4. Biases in the Zürich era: causes and diagnostics

4.1 The ~1885 Rz-Rg divergence (1850-1930)

A powerful way of comparing two time series is to form the ratio between them, avoiding the smallest values – e.g. zero – by restricting the ratio to years where the yearly values are above a suitable threshold. Figure xx1 shows that ratio between the [Hoyt & Schatten] Group Sunspot Number and the 'Wolf' Sunspot Number [as published by SIDC] for each year in the interval 1749-1995:

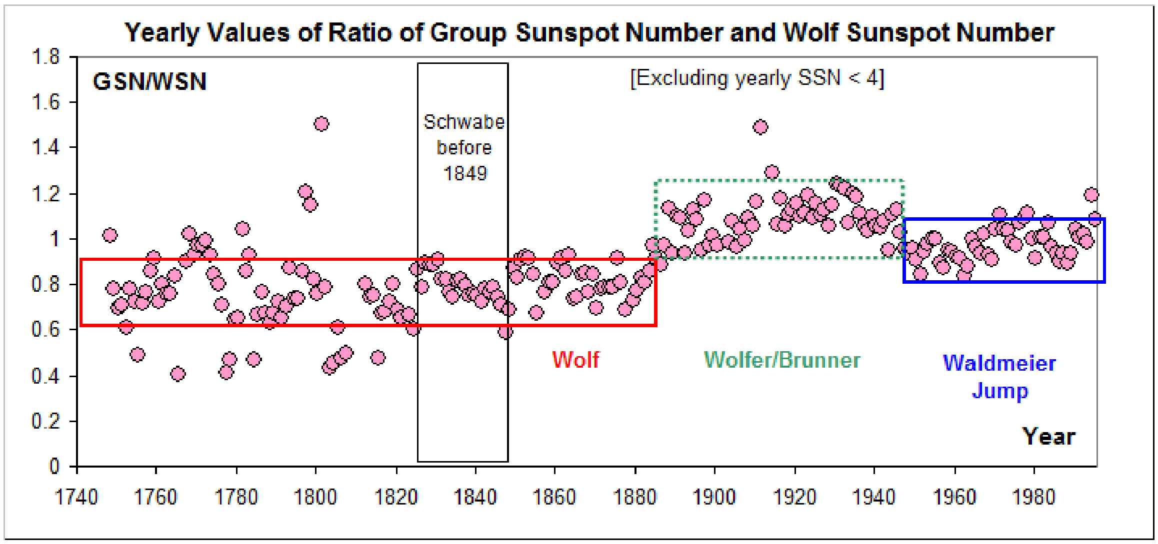


Figure xx1: Ratio between yearly averages of Group and 'Wolf' Sunspot Numbers (when both are not less than 4).

It is clear that there are essentially two discontinuities, as well as minor, short-lived drifts. In this section we shall explore the first jump around 1885. We shall use yearly averages of the original Group numbers as reported by Hoyt and Schatten, calculated by averaging for each year all monthly values for which there is data.

The *backbone-method* used by Svalgaard (REF…) starts by selecting a single 'primary' observer for an interval of time. The selection should be based both on the length of the observational series [as long as possible] as on the perceived 'quality' of the observations such as regularity of observing, suitable telescope, and lack of obvious problems. Two backbones will be discussed first, the Schwabe [1794-1883] and the Wolfer [1841-1944] backbone. The Schwabe backbone is centered on the observing interval for Schwabe and includes all 'reliable' observers who overlap in time with Schwabe. The reliability is judged by how high the correlation is between simultaneous [on a yearly basis] observations by the observer and by Schwabe. Similarly, the Wolfer backbone includes all reliable observers who overlap with Wolfer. The two backbones overlap by 42 years so can be cross-calibrated with confidence. Figure xx2 gives an overview of the time intervals observed by the observers listed:

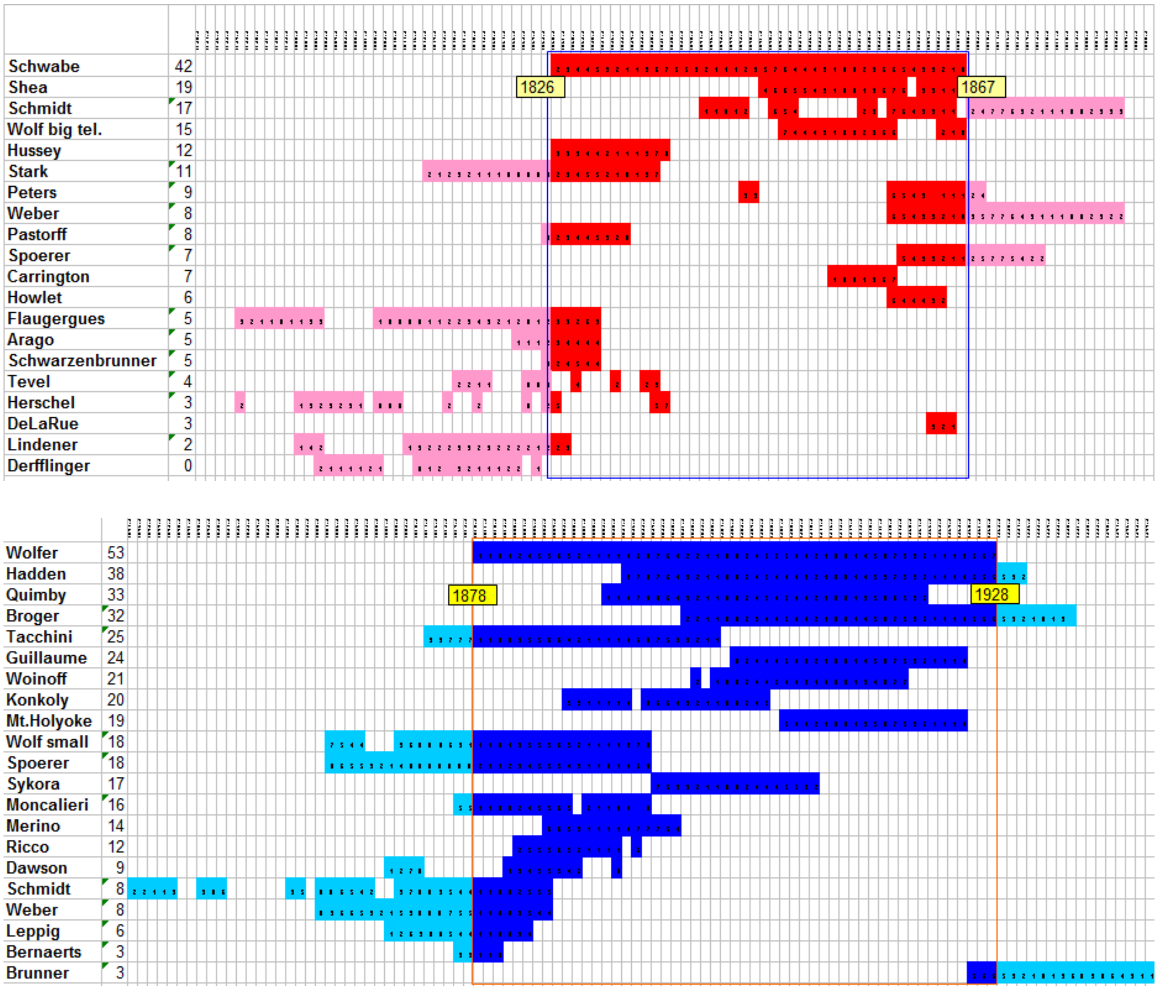


Figure xx2: (Top) Coverage and observers for the Schwabe Backbone (1794-1883). (Bottom) Coverage and observers for the Wolfer Backbone (1841-1944).

For each Backbone, regress the primary observer's group count against each observer's count for each year and plot the result [Figure xx3]. Experience shows that the regression line almost always very nearly goes through the origin, so we force it to do so and calculate the slope and various statistics, such as 1-σ uncertainty and the F-value.

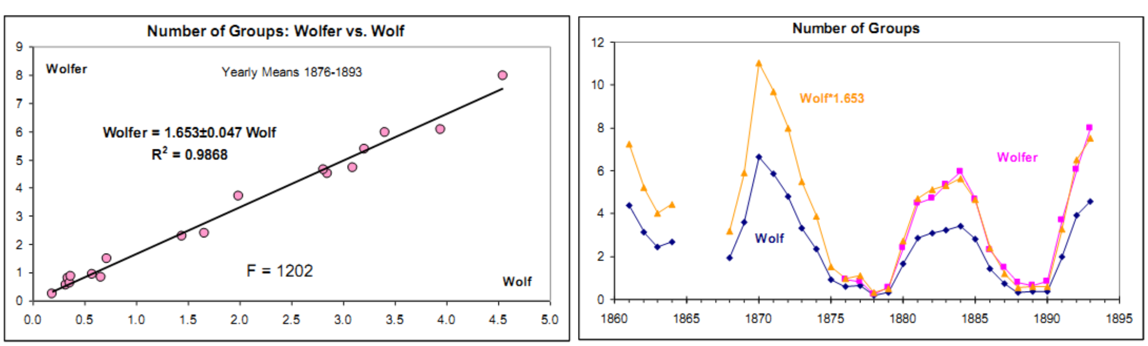


Figure xx3: Regression of number of groups observed by Wolfer [with standard telescope] against the number of groups observed by Wolf [with small telescope].

The slope gives us what factor to multiply the observer's count by to match the primary's count. The right panel shows a result for the Wolfer Backbone: blue is Wolf's count [with his small telescope], pink is Wolfer's count [with the larger telescope], and the orange curve is the blue curve multiplied by the slope, bringing Wolf's observations on the same scale as Wolfer's. It is clear that the harmonization works well and that it shows that Wolfer with the larger telescope saw 65% more groups than Wolf did with the small, handheld telescope [Figure zz] as we would rightly expect. Applying this methodology yields the two backbones [Figure xx4]. We stress that the backbones are *independent* and are based purely on solar observations with no empirical or *ad-hoc* adjustments apart from the [necessary] harmonization just described.

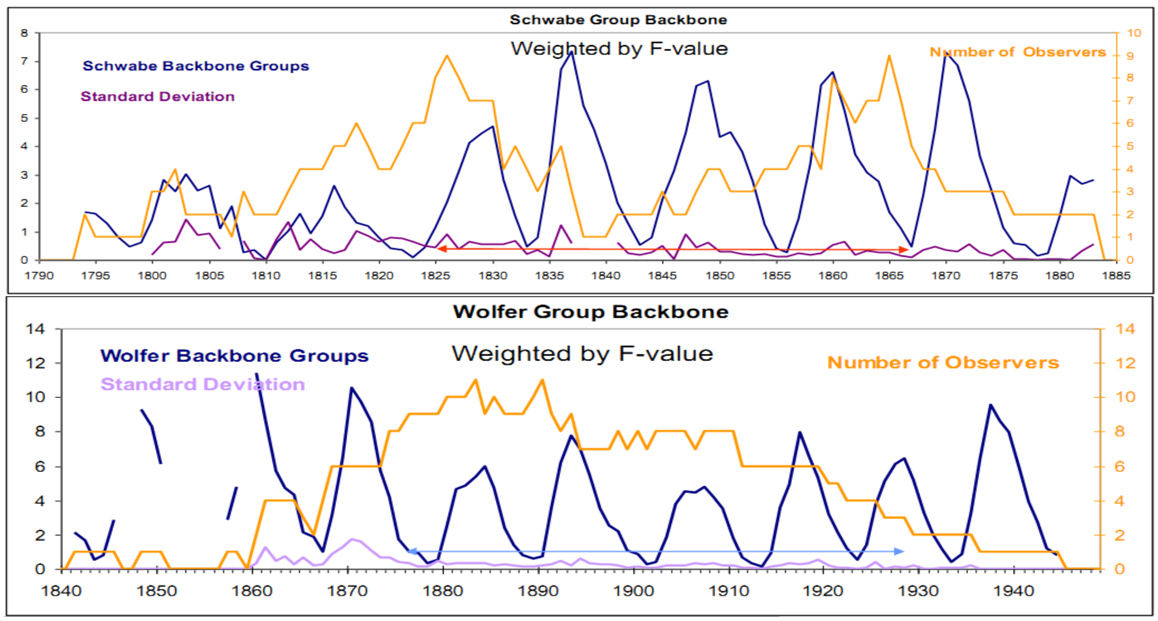


Figure xx4. (Top) Schwabe (interval of observation: red arrow) and (bottom) Wolfer (interval of observation: blue arrow) backbones (blue curves) and the numbers of observers (orange curves) contributing to the mean weighted by their goodness of fit. The standard deviation is shown by the purple curves. For the critical interval 1875-1925, the number of observers per year is high (>5) and the standard deviation is comfortably low.

