FULL TITLE
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Updating the Historical Sunspot Record

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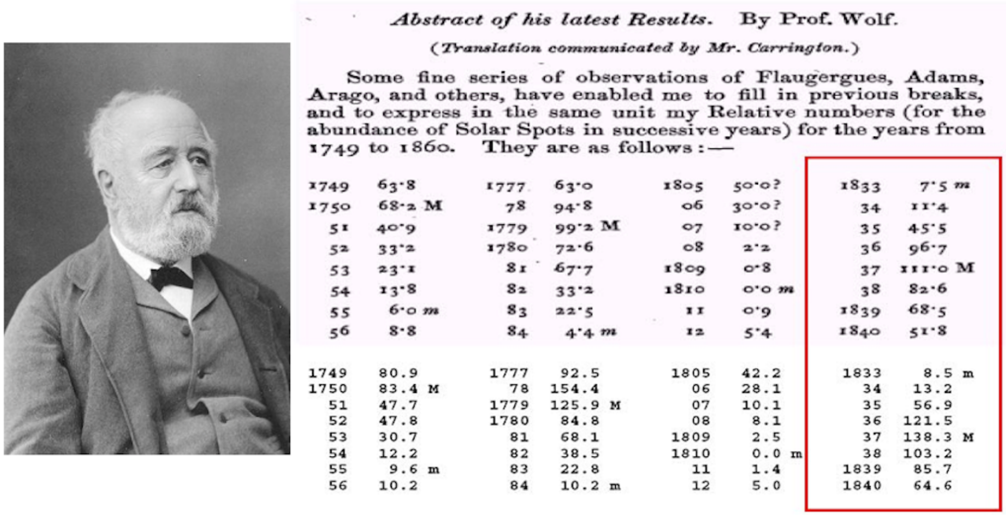
Abstract. We review the evidence for the argument that Rudolf Wolf's calibration of the Sunspot Number is likely to be correct and that Max Waldmeier introduced an upwards jump in the sunspot number in 1945. The combined effect of these adjustments suggests that there has been no secular change in the sunspot number since coming out of the Maunder Minimum ∼1715.

1 The Sunspot Record(s!)

The Sunspot Record goes back 400 years and is the basis for many reconstructions of solar parameters (e.g. TSI), but, how good is it? And can we agree on which one (Wolf Number, International Number, 'Boulder' Number, Group Number, ...)? Are the old values good? Are the new ones? And what is a 'good' or 'correct' Sunspot Number anyway?

Johann Rudolf Wolf (1859) defined his Relative Sunspot Number, taking into account both individual spots and their appearance in distinct groups (what we today call 'active regions'), as $R_W = 10\,Groups + Spots$. Wolf started his own observations in 1849 and assembled observations from earlier observers back to 1749 and beyond (Figure 1).



Abstract of his latest Results. **By Prof. Wolf.**

(*Translation communicated by Mr. Carrington.*)

Some fine series of observations of Flaugergues, Adams, Arago, and others, have enabled me to fill in previous breaks, and to express in the same unit my Relative numbers (for the abundance of Solar Spots in successive years) for the years from 1749 to 1860. They are as follows:—

1749	63·8	1777	63·0	1805	50·0?	1833	7·5 *m*
1750	68·2 M	78	94·8	06	30·0?	34	11·4
51	40·9	1779	99·2 M	07	10·0?	35	45·5
52	33·2	1780	72·6	08	2·2	36	96·7
53	23·1	81	67·7	1809	0·8	37	111·0 M
54	13·8	82	33·2	1810	0·0 *m*	38	82·6
55	6·0 *m*	83	22·5	11	0·9	1839	68·5
56	8·8	84	4·4 *m*	12	5·4	1840	51·8

1749	80.9	1777	92.5	1805	42.2	1833	8.5 m
1750	83.4 M	78	154.4	06	28.1	34	13.2
51	47.7	1779	125.9 M	07	10.1	35	56.9
52	47.8	1780	84.8	08	8.1	36	121.5
53	30.7	81	68.1	1809	2.5	37	138.3 M
54	12.2	82	38.5	1810	0.0 m	38	103.2
55	9.6 m	83	22.8	11	1.4	1839	85.7
56	10.2	84	10.2 m	12	5.0	1840	64.6

Figure 1. Rudolf Wolf and excerpts from his 1861 list of published Relative Numbers compared with his latest list (now the official list from SIDC in Brussels).

