Is there a link between the length of the solar cycle and Earth's temperature?

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Abstract

The Sun provides most of external energy to Earth's system and thus has the potential of influencing it. Various studies reported a correlation between the solar cycle length and the northern hemisphere temperatures on Earth. Here, we reassess the cycle length record by incorporating the newly revised and updated sunspot number series as well as plage area composite, before comparing it to Earth temperature records. We find that cycle length series constructed from sunspot and plage data exhibit the same behaviour, both showing a downward trend after 1940. Our results suggest that the agreement between solar cycle lengths and temperatures found earlier is an artefact of (1) some arbitrary choices made by those studies when constructing the cycle length series as well as (2) a rather short time interval, to which the analyses were restricted. When considering the entire period of reliable sunspot and temperature data, these records diverge before about 1870 and after 1960. We also find a poor agreement between Earth temperatures and cycle length when using plage areas instead of sunspot data to derive cycle lengths. Our result of the divergence between cycle length series and Earth's temperature after 1960 implies that the cycle length cannot be used to support a solar origin for the warming on Earth over the last 5 decades.

Keywords Solar activity · Sun–Earth relations · Solar irradiance · Solar cycle lengths

1 Introduction

The Sun is the main external energy source for Earth (Kren et al. 2017) and thus influences Earth's climate (Haigh 2007; Gray et al. 2010; Solanki et al. 2013; Krivova 2018; IPCC 2021). Various mechanisms have been considered for the solar influence acting on different timescales. The main such mechanism is through variations in the solar radiative output due to short and long-term solar variability (acting on timescales of days to millennia). Variations of total solar irradiance (TSI, being the solar radiative energy flux integrated over all wavelengths and measured at the top of Earth's atmosphere at a mean distance of 1 AU) lead to changes on Earth's energy balance, while various mechanisms, such as the "bottom-up" (effect of TSI on tropical circulations leading to a positive feedback of cloud coverage reduction in subtropical regions and further increase of surface solar forcing) and "top-down" (effect of UV radiation on stratosphere that due to dynamical coupling is affecting troposphere too) effects have been suggested (see Gray et al. 2010; Lockwood 2012, and references therein). Furthermore, indirect empirical correlations between solar and Earth's climate parameters have also been reported, though such studies generally lack and do not provide a causal mechanism. One of them is the anti-correlation between the solar cycle length and the North hemisphere temperature on Earth (Friis-Christensen and Lassen 1991; Baliunas and Soon 1995; Lassen and Friis-Christensen 1995, 2000; Thejll and Lassen 2000; Thejll 2009; Reichel et al. 2001; Solheim et al. 2012; Booth 2018), which is shown in Fig. 1. These studies implied a significant solar influence on Earth's climate.

Such studies have gathered significant criticisms about the arbitrariness of some steps in the production of the cycle length series (e.g. Kelly and Wigley 1992; Thomson 1995; Laut and Gundermann 1998, 2000; Laut 2003; Damon and Peristykh 1999; Damon and Laut 2004; Free and Robock

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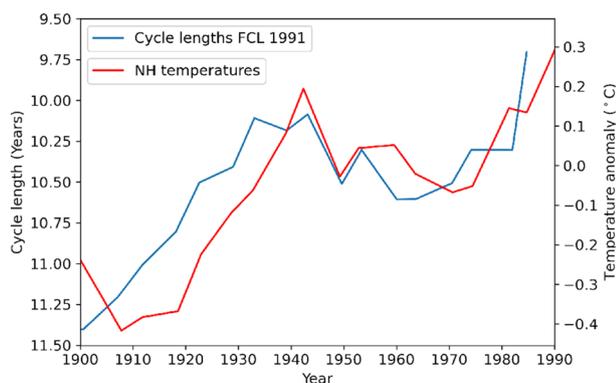
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Fig. 1 Cycle length series by Friis-Christensen and Lassen (1991) along with GISTEMP4 northern hemisphere temperature anomalies

1999; Solanki and Krivova 2003; Stauning 2011; Hansson 2020). In particular, Laut and Gundermann (2000), Laut (2003), and Damon and Laut (2004) argued that the inconsistent weighting in the smoothing process biased the results by Friis-Christensen and Lassen (1991) for the periods after 1970. Furthermore, several studies applied different and more objective approaches to determine the cycle lengths (Fligge et al. 1999; Mursula and Ulich 1998; Usoskin et al. 2021b; Benestad 2005), which showed a significantly reduced agreement between cycle lengths and Earth's temperature than reported by Friis-Christensen and Lassen (1991). Despite that, the cycle length series by Friis-Christensen and Lassen (1991) is still sometimes used to argue for a significant solar influence on Earth's climate (e.g. Connolly et al. 2021; Stefani, 2021).

Previous studies used mostly the international sunspot number series (Clette et al. 2007, ISNv1) to determine the cycle length series. More recently, criticism and concerns were raised about these earlier sunspot series (e.g. Lockwood et al. 2016; Usoskin et al. 2016a). This led to extensive efforts to recover new data and to correct mistakes in the digital databases of old sunspot records (e.g. Arlt et al. 2013, 2016; Vaquero et al. 2016; Carrasco et al. 2018, 2019, 2021a,b; Hayakawa et al. 2020a,b, 2021a,b; Vokhmyanin et al. 2020; Bhattacharya et al. 2021). Sunspot number series were also drastically updated and scrutinized leading to a new version of ISNv2 (Clette and Lefèvre 2016) and a number of alternative group sunspot number (GSN) series (e.g. Lockwood et al. 2014; Cliver and Ling 2016; Svalgaard and Schatten 2016; Usoskin et al. 2016b, 2021a; Chatzistergos et al. 2017; Willamo et al. 2017).

Here, we reassess the relation between the solar cycle length and the temperature on Earth using more recent versions of sunspot number series extending to the beginning of cycle 25 that were not available in the previous studies. We also provide error estimates for various subjective decisions in the creation of such series. This is done in an attempt

to remove part of the arbitrarity of cycle length series and evaluate more objectively their relation to Earth's temperature. In particular, in Sect. 2, we study the change in cycle length with time with various sunspot number series as well as plage area series. In Sect. 3, we compare the cycle length series to northern hemisphere and global temperature records and discuss our results in Sect. 4. Finally, in Sect. 5, we draw our conclusions.

2 Solar cycle length series

There have been a number of different methodologies to produce cycle length series (e.g. Fligge et al. 1999; Mursula and Ulich 1998; Usoskin et al. 2021b); however, here, we will focus on those by Friis-Christensen and Lassen (1991) and Hoyt and Schatten (1993).

