.wikipedia.org/wiki/Mount Tambora).

Ney[7] speculated that there might be a connection between ionization due to GCRs in the lower stratosphere and a change in the storminess of Earth weather. To help test the Ney hypothesis, Ahluwalia[8] created an extended GCR data string (1937-1994) by combining the data of the ion chambers (ICs) at Cheltenham-Fredericksburg (1937-1972) and Yakutsk

(1953-1994). Both are high latitude sea-level sites with an atmospheric cut-off ~4 GV. Svensmark[9] used Ahluwalia IC data string to study the time variations of Earth cloud cover for a limited period (1937-1994). He showed that higher 11-year mean marine and land temperatures correspond to fewer GCRs (high solar activity), arguing that there is a better agreement with GCRs for cloud cover than the total solar irradiance (TSI). Marsh & Svensmark[10,11] showed that the influence of GCRs is strongest in low clouds (< 3 km) in contrast to middle (3.2-6.5 km) and high clouds (>6.5 km); GCRs reach a maximum value (Pfotzer maximum) at an altitude of about 16 km (~100 mb pressure). Yu[12] used Neher[13] balloon measurements of GCR ions to simulate concentrations of ultrafine aerosols >3 nm at different altitudes and showed that they peak at ~680 mb (lower troposphere), the region where low clouds are formed. Before one invokes Yu finding to support Marsh & Svensmark[10,11] argument, it is necessary to show that in the real atmosphere, these small particles can grow by an order of magnitude to become the cloud condensation nuclei. This has not been done.

2 Data

A large database is used for the instrumental age (1937-2013) consisting of data for GCRs, *in situ* measurements of the solar wind velocity (V), magnetic field intensity (B) at Earth orbit, and the Earth surface air temperature change in the US and at global sites (including land and ocean) to explore empirically whether a direct link exists between GCRs and ΔTs. It is known that ΔT depends upon additional variables[14,15]. The direct link between long term trends in GCRs and ΔTs is explicitly explored. It is assumed that the frequency and properties of the low clouds (< 3 km) do not change with time globally. Thus, circumventing the complications from clouds, a proper understanding of the cloud microphysics is extremely difficult[16]; and the cloud data series is too short (1983-2010) and inhomogeneous for a comparison with other data. Hence, there is a dire need for better observational and information system. It would be nice to have a global timeline of the amount of solar energy that makes it to the Earth's surface.

Ahluwalia[17] used an empirical approach to compute the equivalent annual mean hourly rates (%) for Climax neutron monitor (CL/NM), the low energy GCR ions (> 0.1 GeV) at high altitudes and latitudes and B, back to 1937; Svalgaard & Cliver[18] (SC10 hereafter) extended B and V data to 1835.

The present analysis uses these data strings and Earth surface air temperature change (ΔT) (http://data.giss.nasa.gov/gistemp/graphs/), covering 12 sunspot number (SSN) cycles. The annual mean rates are used for all parameters to exclude abrupt and seasonal variations in data strings. The number of weather stations in US decreased markedly after 1970s (and was badly distributed) in favour of sites at the airports; several of them are closer to the urban areas and subject to heat-island effects[19]. The GCR modulation timeline has a period of ~11 yrs. To investigate the long term trend, 11-yr running mean of GCR data beginning 1937 (1835 for B) is taken; smoothing out the effect of the solar cycle and minimizing the variance in the datasets.

2.1 Temperature data

The change in the annual mean Earth surface air temperature is a key indicator of climate change. Figure 1 displays a plot (thin line) of the US surface air temperatures ($^{\circ}$C) for 1900-2010 in 48 contiguous states covering 1.6% of Earth surface but with a limited range of latitudes, spanning nearly ten SSN cycles; deviations (ΔTs) are with respect to the 1951-1980 mean. The data have a large variance before 1940 and the excursions after 1980 match those in the 1930s. The noise level subsides noticeably for 1960-1980 and there has been no net warming after 1980 above the 1930s level. To bring out the trend in the temperature data, 11-yr mean is also plotted (thick line), minimizing the influence of any decadal temperature oscillations in data. One notes that US was warm for 1915-1935, leading to a cluster of dry Dust Bowl years in the 1930s with the largest number of record high temperatures. The US was cool from 1940 to 1975 and warming resumed thereafter, reaching a higher level (~0.8°C) in 2002-2003; a noticeable cooling trend set in later.
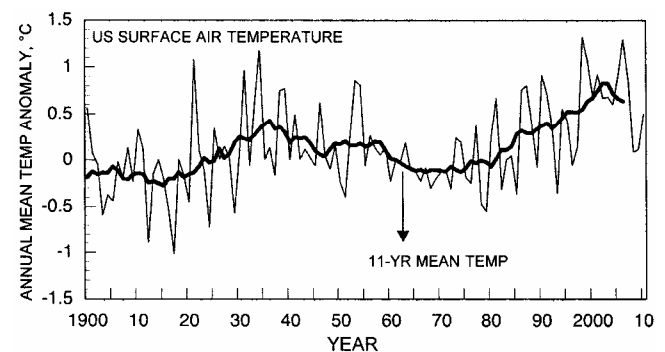