As is clear, the earlier values were subsequently adjusted (upwards) as Wolf were struggling with the difficulty of bringing different observers onto the same 'scale', compensating for telescope size, counting method, acuity, seeing, and personal bias.

Wolf published several versions of his celebrated Relative Sunspot Numbers based on data gathered from many observers from both before and during Wolf's own lifetime (Figure 2). How to 'harmonize' data from different observers?

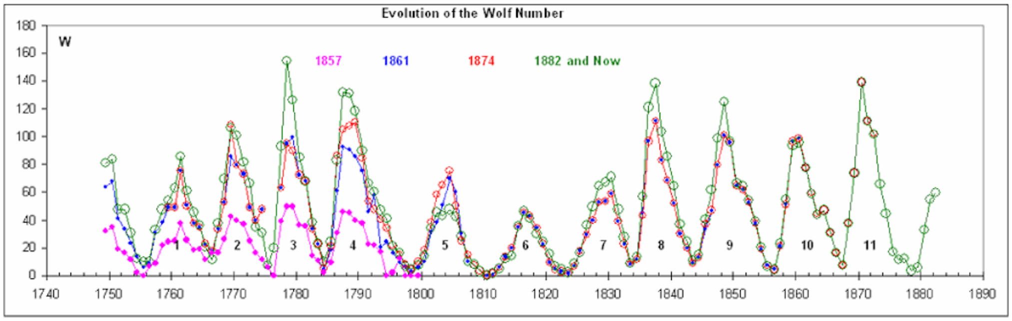


Figure 2. Evolution of the Wolf Number from his first 1857 list to the final version, with color coded symbols and curves for each list

2 Wolf's Elegant Solution

A current system in the ionospheric E-layer is created and maintained by solar UV radiation (Figure 3). The current has a magnetic field of its own which is readily observed on the ground even with 18th Century technology. This variation was, in fact, discovered in 1722 by George Graham (1724) as a regular variation of typically 10 arc minutes during each day of the angle (called the Declination today) a compass needle makes with true North. The amplitude (rD) of this variation is an excellent proxy for solar UV.

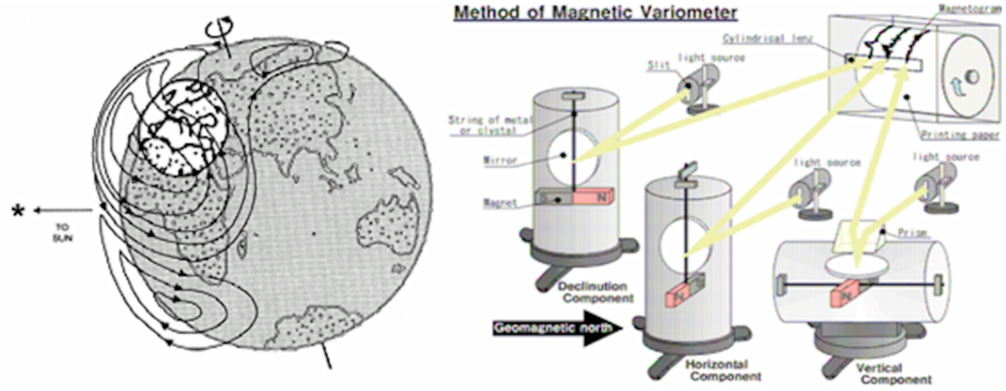


Figure 3. Ionospheric current system (left) fixed with respect to the Sun. Stations rotate into and out of the magnetic field of this system, recording it (right).