Following Friis-Christensen and Lassen (1991), we compute for each solar cycle two points as the time difference between subsequent activity minima and maxima, respectively, which are assigned to the middle of their distance. This results into two separate series, one containing durations of periods between cycle minima, L_i^{min} (where i is the cycle number), and another one the same but between cycle maxima, L_i^{max}, which are then merged together by appending L_i^{max} to L_i^{min} to produce the cycle length series, L_i. The extrema times are identified after applying a 13-month smoothing to the monthly mean sunspot number series (Hathaway 2015). We note that for the determination of L_i^{max} we only considered the highest peak in the smoothed series and we did not take into account any possible secondary peaks. We note that not all cycles exhibit secondary peaks and this is especially reduced after the 13-month smoothing we apply. However, an alternative approach for such cases could have been to estimate the time of activity maximum as the midpoint between the two activity peaks. This choice would introduce an uncertainty of ∼1 year in the determination of L_i^{max} for cycles with two peaks compared to considering only the highest peak of the cycle. For example, over the 20th century this would affect only cycles 22 and 23 for which L_i^{max} would increase by 0.9 year and decrease by 1.9 year, respectively. We also remind that this leaves L_i^{min} unaffected. Overall, this process returns a very noisy series, therefore a smoothing filter is applied to the series. Previous studies used arbitrarily running mean smoothing filters with width of five and three points with weights of 1-2-2-2-1 (e.g. Gleissberg 1944; Friis- Christensen and Lassen 1991) and 1-2-1 (e.g. Thejll and Lassen 2000; Thejll 2009), respectively. We note that the five (three) data point smoothing renders the first and last two (one) cycles of the data essentially unusable. To circumvent this, previous studies introduced an assumed date of the next cycle extrema, arguing that this does not affect the results significantly due to its lower

Fig. 2 Panel **a** Cycle lengths computed from different solar activity records. In particular, we show the HoSc98, SvSc16, CEA17 GSN series, the ISNv1, and ISNv2, and the CEA20 plage area composite series. Panel **b** cycle lengths were computed with ISNv2 and a 1-2-2-2-1 smoothing filter. Two cases are shown when the filter is applied to L_i^{max} and L_i^{min} separately or to them merged together. Panels **c**–**d** Cycle lengths computed with ISNv2 with a 1-2-2-2-1 and 1-2-1 smoothing filters applied to L_i^{max} and L_i^{min} separately (panel **c**) and merged together (panel **d**)
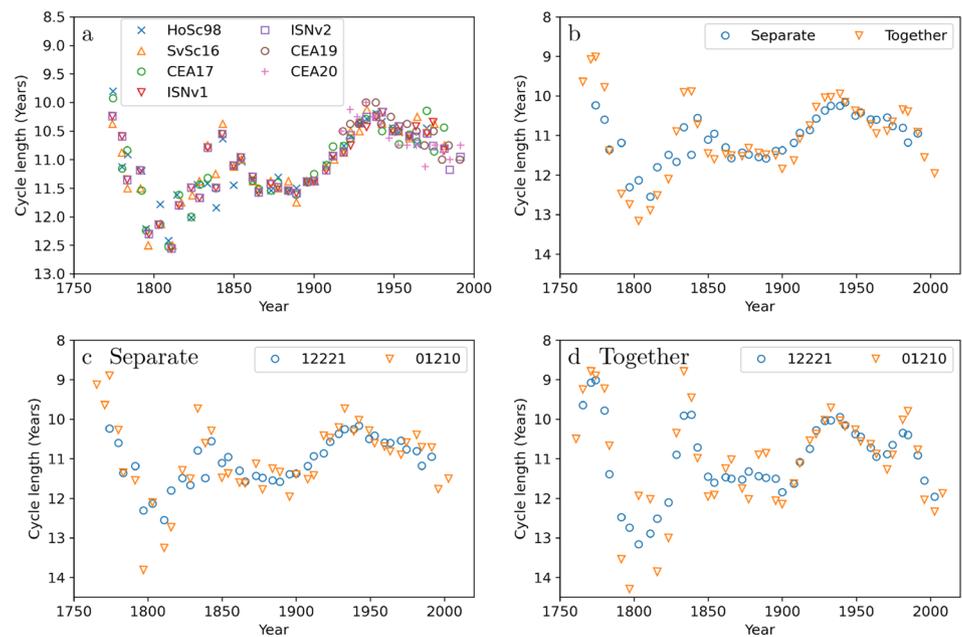
weight in the smoothing process. This was done rather arbitrarily. For example, Thejll and Lassen (2000) estimated the forthcoming two maxima as 2000.3 and 2011.2 and the next minimum as 2007.3, to compare with 2000.3, 2014.3, and 2008.9 as reported by Hathaway (2015). For this reason, the cycle length series by Thejll and Lassen (2000) is biased to shorter lengths over the last 2 estimated points (see also Laut 2003; Damon and Laut 2004). To avoid arbitrariness, in our analysis we did not estimate the periods of the next extrema, but kept only the period over which the extrema dates could be determined from the available data. In Table 1, we list L_i^{min} and L_i^{max} computed from ISNv2 series (without applying the 1-2-2-2-1 or 1-2-1 filter). In the following, whenever we refer to cycle length series, we mean the cycle lengths using reversed ordinate. This is done to ease comparisons with previously published results of the anti-correlation between cycle length series and Earth's temperature.

Smoothing was typically applied separately to L_i^{max} and L_i^{min}, which were then merged to produce one solar cycle length series, L_i. This was also an arbitrary choice and we check how it affects the results. Figure 2b compares the cycle length series produced with ISNv2 for the cases when smoothing was applied to L_i^{max} and L_i^{min} individually before merging or directly to the merged series L_i. We find RMS differences between these two series of 0.6 years, while smoothing L_i returns a slightly greater magnitude of variability than applying the smoothing separately to L_i^{max} and L_i^{min} and then merging them. We also notice that smoothing the series together introduces a secondary peak (that is a drop in terms of the cycle length) at about 1980 (lower than the main peak at about 1940), which is absent in the case of smoothing the minima and maxima series separately.

Panels c and d of Fig. 2 compare the cycle length series produced with the two different smoothing filters that have been used in the literature, in particular a 1-2-2-2-1 (Gleissberg 1944; Friis-Christensen and Lassen 1991) and a 1-2-1 filter (Thejll and Lassen 2000). The 1-2-1 filter increases the magnitude of variations compared to the 1-2-2-2-1 filter, with RMS differences between these two series of 0.5 and 0.6 years when the filter is applied to L_i^{max} and L_i^{min} separately or to L_i. In addition, the 1-2-1 filter applied separately to L_i^{max} and L_i^{min} introduces a weak secondary peak at about 1980, which is absent in the case of the 1-2-2-2-1 filter.

Thus, as demonstrated above, the smoothing filter and whether it is applied on the L_i^{max} and L_i^{min} series separately or their combination L_i lead to differences in the produced cycle length series. However, the choice between these various cases is arbitrary.

