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Prediction of Solar Cycles: Implication for the Trend of Global Surface Temperature

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Abstract: *The findings arising from investigation of the controversy surrounding the predictions of solar cycles and trends of variation of solar activity with global surface temperature during the currently observed deep decline of solar-geomagnetic activity is reported in this work. Solar activity grand minimum expected to be accompanied by little ice age conditions and global surface temperature rise by ~4.8 °C as at 2100 have been proposed. The prediction of the rise in global surface temperature was based on monotonic rise in anthropogenic greenhouse emissions, which was also predicted to occur within the same time frame. There is the need to specify whether or not solar-geomagnetic activity variability determines the trend of variation of global surface temperature. Consequently, low-pass filter functions were used to establish the trends of solar-geomagnetic activity and global surface temperature phenomena. The trends were subjected to auto-correlation and regression analyses which formed the basis of extrapolation and prediction. Results obtained reveal that the recent solar activity Modern Maximum was a recovery from the Maunder Minimum and that the character of the next grand episode may likely be a minimum. It was also found that he expected grand minimum will most likely give rise to low global surface temperature with the coldest phase in 2046±11 and that it will be ~0.1°C above the current base-line in 2100 as opposed to 4.8°C predicted by general circulation models (GCM). Significant evidence indicated that long-term trend of global surface temperature variation is characterised by low-frequency cycles (in the Gleissberg period range or longer) which are most likely related to those of the activity of solar-geomagnetic phenomena with strong conformity to solar activity period change rules. The long-term high solar-geomagnetic activity trend which was observed to persist up to 2003 was the most likely cause of the continued rise of global surface temperature until the decrease in the rate of climate warming since the early 2000s. The results and findings from the present study led to the conclusion that the recent climate scenarios were predominated by the direct solar irradiance climate forcing and indirect amplification processes associated with solar and geomagnetic activity variability.*

Keywords: *Solar cycle, solar-geomagnetic activity, grand episode, greenhouse emission, general circulation model*

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1.0 Introduction

In recent times, the prediction of the evolution and magnitude of solar cycles (SC) during the currently observed trend of declining solar activity has witnessed a lot of contradictions. The just-concluded cycle (SC24)(December 2008 to December 2019)was predicted to be 30-50% stronger than SC23 (Dikpati, *et al*., 2006; Woods, 2007). The cycle, which attained its maximum in April 2014 with 116 sunspots (Hathaway, 2015) did not only manifest a much lower solar activity than predicted but was the weakest in the past one hundred years.

Measurements of sundry upper atmospheric phenomena such as F2-layer ionospheric critical frequency (foF2) and global total electron content (TEC) indicated that the solar activity has been significantly lower and that the ionisation was weaker (in the just concludedSC24) compared to the average levels of SC19-23 (Hao *et al*., 2014). With reference to climate studies, the implication is that the solar electromagnetic radiation in the short wavelength range e.g. ultraviolet(UV) radiation has witnessed a significant reduction during the recent cycles. It would then be of interest to see a concomitant decline in global surface temperature within the same time frame since the absorption of shortwave solar radiation in the ultraviolet range and re-emission in the infrared range by the climate system's components is primarily responsible for climate warming.

The current solar activity cycle (SC25) has also witnessed a wide range of contradictory predictions. According to the forecast made during the annual Space Weather Workshop (in April 2019) that was hosted by the National Oceanic and Atmospheric Administration's Space Weather Prediction Centre, the cycle was scheduled to begin between mid-2019 and late 2020 and was expected to approach its maximum between 2023 and 2026 with sunspot count per cycle between 95 and 130. The prediction anticipated SC25 to be comparable in magnitude to SC24 and concluded that it would terminate the currently observed trend that is characterised by a decline in solar activity.Some studieswhich reported on the current descending phase of solar activity trend [e.g. Cameron, Jiang and Schussler, 2016) seem to agree withthe opinion that SC25 will be of moderate amplitude and is not expected to be much higher than SC24. However, there are also other predictions that suggest further decline of solar activity inSC25, SC26 and possibly SC27 (SinghandBhargawa, 2019). The implication is that the transition into the predicted Grand Minimum might have started considering the long and deep transitions between SC23 to 24 and SC24 to 25 which took one year of transit time. Therefore, observers and researchers may have to wait a while for the manifestation of the prediction but it suffices to state that there is current evidence to support some of the predictions that have been proposed.