Wolf (1859) discovered that this amplitude has a strong linear relationship with his newly defined Relative Number, R_W: $rD = a + b\,R_W$ and used the relationship to calibrate the sunspot number on a yearly basis (Figure 4). Wolf made two overall major calibration changes based on rD:

- (1861) Sunspot numbers before ∼1798 were doubled
- (1875) All values before 1849 (including the ones that were doubled) were increased by 25%

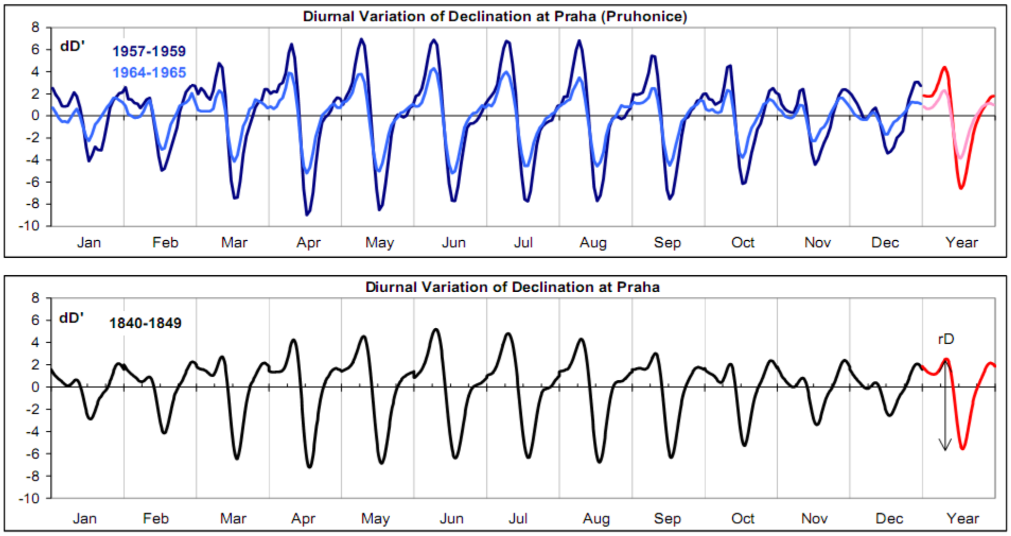


Figure 4. Diurnal variation of Declination at Prague per month. Top: modern data for low sunspot number (light blue) and for high sunspot number (dark blue). Bottom: for the 1840s. The amplitude changes with the solar zenith angle. Wolf used the yearly average (red) to calibrate the yearly R_W.

By comparing sunspot numbers (SSN) reported by other observers with his own, Wolf introduced a scale factor to compensate for the differences: $SSN = k_W(10\,Groups + Spots)$.

3 The Group Sunspot Number

Hoyt & Schatten (1998) proposed basing the Sunspot number solely on the number of groups reported by the observers: $GSN = 12\,Groups$. The calibration constant was used to make the value of the GSN comparable to the modern Sunspot Number. However, the number of sunspot groups is also observer dependent (Figure 5), by up to a factor of two or more, so an observer-dependent adjustment factor is also needed: $GSN = 12\,k_G\,Groups$.

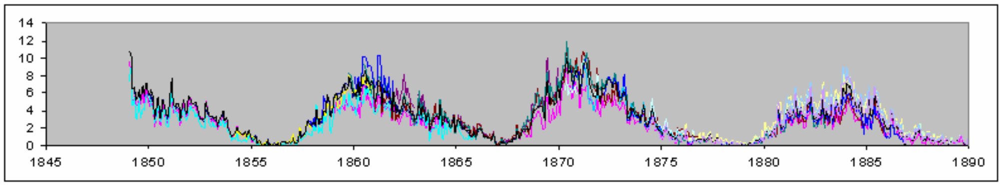


Figure 5. Group counts by several observers: Schwabe, Wolf, Carrington, Shea, Peters, Spörer, Weber, Schmidt, Secchi, Bernaerts, Wolfer, Aguilar, Ricco, and RGO, shown with different color coding.