Another potential source of uncertainty in the derived cycle length is the choice of the input series, employed to determine cycle lengths. To assess the magnitude of this effect, we produced cycle length series from various sunspot number series as well as from plage area series (see Fig. 2a). In particular, we used the ISNv1[1] and ISNv2[1] sunspot number series, the Hoyt and Schatten (1998, HoSc98, hereafter)[1], Svalgaard and Schatten (2016, SvSc16, hereafter)[1], and Chatzistergos et al (2017, CEA17, hereafter)[2] group sunspot number series as well as the Chatzistergos et al. (2019b, CEA19, hereafter) and

Fig. 3 Comparison of previously published cycle length series produced with the methodology by Friis-Christensen and Lassen (1991) to the ones produced here with ISNv2. Panel a shows all series together, while all other panels compare our produced cycle length series to one series from the literature. In particular, we show the ones by Friis-Christensen and Lassen (1991, FCL1991, panel **b**), Lassen and Friis-Christensen (1995, LFC1995, panel **c**), Baliunas and Soon (1995, BS1995, panel **d**), Thejll (2009, panel **e**), as well as a series produced with the extrema dates taken from Hathaway (2015, panel **f**)
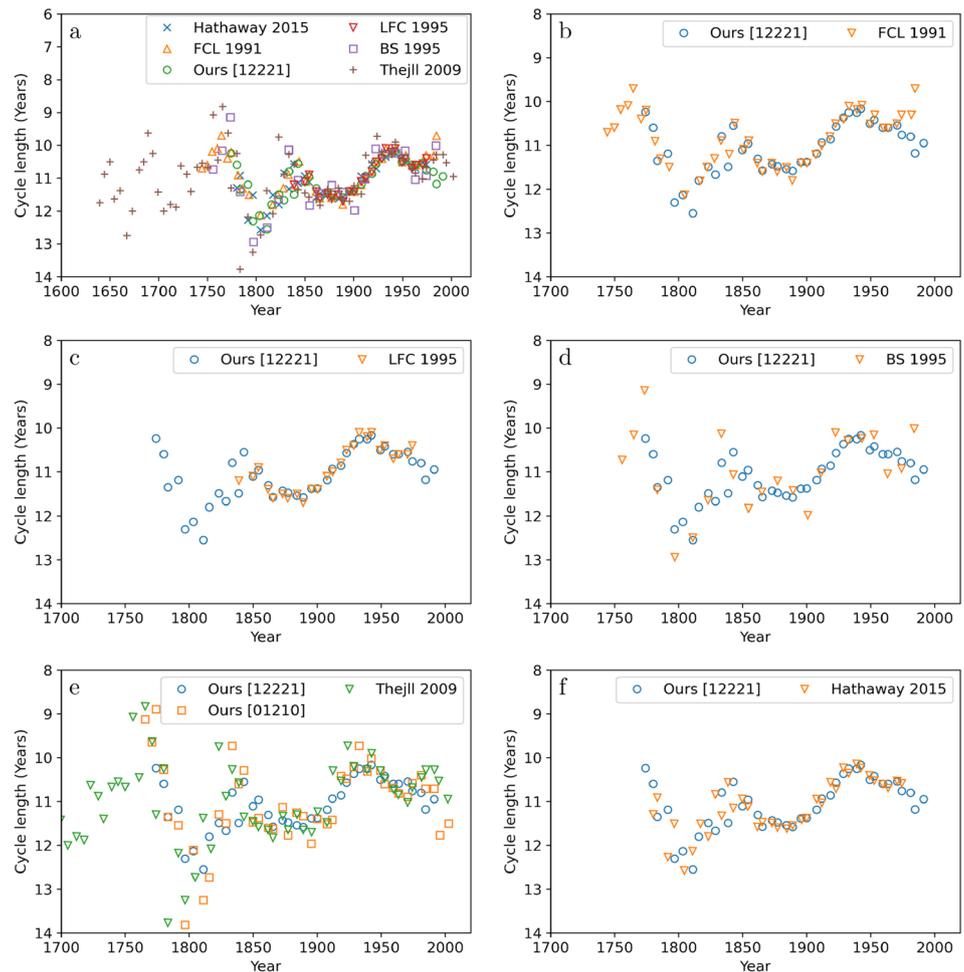
Chatzistergos et al. (2020, CEA20, hereafter)[2] plage area composite series. We found, in general, small variations in our results depending on the input sunspot series. We also notice considerable disagreement between the various series after 1970, even though all series show a decreasing trend over that period. The plage area series covers a shorter period (since 1892 Chatzistergos, 2017; Chatzistergos et al. 2019a, 2022b) than the sunspot data, but the derived cycle length record follows the one from sunspot data quite well. This is unsurprising, considering the relationship between sunspot and plage areas (e.g. Chatzistergos et al. 2022a). The cycle length series derived from both plage area series considered here agree qualitatively. In particular, we find the same peak at about 1940 and a declining trend afterwards, although the values remain rather stable after 1950.

In the following, unless otherwise stated, we show the results for the ISNv2 series smoothed with the 1-2-2-2-1 filter applied separately to L_i^{max} and L_i^{min}. Figure 3 compares our produced cycle length series to those we found in the literature, that is from Friis-Christensen and Lassen

(1991); Baliunas and Soon (1995); Lassen and Friis-Christensen (1995); Thejll (2009) as well as the record produced from solar cycle lengths by Hathaway (2015).

All series agree rather well with each other between 1870 and 1960, but we notice a considerable disagreement among all series for the periods before 1870 and after 1960. All previous cycle length series showed an increase (we note the series was used in inverse) after 1960s. However, we note that even the increase in previously published cycle length series differs. With the cycle length series by Friis-Christensen and Lassen (1991) returning the highest increase after 1970 and Lassen and Friis-Christensen (1995) the lowest, while the one by Thejll (2009) decreases after 1990. Furthermore, our series shows a clear decrease after 1940 which continues to the end of the covered period.

Finally, we also discuss the cycle length series produced by Hoyt and Schatten (1993), which employed a different and less arbitrary methodology than Friis-Christensen and Lassen (1991). They define the cycle length for each year as the mean time difference between years of the previous and next solar cycles with equal percentage levels of activity. They then applied a 23-year running mean smoothing. In
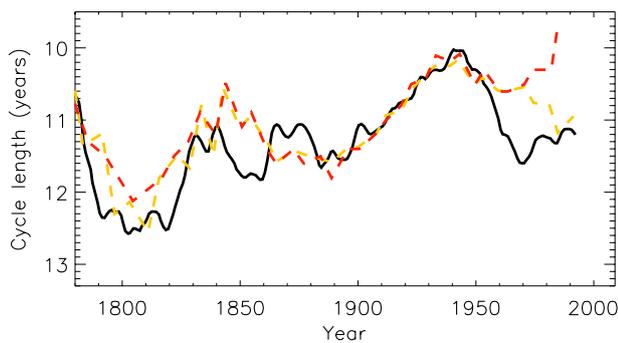
Fig. 4 Comparison between cycle length series by Hoyt and Schatten (1993, solid black), Friis-Christensen and Lassen (1991, dashed red), and the one produced by us with ISNv2 following the methodology by Friis-Christensen and Lassen (1991, dashed yellow)

contrast to other cycle length series, it provides annual values. However, there are some ambiguities in the data selection and methodology used by Hoyt and Schatten (1993), for which reasons we do not reproduce it here ourselves, but use the series presented by Hoyt and Schatten (1993) (after linearly scaling it to our cycle length series, since it was originally provided in fractions of cycle per year). Figure 4 shows the Hoyt and Schatten (1993) cycle length series along with the one by Friis-Christensen and Lassen (1991) and the one produced here with ISNv2 following the methodology by Friis-Christensen and Lassen (1991). This series exhibits a peak at 1940 like the ones produced with the methodology by Friis-Christensen and Lassen (1991), while it decreases afterwards and stays at a rather low level until the end of the covered period.