Fig. 1—Annual mean surface air temperature in United States relative to 1951-1980 mean [thick line is the 11-yr running mean]

To our knowledge, the temperature rise during the Dust Bowl years and the cooling that followed has not been explained such that one may explore whether it has a bearing on the recent warming ~0.8°C, other than the recovery from the Little Ice Age (1450-1850) at the rate ~0.5°C per century suggested by Akasofu[20].

Figure 2 shows a plot (thin line) of ΔTs obtained from the meteorological network at the global sites for 1900-2010; 11-yr mean is the thick line. There are significant differences with respect to the US surface air temperature (UST) such as the greatly reduced variance in data, little change in ΔT for 1940-1970 and no cooling after 2003 but an indication of leveling off. The range of global warming (~0.8°C) after 1975 is the same as in UST. No explanation is known for the absence of a significant prolonged cooling for 1940-1970 for the global surface air temperature (GST).

Figure 3 is a plot of the annual mean land ocean temperature (LOT) changes for 1900-2010, obtained from the GISS website. The cooling trend after 1940 is barely noticeable compared to UST and the range of warming after 1970 is less (~0.6°C); the trend curve suggests a flattening after 2003.

To bring out the differences in the trends between the three sets of ΔTs, their 11-yr means is plotted in Fig. 4. The change in the trend is most pronounced in UST, particularly the warming from 1915 to 1935, followed by cooling for 1940-1970 and after 2003. The rise in LOT after 1970 is more gradual and to a lower level (~0.6°C) compared to the trend in UST and GST data (~0.8°C). It is comparable to recovery from the Little Ice Age (1450-1850) at the rate ~0.5°C per century[20]. One has to know why ΔT trend in UST (for 1940-1970) is so markedly different from that in GST and LOT. It may have implications for the environmental and social policy. The suggestion of leveling off in LOT and GST after 2003 also needs to be understood.

2.2 GCR data

Balloon measurements at high latitudes (> 68°N) in Russia of low energy GCR ions (>0.1 GeV), near the Pfotzer maximum, are available since 1957 (Ref. 21). Ahluwalia[17] extended this data string back to 1937 using IC dataset from the Cheltenham-Fredericksburg-Yakutsk (CYF) sites. The annual mean values of the low energy ions (normalized to 100% in 1965) are plotted in Fig. 5 for 1937-2009 spanning seven sunspot cycles (17-23); SSN maxima
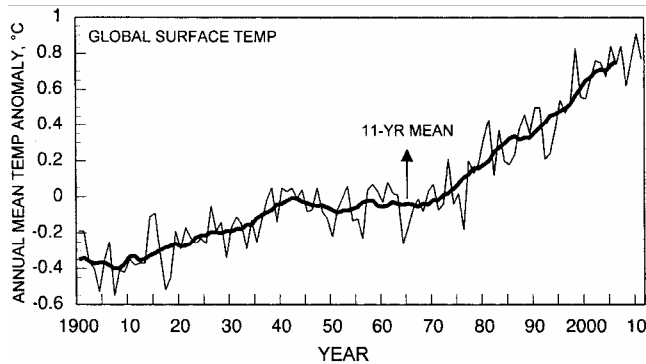

Fig. 2—Annual mean surface air temperature worldwide relative to its 1951-1980 mean [thick line is the 11-yr running mean]

