The Sunspot Number:
Historical base, current recalibration and scientific impact

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Abstract:

The sunspot number (SN), based exclusively on visual sunspot counts, is our only multi-century record retracing the evolution of the 11-year solar activity cycle over more than 400 years. It was recently identified as the longest scientific experiment still ongoing nowadays. As it is based on a worldwide network of solar observers, it is also one of the earliest applications of what is now known as crowdsourcing. Since 1981, this series is maintained, distributed and extended by the World Data Center (WDC) SILSO in Brussels, Belgium (http://www.sidc.be/silso).

We first retrace the history of the construction of this unique solar reference, which involves a lineage of many famous observers like Galileo, Schwabe, Wolf up to Koyama-san in the past century. This allows us to introduce various weaknesses in the construction of the original SN series, and its more recent counterpart, the sunspot group number (GN) introduced in 1998.

Motivated by large inconsistencies between the SN and GN series, a major international effort was initiated in 2011 by the WDC SILSO to fully revise the heritage sunspot time series. In 2015, this joint work led to the official release of the first-ever end-to-end revision of those two data series. We describe the main changes introduced in Version 2.0 and how the corrections were inferred from the original historical sources by implementing modern mathematical techniques currently at our disposal.

Finally, we conclude on the impact of this recent recalibration on key science issues of the 21st century: understanding and modeling the source of the solar activity cycle or the long-term evolution of Earth climate. Looking forward, we also evoke the future role and extension of the sunspot number in the context of present and future technologies, like electronic imaging. Definitely, with ancient historical roots, sunspot science can still help answering crucial questions for years to come.

1. Introduction

The Sun is a fairly ordinary low-mass main-sequence star, which is thus in a very stable phase of its existence, during which its source of energy and thus its internal structure is almost constant over time scales of billions of years. However, stars with masses between about 0.5 solar mass and 1.5 solar masses feature an outer convective layer that leads to a magnetic activity, through a so-called “dynamo” mechanism.

In the case of the Sun and most solar-like stars, this magnetic activity is highly variable in time. In the case of the Sun, those variations are mainly characterized by a primary periodic modulation, the 11-year cycle (Hathaway 2015). In addition, the amplitude of this cycle experiences slower modulations over time scales of decades to millennia, including Grand Minima, during which the cycle essentially vanishes, leaving the Sun in a permanent quiescent state. As planets orbiting the Sun are immersed in the solar radiation and a continuous flux of energetic particles called the solar wind, this variable activity inevitably influence the environment of the planets, via changes in the energy balance (surface temperatures) and the chemistry of their upper atmospheres.

In the case of the Earth, this variable solar influence conditions its long-term habitability, through the evolution of climate. Moreover, given the fast-growing importance of technology in our society, humankind has strongly increased its vulnerability to solar disturbances like solar flares or coronal mass ejections. Many activities thus currently depend directly on the level of solar activity (spaceflight, telecommunications, navigation, energy distribution, etc.), leading to a new field of research called "space weather" (Lanzerotti 2017). Over durations of months to decades, the solar cycle modulates the intensity and the frequency of occurrence of solar eruptive events. It has thus become even more essential to understand the long-term evolution of solar activity, with as ultimate goal the ability to predict the future trend in the solar cycle. By analogy with Earth meteorology, such long-term investigations form the field of "space climate".