So, the conceptually cleaner GSN also needs adjustment and 'bridges' from one observer to the next, and the next, etc, lacking the 'absolute' calibration afforded by another physical observable. This may lead to a possibly spurious secular change (Figure 6).

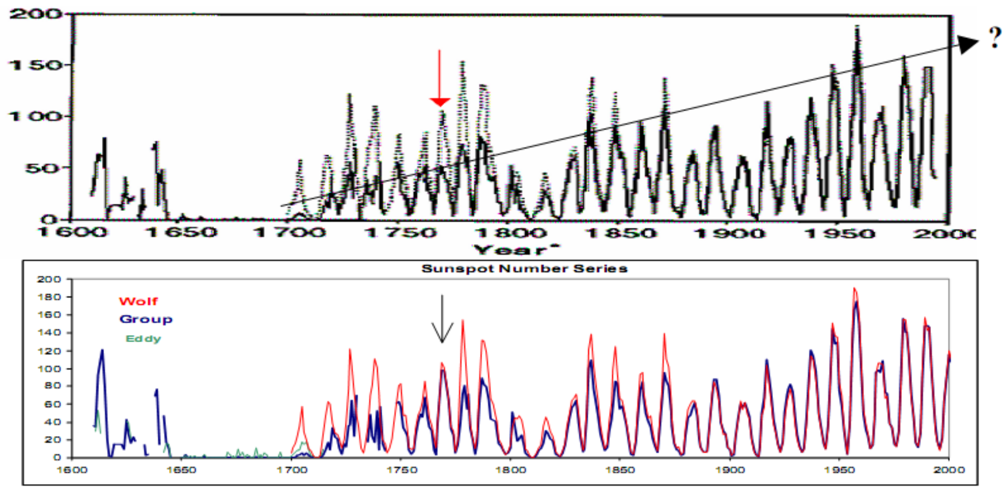
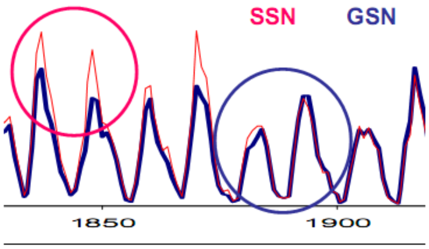


Figure 6. Two versions of the GSN (top: GSN full line, Wolf SSN dotted line). The latest GSN is compared to the Wolf (and International) SSNs in the bottom panel. The GSN is largely based on the RGO (Greenwich) dataset from 1875 onwards.

4 Sunspot Number Relationship with Diurnal Range

Extensive datasets exist (Schmidt (1909)) from the 'Magnetic Crusade' in the 1840s and for times after the First Polar Year 1882 (Figure 7).

obs	name	lat	long	interval
WDC	Washington D.C.	38.9	283.0	1840-1842
DUB	Dublin	53.4	353.7	1840-1843
MNH	Munchen	48.2	11.6	1841-1842
PGC	Philadelphia	40.0	284.8	1840-1845
SPE	St. Peterburg	60.0	30.3	1841-1845
GRW	Greenwich	51.5	0.0	1841-1847
PRA	Praha	50.1	14.4	1840-1849
HBT	Hobarton	-42.9	147.5	1841-1848
MAK	Makerstoun	55.6	357.5	1843-1846
KRE	Kremsmunster	48.1	14.1	1839-1850
TOR	Toronto	43.7	280.6	1842-1848
WLH	*Wilhelmshaven*	53.7	7.8	*1883-1883*
GRW	*Greenwich*	51.5	0.0	*1883-1889*
WDC	*Washington D.C.*	38.9	283.0	*1891-1891*
PSM	*Parc Saint-Maur*	48.8	0.2	*1883-1899*
POT	*Potsdam*	52.4	13.1	*1890-1899*
COP	*Kobenhavn*	55.7	12.6	*1892-1898*
UTR	*Utrecht*	52.1	5.1	*1893-1898*
IRT	*Irkutsk*	52.3	104.3	*1899-1899*



So there are good geomagnetic data for many stations during the intervals marked by ovals above when there is a large systematic difference between GSN and Wolf's SSN. We can use those data to verify the calibrations and to check on Wolf.