It is of considerable interest to compare our [Schwabe] backbone with the Group Counts compiled by Hoyt and Schatten [Figure xx5]. Apart from the very noisy period before 1815, the agreement is very good, as would be expected as the series are based on the same data. The minor disagreement ~1838 for the maximum of solar cycle 8 needs to be resolved, and then, of course, we can see the beginning of the drift after 1882.

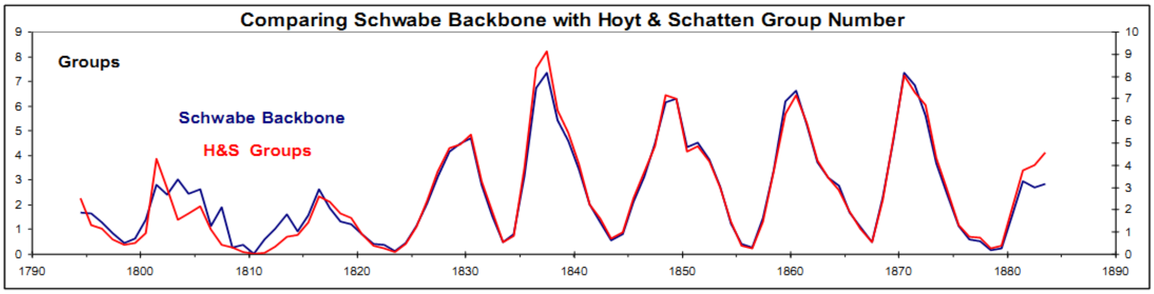


Figure xx5. Number of Groups per year reported by Hoyt and Schatten [REF] (red curve; right-hand scale) and resulting from the Schwabe backbone (blue curve; left-hand scale). The scale of the backbone is at this point 'free floating' and, in fact, 9/10 that of H&S's.

The next order of business is to harmonize the two backbones, i.e. bring them onto the same scale. We shall use the Wolfer scale as the base scale because of its larger number of [better?] observers and choose the common interval 1860-1883 as the basis for the normalization, Figure xx6:

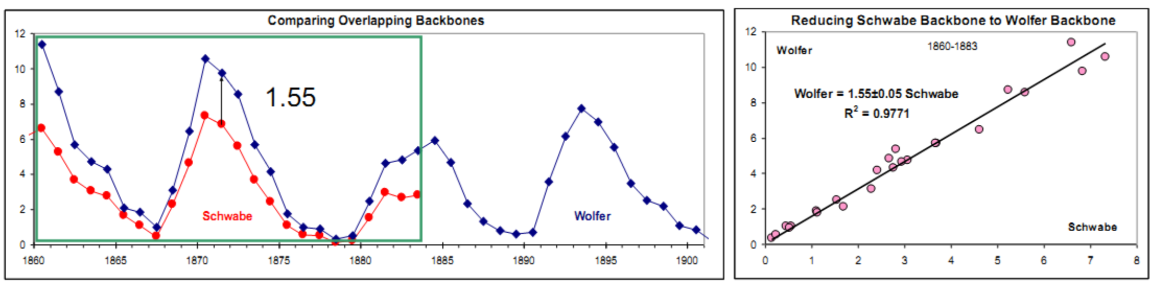


Figure xx6. (Left) overlapping backbones: Wolf (blue) and Schwabe (red). (Right) Linear correlation showing the best (least-square) fit for the interval 1860-1883.

Assuming a normalization factor of 1.55 'explains' 98% of the difference between the two backbones, with no clear systematic variation with time. We can thus get a composite series by multiplying the Schwabe backbone values by 1.55 and then simply average the resulting, normalized Schwabe backbone and the Wolfer backbone, Figure xx7:

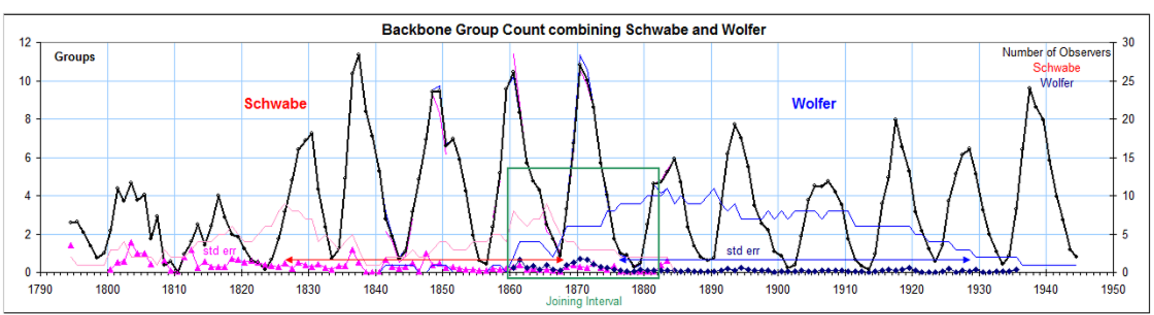


Figure xx7: Composite backbone 1794-1944, with the standard error of the mean.

Hoyt & Schatten used the Group Count from RGO [Royal Greenwich Observatory] as their Normalization Standard. However, the ratio between the RGO group count and the Wolfer backbone count is not stable, Figure xx8:

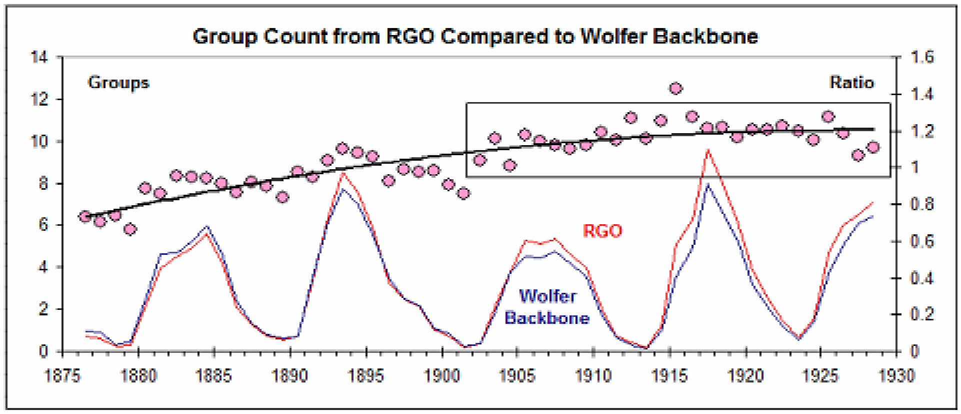


Figure xx8: Ratio (right-hand scale) between Group Count from RGO (red curve) and Wolfer Backbone (blue curve). After ~1900 the ratio is approximately constant, but before there is a clear progressive change. This change translates into the sliding change 1875-1900 seen in Figure xx1.

This and the discrepancy between the Wolfer/Wolf ratio (Figure xx3) that we find (1.65) and that used by Hoyt & Schatten(1.02) seem to be the main reasons behind the large difference between the Group Sunspot Number and the Zurich Sunspot Number before and after ~1885. It is not clear why Hoyt & Schatten's report an almost equal normalization factor for Wolf and for Wolfer with respect to the RGO group count, in spite of the fact that Wolf used the much weaker, handheld 37mm telescope compared to the standard 83mm telescope used by Wolfer.

At this point the composite backbone, so far, is still 'free floating'. We wish to connect it to 'modern' observations so construct yet another backbone (from 1921-2000), based on the counts by the National Astronomical Observatory of Japan (We name the backbone in honor of the principal observer Hisako Koyama, 小山 ヒサ子 (1916-1997), Figure xx9:

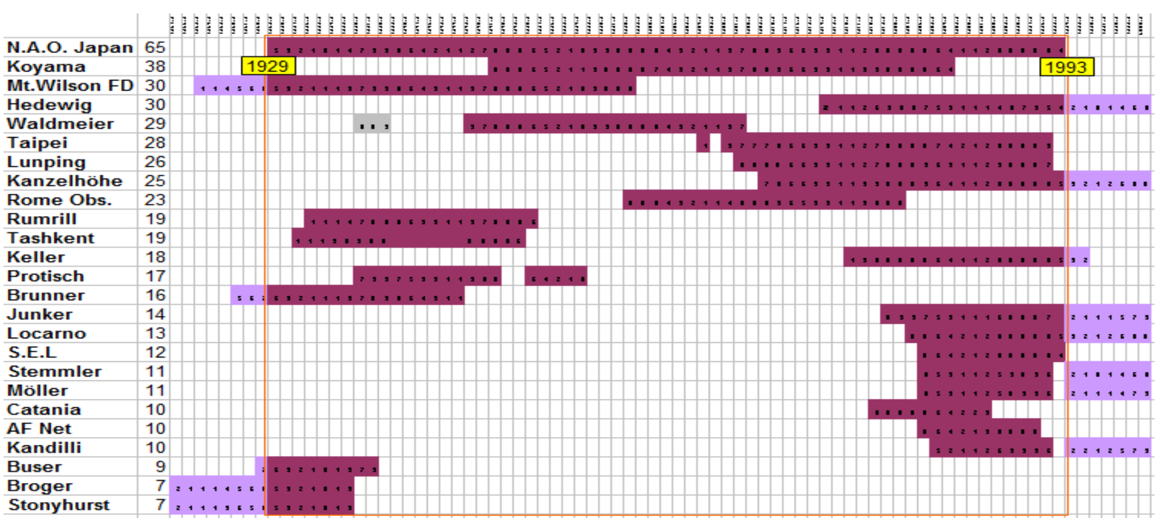


Figure xx9: Coverage and observers for the Koyama Backbone (1921-2000).

The resulting backbone is shown in Figure xx10 in the same format as Figure xx4:

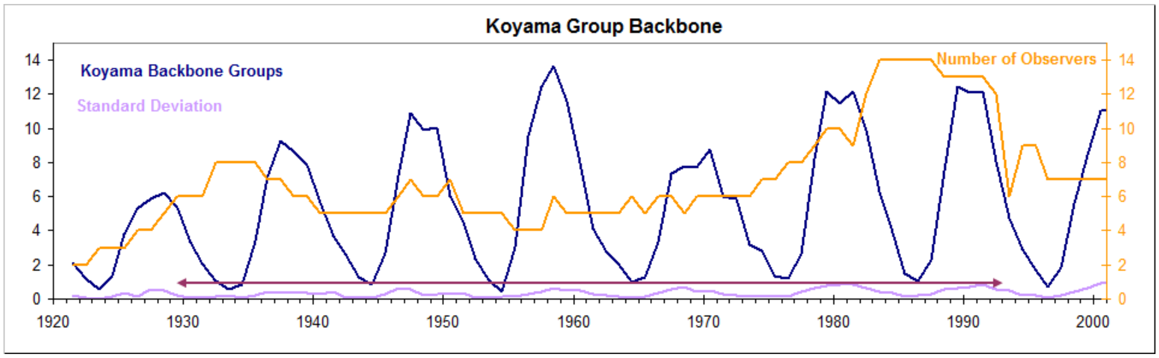


Figure xx10. The Koyama backbone and its number of observers (orange curve). The standard deviation is shown by the bottom purple curve.

The correlation with the Wolfer backbone for the 24 years of overlap (1921-1944) is very high: Wolfer = 1.0002 Koyama (R^2 = 0.9952) firmly establishing the necessary join of the two backbones.

The original set of drawings constituting the long series of observations (1749-1796) by Johann Casper Staudach was examined by Wolf [REF] who determined group counts and sunspot counts for each drawing. Wolf's counts form the basis for the Staudach Backbone. The analysis of this is still ongoing but we shall here report a preliminary result, Figure xx11:

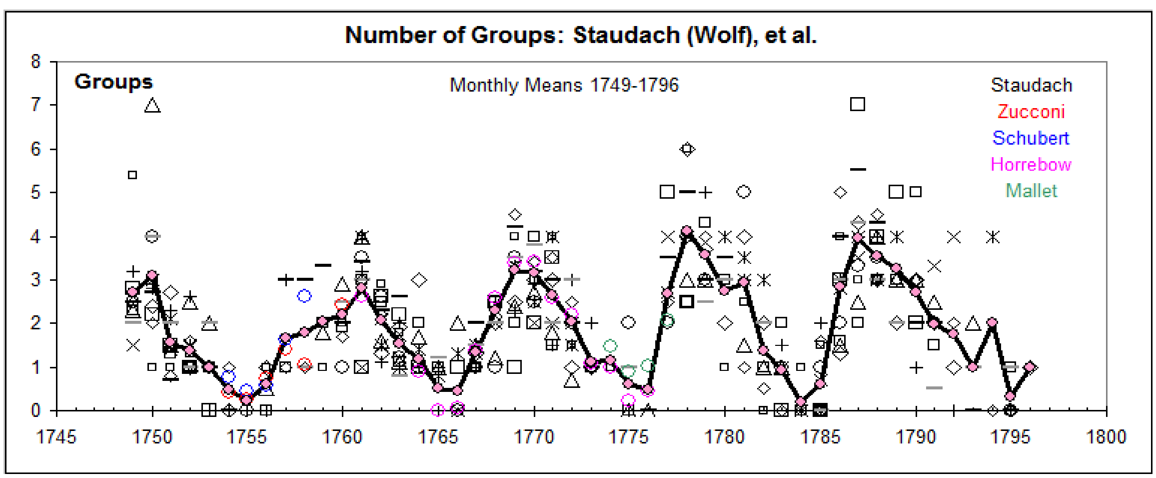


Figure xx11: Open black symbols show the counts of groups by month [as determined by Wolf]. Yearly group counts by Zucconi (Venice), Schubert (Danzig), Horrebow (Copenhagen), and Mallet (Berlin) scaled to the yearly counts by Staudach are shown by colored open circles. The full black curve with small pink circles shows the yearly group counts, averaged over all observers, forming the Staudach Backbone, which is here 'free-floating'. A 'group count' for an interval of time is the average of the number of groups observed by an observer on each day within the interval.