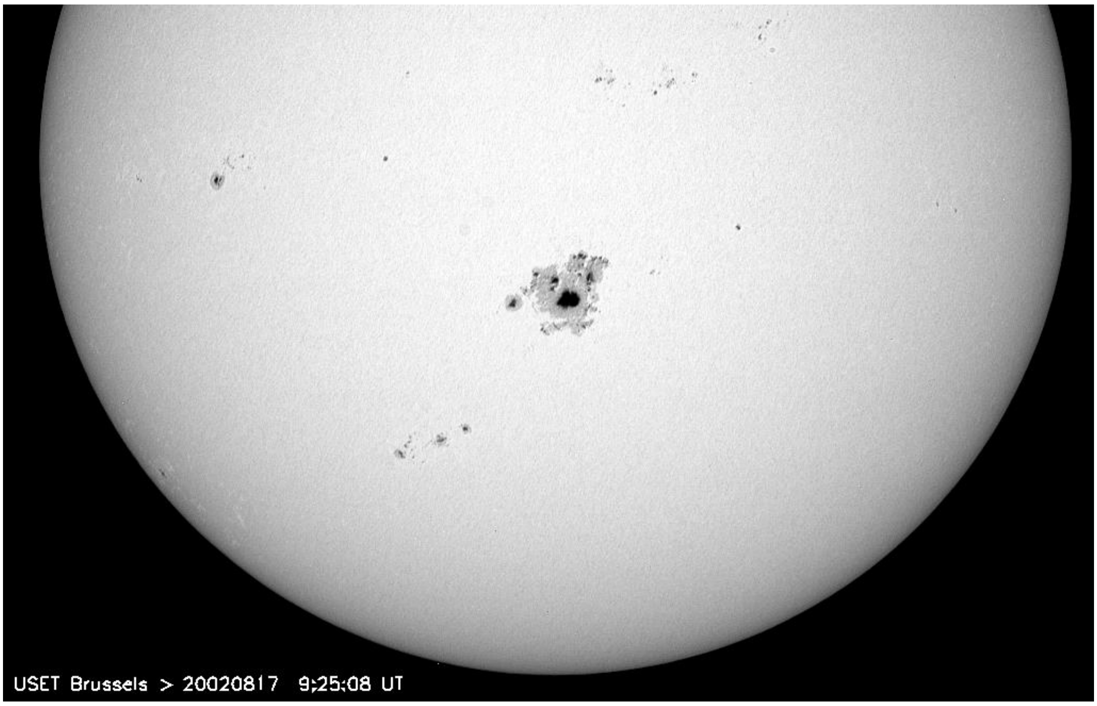


Figure 1: Image of a very active Sun with a giant sunspot and multiple other sunspot groups (Uccle Solar Equatorial Table, Royal Observatory of Belgium, Brussels, August 17, 2002). This image illustrates the morphological diversity of sunspots and their clustering in groups.

Such solar-cycle studies require information spanning as many past solar cycles as possible. Luckily, we have such a multi-century record of solar activity: visual observations of sunspots. Those dark spots at the solar surface are the primary imprint of the presence of magnetic field concentrations at the solar surface (Figure 1). They are clustered in sunspot groups, each corresponding to a magnetic dipole emerging from the sub-surface convective layer. The size and number of spots in a group grow largely proportionally to the magnitude of this emerging magnetic dipole, providing a rather direct measurement of the intensity of the magnetic activity. This is confirmed by the extremely high correlation (>95%) between sunspot counts and most modern activity indices, like sunspot areas (derived from images), the F10.7cm radio flux and the total emerging magnetic flux measured directly by magnetographs, as shown in Figure 2 (Petrovay 2010, Stenflo 2012). Although the sunspot counts are not tied to a physical unit, they thus provide a quantitative measurement of the global magnetic field produced by the solar dynamo and emerging at the solar surface. Moreover, such counts are at our disposal over more than 30 past solar cycles.

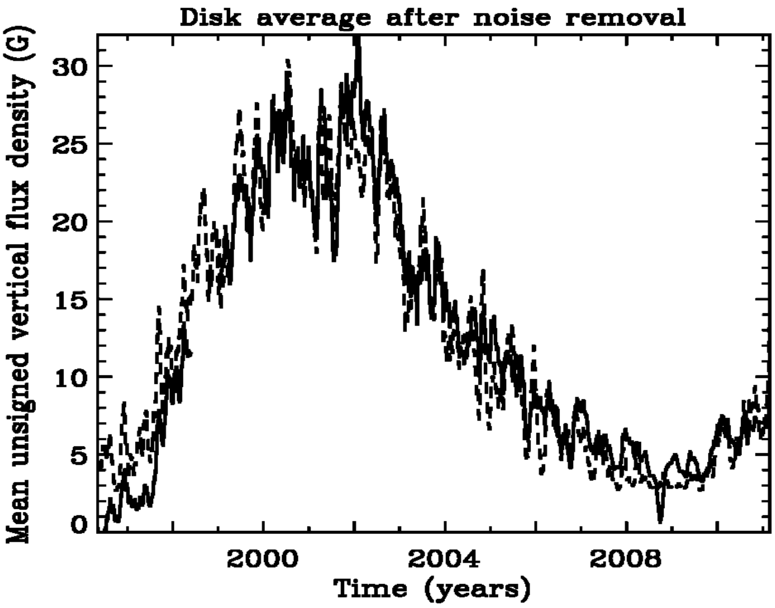


Figure 2: Comparison of the mean unsigned vertical flux density with the sunspot number over solar cycle 23. This modern measure of the global magnetic flux emergence over the whole Sun shows a very high correlation with the sunspot number, indicating that sunspot counts provide a quantitative determination of the level of solar activity (Source: Stenflo 2012)