Figure 7. List of stations for which we know amplitudes ofrD for the intervals indicated

As the current flows along meridians on the morning and evening sides, the magnetic deflection is along latitude circles and the magnitude in force units (nT) is largely constant from station to station over a wide latitude range (20°-60°). From the observed values of *rD* and of the Horizontal component, *H*, the range in force units, *rY*, is readily calculated as shown. Wolf didn't know that the important parameter is *rY* and not *rD*, so he had to contend with regression coefficients that varied from station to station and with time. While not a serious problem once you know why, this variation nevertheless weakened other researchers' confidence in Wolf's procedure.

As shown in Figure 8, after ~1882 the GSN (pink) and the SSN (blue) have the same relation with the range of geomagnetic variation and cluster neatly along a common regression line, also found for SSN for stations regardless of time interval.

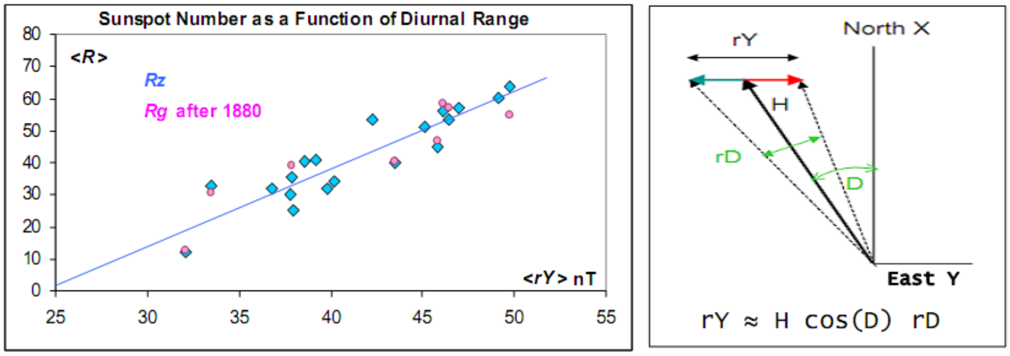


Figure 8. Average sunspot numbers (GSNs in pink and Wolf SSNs in blue) for the intervals in the table above vs. the average range of the diurnal variation of the East Component of the geomagnetic field, *rY*.

If we add the GSN averages (red diamonds) for stations before 1850, we find that they all fall well below the regression line for stations after 1880 (Figure 9).

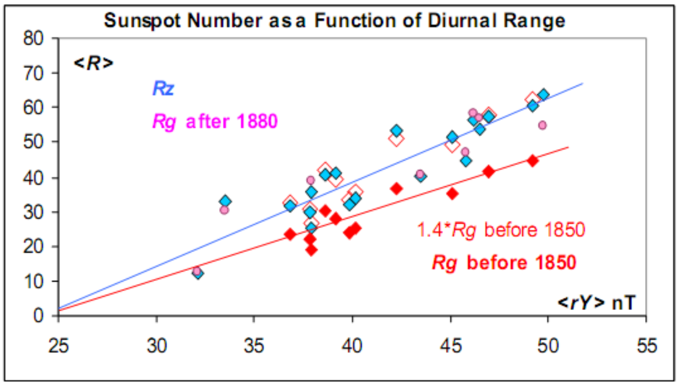


Figure 9. Same as Figure 8, but with the average GSNs for intervals before 1850s added (filled red diamonds). Scaling these values up by a factor of 1.4 (open red diamonds) brings them into fair agreement with the common regression line for the Wolf SSNs and for the GSNs after 1880.