In his 1861 series [REF] Wolf effectively doubled the counts that he had derived for Staudach, followed by a further factor of 1.25-1.5 in the 1882 series. Arlt et al. [REF] suggest that Staudach missed all A- and B-groups [on the modern Waldmeier classification] on account of the relatively low quality of his telescope, perhaps justifying the doubling assumed by Wolf, as A&B-groups make up about 40% of all groups. Comparisons with the geomagnetic and cosmic ray records are consistent with an overall (but still highly uncertain) factor of ~3 to match the combined Schwabe-Wolfer backbone. A task for the Fourth Sunspot Number Workshop is dedicated to improving the determination of that scaling factor, taking into account the recent digitization of Staudach's drawings by Arlt et al. [REF].

Adding the raw group counts from SIDC's database to the Koyama backbone, allows us to present a preliminary synthesis of the evolution of a composite of the average number of groups per year back to 1749 derived from all four backbones, each backbone shown with a different color, Figure xx12:

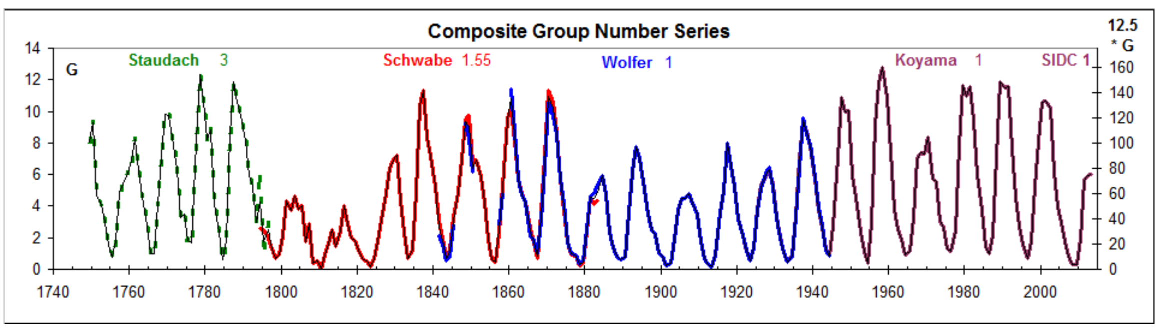


Figure xx12: A composite record of the Group Number, G, back to 1749 derived from the four backbones constructed as described in this section. The numbers to the right of the backbone designations indicate the scale factor applied to each 'raw' backbone to harmonize them to the Wolfer scale. The green *dashed* line marking the Staudach backbone reflects that it is uncertain. The right-hand scale is for the thin black curve showing the quantity 12.5 times the average Group Number, as an 'equivalent' Group Sunspot Number, GSN*.

In this section we have striven to build a series based solely on solar observations. In Chapter 13 we review what Geomagnetism can tell us about Solar Activity, but it is instructive already here to compare the number of groups with the range of the diurnal variation of the geomagnetic field, Figure xx13. Far Ultraviolet Radiation from the Sun, enhanced by solar activity, creates and maintains the E-layer of the Ionosphere where dynamo action causes an electrical current to flow above the dayside of the Earth at about 100 km altitude. The magnetic effect of that current was discovered as early as 1722 by George Graham, is readily observed, and can serve as an independent check on our indices of solar activity.

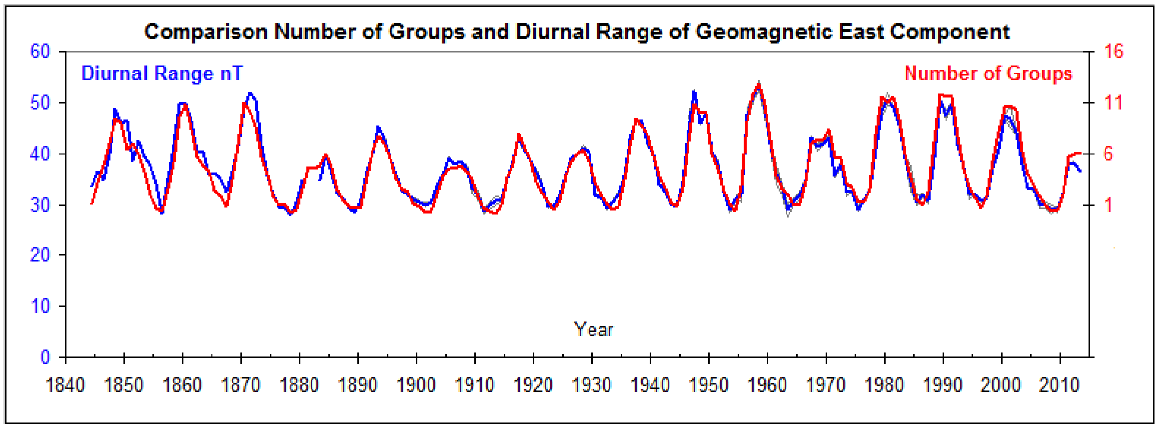
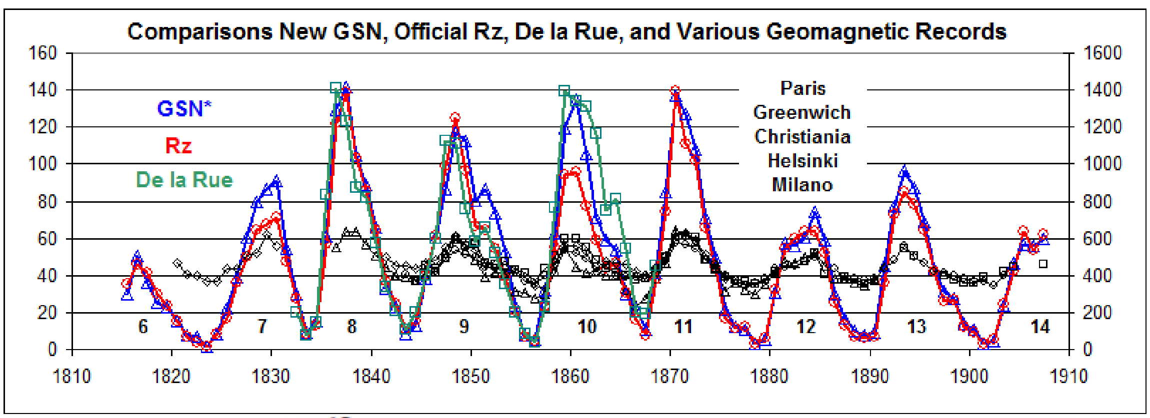


Figure xx13: Number of groups (red curve) compared with the range of the diurnal variation of the East Component (blue curve) of the geomagnetic field.

We can now compare the composite Group Number (GSN*) Series with the Official Zürich Sunspot Number (R_Z) and several geomagnetic indicators, Figure xx14:



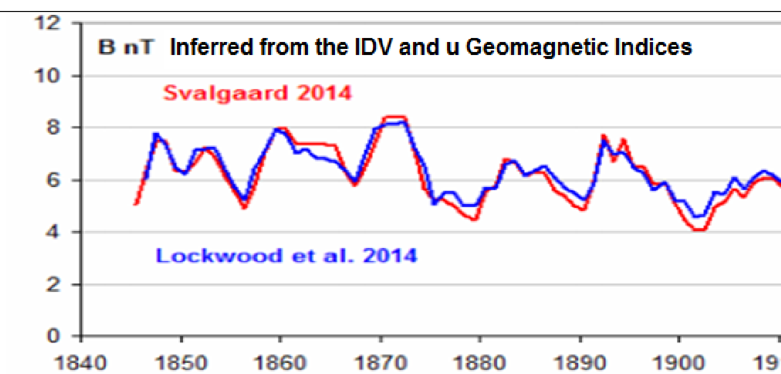


Figure xx14: The composite GSN* matches R_Z well except for cycles 7 and 10. There is also a good match with the (scaled) sunspot areas determined by De la Rue (REF Vaquero et al. 2002).

The geomagnetic record is based on the diurnal ranges of the East Component at the stations listed. The inferred Heliospheric Magnetic Field yields additional support.

Based on these comparisons it does not seem reasonable to apply a wholesale decrease of the Wolf Numbers by 20% before 1849, as advocated in section 6.3. If anything, R_Z is already too low (c.f. cycle 7). The size of cycle 10 (maximum in 1860.1) now becomes an important research problem, possibly a task for resolution at the Locarno 2014 SSN Workshop. This serves as a reminder that much work remains to be done.

Inherent in the concept of the Group **Sunspot** Number is the assumption that the ratio between the number of spots and the number groups, i.e. the average number of spots per group is constant. We can investigate this assumption using data from the German SONNE network of sunspot observers (REF sonne2012} and from the long-running Swiss station Locarno (REF locarno2012} supplemented by observations at Zürich by Waldmeier (REF wald1968) and Zelenka and Keller (REF keller1995). From each data source, the number, *G*, of groups and the number, *S*, of `spots' reported by the observers is extracted and tabulated. `Spots' is in quotation marks because Waldmeier, as we have shown, and to this day Locarno as well, weighted larger spots stronger than small spots. The SONNE observers do not employ weighting: each spot is counted only once. It is important that for both groups of observers, the counting methods (albeit different) have been unchanged over the period of interest.

If the Relative Number, *R*, and the Group count, *G*, are known, the spot count can be calculated as $S = R/k - 10G$, where *k* is the k-factor introduced by Rudolf Wolf to bring observers onto the same scale as Wolf himself, who by definition had $k = 1$. For the later Swiss observers *k* was set by *adoption* to 0.60. The SONNE series is adjusted to match the Swiss k-factor, which, however, is also applied to the group numbers reported by SONNE so that a composite group count can be computed over many observers, effectively resulting in a spot/group ratio that is independent of the k-value. The published data for Waldmeier and SONNE gives us *R* and *G*, so *S* has to be calculated as detailed above. For Locarno, Zelenka, and Keller, both *S* and *G* are available directly. Given *G* and *S*, either determined directly or calculated from *R* and *G*, the average number of spots per group, *S/G*, can now be computed for each year.

Figure xx15 shows that the average number of spots per group has been decreasing steadily for both SONNE and Locarno and is therefore not likely to be due to drifts of calibration or decreasing visual acuity of the primary Locarno observer (Sergio Cortesi since 1957). This is consistent with the conclusion in section 4.2 (Figure zz15) where we compare the weighted counts made by the veteran Cortesi and the new observer Cagnotti from 2008 to the present, and find no systematic difference or variation with time.

Because the Locarno observers weight the spot count according to structure and size of spots, they report more spots that the SONNE observers. This is clearly seen in the bottom panel. Also, in Figure xx15 we plot (top panel) the variation of the ratio between the number of spots and the number of groups for the more than 431,000 SONNE individual daily observations without any correction for k-factors (green line with plus marks). The `raw' data show the same general variation and decline as the adjusted observations. Such a trend could be a solar phenomenon or due to an increasing group count brought about by sharper determination if what constitutes a ‘group’. There seems to be a solar cycle variation as well.