In summary, we find the various arbitrary choices in determining the cycle length series to affect the results by mainly changing the magnitude of variations and introducing artefacts thus changing the trend after 1960s. We were unable to find a reasonable arrangement of parameters with the up-to-date sunspot and plage data that would result in an increase in cycle length series after 1960, in contrast to most cycle length series from the literature (e.g. Friis-Christensen and Lassen 1991; Baliunas and Soon 1995; Lassen and Friis-Christensen 1995, 2000; Thejll and Lassen 2000; Thejll 2009; Reichel et al. 2001; Solheim et al. 2012). Therefore, we conclude that the increase in cycle length series after 1960s was an artefact of previous studies either due to the use of outdated sunspot data or due to the arbitrary estimation of the date of the next extrema. Overall, we report the cycle length series to steadily decrease after 1940s.

3 Comparison to Earth's temperature records

Here, we compare the updated cycle length series we produced with the revised ISNv2 sunspot number series and the CEA20 plage area series to the northern hemisphere and global Earth temperatures by GISTEMP4 (NASA Goddard Institute for Space Studies Surface Temperature Analysis; Lenssen et al. 2019)[3], HadCRUT5 (Hadley Centre/ Climatic Research Unit Temperature; Osborn et al. 2021)[4], the Berkeley Earth (Rohde and Hausfather 2020)[5] global temperature series, and the global temperature reconstruction by Neukom et al. (2019).

A comparison between GISTEMP4 temperatures and the cycle length series by Friis-Christensen and Lassen (1991) and Hoyt and Schatten (1993) as well as the ones computed here from ISNv2 series and the CEA20 plage area series is shown in Fig. 5. All series indeed show similarity roughly over the period 1870–1970, as previously reported, but they noticeably deviate before and after that period. We note that the uncertainty both in temperature and sunspot data increases further back in time, which is partly responsible for the diverse results prior to 1900s. This is not the case for the data after 1970, which have considerably lower uncertainty than the earlier data.

In particular, both global and northern hemisphere temperature series increase sharply after 1970, while the cycle length series produced here with sunspot and plage data decrease. The cycle length series by Hoyt and Schatten (1993) after 1970 remains rather stable at a lower level than most part of 1900s, thus not following the temperature increase over the same period. In contrast to that, the cycle length series by Friis-Christensen and Lassen (1991) does indeed increase, but only when the last data points are included. These points are, however, entirely an artefact of the arbitrary and incorrect guess of the next extrema (see Sect. 2).

Before 1870s, the cycle length series have two main maxima over late 1700s and about 1840. Interestingly, the peak over 1760 in the series by Friis-Christensen and Lassen (1991) is even exceeding the peak at 1940. However, we do not observe the same behaviour in the temperature record by Neukom et al. (2019). In particular, temperatures over 1760 are lower than in 1940. Furthermore, there is a local minimum in the temperature by Neukom et al. (2019) around 1840, in contrast to the peak in cycle length over that period. We find in general poor correlation between the various cycle length and the various temperature series

Fig. 5 Comparison between the cycle length series (red) and Earth's temperature. In particular we show the cycle length series produced here with ISNv2 (panel **a**), and CEA20 plage area series (panel **b**) as well as the Friis-Christensen and Lassen (1991, panel **c**) and Hoyt and Schatten (1993, panel **d**) series, while for Earth's temperature we plot the GISTEMP4 global (blue), GISTEMP4 northern hemisphere (orange), and the Neukom et al. (2019) global series (green). All series are sampled in the same way as the cycle length series shown in each panel. The base period for GISTEMP4 temperature anomalies was 1951–1980
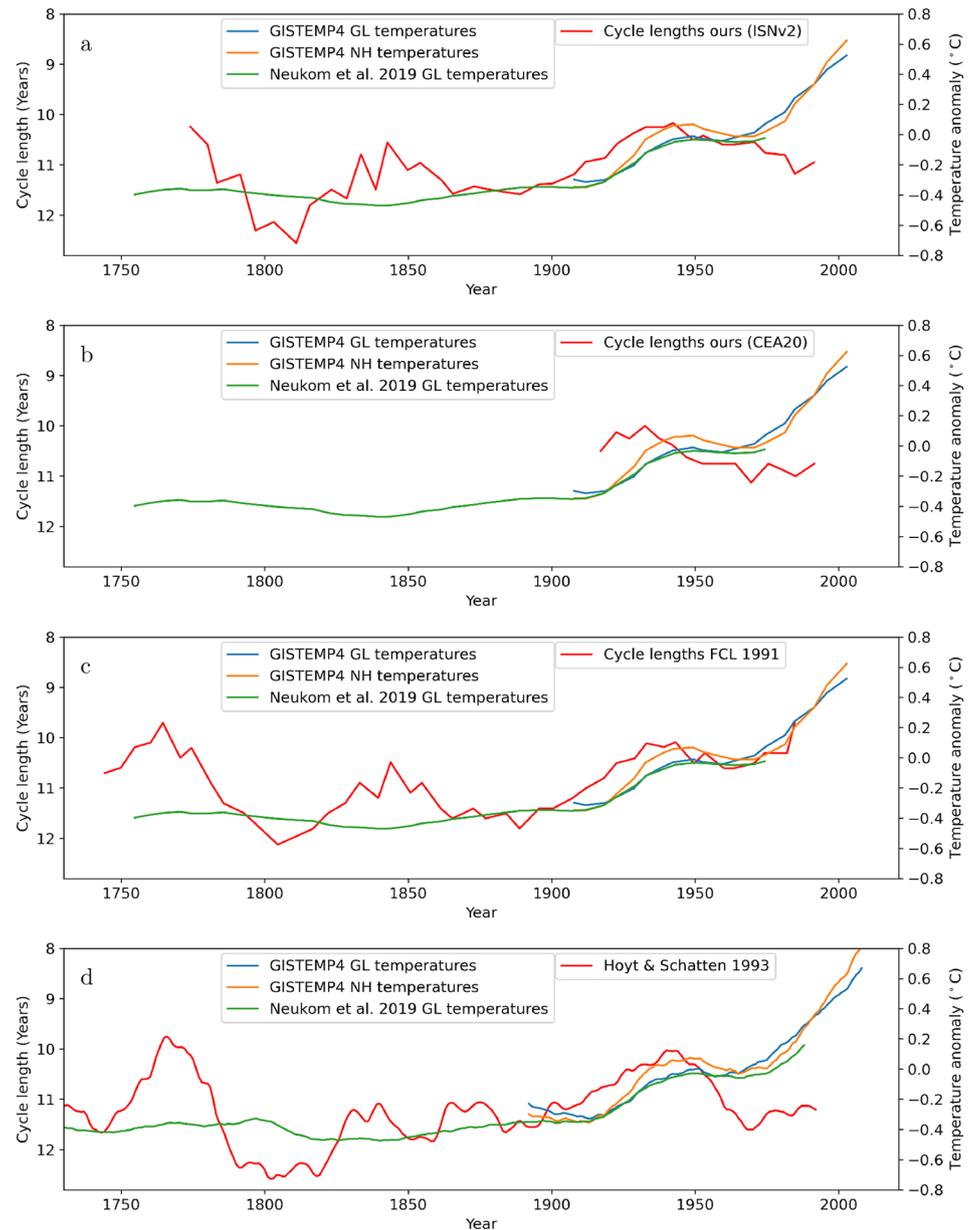
(listed in Table 2). In particular, for GISTEMP4, we find $R = 0.10$ and $R = -0.15$ for the global temperature and the northern hemisphere temperatures, respectively. When arbitrarily limiting the interval to 1907–1970, we find a considerably better agreement, with $R = -0.82$ and $R = -0.67$ for northern hemisphere and global temperatures. We note, that this was done only for the purpose of demonstrating the effect of an arbitrary selection of period. Here, we want to stress one of the main conclusions of IPCC (2021), which states that since 1750 the warming influence on Earth is predominantly due to increases in atmospheric greenhouse gas concentrations, while there are only negligible contributions from solar and volcanic activity.