If the diurnal range, rY, is a satisfactory measure of the kind of solar activity we believe the sunspot should be a proxy for, then the above analysis would suggest that the Group Sunspot Number should be increased by a factor of 1.4 sometime before ∼1880, removing most of the discrepancy between the two sunspot number series.

5 Ratio of Wolf SSN and Group Sunspot Number

It is instructive to plot the ratio of the Wolf number and the Group number (omitting years where either is close to zero). Figure 10 shows that with the above adjustment by a factor of 1.4 before ∼1880, the ratio seems to be near unity, with an expected large noise component early on. A discontinuity in 1945 when Max Waldmeier took over production of the Zürich sunspot Number is apparent. Alfred Wolfer became Wolf's assistant around 1880 and began to influence the 'Wolf' number from then on.

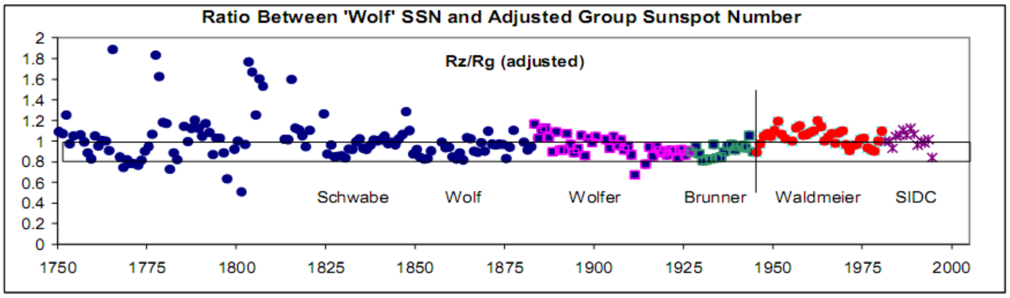


Figure 10. Ratio of yearly values of the Wolf (Zürich) Sunspot Number, Rz, and the Group Sunspot Number, Rg. Different observers are indicated by appropriate color coding.

Wolf did not count pores and the smallest spots. His assistant (and successor) Alfred Wolfer disagreed and argued that all visible pores and spots, no matter how small, should be counted, and of course won the argument by staying longer on the right side of the grass. He used the correction factor, $k_W = 0.6$, to bring his counts into conformance with Wolf's. There is some confusion about k_W being a 'personal' factor or not. As Wolfer used it, k_W compensates for a difference in what is counted, rather than a difference in telescope, seeing, etc. Since the number of groups is rarely influenced by a change in counting the smallest spots, the defining equation should perhaps better have been $SSN = 10\,Groups + \kappa\,Spots$, but this is now probably too late to change.

6 Geomagnetic Ranges; the Waldmeier Discontinuity, I

Friedli (2005) comments on the change of observers in Zürich in 1945 and writes: "The new observer-team was thus relatively inexperienced" and "Waldmeier himself feared that his scale factor could vary". We now know that his fear was not unfounded. Waldmeier's counts are 22% higher than Wolfer and Brunner's, for the same amplitude of the Diurnal Geomagnetic Variation (Figure 11). This is close to the size of the discontinuity deduced from Figure 10. As SIDC took pains to maintain continuity with Waldmeier, the jump carries over to modern SSN values.

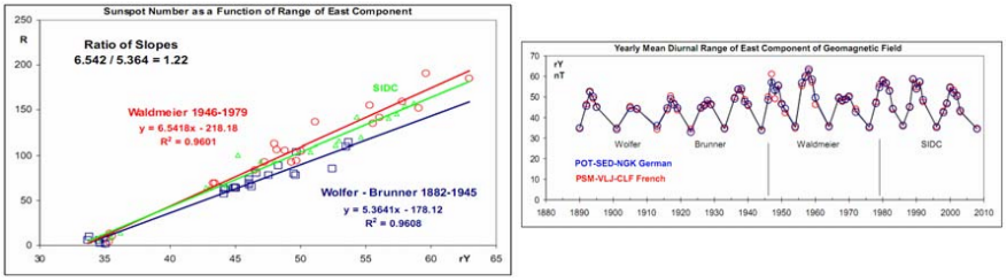


Figure 11. Select years near solar minimum and near solar maximum, then plot the yearly Zürich SSN as a function of the range of the East component for two station chains, one German and one French.