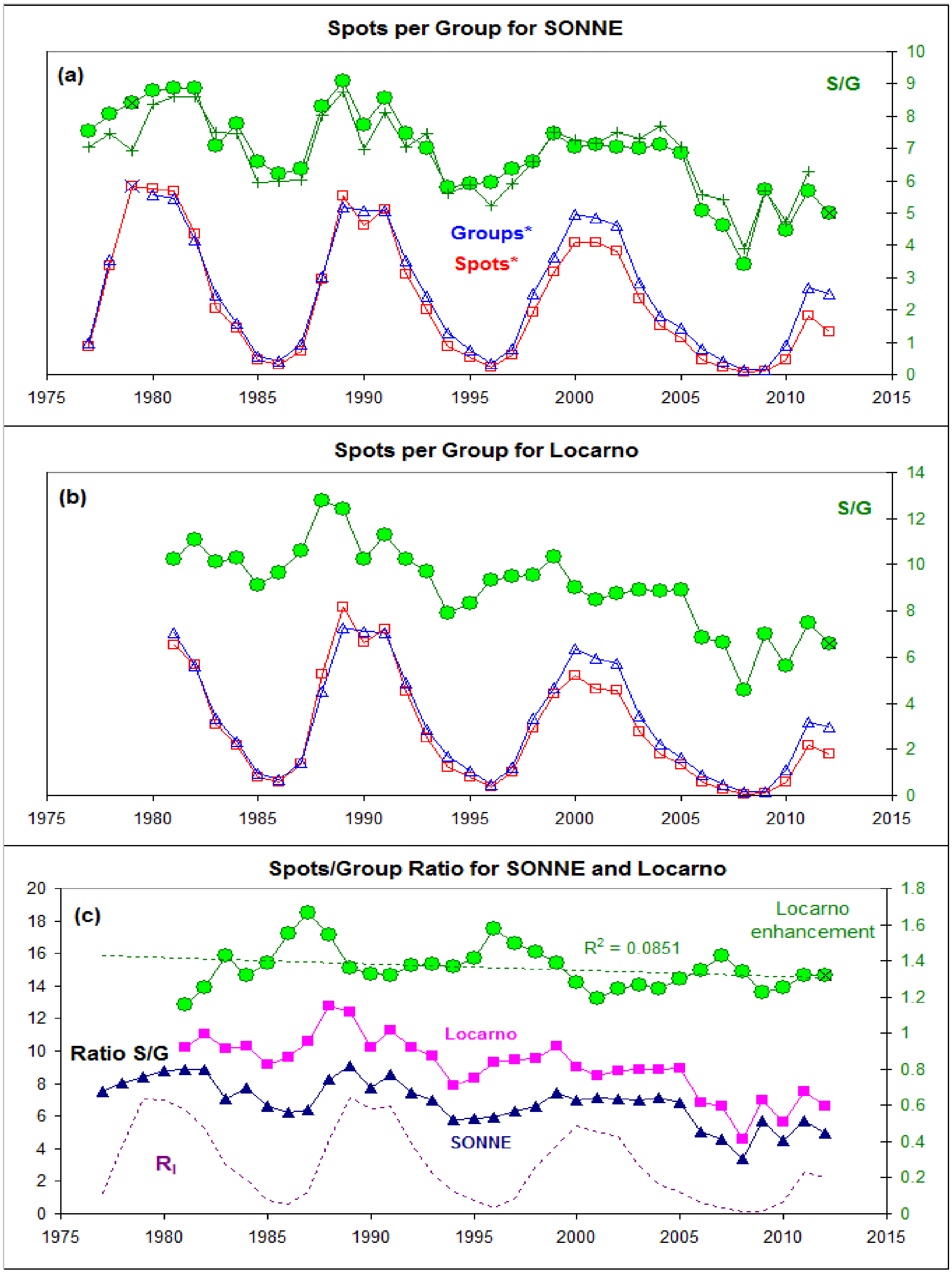


Figure xx15: (Top) The number of spots per group as a function of time (green circles) for SONNE. The green curve with pluses shows the ratio derived from the raw counts, not corrected with k-factors. The lower part of the panel shows the variation of number of groups (blue triangles) and the number spots (red squares) both scaled to match each other before 1992. Note the decreasing spot count, relative to the group count. (Middle) Same, but for Locarno. (Bottom) The decrease of the ratio Spots/Groups for Locarno (pink squares) and for SONNE (blue triangles) using the left-hand scale. The enhancement of the Locarno ratio over SONNE (see text) is shown by the green circles (right-hand scale). The trend indicated is not significant.

When Wolf chose 10 as the weight for Groups in his definition of the Relative Sunspot Number he remarked that he could as well have chosen 9 or 11, but that 10 was close enough to the ratio between spots and groups that he had empirically determined and was certainly 'more convenient'. For Wolfer the ratio spots/groups was on the average 9.0. Figure xx16:

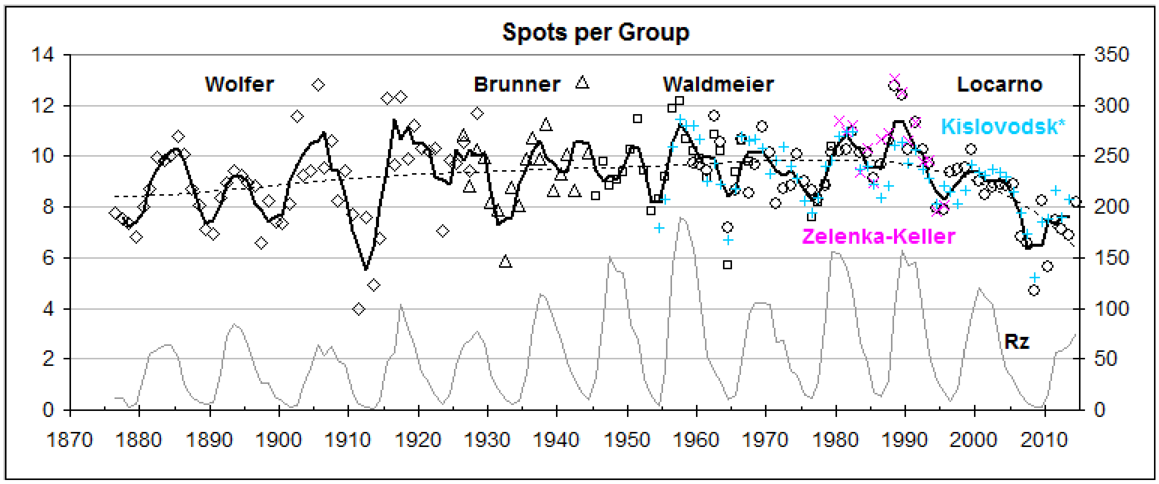


Figure xx16: The ratio between the number of single spots and the number of groups as recorded by the Zurich observers for each year of observation. There is a clear solar cycle dependence (sunspot number shown at bottom) with more spots per group at higher solar activity. The ratio observed at Kislovodsk (with no weighting) scaled to Locarno follows the same general trend.

On account of the weighting one would expect a dramatic increase (~40%) in the ratio when the weighting scheme was introduced. That this is not observed presents a puzzle which at the present time has not been resolved. The recent decrease of the ratio seems also to be seen at Kislovodsk, arguing for a solar cause.

Other solar indicators also tend in the same direction. E.g., for each magnetogram taken at the 150-Foot Solar Tower, a Magnetic Plage Strength Index (MPSI) value is calculated by summing the absolute values of the magnetic field strengths for all pixels where the absolute value of the magnetic field strength is between 10 and 100 gauss. This number is then divided by the total of number of pixels (regardless of magnetic field strength) in the magnetogram. The magnetic calibration after the instrument upgrade in 1982 is believed to be good, or at least stable (REF mpsi2012). On average there is a very nearly linear relationship between MPSI and the sunspot number: SSN* = 54.7 MPSI $^{1.0089}$. We can thus calculate a synthetic SSS* for each (monthly) value of MPSI, and form the ratio between the observed sunspot number and the synthetic one derived from MPSI, Figure xx17. A 5-month, centered running average is shown by blue diamonds. The ratio is high in the approach to solar minimum and in the very early part of the ascending phase of the cycle (large boxes) before settling down at solar maximum where it is well-defined

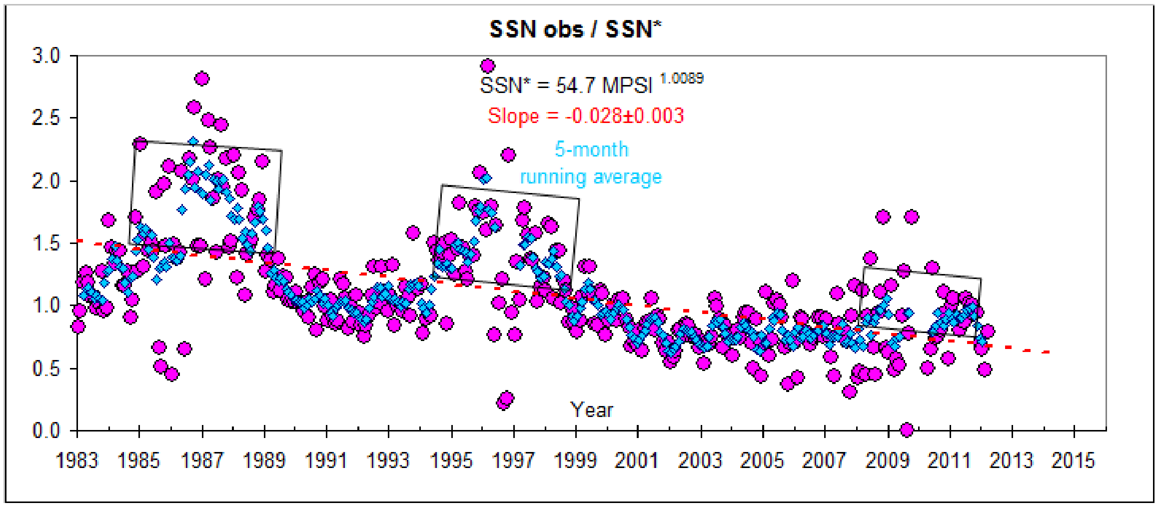


Figure xx17: The observed International Sunspot Number (SSN) divided by a synthetic sunspot number derived from the MWO Magnetic Plage Strength Index (pink circles for monthly values). A 5-month, centered running average is shown by blue diamonds. The ratio is high in the approach to solar minimum and in the very early part of the ascending phase of the cycle (large boxes) before settling down at solar maximum. For solar minimum years, the ratio is between two very small numbers and is thus very noisy and at times undefined. There is also a second-order annual variation of unknown origin, phased with solar distance.

Again we find that the ratio has been declining the past two cycles, consistent with the similar findings by Svalgaard & Hudson (REF sval2010} using the F10.7 microwave flux as a proxy for the magnetic flux, and by Lefèvre & Clette (REF lefev2011) analyzing the time variation of the distribution of group classes. Observations at or after the current maximum should settle the matter of the reality of a secular change. Unfortunately, MWO is currently not taking magnetograms, teaching us the detrimental effect of stopping a valuable synoptic observing program).

4.2 The 1947 Waldmeier 'Jump' (1930-1980)

In 1961 Max Waldmeier published [REF] the definitive Zürich sunspot numbers up until 1960. He noted that "Wolf counted each spot – independent of its size – but single. Moreover, he did not consider very small spots, which are visible only if the seeing is good. In about 1882 Wolf's successors changed the counting method, which since then has been in use up to the present. This new method counts also the smallest spots, and those with a penumbra are weighted according to their size and the structure of the umbra". In 1968 [and 1948, REFS] Waldmeier codified the weighting scheme as follows "Später wurden den Flecken entsprechend ihrer Größe Gewichte erteilt: Ein punktförmiger Fleck wird einfach gezählt, ein größerer, jedoch nicht mit Penumbra versehener Fleck erhält das statistiche Gewicht 2, ein kleiner Hoffleck 3, ein größerer 5"[1]. However, Wolfer in 1907 (REF Mitteilungen, Nr. 98) explicitly states: "Notiert ein Beobachter mit seinem Instrumente an irgend einem Tage *g* Fleckengruppen mit insgesamt *f* Einzelflecken, ohne Rücksicht auf deren Grösse, so ist die daraus abgeleitete Relativzahl jenes Tages $r = k(10g+f)$"[2]. We can verify that Wolfer, contrary to Waldmeier's assertion that the Zürich observers began to use weighting 'around 1882', did not weight the spots according to Waldmeier's scheme by comparing Wolfer's recorded count with sunspot drawings made elsewhere, e.g. Figure zz1:

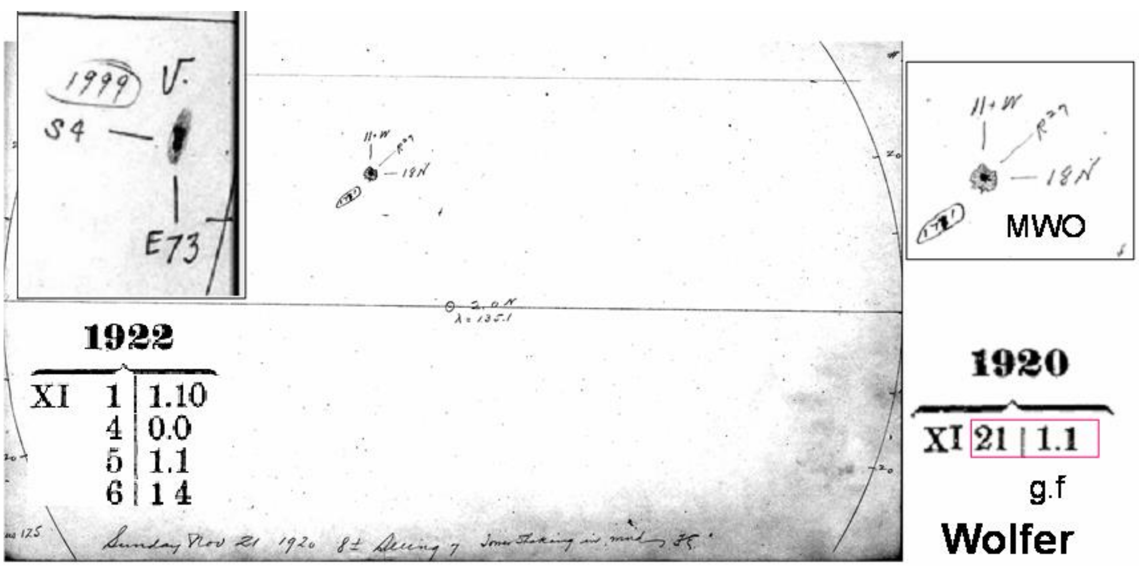


Figure zz1: Drawing from Mount Wilson Observatory (MWO) of the single spot with penumbra on 21st Nov. 1920. The insert at the left shows a similar group observed at MWO on 5th Nov., 1922. For both groups, Wolfer should have recorded the observation as '1.3' if he had used the weighting scheme, but they were recorded as '1.1', thus counting the large spots only once (*with no weighting).*

[1] A spot like a fine point is counted as one spot; a larger spot, but still without penumbra, gets the statistical weight 2, a smallish spot within a penumbra gets 3, and a larger one gets 5.