Therefore, the agreement between the cycle length series and temperature of northern hemisphere on Earth that was previously reported appears to be an artefact. Two factors that contributed to that are the selected period and the arbitrariness of various parameters when constructing the cycle length series (see Sect. 2), which rendered the previously reported cycle length series to increase after 1960. We note that there have been more criticisms on the connection between the cycle length series and temperatures on Earth (e.g. Kelly and Wigley 1992; Thomson, 1995; Laut and Gundermann 1998, 2000; Laut 2003;

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Table 1 Computed $L_i^{\min}$ and $L_i^{\max}$ from ISNv2

Cycle	$L_i^{\min}$ [year]	$L_i^{\max}$ [year]
1	11.25	11.17
2	09.08	08.34
3	09.17	08.66
4	13.66	09.92
5	09.67	16.91
6	15.41	11.50
7	10.42	13.08
8	09.75	07.50
9	12.50	10.84
10	11.16	12.00
11	11.59	10.67
12	10.17	13.17
13	13.08	10.08
14	11.50	12.00
15	10.00	11.50
16	10.17	10.67
17	10.50	09.08
18	10.08	10.08
19	10.50	10.83
20	11.67	10.67
21	09.75	11.08
22	10.42	09.50
23	12.25	12.75
24	11.08	12.08

For each cycle we give the time difference to the previous extremum. For $L_i^{\min}$, we consider the minimum at the end of the cycle

Table 2 Correlation coefficients between cycle length series produced here with ISNv2 and various datasets of global and northern hemisphere tempeartures on Earth

Temperature dataset	R	
GISTEMP4 GL	0.1	− 0.26
GISTEMP4 NH	− 0.15	− 0.44
HADCRUT5 GL	− 0.01	− 0.30
HADCRUT5 NH	− 0.18	− 0.41
Berkeley GL	0.07	− 0.26

The correlation coefficients are shown for concurrent cycles and lag one solar cycle between the length and temperature series

Damon and Peristykh 1999; Damon and Laut 2004; Free and Robock 1999; Solanki and Krivova 2003; Benestad 2005; Stauning 2011; Hansson 2020).

Table 3 Correlation coefficients between the cycle length and amplitude for the CEA17 GSN, ISNv2, and CEA20 plage area series

Series	R		
CEA17	− 0.64	− 0.68	− 0.72
ISNv2	− 0.58	− 0.73	− 0.71
CEA20	− 0.64	− 0.66	− 0.74

The correlation coefficients are shown for concurrent cycles and lags of half and one solar cycle between the length and amplitude series

4 Discussion

We reported that the previously reported agreement between cycle length series and temperatures after about 1960s was an artefact due to various arbitrary choices in the creation of the series. The partial agreement of cycle length series to temperatures on Earth for earlier periods, can potentially be explained with the Waldmeier rules (Waldmeier 1935, 1939). The classical Waldmeier rule relates the amplitude of a cycle to the duration of the ascending phase of the same cycle. However, different variations exist, with the (n+1) rule connecting the length of a cycle to the amplitude of the next one and being the more relevant one for our discussion. We just note that there is also the simplified Waldmeier rule connecting the length and amplitude of the same cycle, for which however the reported correlations are significantly lower than for the other two rules (Hathaway, 2015; Usoskin et al., 2021a). In Table 3, we list the correlation coefficients between the cycle lengths and amplitude for the CEA17 GSN, ISNv2, and CEA20 plage area series. The correlation coefficients are − 0.64 for both CEA17 and CEA20 series, while it is − 0.58 for ISNv2. Allowing for a lag of half or one cycle increases the correlations significantly, becoming − 0.74 for CEA20, − 0.72 for CEA17, and − 0.71 for ISNv2 for a lag of one cycle. Our result for ISNv2 for a lag of 1 cycle is the same as that by Usoskin et al. (2021a) who used the cycle lengths without smoothing. However, we see a higher correlation for ISNv2 without any lag compared to the value of -0.29 reported by Usoskin et al. (2021a), this is most likely because of the smoothing process by Friis-Christensen and Lassen (1991). It is noteworthy, that the Waldmeier rule has been used for predictions of a cycle amplitude in sunspot number (Petrovay 2020; Pesnell 2020; Nandy 2021, and references therein). So that the cycle length series are better viewed as representing the amplitude of variations of the next cycle rather than the concurrent one.

Interestingly, there are studies which used the cycle length series to make predictions for Earth's temperature in the future on the assumption of a strong solar influence on Earth's climate. For instance, Archibald (2006) predicted that the global temperature should have decreased by 1.5 °C between solar cycles 23 and 24, while over the same period

Archibald (2009) predicted a 2.2 °C decrease in mid-latitude regions. Solheim et al. (2012) predicted a greater than 1 °C decrease in annual mean northern hemispheric temperatures between cycles 23 and 24 and a drop of 3.5 °C for the region of Svalbard. All of those predictions proved to be wrong, considering that both the annual mean temperature of the northern hemisphere (and the global one for that matter; e.g. Lenssen et al. 2019; Rohde and Hausfather 2020; Osborn et al. 2021; Voosen, 2021) as well as the temperature at Svalbard increased over the course of solar cycle 24 (e.g. Dahlke et al. 2020; Nordli et al. 2020).

5 Conclusions

The reported correlation between cycle length series and temperature on Earth has been (and continue to this day to frequently be) used to attribute the observed increase of temperature on Earth over the last century to solar activity. We reassessed the methodologies used in the literature to produce the cycle length series and showed that they included a number of rather arbitrary steps (e.g. guess of dates of following extrema, the smoothing filter, whether the minimum to minimum and maximum to maximum length series are smoothed together or separately before merging them, as well as the choice of sunspot series to determine the cycle lengths), which affect the produced series. Using the most up-to-date sunspot data to determine the cycle length, while also removing the uncertainty introduced in previous studies by guessing the date of the next extrema, we find that the cycle length exhibits a steady decrease after 1940s. This is in contrast to most previous studies which reported an increase after 1960 (e.g. Friis-Christensen and Lassen 1991; Baliunas and Soon 1995), but in agreement with Laut (2003), Damon and Laut (2004), and Stauning (2011). However, using directly measured data (without the need for guessing the dates of following extrema), we were able to show that the decreasing trend of cycle length series extends even one cycle later than the end of the period considered by Friis-Christensen and Lassen (1991). The results remain qualitatively the same when various *recent* sunspot series are employed. We also used the plage area composite by Chatzistergos et al. (2020) to compute the cycle length and found qualitatively the same results as for sunspot data. However, we note that the results from the various sunspot number and plage series disagree quantitatively after 1950s.