7 The RGO Sunspot Area Series; the Waldmeier Discontinuity, II

There is a strong correlation (with zero offset) between the Sunspot area (SA) and $R_Z = (1/r)SA^{0.775}$. The ratio $r = SA^{0.775}/R_Z$ is observer dependent. Histograms of the ratio values indicate that Waldmeier's R_Z values are a factor of $3.39/2.88 = 1.18$ too high (Figure 12), or 18%.

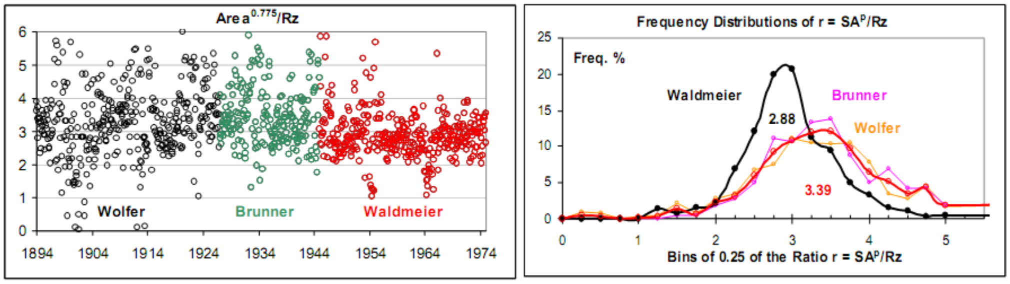


Figure 12. Monthly values of the ratio between the sunspot areas (to power $p = 0.775$) for different observers as indicated.

8 CaK Spectroheliograms; the Waldmeier Discontinuity, III

From ~40,000 CaK spectroheliograms from the 60-foot tower at Mount Wilson between 1915 and 1985 a daily index of the fractional area of the visible solar disk occupied by plages and active network has been constructed Bertello et al. (2008). Monthly averages of this index are strongly correlated with the sunspot number. The relationship is not linear, but can be represented by the equation: $R_Z = [(CaK - 0.002167) * 8999)]^{1.29}$ using data from 1915-1945, i.e. the pre-Waldmeier era. The SSN reported by Waldmeier is ~20% higher than that calculated from CaK using the above pre-Waldmeier relation, as can be seen in Figure 13. Foukal (1998) reports a similar result.

9 Ionospheric Critical Frequency; the Waldmeier Discontinuity, IV

The value of the Ionospheric Critical Frequency *foF2* depends strongly on solar activity Phillips (1948) and is perhaps the parameter with the clearest response to solar activity. The slope of the correlation changed 24% between solar cycles 17 and 18 when Waldmeier took over, corresponding to a 24% higher SSN after 1945 than that which would be expected from the *foF2* relation.

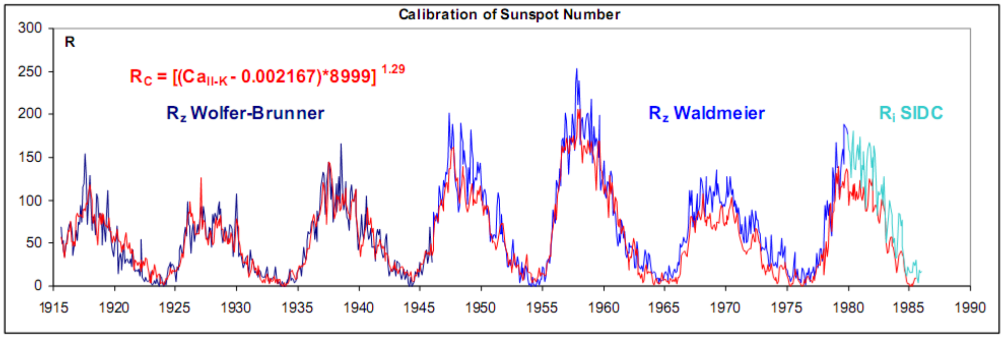


Figure 13. Comparison of Zurich SSN (blue colors) and a synthetic SSN (red) calculated from a Ca II K-line index using a pre-Waldmeier relationship.