[2] When an observer at his instrument on any given day records *g* groups of spots with a total of *f* single spots, without regard to their size, then the derived relative sunspot number for that day is $r = k(10g+f)$.

There are many other such examples (e.g. 16th September, 1922 and 3rd March, 1924) for which MWO drawings are available. We thus consider it established that Wolfer did not apply the weighting scheme. This is consistent with the fact that nowhere in Wolf's and Wolfer's otherwise meticulous yearly reports in the *Mittheilungen über Sonnenflecken* series is there any mention of a weighting scheme.

We shall not here speculate about the motive or reason for Waldmeier ascribing the weighting scheme to Wolfer. Waldmeier himself was an assistant to Brunner since 1936 and performed routine daily observations with the rest of the team so would presumably have known what the rules were. Figure zz2 shows that Brunner and Waldmeier were observing very close to the same scale in 1937:

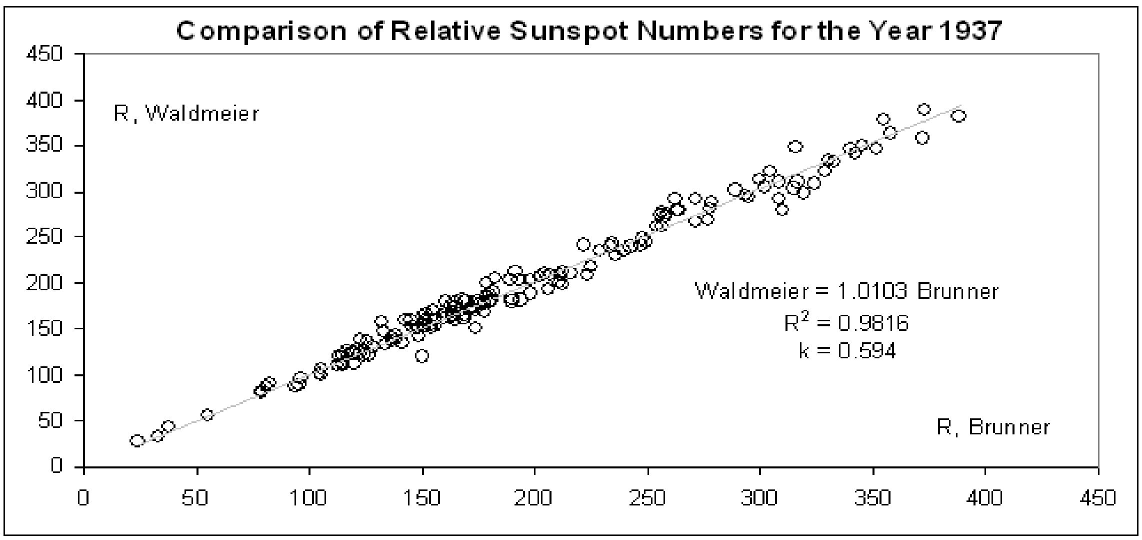


Figure zz2: Comparison of daily `raw' (i.e. with no *k*-factor applied) relative sunspot numbers derived by Waldmeier and Brunner for the year 1937. The *k*-factor for Waldmeier comes to 0.594=0.6/1.0103 (Brunner reports 0.59).

All the archives at Zürich appear to be lost, but in spite of the lack of original material it is possible to perform a statistical analysis as follows. From the RGO series of sunspot areas (REF, Hathaway) we select days where only one group was recorded on the disk. If that group had precisely one spot, the sunspot number for that day would be recorded as 11 by Wolf and as 7 (0.6*(10*1+1) = 6.6) by Wolfer and later observers, if there were no weighting by size and complexity. Figure zz3 shows the distribution of solitary large spots over time. During the Wolf period, the largest single-spot groups had a sunspot number of 11 (there were scattered lower values in the 1880s due to averaging with Wolfer). Starting with Wolfer, there were many large groups with a single spot counted as just one spot (sunspot number 7), i.e. no weighting. With Brunner and later, the 7s effectively disappear. This seems to indicate that some weighting was done already by Brunner, explaining why Waldmeier matched Brunner's counts. On the other hand, there are many 8s, so any weighting must have been slight and there simply were very few solitary spots during the active 1940s and 1950s, so it is difficult to draw a definite conclusion from this analysis about the amount of weighting done by Brunner.

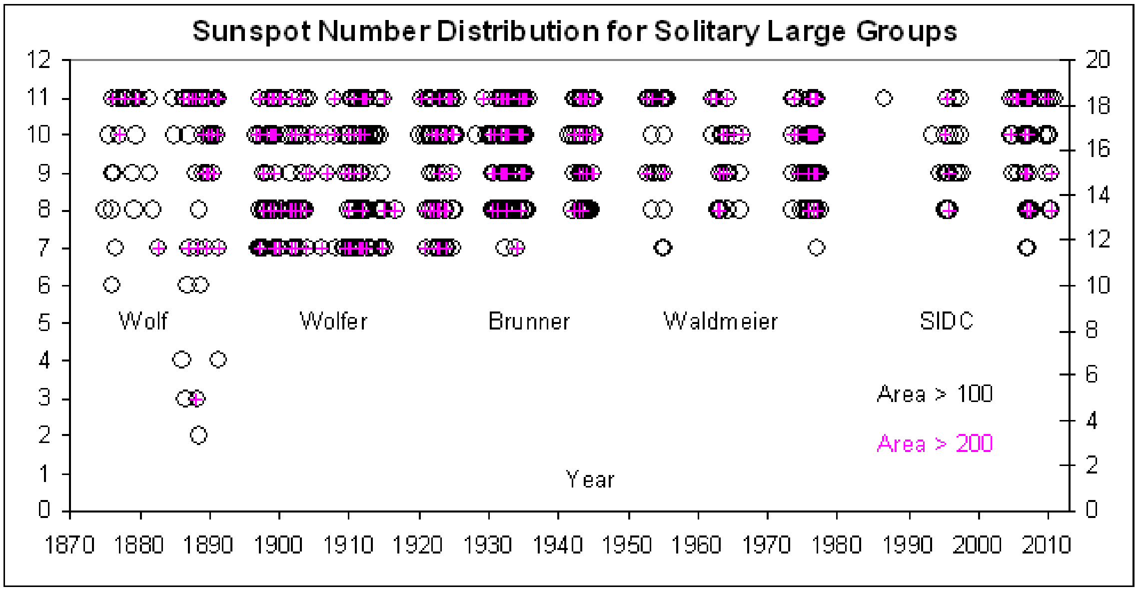


Figure zz3: For days where only *one* group was observed, the sunspot number (if less than 12) for that day (i.e. for that solitary group) is plotted if the projected area of the group is larger than 100 μHemisphere (circles) and larger than 200 μH (pink '+' symbols). The right-hand scale is for sunspot number divided by 0.6, i.e. on the original Wolf scale.

Brunner himself writes in 1936 [REF TE041i002p00210] that "The subjective method of counting may also have an influence. In large centers of activity one is inclined – and this perhaps rightly – to give some single spots according to their sizes a different weight", but then continues "In the spot-statistics, introduced for our observatory by Rudolf Wolf 80 years ago, all these circumstances have been considered as far as possible by introducing a reduction-factor on Wolf's unit. The latter is determined by comparison of corresponding observations. In determining the Wolf relative-number a weight of ten is given for the groups of spots and a weight of one for the number of single spots or nuclei"[3]. This seems to indicate that spots were not weighted although Brunner at times might be inclined to do so. His assistant Max Broger (observed 1897-1936) appears to have weighted some of his counts, so it is conceivable that discussion was going on at Zürich about the preferred counting method.

The long-time observer Herbert Luft (1908 Breslau, Germany; 1988 New York, USA) was a corresponding contributor to the Zürich series. As a teenager he joined various Amateur Associations and was mentored by the slightly older Wolfgang Gleissberg who suggested Luft concentrate on Sunspots. Luft's notebooks are archived at AAVSO [REF] and L.S. recently digitized the observational material. The nearly 12,000 pages yielded 10,434 usable observations [when image quality was good enough] during 1924-1987. Interesting enough, Luft started used the weighting scheme 24th February 1947, but

[3] Presumably meaning umbrae (spots) within each penumbra

abandoned the scheme April 5th the next year. Figure zz4 shows two pages from March 1948. Luft also started to use the Zürich Group Classification System at the same time (and did not later abandon the classification). The spot count for the A-groups were the same with (number to the right of the class letter) and without weighting (number to the left of the class), while the H-I, D, and E class groups had a weighted spot count on average 45% higher.

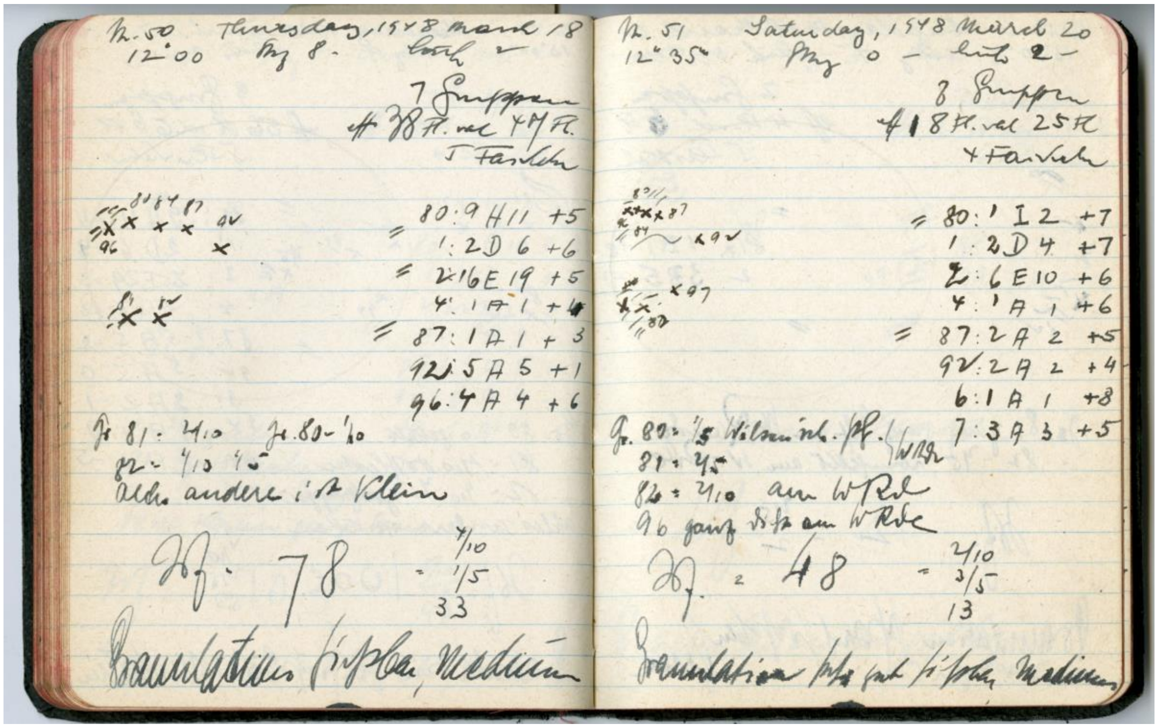


Figure zz4: Pages from Herbert Luft's notebook for March 18th and 20th, 1948. South is up and West is left. The letters in the columns at the right on each page show the Zürich Group Class for each numbered group, flanked left and right by the raw and the weighted count of spots in each group. The telescope was a superb 54mm aperture Merz used at 96X magnification. In spite of the crude-looking drawings, the counts of groups and spots are of high quality as can be seen from comparisons with MWO.