However, apart from its utility in the planning of long-term space missions and flights of airlines over transpolar routes, solar cycle prediction is of interest to climate studies due to its link with global surface temperature conditions. Studies conducted by Eddy (1976) confirmed the past grand episodes of solar activity were accompanied by extrema of global surface temperature. For instance, the Medieval Climatic Optimum (MCO) (1100-1250) was associated with high global surface temperature (about 0.5°C warmer than the current warm period).Scafetta(2013)observed that despite the accompaniment of MCO by warm surface temperatures, the polar ice caps did not disappear. Also, the Maunder Minimum(MM) (1645-1715) and the Dalton Minimum (DM) (1809-1821) were accompanied by little ice age (LIA) conditions (Scafetta, 2010). However, research opinions are diversional but it has been remarked that the evolution of global surface temperature up to 2100 indicates that it will be accompanied by a slight decrease in temperature (not more than ~0.3 °C) from the expected ModernGrand Minimum, which will be much smaller than the warming due to the expected rise in atmospheric greenhouse gases (GHGs) emission within the same interval (Feulner and Rahmstorf, 2010). Several works of literature have however supported the expected deep decline of solar activity and its possible timing, but disagreed on the possibility of its accompaniment by decreasing global surface temperature (Hady, 2013). Yet still, others predict that the expected Grand Minimum will be accompanied by terrestrial cooling (Herrera *et al*., 2015; Mörner, 2015;Abddusamatov; 2016; Upton and Hathaway, 2018; Zharkova, 2020). In line with the expected lowering of terrestrial temperature, Ibanga and Agbo (2020) predicted that the lowest phase of global surface temperature might occur in 2039±11.

In view of the increasing atmospheric concentration of GHGs, Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) projected a rise in global surface temperature by ~4.8 °C as at the beginning of 2100 (IPCC, 2014).On the other hand, there is the prediction that the character of the next solar activity grand episode will be a minimum to be accompanied by low global surface temperature similar to LIA conditions. The predicted event is expected to last for at least a Gleissberg cycle with the expected coldest phase between 2030 and 2040. The two predictions fall within the same interval of time and are evidently contradictory. Therefore, the aim of the present study is to investigate the near-future trends of solar activity and global surface temperature up to2100. The investigation shall be based on their trends in the recent past and the assumption of cyclic variability of the response of global surface temperature to periodic excitations of astrophysical phenomena. The essence is to determine whether or not the trend of variation of solar-geomagnetic activity determines the trend of variation of global surface temperature or the exponential rise of anthropogenic greenhouse emission is the control knob of the current climate change scenario.

2.0 Method of Analysis

The data for solar activity phenomena comprise annual means total sunspot number R_Z(1700-2018) and solar F10.7 cm radio flux (1947-2018) time series, sourced from world Data Centre (WDC)-Sunspot Index and Long-term Solar Observations (SILSO) and National Aeronautics and Space Administration (NASA) Goddard Flight Centre Space Physics Data Facility with the following web addresses:http://www.sidc.be -/silso/datafilesandhttps://omniweb.gsfc. nasa. gov/form/dx1.html.Geomagnetic activity data (aa-index: 1868-2018) were sourced from the International Service of Geomagnetic Indices (ISGI)at http://isgi.unistra.fr/data_download.php. Global surface temperature data used in this study comprises the instrumental record of land and sea-surface temperature represented by HadCRUT.4.6.0.0 time series available since 1850 (Morice*et al.*, 2012).

The low-pass filter structure was applied on the time series to reveal trends of variation in the time domain, based on the difference equation(Difference Equations and Filtering, 2021):

$$y(t) = \frac{1}{a(1)}[b(1)x(t) + b(2)x(t-1) + \cdots + b(N_b)x(t-N_b+1) - a(2)y(t-1) - \cdots - a(N_a)x(t-N_a+1)] \quad (1)$$

where, t is the index of the current sample, N_a is the order of the polynomial described by vector a, and N_b is the order of the polynomial described by vector b.The output $y(t)$ is a linear combination of current and previous inputs, $x(t)x(t-1)\ldots$, and previous outputs, $y(t-1)y(t-2)\ldots$

Regression analyses were performed to quantify the trends and the regression equations obtained formed the basis of extrapolation and prediction.