Based on these several lines of independent evidence there seems little doubt that Waldmeier introduced a spurious increase of the Zürich sunspot number of that magnitude.

10 Geomagnetic Range is an Excellent Proxy for F10.7 Radio Flux

Wolf's linear relationship (on which the calibration hangs) is completely vindicated by modern data using the F10.7 cm flux as a measure for general solar activity. The coefficient of determination R^2 is in excess of 0.98 for yearly averages of the flux (itself a proxy for solar UV) and the amplitude of the ensuing geomagnetic diurnal variation (Figure 14). This establishes that Wolf's procedure and calibration are physically sound and precise enough to be applicable.

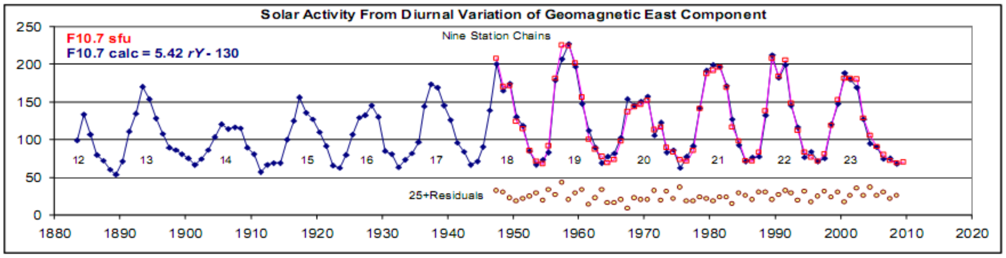


Figure 14. The yearly average range, rY, derived from nine long-running chains of geomagnetic observatories (blue) compared with the average F10.7 cm solar flux (red).

11 Conclusion

Modern data shows that the diurnal range of the geomagnetic variation is an extremely good proxy for the solar microwave flux. To the extent that we take the flux to be a measure of general solar activity of which the sunspot number was meant to be an indicator, we argue that Wolf's calibration makes his sunspot series essentially an equivalent F10.7 series. Accepting the soundness of Wolf's procedure and correcting for the Waldmeier discontinuity (+20%) lead to a picture of solar activity with but little difference between activity levels in the 18^{th}, 19^{th}, and 20^{th} centuries (Figure 15).

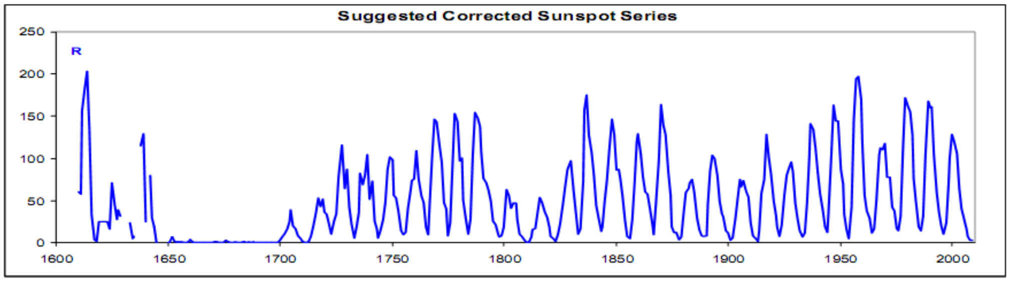


Figure 15. Suggested equivalent sunspot numbers calibrated by the geomagnetic record.

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