GC31B-0351

(No?) Century-scale Secular Variation in HMF, EUV, or TSI

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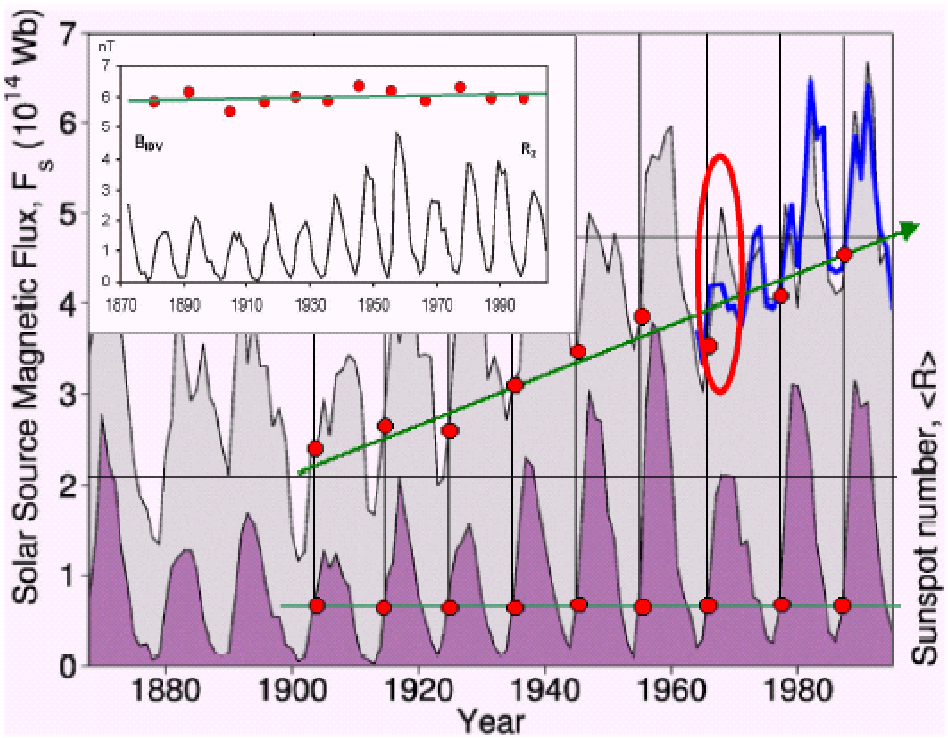
Abstract. Recent work suggests that the Heliospheric Magnetic Field (HMF) strength, B, at each sunspot minimum varies but little (less than a nT). The variation of B within a solar cycle seems to be due to extra (and likely closed) magnetic flux added by Coronal Mass Ejections (CMEs) riding on top of a "floor" of somewhere between 4 and 5 nT, leading to the conclusion that the open magnetic flux is nearly constant with time, and that, in particular, there is no secular variation of the open flux. B inferred from geomagnetic data back to the 1840s further support this conclusion. In fact, B for the current cycle 23 matches well B for cycle 13, 107 years earlier. The amplitude rY of the diurnal variation of the geomagnetic Y-component is an excellent proxy for the F10.7 radio flux and thus also for the EUV flux (more precisely, the FUV, as the Sq current flows in the E layer). As for the HMF there seems to be a "floor" in rY and hence in F10.7 and hence in the FUV flux, thus the geomagnetic evidence is that there has been no secular change in the background solar minimum EUV (FUV) flux in the past 165 years. Direct measurements (although beset by calibration problems) of the Total Solar Irradiance (TSI) from satellites have only been available for 30 years and indicate that solar irradiance increases with solar activity. Correlating mean annual TSI and sunspot numbers allows one to estimate the part of TSI that varies with the sunspot number. If TSI only depends linearly on the sunspot number then irradiance levels during the Maunder Minimum would be similar to the levels of current solar minima. But TSI is a delicate balance between sunspot darkening and facular brightening, and although both of these increase (in opposite directions) with increasing solar activity, it is not a given that there could not be secular variations in the relative importance of these competing effects. Reconstructions of TSI, all postulate a source of long-term irradiance variability on centennial time scales. Each group of researchers have their own preferred additional source of changes of the "background" TSI, such as evidence from geomagnetic activity, open magnetic flux, ephemeral region occurrence, umbral/penumbral ratios, and the like. The existence of "floors" in HMF and FUV over ~1.6 centuries argues for a lack of secular variations of these parameters on that time scale. I would suggest that the lack of such secular variation undermines the circumstantial evidence for a "hidden" source of irradiance variability and that there therefore also might be a floor in TSI, such that TSI during Grand Minima would simply be that observed at current solar minima. This obviously has implications for solar forcing of terrestrial climate.