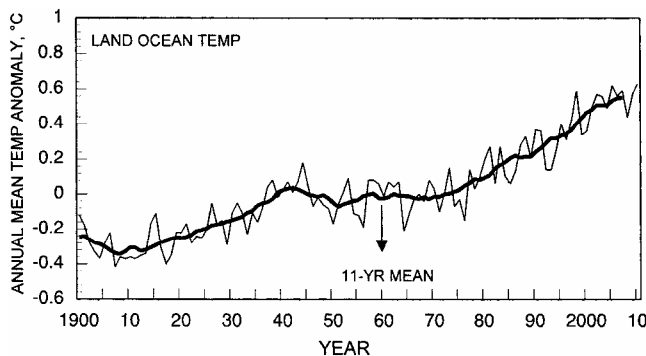Fig. 3—Annual mean land ocean temperature (thin line) relative to its 1951-1980 mean [thick line is the 11-yr mean]
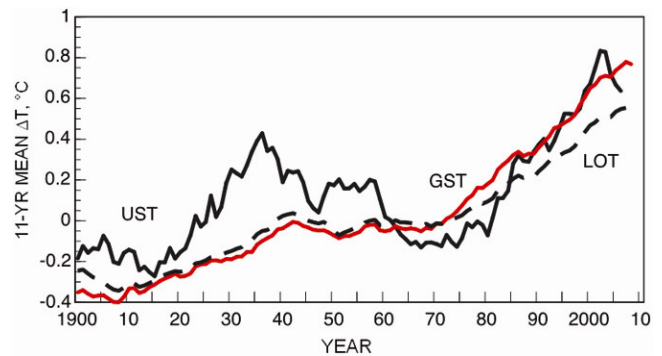

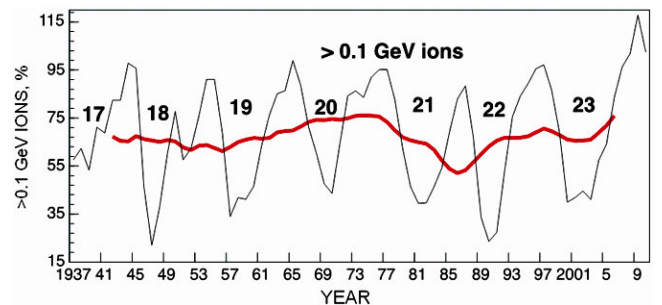Fig. 4—11-yr means relative to 1951-1980 mean for UST, GST, and LOT

Fig. 5—Annual mean hourly rates (%) for low energy GCR ions for 1937-2010 [thick red line is 11-yr running GCR ion mean]

(low GCRs) occur in the years 1947, 1958, 1968, 1979, 1989, and 2000. GCRs recovered to the highest level of the instrumental era in 2009 (Ref. 22), perhaps in keeping with prolonged sunspot minimum for cycle 23 (unexplained). The 11-yr mean (red line) is also plotted indicating that GCRs reached a minimum in 1986 and the future trend is upward.

3 Results and Discussion

3.1 GCR-B correlation

GCRs at Earth orbit are modulated by solar activity through the flux of open field lines[23-32]. The annual mean values of B from SC10 are plotted in Fig. 6 (thin black line). One sees a rising trend for the first half of the century followed by a decreasing trend for the latter half; the value of B in 2009 is nearly the same as in 1901. The 11-yr average is shown by thick red line. It suggests that B values increase nearly monotonically until the start of cycle 19, followed by a sharp decrease, a gradual rise for the next two cycles (20 and 21) and a decline thereafter.

Figure 7 shows a plot of the 11-yr average for B and low energy GCR ions for 1940-2006. As noted earlier, the trend in the GCR flux is to the highest level of the instrumental era[22], in a variety of species of energetic charged particles in the heliosphere[33], while that in B to the lowest value ever measured[34].
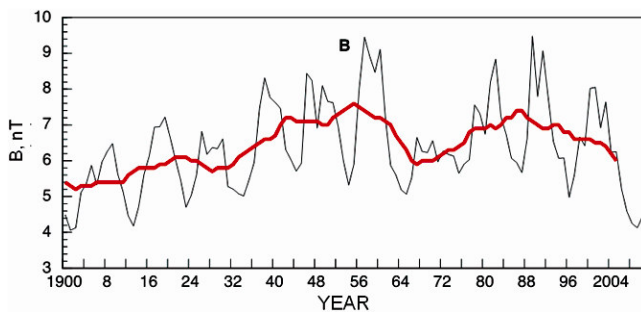