We interpret this to indicate that Waldmeier was trying to get other observers to adopt the weighting scheme, but with little success. To our knowledge, the weighting was only adopted on a continuing basis by the Zürich observers and not by any others. Wolf and Wolfer published all raw observations from corresponding observers. Brunner reduced that to only the Zürich observers, and Waldmeier stopped the publication of all raw observations completely, noting that all data would be available in the archives of the observatory. Unfortunately, it appears that all data in the archives are lost for times since the employment of Waldmeier in 1937. We make a plea here that anybody who has archived correspondence with the Zürich observatory since 1925 to send copies of the material to us so that we can recover at least some of the raw data.

One such case is that of Harry B. Rumrill (1867-1951) who was a friend of Rev. Quimby (American observer 1897-1921 whose data was utilized in the Group Backbone Construction). Rumrill continued Quimby's observations of sunspots through to 1951. His data and notebooks were considered lost until L.S. with the help of 'The Antique Telescope Society' (Bart Fried, Jack Koester) located most of them in early 2012. Rumrill used 2" telescopes early on, but from 1942 employed exclusively a 4" Brashear refractor (Figure zz5, left). The ratio between the Zürich Sunspot Number and Rumrill's shows the increase of the Zürich values from ~1945:

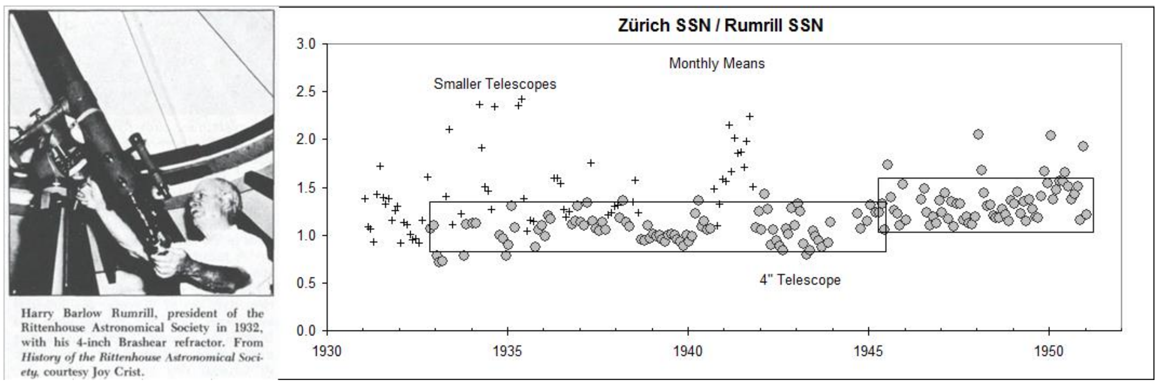


Figure zz5: Ratio of monthly means R_Z/(Rumrill SSN). Data taken with small telescopes are plotted as small '+' symbols.

The sunspot area data can be utilized further as there is a strong (slightly non-linear) relationship between the sunspot number, R_Z, and the projected (i.e. observed) sunspot area, S_A, on average: $R_Z \approx K\ S_A^{0.732}$ with no linear offset, so we can meaningfully form the ratio between the quantities, Figure zz6; it seems clear that the ratio is lower than average before ~1947 and higher thereafter. We ascribe the difference to introduction of the full weighting scheme, as there is no metadata indicating a change in derivation of the RGO sunspot areas at that time

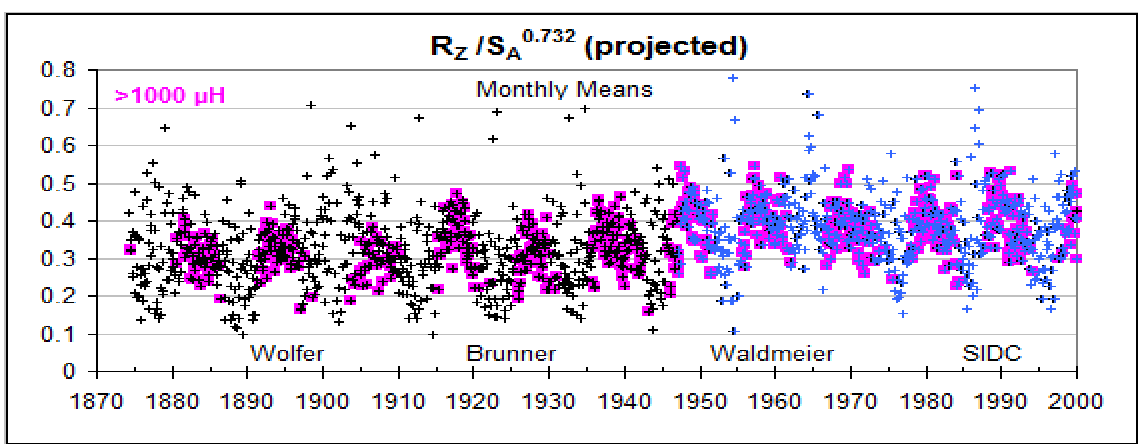


Figure zz6: The ratio $R_Z/S_A^{0.732}$ (see text) for monthly means. If the mean area, S_A, is in excess of 1000 μHemispheres, the data point (+) is marked by a pink square.

Using the value for the factor K derived from the pre-1947 data to calculate the monthly mean R_Z from S_A we get excellent agreement before 1947, Figure zz7, but a definite discrepancy thereafter, with the observed R_Z being larger by a factor of 1.22 than the calculated value, call it R_C, we would expect from S_A. This suggests that the weighting was fully implemented by 1947.

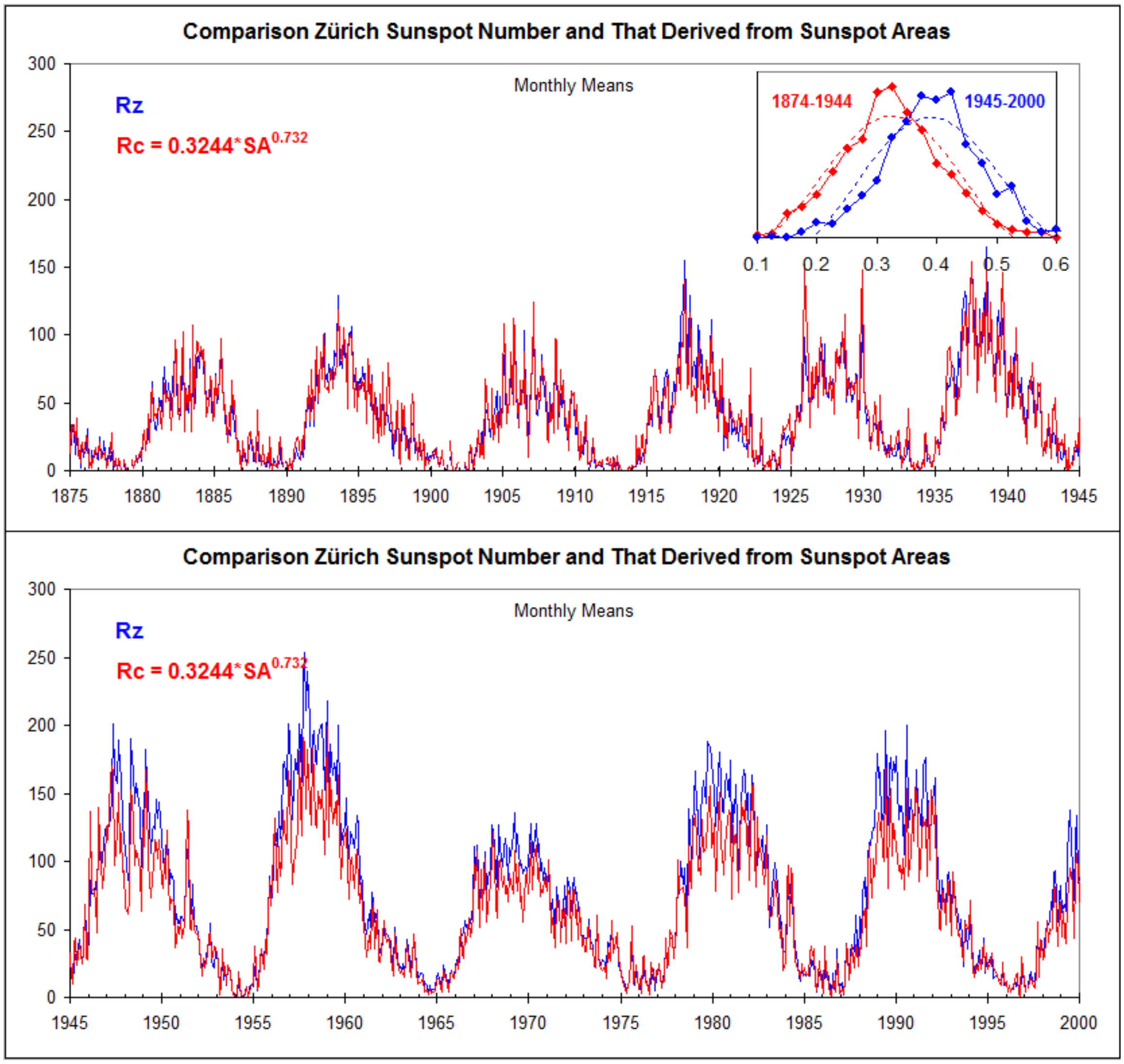


Figure zz7: Calculated, R_C red, and observed, R_Z blue, Zürich Sunspot Number using the relationship derived before 1945. The constant K = 0.3244 is determined from the best fit before 1945. The insert shows the distribution of data points in Figure zz6 partitioned by the year 1945.

From ~40,000 Ca-K spectroheliograms taken at the 60-foot tower at Mount Wilson between 1945 and 1985 a daily index of the fractional area of the visible solar disk occupied by plages and active network has been constructed (REF Bertello et al. 2008). Monthly averages of this index are strongly correlated (R^2=0.8) with the sunspot number.

Using the correlation based on the Wolfer-Brunner era we can calculate the expected sunspot number for the Waldmeier era from the Ca-K index, Figure zz8. On average, the observed sunspot number after 1945 is a factor 1.21 higher than the expected value, again showing the influence of the weighting of sunspots according to size, coinciding with the tenure of Waldmeier:

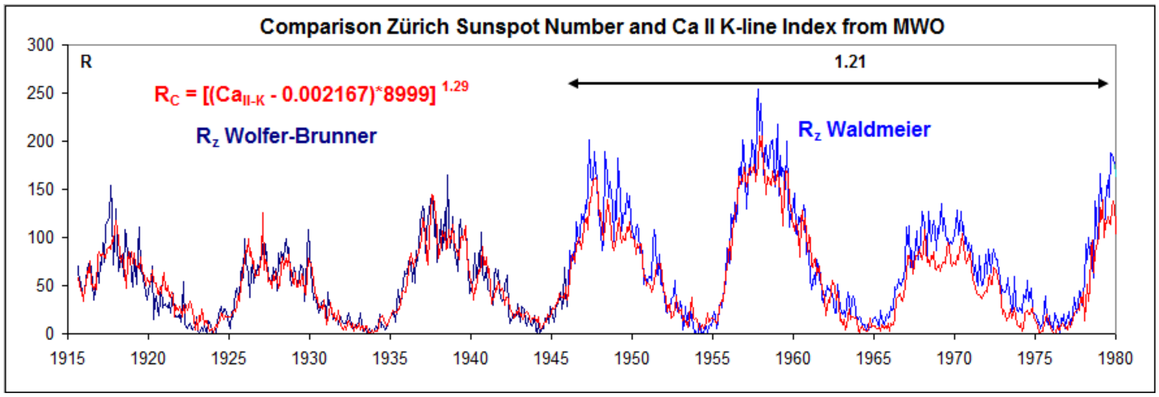


Figure zz8: Comparison of the MWO Ca II K-line index with the Zürich sunspot number.

The ionospheric F2-layer critical frequency, f^oF2, is the maximum radio frequency that can be reflected by the F2-region at vertical incidence (that is, when the signal is transmitted straight up into the ionosphere). The critical frequency has been found to have strong solar cycle dependence [REF, Sethi et al., angeo-20-1677-2002]. Back in 1952 Ostrow and PoKempner [REF JGR, 1952 JZ057i004p00473] compared the dependence of f^oF2 on the Zürich sunspot number and concluded that there are “differences in the relationship between f^oF2 and sunspot number for the current (18th) and preceding (17th) sunspot cycles”, Figure zz9.