The Doubling of the 'Open Magnetic Flux'

Many years ago, I suggested (GRL, *5(5)*, 411, 1978) that the coronal field may have doubled since 1900:

> **It should also be noted that some of the scatter of the points near Ludendorf index 0.23 may be related to the possibility (Svalgaard, 1978) that the interplanetary and coronal fields may have increased progressively by a factor of two from 1900 to the present time   The Ludendorf**

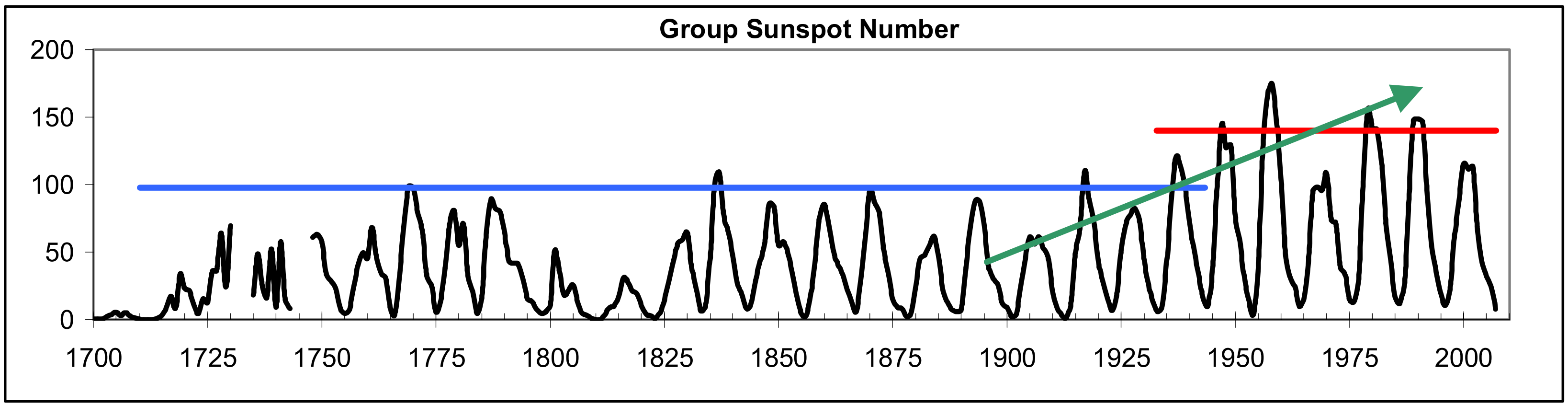


Lockwood et al. (Nature , *399(6735)*, 437, 1999) extended that analysis using the *aa*-index and found that there was a *non-sunspot* related 'background' magnetic flux that had increased by a factor of 2.31 since 1900 (Figure below, left).

To show this clearly I have selected years where the (Zürich sunspot number was near 40 on the ascending part of the solar cycle away from recurrent coronal holes). These are marked by the lower string of red dots. Vertical lines drawn through the dots upwards to meet the Lockwood et al. computed open flux define another string of red dots showing the almost linear increase (**green** arrow) of the flux for constant sunspot number. The agreement with the observed flux (heavy blue line) was not always good: **red** oval, but the result was widely accepted and even hailed as 'one of the major advances in solar and heliospheric physics of recent years' [Solanki et al., A&A *383*, 706–712 (2002)].