Indeed, it turns out that those spots can be detected with very basic means in visible light (broadband "white-light"). This is why sunspots provide our only direct record of solar activity spanning more than 400 years, long before more modern techniques like photography were invented. The exceptional longevity of this sunspot monitoring actually makes it the longest scientific experiment still ongoing nowadays (Owens 2013). This explains the unique role of the sunspot time series in solar physics. However, for quantitative studies and models, it is essential that a sunspot time series is fully homogeneous, so that counts separated by centuries are equivalent and can be directly compared.

In this article, we first present the construction of the sunspot number series, the primary standard index built from sunspot counts, illustrating its progressive construction using historical sunspot observations. We present the current production of this index, based on a worldwide network. As recent investigations showed evidence of inhomogeneities in the original sunspot number series and the corresponding sunspot group number series, we review the latest advances in diagnosing and correcting those defects. Finally, we outline future work as well as prospects for further improving and extending the heritage sunspot series by using state-of-the-art methods.

2. History of the sunspot number

The first mentions of sunspots were found in Chinese chronicles from 200 BC (Wittmann and Xu 1987, Yau and Stephenson 1988, Vaquero and Vazquez 2009). Those observations made with the naked eye were limited to the biggest sunspots and remained occasional until the invention of the astronomical telescope by Galileo Galilei in 1610 (Figure 3). Galileo was not the only one who pointed his telescope at the Sun, and there were immediately a number of other independent observers of sunspots: Thomas Harriot (1560-1621), Christoph Scheiner (1575-1650) and Johann Fabricius (1587-1616). Those early observers often made drawings of the solar disk, often using the projection method (Figure 4). This method, where spots are marked on paper where their image is projected gives a rather accurate rendition in terms of spot position, size and shape. However, the accuracy of the drawings varies between observers, depending on the quality of the image given by the telescope and also the care they took to accurately reproduce the spot images.

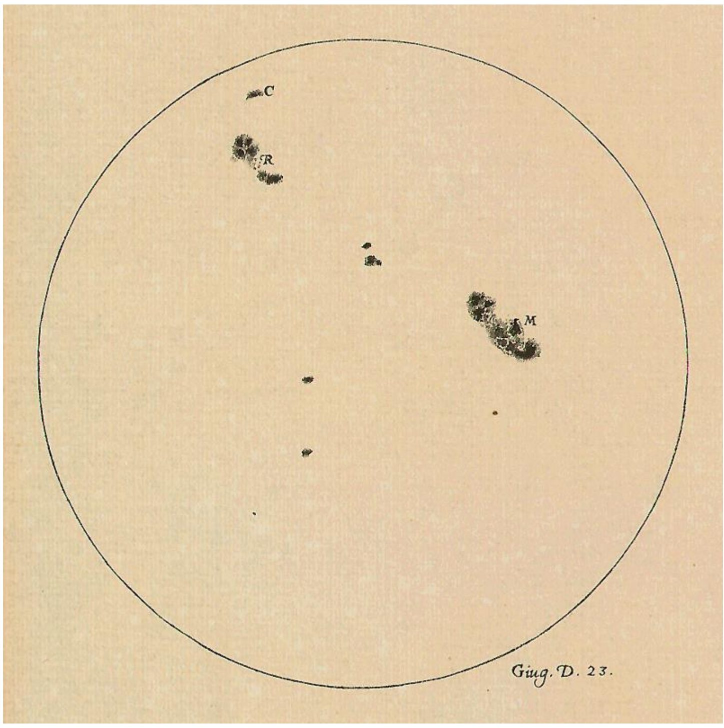


Figure 3: Sunspot drawing by Galileo Galilei made on June 23, 1612, from" Istoria e Dimostrazioni Intorno Alle Macchie Solari e Loro Accidenti Rome" (History and Demonstrations Concerning Sunspots and their Properties), published in 1613 (Source: The Galileo Project, Rice University, Owen Gingerich)