Fig. 6—Annual mean values of B (thin line) for 1900-2010 [red thick line is the 11-yr mean]
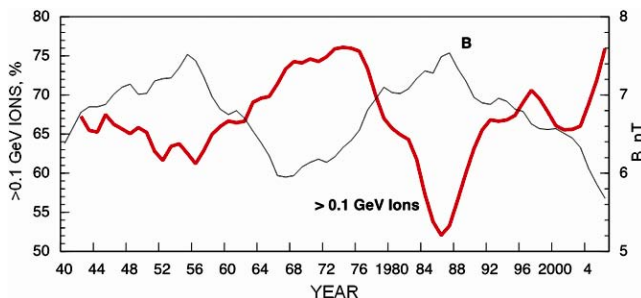

Fig. 7—11-yr means for B (thin line) and low energy GCR ions (thick red line) at the balloon altitudes at high latitudes in Russia

The steep rise in low energy GCR flux accompanied by a dramatic decrease in B suggests that in future the radiation dose will be higher for activities in space (travel to Mars?), equivalent to the pre-1940 levels. Figure 8 shows a scatter plot of 11-yr mean of GCR ions and B. The inverse correlation between the variates (cc = -0.83) is expected[17,28,35]. The fit parameters in the inset are used to compute pseudo GCR values for 1900-1940 (using SC10 values for B) covering four additional SSN cycles, namely 14 (1902-1913), 15 (1913-1923), 16 (1923-1933), and 17 (1933-1944).

3.2 ΔT-GCR correlation

The 11-yr mean GCR intensity (1900-2008) is plotted in Fig. 9, alongside 11-yr mean GST data (the epochs of World Wars I, II are indicated). One
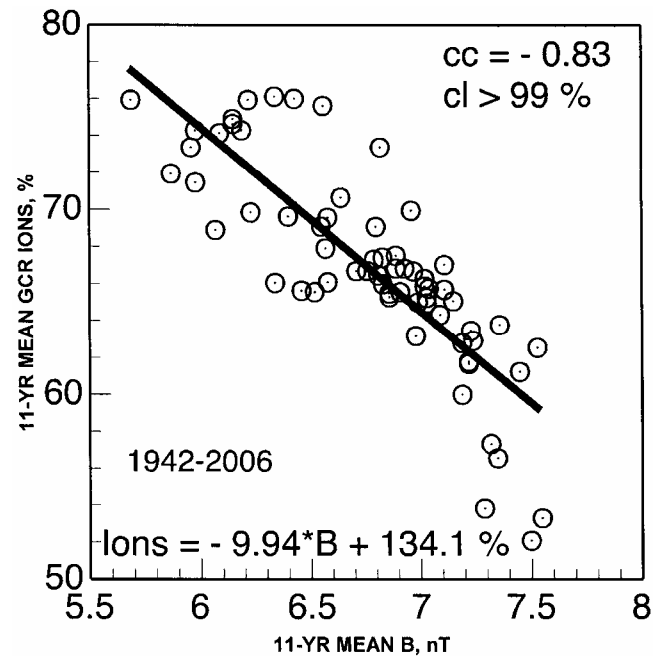

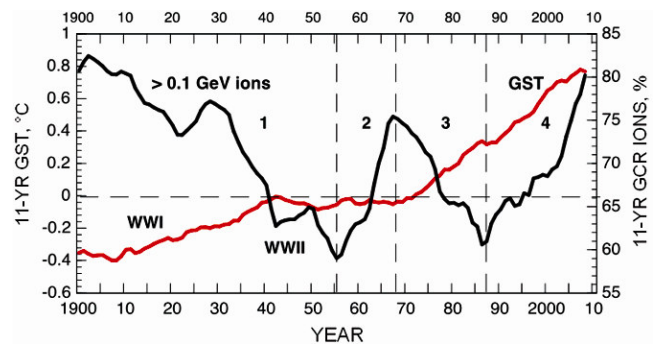Fig. 8—Linear correlation between 11-yr mean for GCR ions and B

Fig. 9—11-yr means for GST (red line) and low energy GCR ions (black line) at the balloon altitudes at high latitudes in Russia [epochs of the World Wars (WW) I, II also shown]

notes that in pre-1940 era, GCR flux is far in excess of that in the instrumental era and it may be headed that way again after 2005 as noted in Fig. 7. To understand the correlation between two data strings, the data is sub-divided into four intervals: 1 (1900-1955), 2 (1956-1967), 3 (1968-1987), and 4 (1988-2008). For 1 and 3, both curves show a negative correlation with ΔT; for 2, GCRs change by a large amount (~18%) with little change in GST; for 4, the curves show a positive correlation, implying that GCRs contribute to global warming. So the correlation coefficient between GCRs and global temperature varies erratically, exhibiting both positive and negative correlations over time scales varying from about five to 20 years (this result is consistent with related short term searches by other researchers). Since the finding of no persistent correlation is not supported by predictive theory but is what one should expect for two random, un-correlated time series, it is concluded that GCRs do not influence global surface air temperature.