3.0 Results and discussion

Plots showing the annual mean sunspot time series with the highlights of the various grand episodes are presented in Fig.1 (a). Solar cycles are numbered from cycle 1 (1755) to cycle 24.

From the plots, it is evident that the eleventh year (Schwabe) solar activity cycles are quite prominent. The Maunder (1645-1715),the Dalton (1809-1821) Minima and the modern Maximum (1914-2008) are clearly labelled. Also, the yet apparently unspecified quasi-grand episodes labelled as A Maximum and B Maximum as well as the Modern Minimum (or Gleissberg Minimum) respectively are shown(see the arrowsin Fig. 1a). It is clear that the grand episodes alternate between maxima and minima, albeit of different time lengths. The Modern Maximum, which began in 1914 during cycle 15, attained its peak in the International Geophysical Year (IGY), 1957 during cycle 19. The IGY was a year of very high solar activity (R_z=269.3) in 179 years since 1778 (R_z=257.3). Modern Maximum is believed to have ended during cycle 23 which ended in 2008. It is also easily discernible that Modern Maximum appears to give way to a minimum beginning in 2008 withR_Z=4.2 (R_4 in Fig.1 (a)). Although the end of the Modern Maximum was tentatively put at the end of cycle 23 in 2008 for the purpose of determining the cycle length, solar activity in cycle 24 continued to decline. The cycle attained its maximum in 2014 with R_Z=114.1 and as at the end of 2019was still in the declining phase and possible transition to cycle 25.Fig.1 (b) shows the eleven-year running mean of sunspot number, implemented in accordance with equation1, as well as the fourth-degree polynomial model that best fits the trend. The trend reveals a cyclicity of solar activity of approximately 99years (Gleissberg period), estimated from minimum-to-minimum of the grand episodes which are labelled as Maunder(see the arrow on the left of Fig.1b), Dalton, Modern and Expected Minimum (see the arrow on the right of Fig.1b).Quasi-grand episodes, such as those marked, A, B, and C are approximately 114 years apart (which is in the low-frequency Gleissberg period range).Therefore ,the average for Gleissberg cycle could be taken as 105.5 years. Furthermore, it is found that minimum-to-minimum, taking into the consideration of the quasi-minima, is approximately 52.4 years on the average. The observation suggests that, in addition to the well-established Schwabe, Hale and Gleissberg periods, other cycles of intermediate cycle lengths are possible. Thus, this analysis identifies sunspot activity of 11-, 52.4- and 105.5-year periodicities. These results are consistent with those obtained by other workers using other techniques. For instance, Le and Wang (2003), using wavelet analysis, identified 11-, 53- and 101-year periodicities of sunspot activity. While some researchers, for instance, Garcia and Mouradian (1998), regard the half-century cycle as another of the multi-cycle periodicities of solar activity amplitudes, others such as Hathaway (2015) interpreted it as one of the components of Gleisberg cycle, the one having 90-100-year low-frequency period and the other having 50-60-year high-frequency period.