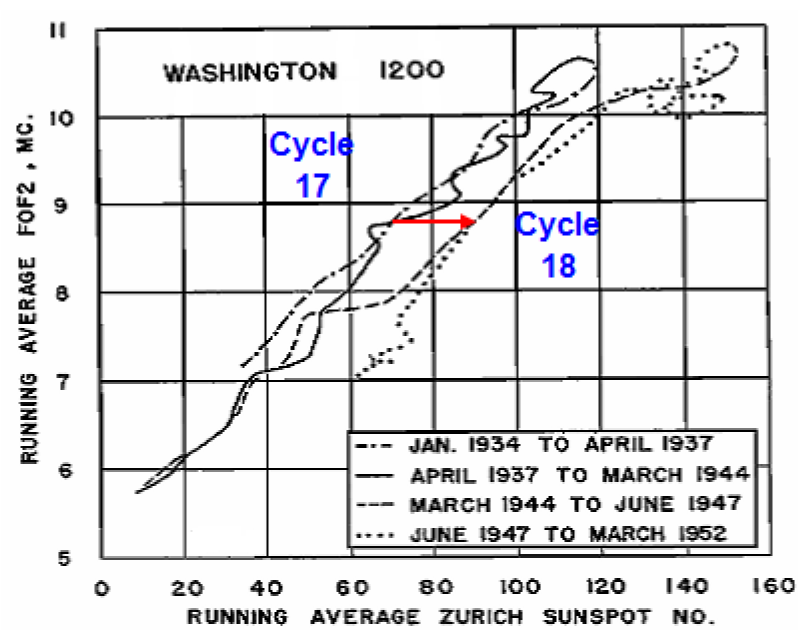


Figure zz9: 12-month running average of the monthly median f^oF2 at local noon against 12-month running average of the monthly Zürich sunspot number. It is instructive to follow the dashed line (March 1944 to June 1947) from the low sunspot numbers of cycle 17 to the high values of cycle 18. Adapted after Qstrow and PoKempner (1952).

The shift (red arrow) in sunspot number to bring the curves for cycles 17 and 18 to overlap is the now familiar ~20%. Today we can ascribe their further conclusion that "the sunspot number is therefore not entirely satisfactory as an index for ionospheric variations" to the result of the introduction of Waldmeier's weighting scheme. The 'fault' is not with the relationship, but with the sunspot number.

As we shall see in Chapter 13, Far Ultraviolet radiation from the Sun, enhanced by solar activity, creates and maintains the E-layer of the Ionosphere where dynamo action from moving air causes an electric current to flow above the dayside of the Earth at about 100 km altitude. The magnetic effect of this current is readily measured by magnetometers on the ground and is best seen in the East Component of the geomagnetic field. The current stays fixed with respect to the direction to the Sun and its magnetic effect, deflecting the 'magnetic needle' at a right angle to the current, increases to a maximum at about 8^h local time, then disappears when the current is overhead, and finally increases again, but in the opposite direction, to a maximum at about 2^h. The range, rY, from the morning deflection to the afternoon deflection, depends essentially on the solar zenith angle and the FUV flux. In the yearly average, the zenith angle dependence averages out, and for geomagnetic stations in the latitude range 20º-60º the remaining variation of rY from station to station is small, mainly due to local inhomogeneities in underground conductivity. Normalizing the range for a given station to a reference station (POT-SED-NGK) eliminates those small variations and allows us to make a composite of all stations. The result for observations since 1890 from a large number of observatories is shown in Figure zz10.

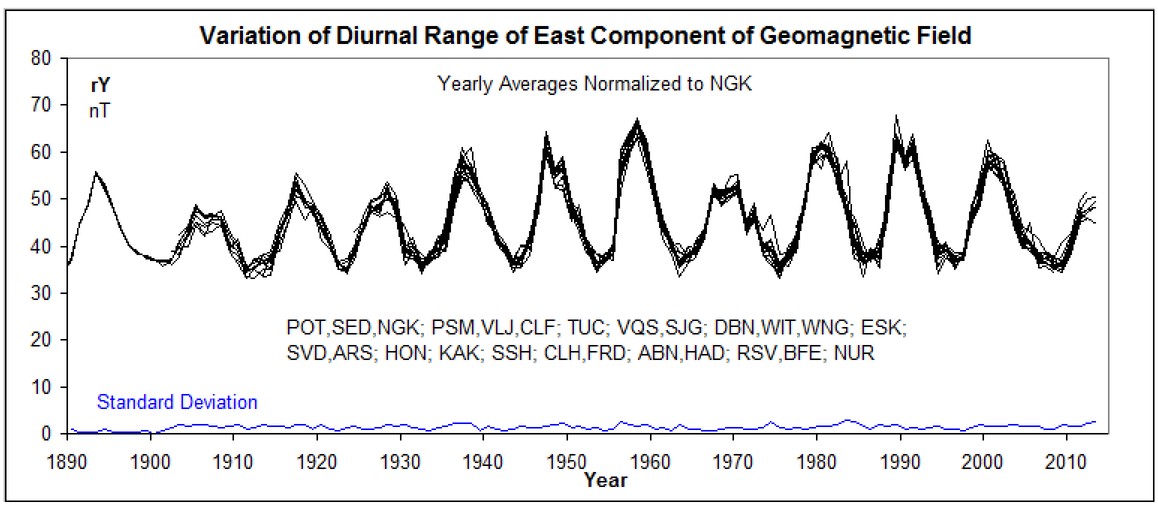
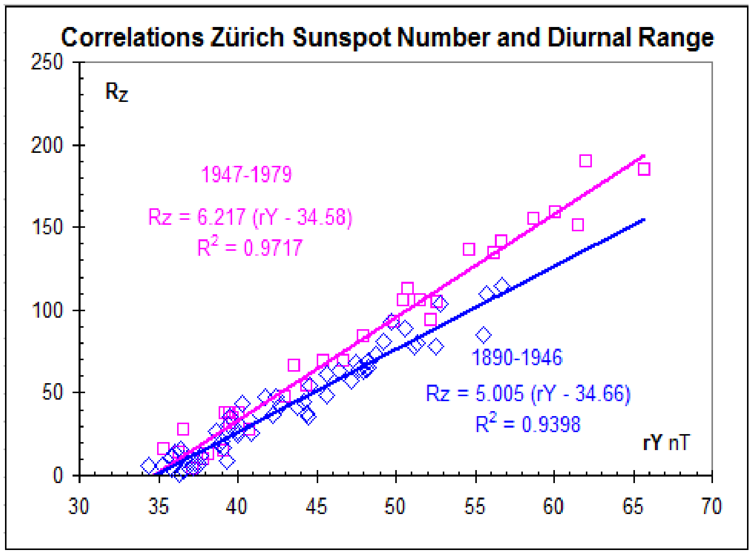


Figure zz10: Composite record of the ranges of the diurnal variation of the East Component of the geomagnetic field. The composite is the average of long series of observations from 14 'chains' of stations (identified by their standard station codes), each chain plotted with a thin black line. A chain is the combined record of a station and its replacement stations that were necessary over time to escape urban development, normalized to the POT-SED-NGK chain. The very small standard deviation is shown in blue at the bottom of the Figure.

That Figure zz10 looks very much like a plot of the sunspot number is, of course, not a surprise as the linear correlation coefficient is in excess of 0.97. With such high correlation it should be possible to see the influence of weighting. Indeed, Figure zz11 shows that the slope of the regression line is different before and after 1947, and that in the ratio 6.217/5.005 = 1.24, again suggesting that weighting increases the sunspot number by about that amount.



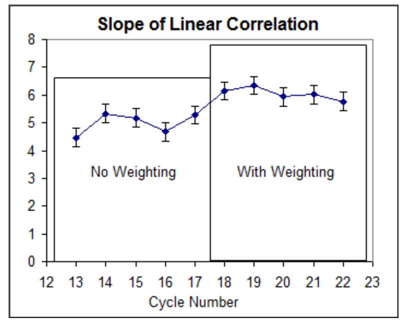


Figure zz11: (Left) Linear correlations R_Z as a function of rY for time before and after 1947. (Right) Variation of slope with time.

Calculating the slope of the correlation for each sunspot cycle (Figure zz11, right) we find, as before, that the increase in slope takes place between the 17th and 18th sunspot cycle [see also REF CAWSES Newsletter]. There is therefore little doubt that Waldmeier introduced the weighting scheme in full force in or about 1947.

At the reference station Locarno weighting has been used since the beginning in 1957, closely following Waldmeier's prescription [Sergio Cortesi, Personal Communication]. To assess the magnitude of the increase due to weighting L.S. undertook to examine all the drawings and individual counts of groups and spots made at Locarno for the past decade and re-count the spots with and without weighting. There were 3229 observation days with 9532 groups containing 49,318 un-weighted spots at the time of writing. The weighted spot count was 72,548, for an excess of 47%. The counts translate into an average sunspot number of 26.88 [(10*9532+49318)/3229*0.6] without weighting and 31.19 with weighting, for an excess of 16% for this rather low solar activity. It is, perhaps, noteworthy that the average number of (unweighted) spots per group for this period (2003-2014) is low, only 5.17.

To verify that the re-count is valid, i.e. that L.S. has understood and applied correctly the Waldmeier weighting scheme, the observer Marco Cagnotti in Locarno have agreed to maintain a parallel count of unweighted spots at a continuing basis since January 1st, 2012, following a brief trial in August 2011. We remind the reader that the sunspot count that Locarno is reporting is done visually at the telescope and not from the drawings. It is rare, though, that there is a difference.

Figure zz12 shows that Svalgaard and Cagnotti very closely match each other in applying the weighting scheme, thus sufficiently validating the approach.

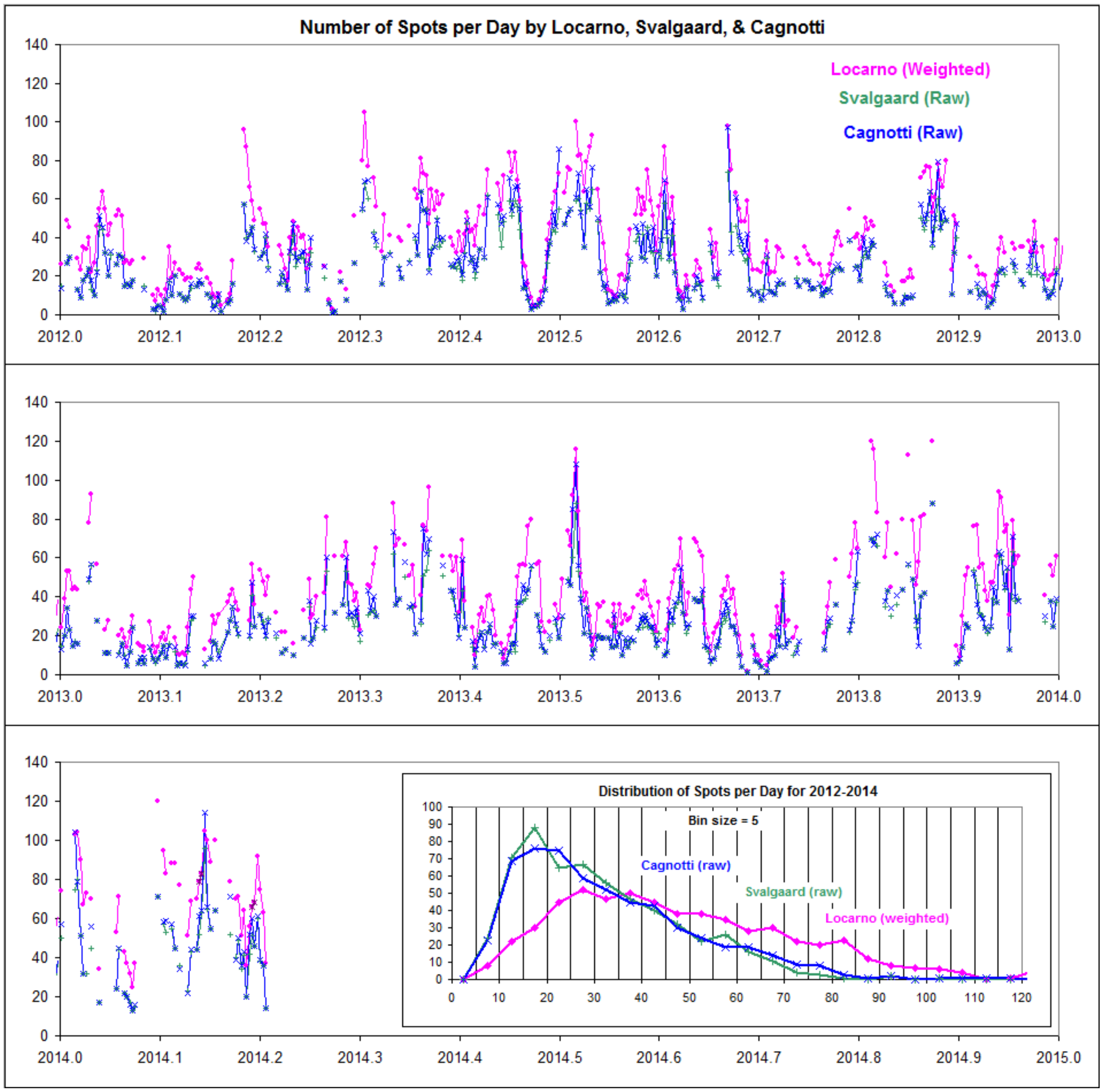


Figure zz12: Comparison of the number of sunspots per day determined by Cagnotti (blue) and Svalgaard (green) without weighting, i.e. by counting each spot singly as prescribed by Wolfer and Brunner with the number reported by Locarno (pink) employing the Waldmeier weighting scheme. The insert shows the distribution of counts in bins of five.