The Increase in Sunspot Numbers

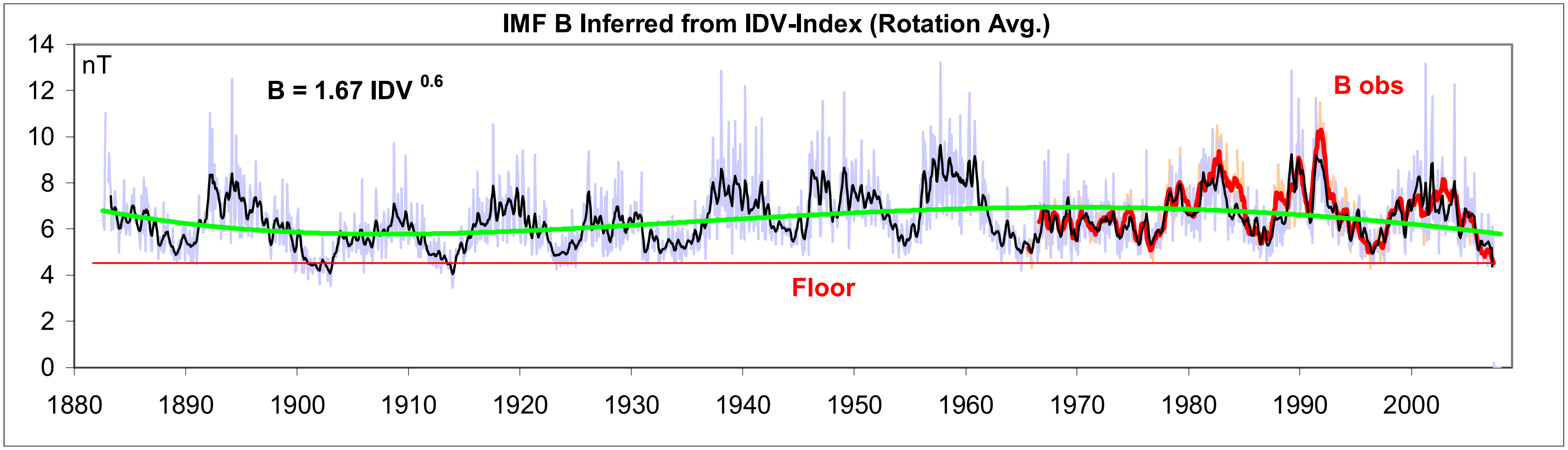
The Group Sunspot Number shows a similar increase. One can to first approximation state that solar activity according to the Group Sunspot Number (GSN) has been highest in the last fifty or so years, and that it was significantly lower for the 250 years before that:



Most reconstructions of the Total Solar Irradiance (TSI) before the spacecraft measurements do in one way or another, directly or indirectly, rely on either [or both] the 'doubling of the open flux' and the increase of the GSN.

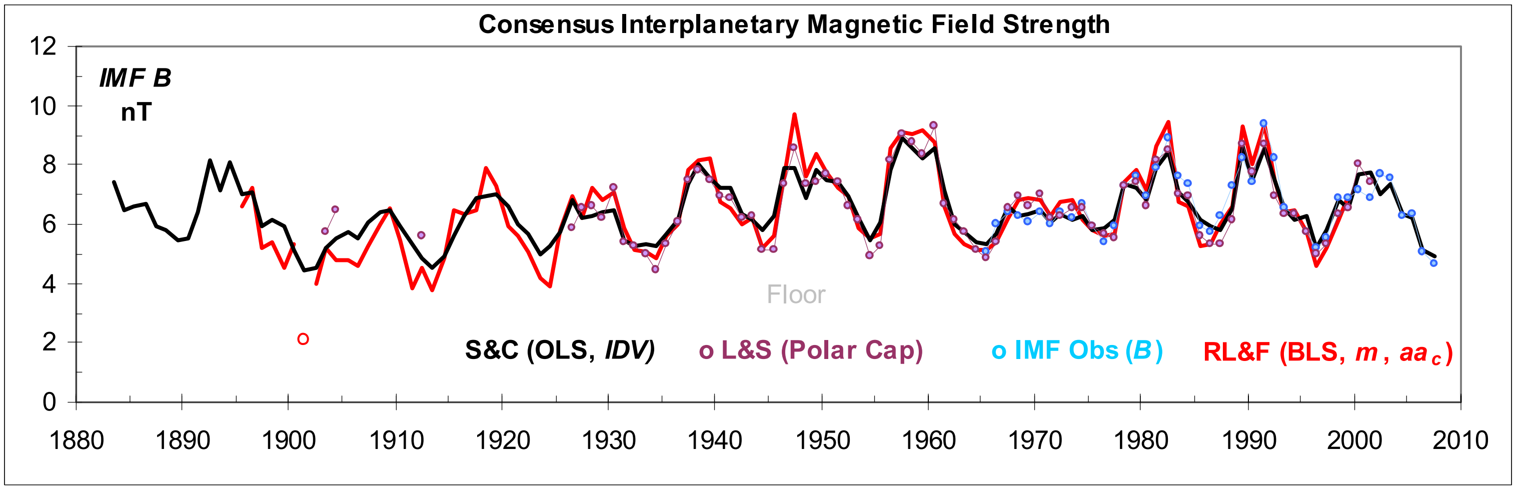
Determination of Interplanetary Magnetic Field Strength