Scatter plots for intervals 1 and 3 are shown in Fig. 10(a, b); for both cases cc < − 0.9, at cl > 99%, the high value of cc implies that when GCR intensity is high, GST is low and vice versa. This is consistent with past observations, e.g. GST during the grand minima was significantly lower[36] and GCR flux was high[37]. For the interval 4, the scatter plot is depicted in Fig. 10(c). It gives cc = 0.92; positive sign implies that GCRs contribute to global warming. Sloan & Wolfendale[38] argue that changing GCR flux contributes less than 8% to the increase in the annual mean GST for 1900-2000; they cannot rule out 0%. For 2, a significant increase in GCRs (~18%) yields no change in GST. Svensmark[9] investigated the connection between GCRs and earth cloud cover (not temperature) for a limited time interval. He obtained a strong correlation between low clouds and GCRs for July 1983 to August 1994, but the results are marginal when data upto September 2001 is included in the analysis. Marsh & Svensmark[39] believe that the discrepancy may be due to a calibration gap between the two datasets for September 1994 and January 1995. Alternately, the discrepancy may arise from a systematic change in global cloud properties. Usoskin & Kovaltsov[40] state that low-cloud-GCR link is only valid in limited geographical regions since 1984. If these facts are put alongside, the correlations obtained show one sign during one period, the opposite sign during
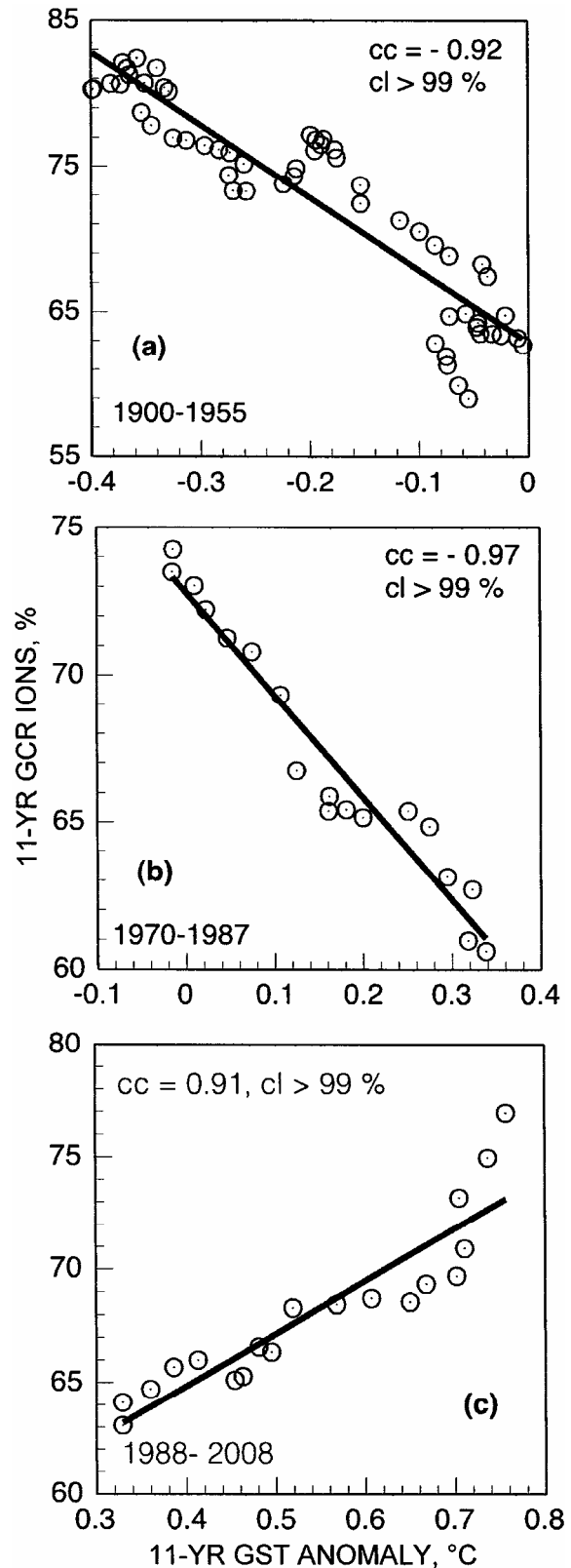