To determine the effect on the Relative Sunspot Number of the weighting we evaluate the Relative SSN = 10 Groups + Spots for Locarno, Cagnotti, and Svalgaard and compare that with the International Relative Number Ri divided by the k-factor of 0.6, Figure zz13. Ideally the ratio between SSN and Ri/k should be unity, which it very closely is (0.99).

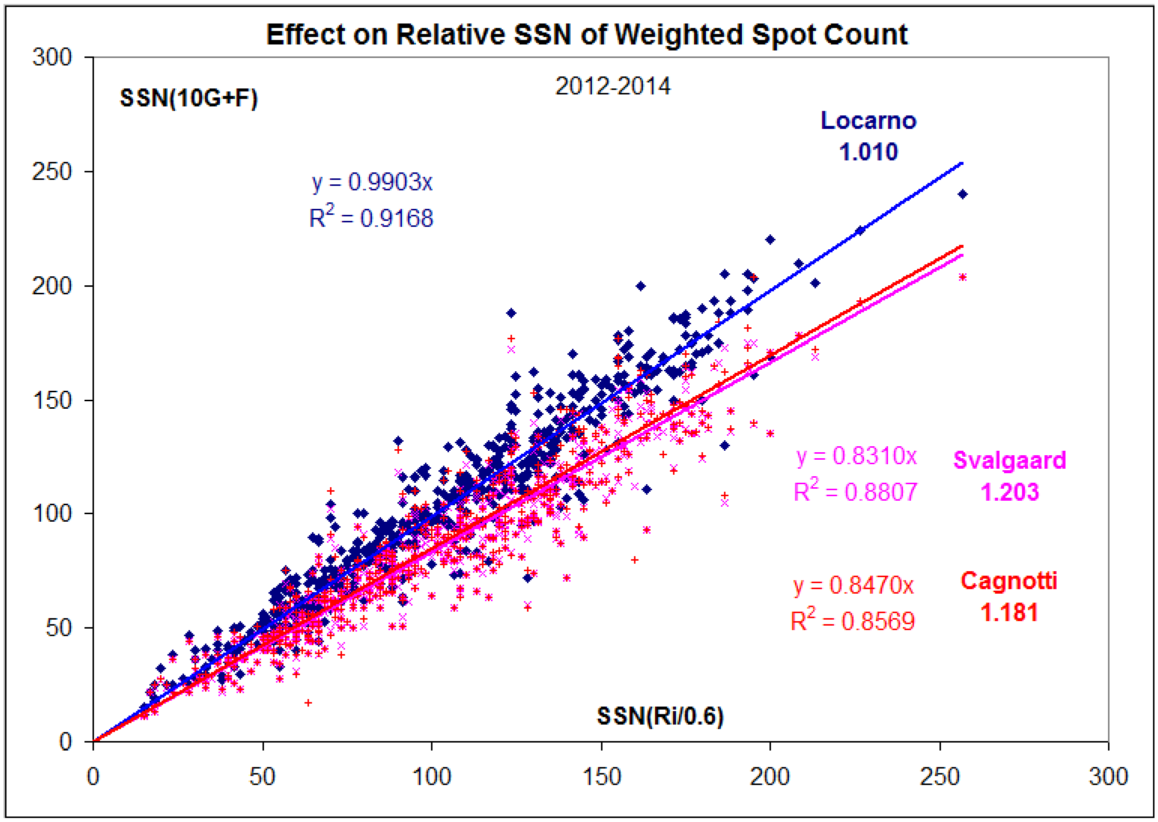


Figure zz13: The relative sunspot number calculated from the weighted spot count reported by Locarno (blue) compared to the International Sunspot Number without k-factor. The unweighted counts by Svalgaard (pink) and Cagnotti (red) agree very well with each other and translate into a Sunspot Number that is only 0.839 of the International Number (which then is higher by a factor of 1.19 on average).

Calculating the weight factor as in Figure zz13, but for each year separately, shows that there is clear, but weak, sunspot cycle dependence, Figure zz14, with a slightly higher weight factor for higher solar activity.

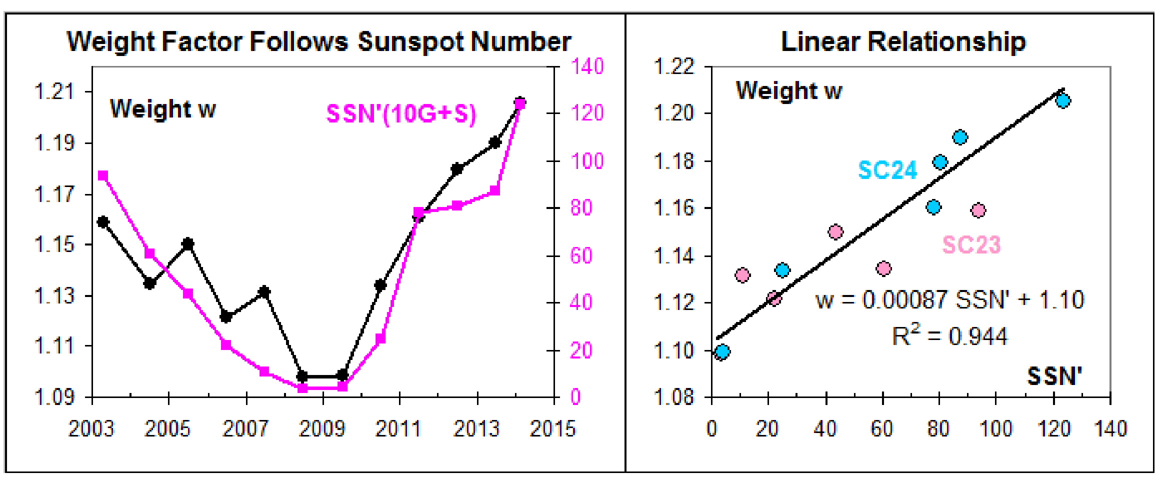


Figure zz14: (Left) The weight factor, w, separately for each year (black). Also plotted is the 'true' Wolf Number (pink) calculated as SSN' = 10*G + S, using for S the number of unweighted spots determined by L.S. (as Wolf and Wolfer would have done it). (Right) The linear relationship between weight factor and 'true' relative sunspot number. With the International Sunspot Number (encumbered by the 0.6 k-factor and weighting), the slope is, of course, larger and stands at 0.00107.

Is the weight factor observer dependent? With a novice one might be inclined to think so, but with training, observers tend to converge to agreement. We can compare the weighted counts made by the veteran Cortesi and the new observer Cagnotti from 2008 to the present, Figure zz15; there does not seem to be any systematic difference:

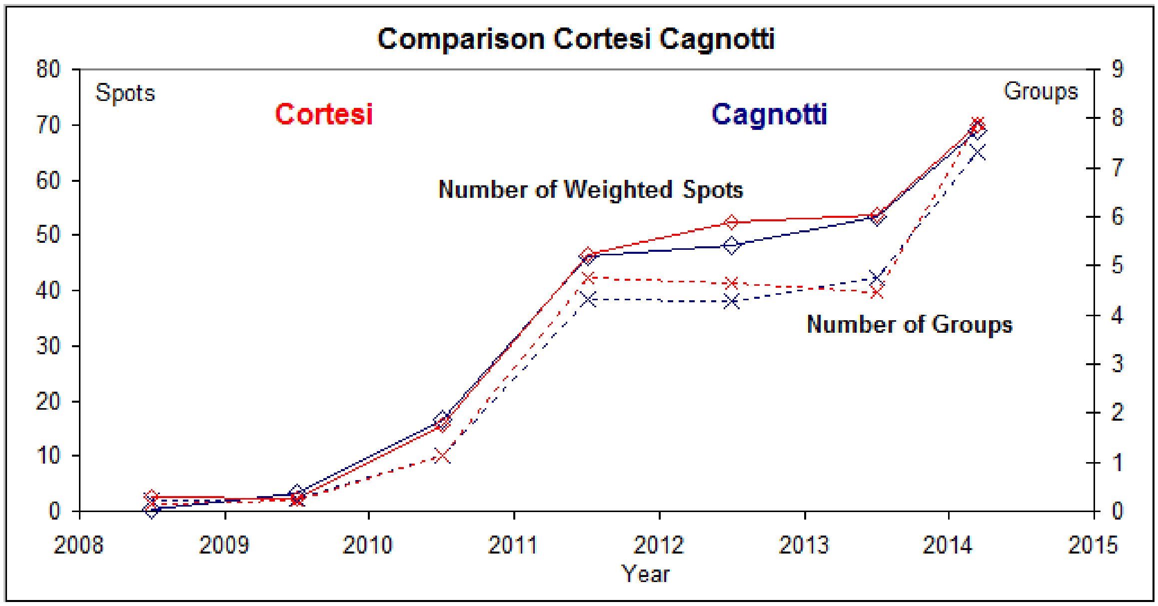


Figure zz15: The yearly average group count (dashed lines and crosses) and weighted sunspot count (full lines and diamonds) for observers Cortesi (red) and Cagnotti (blue).

Waldmeier also introduced a new classification of groups (the Zürich classification) based on understanding of the evolution of the group rather than mere proximity of the spots. This tends to increase the number of groups over that that mere proximity would dictate. We find that, on average, on a fifth of all days an additional group is reported over what is observed at MWO, which means that the relative sunspot number increases by about 3% due to this inflation of the group count brought about by the better understanding of what constitutes a group. Kopecky et al. (REF 1980) quote the observer Zelenka suggesting a possible influence of the new Zürich classification of groups. This problem deserves a full, future investigation.

Figure zz16 illustrates the problem. Today we may use the magnetic field information to discriminate between groups, but such information was not available to observers in earlier times so proximity and longitudinal extent were the primary criteria for groups.

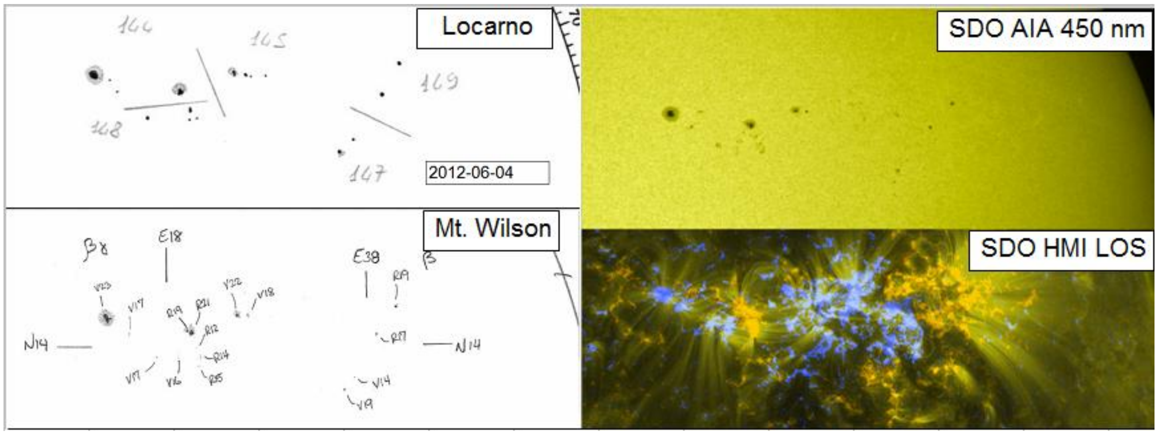


Figure zz16: Groups and spots observed 4th June 2012 at Locarno (upper left), MWO (lower left with polarities indicated), SDO AIA at 450 nm (upper right), and their magnetic fields (lower right).