Recent work [Svalgaard, L & E. W. Cliver, Ap. J. Lett., 661, L203, 2007] suggests that the Interplanetary Magnetic Field (IMF) strength, B, at each sunspot minimum varies but little (less than a nT). This is clearly seen in Figure below. The variation of B within a solar cycle seems to be due to extra (and likely closed [Owens, M. J. & N. U. Crooker, J. Geophys. Res., 111(A10), A10104, 2006] magnetic flux added by Coronal Mass Ejections (CMEs) riding on top of a "floor" of somewhere between 4 and 5 nT, leading to the conclusion that the open magnetic flux is nearly constant with time, and that, in particular, there is no secular variation of the open flux. Geomagnetic data back to the 1840s [Svalgaard, L. & E. W. Cliver, JGR., 110(A12), A12103, 2005, further support this conclusion. In fact, B for the current cycle 23 matches well B for cycle 13, 107 years earlier.



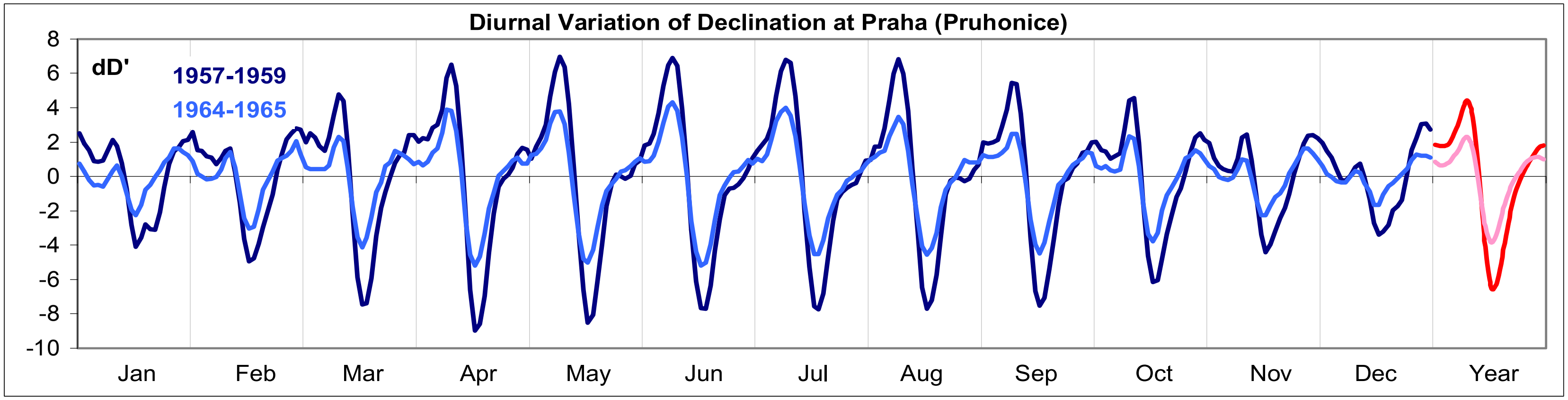
This result is at variance with the 1999 Lockwood et al. finding. However, recognizing the finding by Svalgaard et al. (Adv. Space Res. 34(2), 436, 2004) that the *aa*-index has incorrect calibration before 1957 [is too low], the Lockwood group has published a new analysis (Rouillard et al., JGR, 112, A05103, 2007) that supercedes their 1999 result.