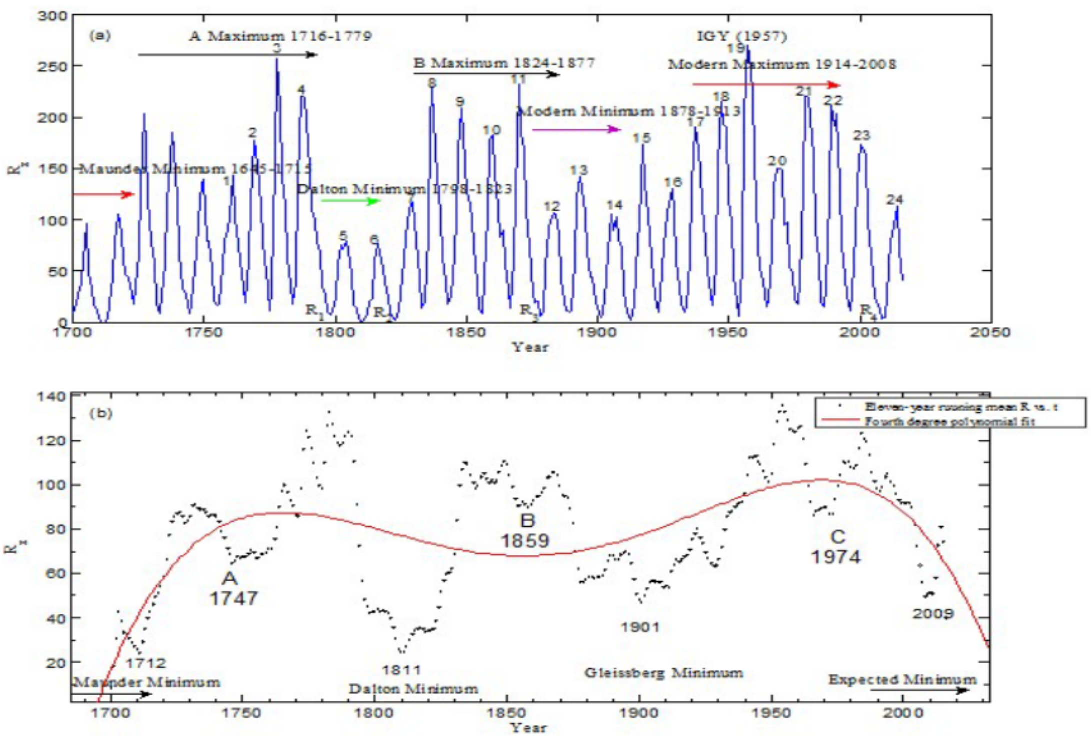


Fig. 1: (a) Plots of annual mean sunspot number time series and (b) eleven year running mean trend with the fourth-degree polynomial model

The eleven-year running mean sunspot activity is illustrated in Fig.1 (b). It shows a trend that suggests solar activity has gradually increased in strength since the Maunder Minimum (a recovery). In other words, the strength of solar activity during the Dalton minimum was not as low as during the Maunder Minimum. The next minimum, the Gleissberg Minimum was not as low as the Dalton Minimum. The polynomial model shows the outline of the trend of variation.It suggests that the expected grand episode will be a minimum which is most likely to be lower than the Gleissberg Minimum and, possibly, Dalton Minimum.

The time series of solar F10.7 cm radio flux, a good proxy for solar irradiance variability in the ultraviolet band, is shown together with the sunspot index in Fig.2. The solar cycles are also clearly labelled. Fig.2 (a) shows the monthly mean, while Fig.2 (b) shows the annual mean variation. It is observed that both time series are very strongly correlated, although, monthly means exhibit greater variability. The correlation coefficients of both variability are respectively r= 0.9915 and 0.9766with 95% confidence