We have also reassessed the relation between the solar cycle length and the temperature on Earth using the most recent versions of the sunspot and Earth's temperature datasets available. Our results suggest that the good correlation between the solar cycle length and the temperature on Earth found earlier breaks down when the entire record of reliable sunspot data (since 1740s) is considered. The

previously reported agreement between the cycle length and the northern hemisphere temperatures on Earth appears to have been an artefact due to mainly two factors: (1) restricting the studied period to roughly 1870–1970, while the series diverge before and after that period and (2) arbitrarily estimating the date of the following extrema (instead of ignoring these data points) and in this way biasing upwards the cycle length series. The divergence of the series over the more recent years, which includes in principle higher quality data acquired in a more systematic way than in the past, precludes the divergence being an artefact of sunspot or temperature data.

The possible physical connection between cycle length series and temperature on Earth is also unclear. Potentially, the good agreement between the two series over certain periods might be simply a consequence of the relationship between the cycle length and the strength of the next cycle, whereas the latter is an indicator of increased solar activity accompanied by an increased level of the total solar irradiance (describing the total radiative energy input to Earth's climate system) and UV irradiance (Ermolli et al. 2013). However, we emphasize that since the cycle length series do not follow the temperature increase since 1970s, they at least cannot be used to suggest that the warming on Earth over the last 5 decades has a solar origin.

Declarations

Conflict of interest The author declares that he has no conflict of interest.

References

Archibald DC (2006) Solar cycles 24 and 25 and predicted climate response. Energy Environ 17(1):29–35. https://doi.org/10.1260/095830506776318796

Archibald DC (2009) Solar cycle 24: expectations and implications. Energy Environ 20(1):1–10. https://doi.org/10.1260/095830509787689204

Arlt R, Leussu R, Giese N et al (2013) Sunspot positions and sizes for 1825–1867 from the observations by Samuel Heinrich Schwabe. Mon Notices R Astron Soc 433:3165–3172. https://doi.org/10.1093/mnras/stt961. (**adsabs.harvard.edu/abs/2013MNRAS.433.3165A**)

Arlt R, Senthamizh Pavai V, Schmiel C et al (2016) Sunspot positions, areas, and group tilt angles for 1611–1631 from observations by Christoph Scheiner. Astron Astrophys 595:A104. https://doi.org/10.1051/0004-6361/201629000. (**adsabs.harvard.edu/abs/2016A**)

Baliunas S, Soon W (1995) Are variations in the length of the activity cycle related to changes in brightness in solar-type stars? Astrophys J 450:896. https://doi.org/10.1086/176193. (**adsabs.harvard.edu/abs/1995ApJ...450.896B**)

Benestad RE (2005) A review of the solar cycle length estimates. Geophys Res Lett 32(L15):714. https://doi.org/10.1029/2005GL023621. (**ui.adsabs.harvard.edu/abs/2005GeoRL.3215714B ', aDS Bibcode: 2005GeoRL.3215714B**)

Bhattacharya S, Teague ETH, Fay S et al (2021) A modern reconstruction of Richard Carrington's observations (1853–1861). Solar Phys 296(8):118. https://doi.org/10.1007/s11207-021-01864-8

Booth RJ (2018) On the influence of solar cycle lengths and carbon dioxide on global temperatures. J Atmos Solar-Terr Phys 173:96–108. https://doi.org/10.1016/j.jastp.2018.01.026

Carrasco VMS, Vaquero JM, Arlt R et al (2018) Sunspot observations made by Hallaschka during the Dalton minimum. Solar Phys 293(7):102. https://doi.org/10.1007/s11207-018-1322-5

Carrasco VMS, Vaquero JM, Gallego MC et al (2019) Two debatable cases for the reconstruction of the solar activity around the Maunder Minimum: Malapert and Derham. Mon Notices R Astron Soc Lett 485(1):L53–L57. https://doi.org/10.1093/mnrasl/slz027. (**academic.oup.com/mnrasl/article/485/1/L53/5366750**)

Carrasco VMS, Nogales JM, Vaquero JM et al (2021a) A note on the sunspot and prominence records made by Angelo Secchi during the period 1871–1875. J Space Weather Space Clim 11:51. https://doi.org/10.1051/swsc/2021033

Carrasco VMS, Vaquero JM, Gallego MC (2021b) A forgotten sunspot record during the Maunder Minimum (Jean Charles Gallet, 1677). Publ Astron Soc Jpn 73(3):747–752. https://doi.org/10.1093/pasj/psab035

Chatzistergos T (2017) Analysis of historical solar observations and long-term changes in solar irradiance. PhD thesis, Uni-edition. https://doi.org/10.53846/goediss-6507. https://ui.adsabs.harvard.edu/abs/2017PhDT.......259C

Chatzistergos T, Usoskin IG, Kovaltsov GA et al (2017) New reconstruction of the sunspot group numbers since 1739 using direct calibration and "backbone'' methods. Astron Astrophys 602:A69. https://doi.org/10.1051/0004-6361/201630045

Chatzistergos T, Ermolli I, Falco M, et al (2019a) Historical solar Ca II K observations at the Rome and Catania observatories. In: Il Nuovo Cimento, p 5, https://doi.org/10.1393/ncc/i2019-19005-2, https://www.sif.it/riviste/sif/ncc/econtents/2019/042/01/article/4

Chatzistergos T, Ermolli I, Krivova NA et al (2019b) Analysis of full disc Ca II K spectroheliograms—II. Towards an accurate assessment of long-term variations in plage areas. Astron Astrophys 625:A69. https://doi.org/10.1051/0004-6361/201834402

Chatzistergos T, Ermolli I, Krivova NA et al (2020) Analysis of full-disc Ca II K spectroheliograms—III. Plage area composite series covering 1892–2019. Astron Astrophys 639:A88. https://doi.org/10.1051/0004-6361/202037746

Chatzistergos T, Ermolli I, Krivova NA et al (2022a) Scrutinising the relationship between plage areas and sunspot areas and numbers. Astron Astrophys 667:A167. https://doi.org/10.1051/0004-6361/202244913

Chatzistergos T, Krivova NA, Ermolli I (2022b) Full-disc Ca II K observations—a window to past solar magnetism. Front Astron Space Sci. https://doi.org/10.3389/fspas.2022.1038949

Clette F, Lefèvre L (2016) The new sunspot number: assembling all corrections. Sol Phys 291(9–10):2629–2651. https://doi.org/10.1007/s11207-016-1014-y

Clette F, Berghmans D, Vanlommel P et al (2007) From the Wolf number to the International Sunspot Index: 25 years of SIDC. Adv Space Res 40:919–928. https://doi.org/10.1016/j.asr.2006.12.045. (**adsabs.harvard.edu/abs/2007AdSpR.40.919C**)