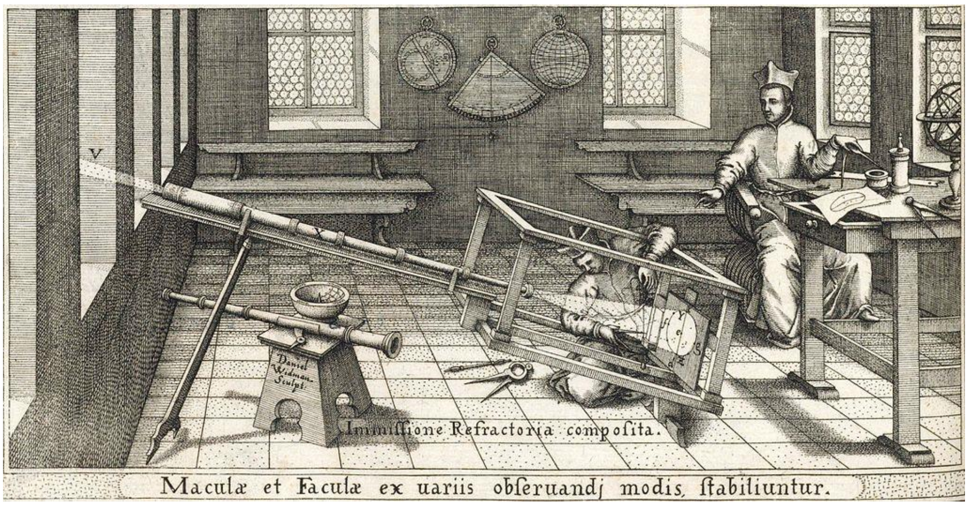
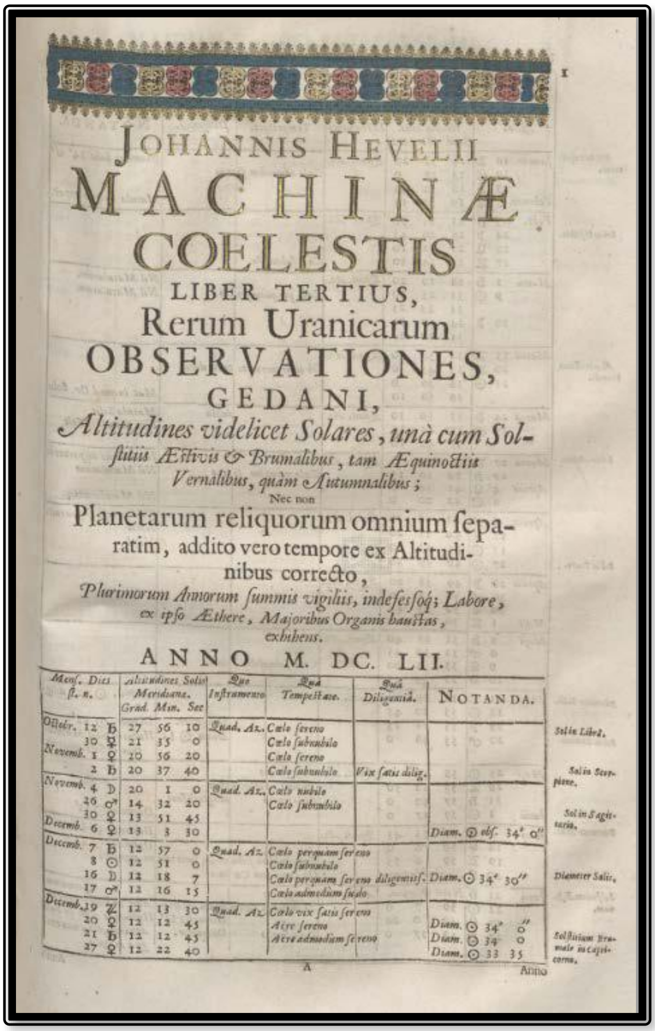


Figure 4: Illustration of the solar projection method used early on for drawing sunspots on a sheet of paper. Sunspots are marked where they are projected, allowing an accurate rendition and positioning of the recorded sunspots (from C. Scheiner, "Rosa Ursina", 1626-1630, page 150; Source: Houghton Library, Harvard University)

However, some observers only drew in detail enlarged portions of the solar disk, and not all observers made drawings. There were indeed many isolated textual mentions of the presence of spots (or groups). Some observers also reported systematically the number of spots in published tables that were often meant for other purposes, like the timing of meridian transits for the maintenance astronomical clocks or determination of the local meridian (Figure 5). As a consequence, those observations were not made systematically, were not standardized and were rather sparse and randomly distributed over time.