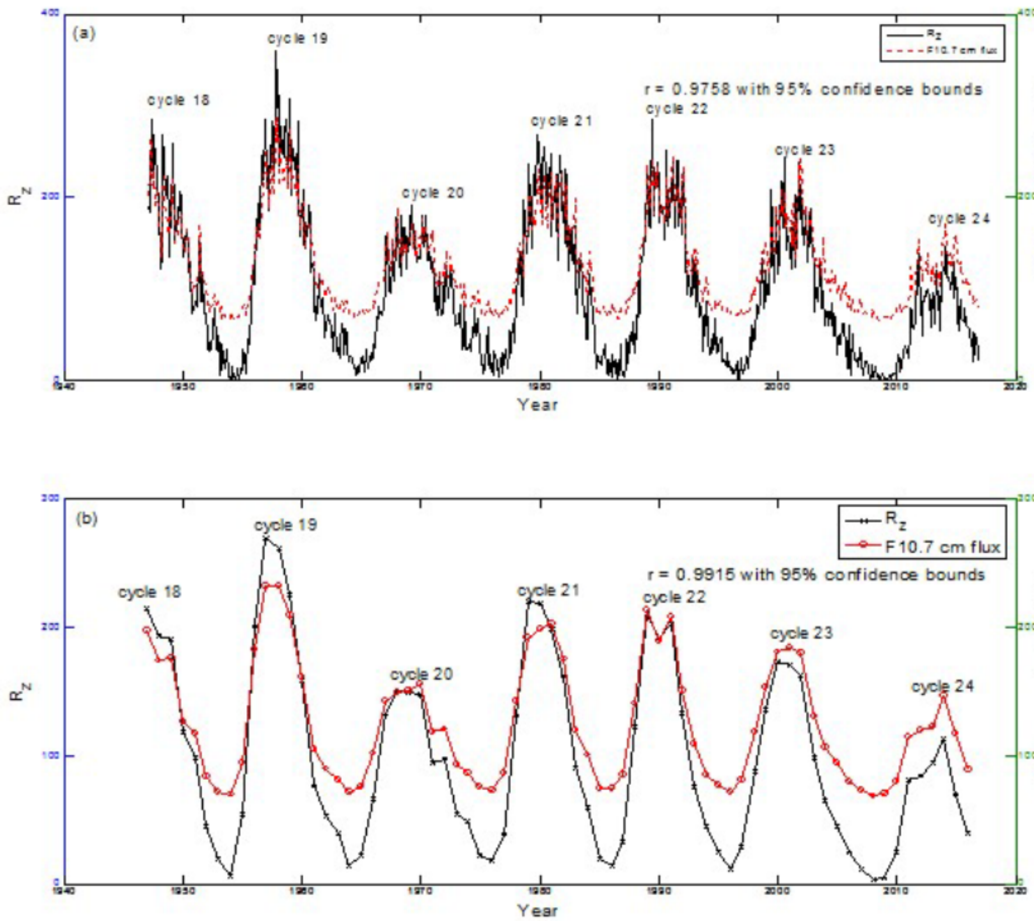
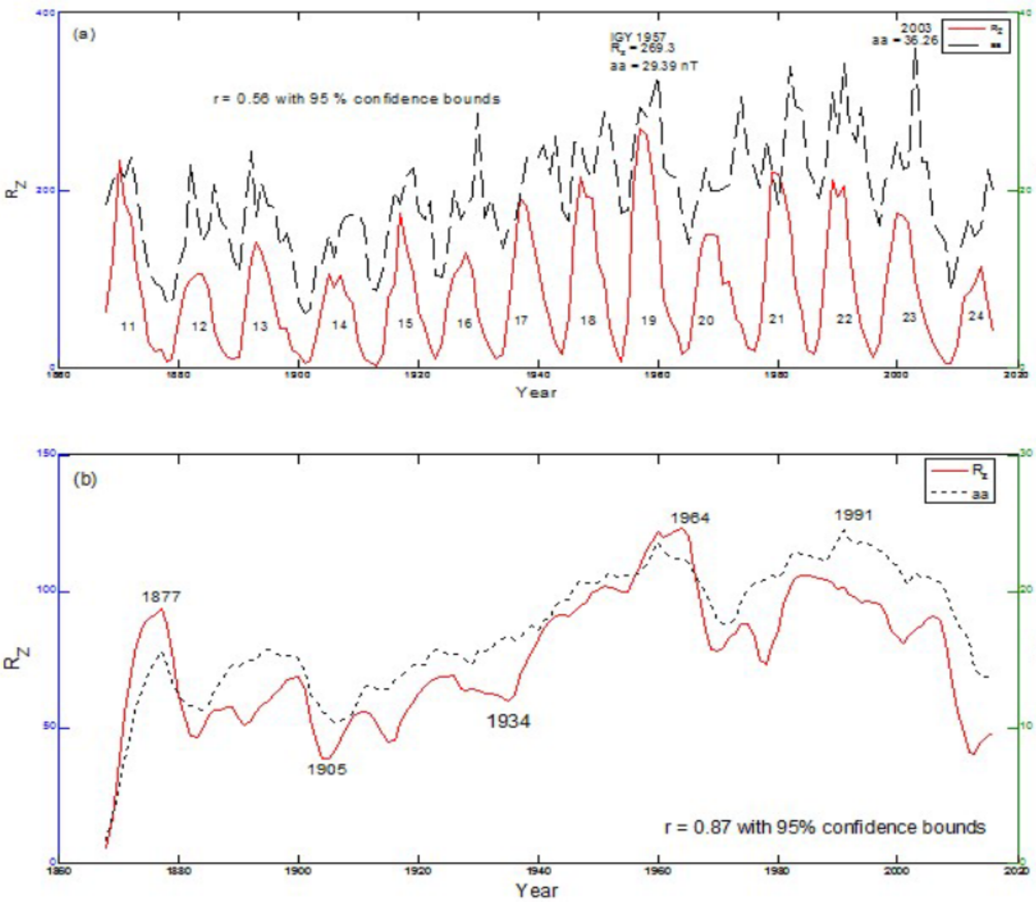