Fig. 10—Correlation between GST and low energy GCR ions at balloon altitudes at high latitudes in Russia for: (a) 1900-1955, and (b) 1970-1987; (c) 11-yr means for GCR ions and GST for 1988-2008

other period, and a zero correlation during a third period, it leads to infer that there is no connection between the two datasets.

3.3 ΔT-BV correlation

The correlation, between the long-term trend in the amplitude of the solar wind electric field at Earth orbit and ΔT suggested by Tinsley[6], is further explored. The amplitude of the solar wind electric field is ∝ BV (Ref. 41). The plots for 11-yr mean BV (red) and ΔT (black) are shown in Fig. 11 for 1900-2006. The data is sub-divided into four intervals as in Fig. 9. For 1 and 3, both curves show a positive correlation with ΔT; for 2, BV changes by a large amount (~1000 µV m^{-1}) with little change in GST; for 4, the curves show a negative correlation, implying that a decrease in the amplitude of the solar wind electric field contributes to global warming. Again, an inconclusive result is got. This is not surprising given that the solar wind electric field modulates GCRs (Refs 23,42,43). This takes back to the inconclusive correlations between GCR and GST. Other details of the Tinsley hypothesis have to do with the cloud microphysics. They imply GCRs modulated by solar activity, through solar wind, may influence the cloud formation leading to GST changes.

3.4 ΔT-TSI correlation

Figure 12 shows a plot of the 11-yr mean for TSI and GST for 1900-2010; TSI data are normalized to 100% for May 1965 value of 1365.72 Wm^{-2}. A private communication from Kopp in 2011 states, "The actual TSI measurements are only from 1978 onward with the Total Irradiance Monitor (TIM) on NASA's Solar Radiation and Climate Experiment (SORCE) and even those have been adjusted between many contributing instruments to fit the same scale. Also, they rely on the observations (MgII, CaK, F10.7) going back to about 1950 and proxies (SSNs and cosmogenic isotopes) before that." The reader may refer to Kopp & Lean[44] for more details on data manipulation.
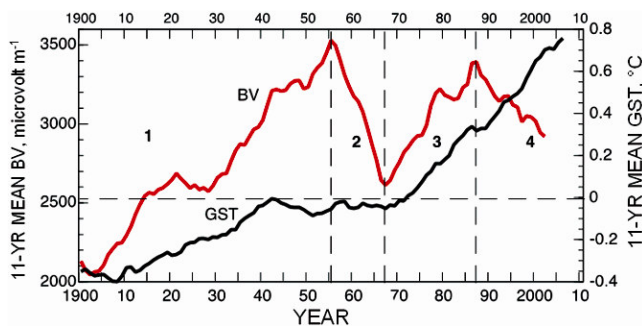
Again, the data is sub-divided into four segments as in Fig. 9. It is clear that GST data string does not follow the pronounced undulations in the reconstituted TSI data string after 1940; it seems to have leveled off for 1940-1973, increased for 1974-1985, trending downward after 2002. This suggests that drivers other than TSI dominate the long-term GST change[45].

3.5 ΔT-SSN correlation

Finally, the role of the Sun in global climate change is explored. It is an issue of modern science with far reaching scientific, political, and economical consequences. How much of the observed GST change is due to variations in solar activity is controversial because the mechanisms through which solar activity affects GST are not known. However, there is little doubt that at least a part of the observed temperature change in the past has been due to solar activity (as discussed above), and at least a part of future surface temperature change may come from solar variability. Regrettably, IPCC (Ref. 2) report trivializes the contributions of solar variability[46].