Cliver EW, Ling AG (2016) The Discontinuity Circa 1885 in the Group Sunspot Number. Sol Phys 291(9–10):2763–2784. https://doi.org/10.1007/s11207-015-0841-6

Connolly R, Soon W, Connolly M et al (2021) How much has the Sun influenced Northern Hemisphere temperature trends? An ongoing debate. Res Astron Astrophys 21(6):131. https://doi.org/10.1088/1674-4527/21/6/131

Dahlke S, Hughes NE, Wagner PM et al (2020) The observed recent surface air temperature development across Svalbard and concurring footprints in local sea ice cover. Int J Climatol 40(12):5246–5265. https://doi.org/10.1002/joc.6517

Damon PE, Laut P (2004) Pattern of strange errors plagues solar activity and terrestrial climate data. Eos Trans Am Geophys Union 85(39):370–374. https://doi.org/10.1029/2004EO390005

Damon PE, Peristykh AN (1999) Solar cycle length and 20th Century northern hemisphere warming: revisited. Geophys Res Lett 26:2469–2472. https://doi.org/10.1029/1999GL900578

Ermolli I, Matthes K, Dudok de Wit T et al (2013) Recent variability of the solar spectral irradiance and its impact on climate modelling. Atmos Chem Phys 13:3945–3977. https://doi.org/10.5194/acp-13-3945-2013

Fligge M, Solanki SK, Beer J (1999) Determination of solar cycle length variations using the continuous wavelet transform. Astron Astrophys 346:313–321. http://adsabs.harvard.edu/abs/1999A

Free M, Robock A (1999) Global warming in the context of the Little Ice Age. J Geophys Res 104:19. https://doi.org/10.1029/1999JD900233. (**adsabs.harvard.edu/abs/1999JGR...10419057F**)

Friis-Christensen E, Lassen K (1991) Length of the solar cycle: an indicator of solar activity closely associated with climate. Science 254:698–700. https://doi.org/10.1126/science.254.5032.698. (**adsabs.harvard.edu/abs/1991Sci...254.698F**)

Gleissberg W (1944) A table of secular variations of the solar cycle. Terr Magn Atmos Electric (J Geophys Res) 49:243–244. https://doi.org/10.1029/TE049i004p00243. (**adsabs.harvard.edu/abs/1944TeMAE.49.243G**)

Gray LJ, Beer J, Geller M et al (2010) Solar influences on climate. Rev Geophys 48:4001. https://doi.org/10.1029/2009RG000282. (**adsabs.harvard.edu/abs/2010RvGeo.48.4001G**)

Haigh JD (2007) The sun and the earth's climate. Living Rev Solar Phys 4:2. https://doi.org/10.12942/lrsp-2007-2 (http://adsabs.harvard.edu/abs/2007LRSP....4....2H)

Hansson SO (2020) Social constructionism and climate science denial. Eur J Philos Sci 10(3):37. https://doi.org/10.1007/s13194-020-00305-w

Hathaway DH (2015) The solar cycle. Living Rev Solar Phys. https://doi.org/10.1007/lrsp-2015-4. (**adsabs.harvard.edu/abs/2015LRSP...12....4H**)

Hayakawa H, Besser BP, Iju T et al (2020a) Thaddäus Derfflinger's sunspot observations during 1802–1824: a primary reference to understand the Dalton minimum. Astrophys J 890(2):98. https://doi.org/10.3847/1538-4357/ab65c9

Hayakawa H, Clette F, Horaguchi T et al (2020b) Sunspot observations by Hisako Koyama: 1945–1996. Mon Notices R Astron Soc 492:4513–4527. https://doi.org/10.1093/mnras/stz3345. (**adsabs.harvard.edu/abs/2020MNRAS.492.4513H**)

Hayakawa H, Iju T, Murata K et al (2021a) Daniel Mögling's sunspot observations in 1626–1629: a manuscript reference for the solar activity before the Maunder minimum. Astrophys J 909(2):194. https://doi.org/10.3847/1538-4357/abdd34

Hayakawa H, Uneme S, Besser BP et al (2021b) Stephan Prantner's sunspot observations during the Dalton minimum. Astrophys J 919(1):1. https://doi.org/10.3847/1538-4357/abee1b

Hoyt DV, Schatten KH (1993) A discussion of plausible solar irradiance variations, 1700–1992. J Geophys Res 98:18. https://doi.org/10.1029/93JA01944. (**adsabs.harvard.edu/abs/1993JGR....9818895H**)

Hoyt DV, Schatten KH (1998) Group sunspot numbers: a new solar activity reconstruction. Solar Phys 181:491–512. https://doi.org/10.1023/A:1005056326158. (**adsabs.harvard.edu/abs/1998SoPh.181.491H**)

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009157896

Kelly PM, Wigley TML (1992) Solar cycle length, greenhouse forcing and global climate. Nature 360:328–330. https://doi.org/10.1038/360328a0. (**adsabs.harvard.edu/abs/1992Natur.360.328K**)

Kren AC, Pilewskie P, Coddington O (2017) Where does Earth's atmosphere get its energy? J Space Weather Space Clim 7:A10. https://doi.org/10.1051/swsc/2017007. (**adsabs.harvard.edu/abs/2017JSWSC...7A.10K**)

Krivova NA (2018) Solar irradiance variability and earth's climate. Climate changes in the holocene. CRC Press, New York, pp 107–120. https://doi.org/10.1201/9781351260244-4

Lassen K, Friis-Christensen E (1995) Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate. J Atmos Terr Phys 57:835–845. https://doi.org/10.1016/0021-9169(94)00088-6. (**adsabs.harvard.edu/abs/1995JATP...57.835L**)

Lassen K, Friis-Christensen E (2000) Reply. J Geophys Res 105:27493–27496. https://doi.org/10.1029/2000JA900067 (http://adsabs.harvard.edu/abs/2000JGR...10527493L)

Laut P (2003) Solar activity and terrestrial climate: an analysis of some purported correlations. J Atmos Solar-Terr Phys 65:801–812. https://doi.org/10.1016/S1364-6826(03)00041-5. (**adsabs.harvard.edu/abs/2003JASTP.65.801**)

Laut P, Gundermann J (1998) Solar cycle length hypothesis appears to support the ipcc on global warming. J Atmos Solar-Terr Phys 60:1719–1728. https://doi.org/10.1016/S1364-6826(98)00155-2. (**adsabs.harvard.edu/abs/1998JASTP.60.1719L**)

Laut P, Gundermann J (2000) Solar cycle lengths and climate: a reference revisited. J Geophys Res 105(A12):27489. https://doi.org/10.1029/2000JA900068

Lenssen NJL, Schmidt GA, Hansen JE et al (2019) Improvements in the GISTEMP uncertainty model. J Geophys Res Atmos 124(12):6307–6326. https://doi.org/10.1029/2018JD029522

Lockwood M (2012) Solar influence on global and regional climates. Surv Geophys 33(3):503–534. https://doi.org/10.1007/s10712-012-9181-3