Fig. 2: (a) Plots of monthly mean and (b) annual mean of solar F10.7 cm radio flux versus sunspot activity (1947-2016)

bounds. It implies that during high solar activity, climate forcing through the direct solar irradiance and indirect mechanisms associated with stratospheric ozone reduction and increased atmospheric transparency are amplified. The transient variations in the monthly means is an indication of the existence of solar activity cycles of shorter (high frequency) time scales.

The indirect amplification through cloud condensation nucleation (CCN), regulated by the influx of galactic cosmic rays (GCR) which is modulated by solar magnetic activity is demonstrated in the strong correlation between geomagnetic antipodal activity (aa) (which is proxy for the activity of solar poloidal field) with sunspot activity (Fig.3). The existence of transient activities on a shorter time-scale superposed on the long-term trend of variation accounts for the lower coefficient of correlation ($r = 0.56$) in the annual means variation (Fig.3a) compared to the eleven-year running means ($r =$ 0.87) (Fig.3b).It could be observed that, although toroidal and poloidal components of solar magnetic activity correlated on temporal scales, they actually differed in intensity. Geomagnetic activity reached the peak of its long-term trend in 2003 with aa = 36.26 nT and R_Z = 99.3, compared to aa = 29.39 nT and R_Z = 269.3 in the International Geophysical Year (IGY), 1957which were 46 years apart (Fig.3a).

The long-term geomagnetic activity trend shows two prominent peaks of nearly equal amplitudes (23.54 nT in 1960and 24.46 nT in 1991), 31 years apart (Fig.3b). The effect of sustained high solar-geomagnetic activity into the early 2000s, together with the large thermal inertia of the oceans which is about 72% of the climate system, explains why global surface temperature continued to rise when solar activity had apparently declined since the mid-1980s. It implies that the decoupling of trends of variation of solar activity and global surface temperature observed since 1987(Lockwood and Frölich, 2007) is most likely not related to the observed increase in anthropogenic GHGs emissions. Furthermore, the observed and continuous decrease in the rate of global warming, which commenced with a hiatus (1998-2013), should be seen as the response of the climate system to the current deeply declining solar activity after the long-term trend of solar-geomagnetic activity maximum in 2003.



Fig, 3: Plots of sunspot number versus geomagnetic activity (a) annual mean (b) eleven year running mean

On the accompaniment of the identified cycles of solar activity by corresponding global temperature extrema, the time series of instrumental record of annual mean global surface temperature (land and sea) time series, together with their eleven-year running means and polynomial regression model of HadCRUT4 which closely fits both data and trend are shown in Fig.4.It is clear that the time series began in a descending phase from a maximum which must have occurred sometime before 1850 and reached a minimum in 1911, exhibiting two maximum-to-maximum markedM_1 (1878) to M_2 (1944),M_2 (1944)to M_3 (2016)of an average length of 64 years and minimum-to-minimum marked m_1 (1862) to m_2 (1911) and m_2 (1911) tom_3 (1976) of the average time length of 57 years (the average of the two periods ~60.5 years). It demonstrates that the half-century cycle identified with solar and geomagnetic activities also characterises the variability of global surface temperature on a decade-to-century time scale. This implies that the observed long-term trend in the climate record, including the recently observed global warming, is less likely to be an instrumental or solely internal climate variability effect, but rather solar activity related.A comparison with Fig.1 (a), it is clear that the descending phase at the beginning of the global temperature time series to the minimum around 1911 appears to be a response to the descending phase from the B(1824-1877) quasi-maximum to the Modern Minimum. Similarly, the rise to a ma maximum around 2016 appears to be a response to the Modern Maximum.