Figure 13 shows an updated plot of the annual mean SSNs for 1700-2012, every fourth cycle is labeled bold. One notes that beginning with cycle 10, there is a pattern where even cycles of the even-odd pairing are less active; it disappears after cycle 21. Also, every third cycle is less active (cycles 14, 17, 20, and 23). There is no understanding of the physical processes leading to these solar features. The thick black line is 11-yr mean, showing that the Sun is a variable magnetic star, undergoing periods of enhanced activity interspersed with periods of noticeable lower activity. The grand minima are labeled bold, namely the Maunder Minimum (MM) (1645-1715), the Dalton Minimum (DM) (1790-1830), and the Gleissburg Minimum (GM) (1889-1902). The world has emerged from a period of the grand maximum for SSN cycles; it includes

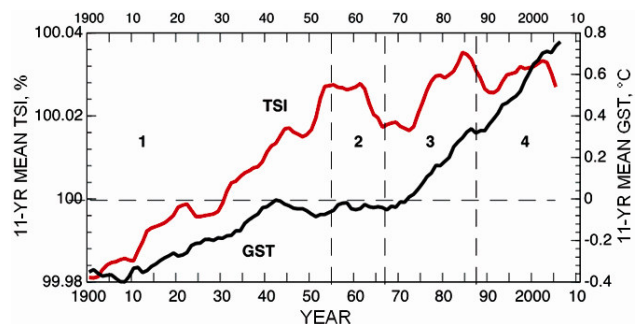Fig. 11—11-yr averages for BV and GST for 1900-2006

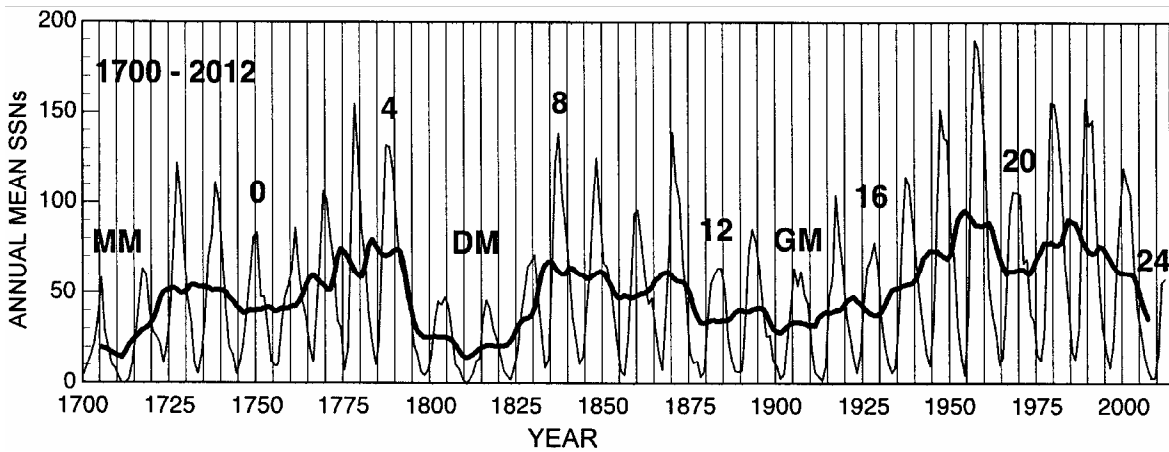Fig. 12—11-yr averages for TSI and GST for 1900-2006

Fig. 13—Annual mean SSNs for 1700-2012 (thin line); 11-yr mean (thick line) [epochs of three recent grand minima (MM, DM, GM) are labeled bold]
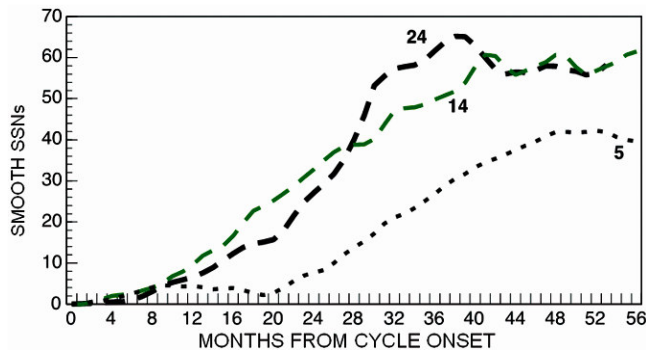

Fig. 14—Timeline of cycle 24 is compared with those of cycles 5 and 14; they preceded DM and GM

cycle 19, the most active cycle ever observed for the last four centuries. The trend line indicates that the Sun is descending into a period of lower activity. Ahluwalia & Jackewicz[1] (hereafter, AJ12) suggest that the world is at the advent of a Dalton-like minimum when Earth was cooler (made worse by the Mt Tambora volcanic eruption described above). The ascending phase of cycle 24 observed to-date appears to be consistent with the prediction[47]; the methodology used therein led to the best prediction for cycle 23 (Refs 48,49). The development of cycle 24 timeline is compared with those of cycles 5 and 14 in Fig. 14; they preceded DM and GM, respectively. The cycle 24 is closely following the timeline of cycle 14 (56 months after its onset). It has reached the maximum (AJ12 prediction) and is beginning to linger near the maximum[50]; it may develop into a GM-like grand minimum in future (Ref. 51 and references therein). The Earth was cooler in 1900s and during other grand minima. The three timelines will be tracked as the cycle 24 continues to develop past the maximum.