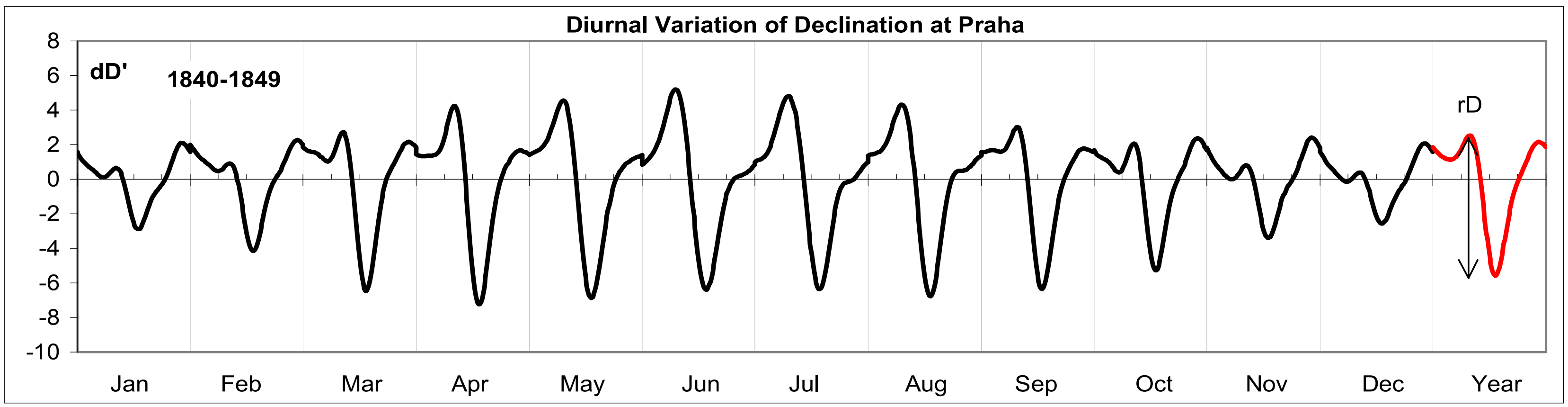
The following Figure shows the interplanetary magnetic field strength, B, derived by Svalgaard & Cliver (JGR, 110, A12103, 2005) [black curve], by LeSager & Svalgaard (GR 109, A07106, 2004) [purple curve], spacecraft observations [blue curve], and Rouillard et al. [red curve]. A rather remarkable consensus seems to be emerging as to value of B and its long-term variation for are for the past ~130 years. An outlying point in 1901 is likely erroneous (Rouillard, personal communication, 2007). The doubling of the field [the open flux calculated by Lockwood et al, 1999 was simply proportional to B] has now disappeared