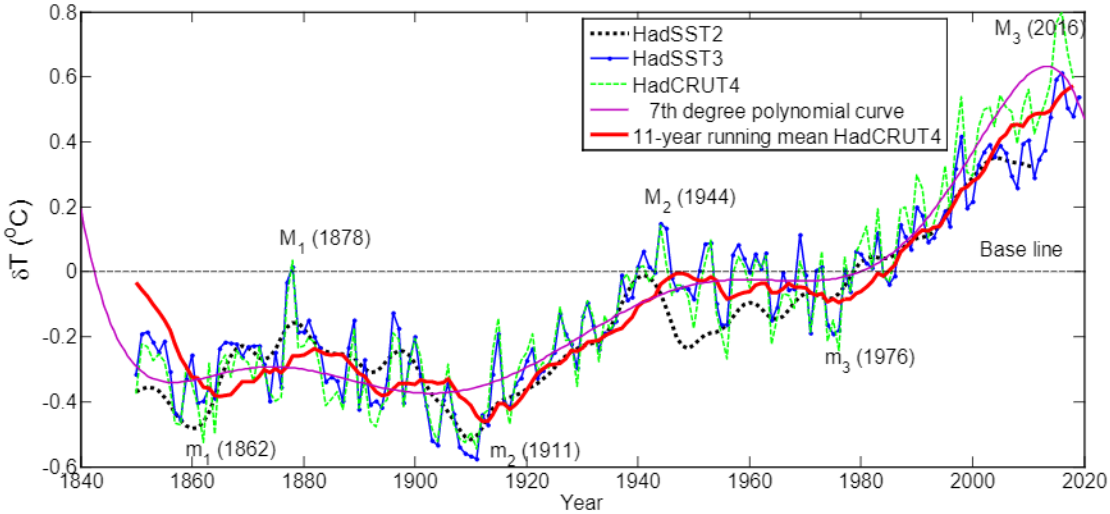


Fig. 4: Global sea surface temperature (HadSST2and 3), surface temperature, land and sea (HadCRUT4), eleven-year running mean of HadCRUT4, and the seventh degree polynomial fit

Also, three prominent cooling phases are clearly observed. The first is the descent to a quasi-minimum in 1862 (marked m_1), the descent from 1878 to the Modern Minimum (with the coldest phase around 1911), and then a shallow trough between 1944 and 1976. The cooling phase observed after 2016 needs more time to be fully established. However, on the assumption of long-term cyclic variability of global surface temperature, a cooling phase should succeed a warming phase and the polynomial fit clearly suggests the trend. The adjusted fourth-degree polynomial regression model was found to be given by

$$\delta T = 0.7974 + Nk[-0.1202x^7 - 0.01291x^6 + 0.6263x^5 + 0.02995x^4 - 0.906x^3 - 0.09832x^2 + 0.4786x - 0.2632] \quad (2)$$

where δT is the temperature anomaly, t is time in years and the coefficients are determined within the 95% confidence bounds. $k = \frac{1}{7.43}$ is constant and N=0,1,2,…,85. The variable x is normalized by the mean 1934 and standard deviation 48.93, i.e. $x = \frac{t-1934}{48.93}$. The regression model predicts the trend of variation of global surface temperature anomaly in the near-future (e.g. to the end of 21st century) as shown in Fig.5. It is found that the values of the global surface temperature anomaly for this period are expected to be lower than the present values. It predicts a descent from 0.6 °C in 2018 to a minimum of -0.54 °C in 2046 ± 11 yrs, and a rise through 2100 thereafter. This cold phase is expected to last for, at least, 45 years.

It is realised that the predicted minimum coincides with the forecasts (using various other methods) of global climate cooling expected to commence in solar cycle 25. The result is novel in the sense that it is predicted purely from instrumental records of global surface temperature with the assumption of cyclic variability, and yet agrees with the causation principle based on the prediction of solar activity grand minimum. Solar cycle 25 which began in 2020 is expected to reach its maximum around 2025-2026 ± 1 (Courtillot, Lopes and Mouël,2021). Assuming an average cycle length of 11± 1 years, the cycle should end between 2031 and 2032. In consideration of the need to fulfil the causation requirement that solar activity leads global temperature by about 6 to 8 years (average, 7 years), the coldest phase of global temperature should occur between 2038-2039 ± 11 years. Thus our result is within the predicted range. Furthermore, the predicted temperature anomaly for 2100 is approximately0.0893 °C, which is about 0.5 °C lower than the temperature anomaly at the end of 2018.