Lockwood M, Owens MJ, Barnard L (2014) Centennial variations in sunspot number, open solar flux, and streamer belt width: 1. Correction of the sunspot number record since 1874. J Geophys

Res (Space Phys) 119:5172–5182. https://doi.org/10.1002/2014JA019970. (**adsabs.harvard.edu/abs/2014JGRA.119.5172L**)

Lockwood M, Owens MJ, Barnard L et al (2016) An assessment of sunspot number data composites over 1845–2014. Astrophys J 824:54. https://doi.org/10.3847/0004-637X/824/1/54. (**adsabs.harvard.edu/abs/2016ApJ...824...54L**)

Mursula K, Ulich T (1998) A new method to determine the solar cycle length. Geophys Res Lett 25:1837–1840. https://doi.org/10.1029/98GL51317. (**'ui.adsabs.harvard.edu/abs/1998GeoRL.25.1837M ', aDS Bibcode: 1998GeoRL.25.1837M**)

Nandy D (2021) Progress in solar cycle predictions: sunspot cycles 24–25 in perspective. Sol Phys 296(3):54. https://doi.org/10.1007/s11207-021-01797-2

Neukom R, Barboza LA, Erb MP et al (2019) Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. Nat Geosci 12(8):643–649. https://doi.org/10.1038/s41561-019-0400-0

Nordli Y, Wyszyński P, Gjelten HM, et al (2020) Revisiting the extended Svalbard Airport monthly temperature series, and the compiled corresponding daily series 1898–2018. Polar Res https://doi.org/10.33265/polar.v39.3614

Osborn TJ, Jones PD, Lister DH et al (2021) Land surface air temperature variations across the globe updated to 2019: the CRUTEM5 data set. J Geophys Res Atmos 126(2):e2019JD032352. https://doi.org/10.1029/2019JD032352

Pesnell WD (2020) Lessons learned from predictions of Solar Cycle 24. J Space Weather Space Clim 10:60. https://doi.org/10.1051/swsc/2020060. (**ui.adsabs.harvard.edu/abs/2020JSWSC.10...60P**)

Petrovay K (2020) Solar cycle prediction. Living Rev Sol Phys 17(1):2. https://doi.org/10.1007/s41116-020-0022-z

Reichel R, Thejll P, Lassen K (2001) The cause-and-effect relationship of solar cycle length and the Northern Hemisphere air surface temperature. J Geophys Res 106:15. https://doi.org/10.1029/2001JA900027. (**adsabs.harvard.edu/abs/2001JGR...10615635R**)

Rohde RA, Hausfather Z (2020) The Berkeley earth land/ocean temperature record. Earth Syst Sci Data 12:3469–3479. https://doi.org/10.5194/essd-12-3469-2020. (**'ui.adsabs.harvard.edu/abs/2020ESSD...12.3469R ', aDS Bibcode: 2020ESSD...12.3469R**)

Solanki SK, Krivova NA (2003) Cycles and cyclicities of the Sun. p 423, http://adsabs.harvard.edu/abs/2003ASPC..292..423S

Solanki SK, Krivova NA, Haigh JD (2013) Solar irradiance variability and climate. Ann Rev Astron Astrophys 51(1):311–351. https://doi.org/10.1146/annurev-astro-082812-141007

Solheim JE, Stordahl K, Humlum O (2012) The long sunspot cycle 23 predicts a significant temperature decrease in cycle 24. J Atmos Solar-Terr Phys 80:267–284. https://doi.org/10.1016/j.jastp.2012.02.008

Stauning P (2011) Solar activity-climate relations: a different approach. J Atmos Solar-Terr Phys 73(13):1999–2012. https://doi.org/10.1016/j.jastp.2011.06.011

Stefani F (2021) Solar and anthropogenic influences on climate: regression analysis and tentative predictions. Climate 9(11):163. https://doi.org/10.3390/cli9110163

Svalgaard L, Schatten KH (2016) Reconstruction of the sunspot group number: the backbone method. Sol Phys 291(9–10):2653–2684. https://doi.org/10.1007/s11207-015-0815-8

Thejll P (2009) Update of the Solar Cycle Length curve, and the relationship to the global mean temperature. Technical report. https://www.researchgate.net/publication/252743362_Update_of_the_Solar_Cycle_Length_curve_and_the_relationship_to_the_global_mean_temperature

Thejll P, Lassen K (2000) Solar forcing of the Northern hemisphere land air temperature: new data. J Atmos Solar-Terr Phys 62:1207–1213. https://doi.org/10.1016/S1364-6826(00)00104-8. (**adsabs.harvard.edu/abs/2000JASTP.62.1207T**)

Thomson DJ (1995) The seasons, global temperature, and precession. Science 268(5207):59–68. https://doi.org/10.1126/science.268.5207.59

Usoskin IG, Kovaltsov GA, Chatzistergos T (2016a) Dependence of the sunspot-group size on the level of solar activity and its influence on the calibration of solar observers. Sol Phys 291(12):3793–3805. https://doi.org/10.1007/s11207-016-0993-z

Usoskin IG, Kovaltsov GA, Lockwood M et al (2016b) A new calibrated sunspot group series since 1749: statistics of active day fractions. Solar Phys 291(9–10):2685–2708. https://doi.org/10.1007/s11207-015-0838-1. (**number: 9-10**)

Usoskin I, Kovaltsov G, Kiviaho W (2021a) Robustness of solar-cycle empirical rules across different series including an updated active-day fraction (ADF) sunspot group series. Sol Phys 296(1):13. https://doi.org/10.1007/s11207-020-01750-9

Usoskin IG, Solanki SK, Krivova NA et al (2021b) Solar cyclic activity over the last millennium reconstructed from annual 14C data. Astron Astrophys 649:A141. https://doi.org/10.1051/0004-6361/202140711

Vaquero JM, Svalgaard L, Carrasco VMS et al (2016) A revised collection of sunspot group numbers. Sol Phys 291(9–10):3061–3074. https://doi.org/10.1007/s11207-016-0982-2

Vokhmyanin M, Arlt R, Zolotova N (2020) Sunspot positions and areas from observations by Thomas Harriot. Solar Phys 295:39. https://doi.org/10.1007/s11207-020-01604-4. (**adsabs.harvard.edu/abs/2020SoPh.295...39V**)

Voosen P (2021) Global temperatures in 2020 tied record highs. Science 371:334–335. https://doi.org/10.1126/science.371.6527.334. (**'ui.adsabs.harvard.edu/abs/2021Sci...371.334V ', aDS Bibcode: 2021Sci...371.334V**)

Waldmeier M (1935) Neue Eigenschaften der Sonnenfleckenkurve. Astronomische Mitteilungen der Eidgenössischen Sternwarte Zurich 14:105–136

Waldmeier M (1939) Über die Struktur der Sonnenflecken. Astronomische Mitteilungen der Eidgenössischen Sternwarte Zurich 14:439–450

Willamo T, Usoskin IG, Kovaltsov GA (2017) Updated sunspot group number reconstruction for 1749–1996 using the active day fraction method. Astron Astrophys 601:A109. https://doi.org/10.1051/0004-6361/201629839

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