Determination of FUV Flux

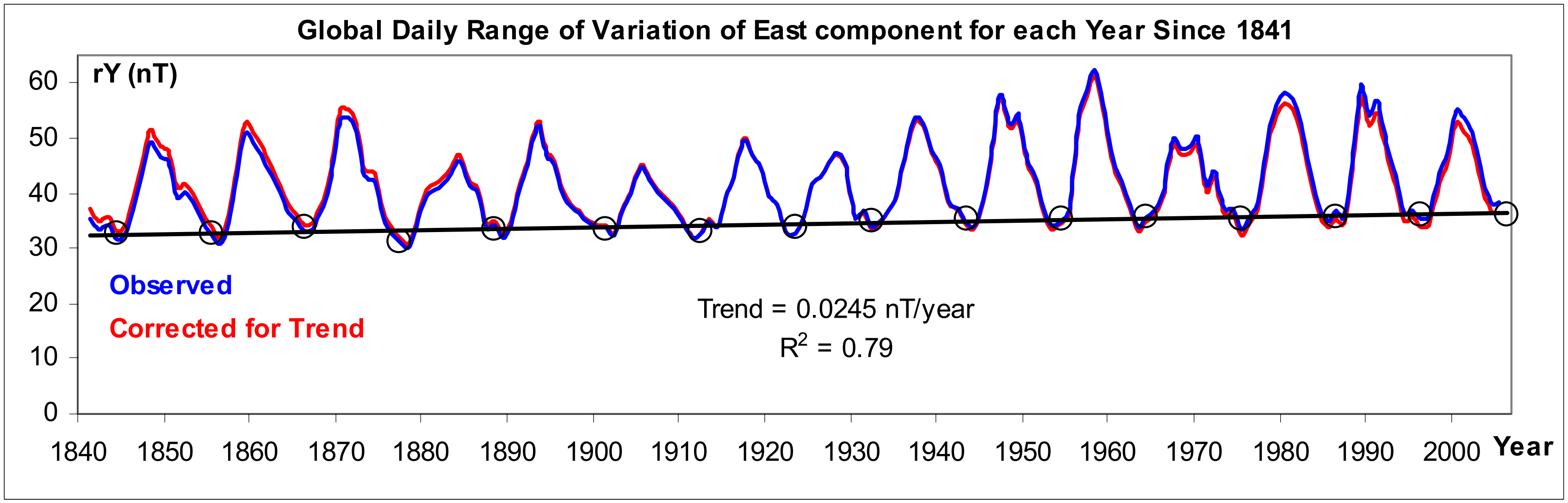
The amplitude of the diurnal variation of the geomagnetic *Y*-component is an excellent proxy for the *F10.7* radio flux and thus also for the EUV flux (more precisely, the FUV, as the *Sq* current flows in the E layer). The diurnal variation is caused by current vortices in the ionosphere due to dynamo action and stays fixed in relation to the Sun. As the Earth's rotation carries a geomagnetic station across the current [underneath it], the compass needle is deflected one way in the morning as the Sun comes up, and the other way in the afternoon. The total range, rY, of this deflection from the morning extremum to the afternoon extremum depends on the ionospheric conductivity controlled in the end by the solar FUV flux. The Y-component is calculated from the Horizontal Force and the Declination, which is easily measured:





The range is simply the difference between the morning and Afternoon readings.

Using many geomagnetic stations a global value of the range in Y can be constructed:



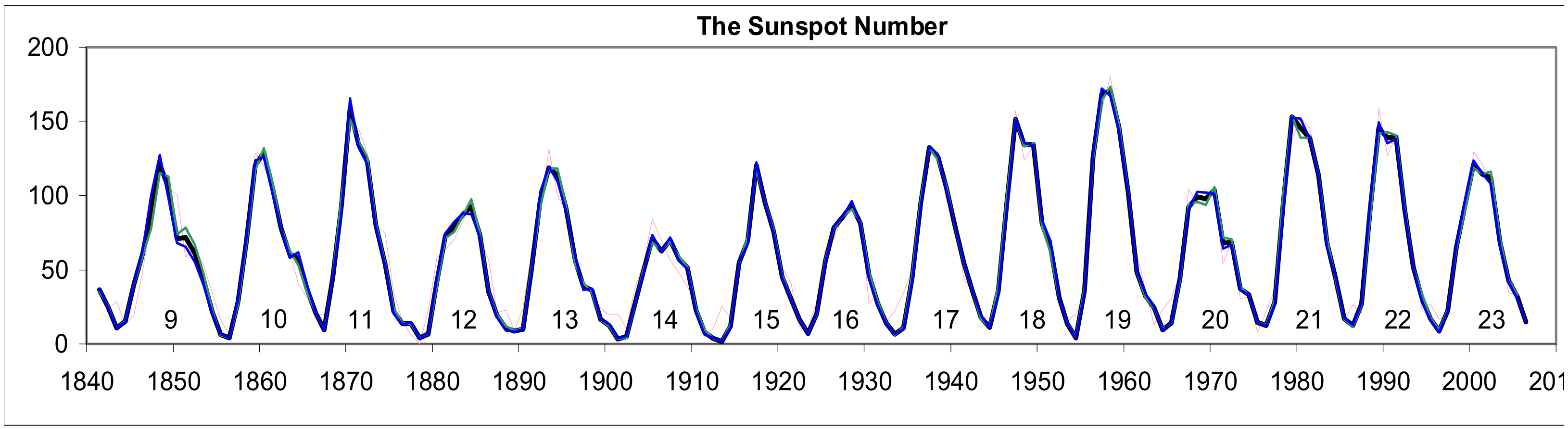
The Figure shows a weak trend in the amplitude of 10% since the 1840s that can be understood as being due to an increase of ionospheric conductance resulting from the 10% decrease of the Earth's main field. Correcting for this effect yields the red curve in the Figure.