It is also realized from the analysis that the interval between the 1911 minimum and the predicted minimum in 2046 is 135 years, which is near the low-frequency Gleissberg period range. Also, from Dalton minimum in 1809 to the predicted minimum is 237 years, which is close to the low-frequency end of the De Vries (Suess) period range. Thus, it is found that our analyses approximately satisfy the solar activity period change rule.

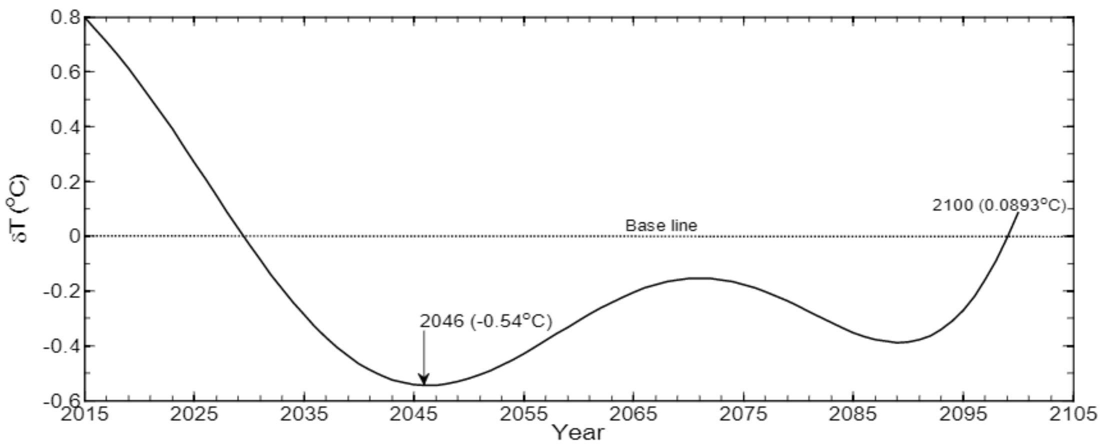


Fig.5: Predicted global mean surface temperature anomaly trend in the 21st century.

Comparing the predicted minimum (-0.5448°C) with the 1911 minimum (−0.5454 °C), it is found that the expected grand minimum may not be as cold as MM or DM. The model demonstrates that, indeed, a fall in global surface temperature is expected to accompany the much predicted, though disputed, deep decline of solar activity. Furthermore, compared to 2018 value (0.6°C) translates into 1.14°C change in global surface temperature, which is comparable to the change in northern hemisphere temperature of 1.1-1.5°C during MM that led to cold long winters, cold summers and freezing of rivers in Europe during the era (Zharkova, 2020).It is evident that, from the predicted minimum, global temperature will again be expected to rise toward another maximum. It is clear that the impact of solar activity alternations on climate change becomes prominently measurable with longer (lower frequency) cycle lengths.

4.0 Conclusion

This brief communication examined the controversial predictions of solar activity grand minimum expected to be accompanied by LIA conditions and global surface temperature rise by ~4.8 °C as at the beginning of 2100 occasioned by a continuous rise in anthropogenic GHGs emissions, both of which situate simultaneously in the remaining part of the 21st century. Results show that the character of the next grand episode will most likely be a minimum which will give rise to low global surface temperature with the coldest phase around 2046±11. Also, it will most likely be 0.1°C above the current baseline in 2100 as opposed to 4.8°C predicted by global circulation models. The persistence of long-term high solar-geomagnetic activity trend into the early 2000s most likely contributed to the observed warming through the direct solar irradiance climate forcing and indirect amplification through ultraviolet absorption, modification of stratospheric ozone and atmospheric transparency. The implication of these is that the contributions of solar and geomagnetic activity forcing of the recently observed climate scenarios may most likely have been underestimated in climate model experiments. The currently observed decrease in the rate of climate warming, which commenced with the hiatus (1998-2013) is most likely due to the declining solar-geomagnetic activity and not exclusively GHGs emissions.

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Conflict of interest

The authors declared no conflict of interest.