In this context, one should take a note of the recent pause in GST / LOT. A stratospheric-aerosol-producing volcano happening in future may turn into a cooling trend; the physical process of cooling remains undiscovered at this time. All variables used in the present analysis are correlated with SSNs. So, one expects GCR flux to increase at Earth[27] and values of B and TSI to be lower. If historical precedent holds, Earth may cool measurably in coming decades.

4 Summary and Conclusions

The annual mean Earth surface air temperature change (ΔT) is a key indicator of the climate change. The connection is explored between ΔT, the ionization caused by GCRs in the upper atmosphere, the interplanetary magnetic field (IMF) intensity (B) at Earth orbit, the total solar irradiance (TSI) and SSNs. Several scenarios are investigated, using the longest and robust GCR data string for the instrumental era (1937-2013) covering eight SSN cycles (17-24); the data string is further extended to 1900 to include three more SSN cycles (14-16). For 1900-1955 and 1968-1987, an inverse correlation is obtained between GCRs and ΔT. For 1956-1967, GCR intensity changes significantly (~18%) with little change in GST. A positive correlation is obtained between GCRs and ΔT for 1988-2008, implying that GCRs contribute to global warming. The positive correlation is puzzling because GCR data indicate that future trend is towards pre-1940 level when Earth was cooler. It would be very exciting to see if and when the correlation turns negative again to correspond to pre-1940 era. Also, it would be interesting to see if the present discrepancy arises

from a systematic change in the frequency and/or global cloud properties and if the cause(s) for such a change are identified.

Svensmark[9] investigated the connection between GCRs and earth cloud cover with a limited dataset, obtaining a strong correlation between low clouds and GCRs for July 1983-August 1994; the results are marginal when data until September 2001 are included in his analysis. Marsh & Svensmark[39] believe that the discrepancy is due to a calibration gap between datasets for September 1994 to January 1995. Gray et al.[52] question the merit of this suggestion. Alternately, the discrepancy may arise from a systematic change in global low cloud properties and frequency. These issues need to be clarified for the GCR-low cloud-cover hypothesis to survive. Putting these results alongside the correlations obtained, in the present study, between GCRs and ΔT (Fig. 9) compel to infer that there is no connection between these datasets for 20th century. Furthermore, the observed warming in LOT is within the range of recovery from the Little Ice Age (1450-1850) at the rate ~0.5° C per century, predicted by Akasofu[20]. Moreover, what is one to make of the recent pause in GST / LOT rise? It would be very interesting for climate science if this flattening continues or turns into a decreasing trend for ΔT.

The amplitude of the solar wind electric field at Earth orbit is ∝ BV (Ref. 41). Tinsley[6] suggests that this electric field may serve as the liaison between the solar wind and ΔT. Again, the present investigation yields an inconclusive result. This is not surprising given that the solar wind electric field modulates GCRs (Ref. 23,42,43,50) and correlations between GCR and GST are inconclusive. Other details of the Tinsley hypothesis relate to the cloud microphysics. They imply GCRs modulated by solar activity through solar wind, may influence cloud formation, leading to ΔT. This discrepancy has to be explained and details of the cloud microphysics have to be worked out, if Tinsley hypothesis is to work. The present analysis shows that there is no sustained GCR- GST relationship. All facts known at this time and the correlations obtained in this paper (Fig. 9) lead to infer that changes in GCRs do not affect GST. Recent results from the CLOUD experiment support this inference[53].

The historic evidence and the predicted peak activity [AJ12] of future sunspot cycles (25 and 26), suggests that a global cooling cannot be ruled out in the next three decades, in contrast to IPCC (Ref. 2) consensus that Earth surface temperature will rise 4°C ± 2°C in 2100, and Akasofu prediction that temperature rise will be 0.5°C ± 0.2°C in 2100.

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