A Floor in the IMF and the FUV

As for the IMF there seems to be a "floor" in *rY* and hence in *F10.7* and hence in the FUV flux, thus the geomagnetic evidence is that there has been no secular change in the background solar minimum EUV (FUV) flux in the past 165 years.

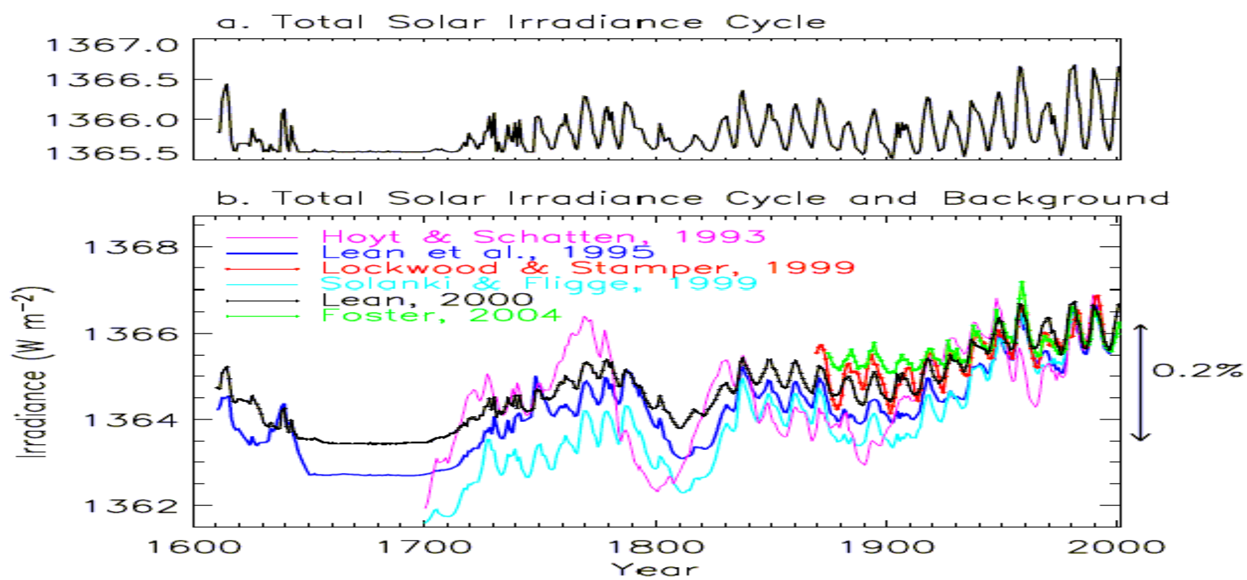
Correcting the Sunspot Number

From the range, *rY*, the sunspot number can be computed as there is also a strong correlation between *rY* and the sunspot number. As shown in my poster on Monday ***SH13A-1109***, both the Zürich/International SSN and the Group SSN are underestimated in the past and need to be corrected upwards. The Figure below shows the corrected sunspot number since 1841:



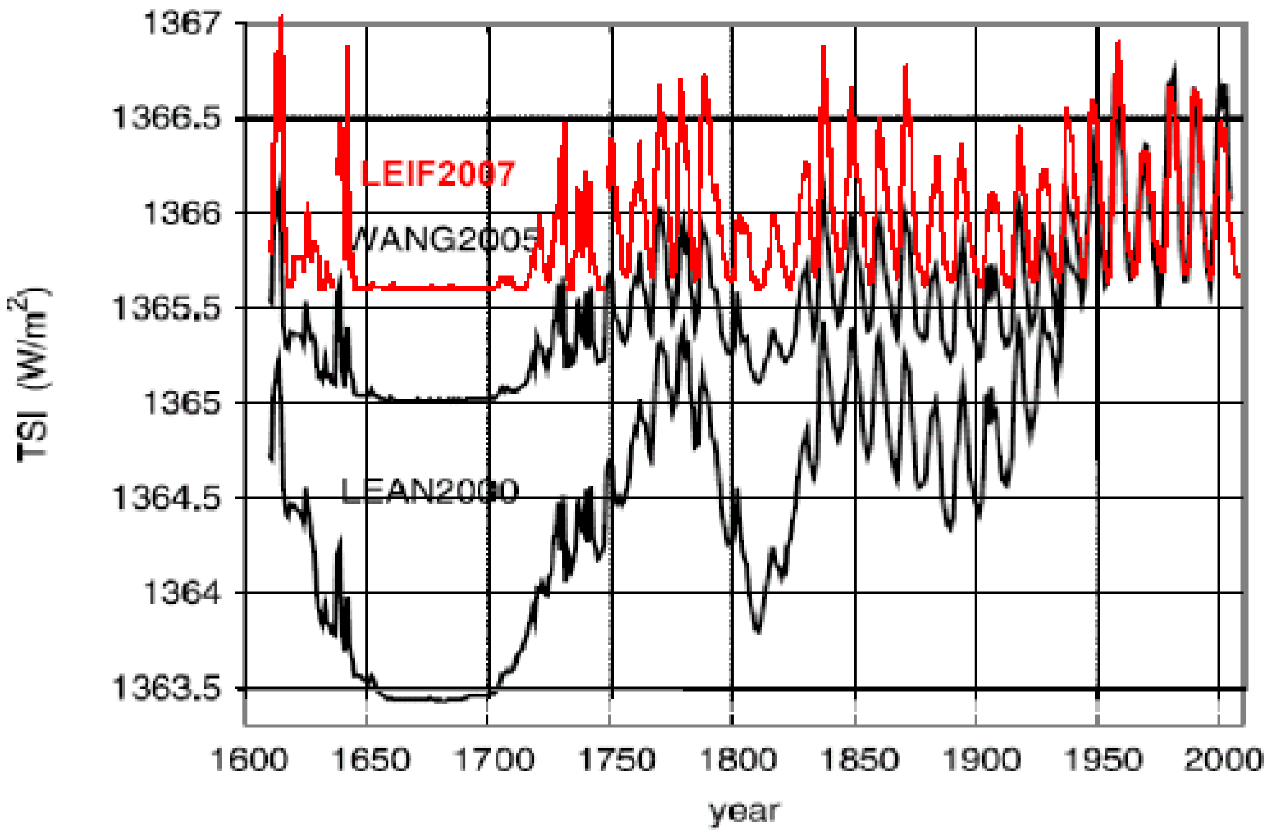
There is no significant difference now between the 19th and 20th centuries. And a further rationale for an increasing 'background' in TSI has now disappeared too.

Direct measurements (although beset by calibration problems) of the Total Solar Irradiance (TSI) from satellites have only been available for 30 years and indicate that solar irradiance increases with solar activity. Correlating mean annual TSI and sunspot numbers allows one to estimate the part of TSI that varies with the sunspot number, as shown in the upper panel of Figure below. If TSI only depends linearly on the sunspot number then irradiance levels during the Maunder Minimum would be similar to the levels of current solar minima. But TSI is a delicate balance between sunspot darkening and facular brightening, and although both of these increase (in opposite directions) with increasing solar activity, it is not a given that there could not be secular variations in the relative importance of these competing effects. Several reconstructions, reviewed in Fröhlich, C. & J. Lean, A&A, *12(4)*, 273, 2004 and reproduced in the lower panel of Figure below, all postulate a source of long-term irradiance variability on centennial time scales. Each group of researchers have their own preferred additional source of changes of the "background" TSI, such as evidence from geomagnetic activity, open magnetic flux, ephemeral region occurrence, umbral/penumbral ratios, and the like. The existence of "floors" in IMF and FUV over ~1.6 centuries argues for a lack of secular variations of these parameters on that time scale. I would suggest that the lack of such secular variation undermines the circumstantial evidence for a "hidden" source of irradiance variability and that there therefore also might be a floor in TSI, such that TSI during Grand Minima would simply be that observed at current solar minima. This obviously has implications for solar forcing of terrestrial climate.



Reconstructing TSI since 1600

But since not only the background has disappeared but also the trend in the sunspot numbers, a better reconstruction is one that takes both effects into account, namely:



If TSI varies less, then the climate system's sensitivity to solar forcing must be substantially larger to maintain a solar influence on climate, if any.