JOHANNIS HEVELII
MACHINÆ
COELESTIS
LIBER TERTIUS,
Rerum Uranicarum
OBSERVATIONES,
GEDANI,
Altitudines videlicet Solares, unà cum Solstitiis Æstivis & Brumalibus, tam Æquinoctiis Vernalibus, quàm Autumnalibus;
Nec non
Planetarum reliquorum omnium separatim, addito vero tempore ex Altitudinibus correcto,
Plurimorum Annorum summis vigiliis, indefessoq; Labore, ex ipso Æthere, Majoribus Organis haustas, exhibens.
ANNO M. DC. LII.

Mens. Dies st. n.	Altitudines Solis Meridianæ. Grad. Min. Sec.	Quo Instrumento	Qua Tempestate.	Qua Diligentiâ.	NOTANDA.	
Octobr. 12 ♄	27 56 10	Quad. Az.	Cælo sereno			Sol in Librâ.
30 ☿	21 35 0		Cælo subnubilo			
Novemb. 1 ♀	20 56 20		Cælo sereno			
2 ♄	20 37 40		Cælo subnubilo	Vix satis dilig.		Sol in Scorpione.
Novemb. 4 ☽	20 1 0	Quad. Az.	Cælo nubilo			
26 ♂	14 32 20		Cælo subnubilo			
30 ♀	13 51 45					Sol in Sagittario.
Decemb. 6 ♀	13 3 30				Diam. ☉ obs. 34′ 0″	
Decemb. 7 ♄	12 57 0	Quad. Az.	Cælo perquam sereno			
8 ☉	12 51 0		Cælo subnubilo			
16 ☽	12 18 7		Cælo perquam sereno	diligentiss.	Diam. ☉ 34′ 30″	Diameter Solis.
17 ♂	12 16 15		Cælo admodum sudo			
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20 ♀	12 12 45		Aëre sereno		Diam. ☉ 34′ 0″	
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27 ♀	12 22 40				Diam. ☉ 33 35	

A Anno

Figure 5: Front page and table for year 1652 from "Machina Coelestis" (1679) by Johannes Hevelius (1611-1687). Part of the known sunspot counts are recovered from such tabulated sunspot counts that were not registered for the study of the Sun (here meridian transit timings) and do not have associated drawings.

2.1. The Wolf number

The first breakthrough came with Samuel Heinrich Schwabe (1789-1875), a pharmacist and amateur astronomer, who started systematic sunspot observations in 1825 (8468 drawings over 1825-1867). From his drawings, he counted the spots and groups, and after accumulating 17 years of observations, he found evidence of a period of about 10 years in the occurrence of sunspots. This discovery really marks the birth of solar physics. Its publication (Schwabe 1843) drew the attention of a young Swiss astronomer, Rudolf Johann Wolf (1816 – 1893; Figure 6), who immediately identified the need to confirm the existence of this cycle over long durations and to refined the determination of the period. For this purpose, he created a standard index characterizing the global level of sunspot activity, the so-called "Wolf Number" (Wolf 1856)]:

$$W = 10\,N_g + N_s \qquad \text{Equation 1}$$

with N_g the group count and N_s the total spot count.

Figure 6. Rudolf Johann Wolf (1816-1893) in 1855, near the epoch when he initiated the systematic production of the sunspot number (Source: Rudolf Wolf Gesellschaft, Bern; http://www.wolfinstitute.ch).

By using only counts, Wolf could also exploit a wider range of past historical observations, as only some observers made drawings, while counts can be derived from all kinds of historical sources. In 1849, Wolf started a program of system observations leading to daily Wolf numbers that he continued until his death in 1893. For his observations, he chose as standard instrument a Fraunhofer refractor (Aperture: 83 mm; Focal length: 1320 mm; magnification: 64x), which remains the reference instrument for the sunspot number up to the present (Figure 7). This Standard telescope is still in working condition and daily use nowadays.

Figure 7: The Standard 83mm Fraunhofer refractor set up on the main terrace of the Observatory of Zürich (Source: Rudolf Wolf Gesellschaft, Bern; http://www.wolfinstitute.ch).

As accumulating new data is a slow and patient process, Wolf simultaneously started travelling across Europe to recover all possible historical sunspot observations, which allowed to quickly recover data spanning more than 150 years, from 1700 to Wolf's epoch. Figure 8 shows the timeline of the main observers who were active during the 18th and early 19th century, with the interval over which they produced sunspot counts. Johann Caspar Staudacher (1731-1799) stands out as the primary observer of the second half of the 18th century, with 1016 sunspot observations made between 1749 and 1796.

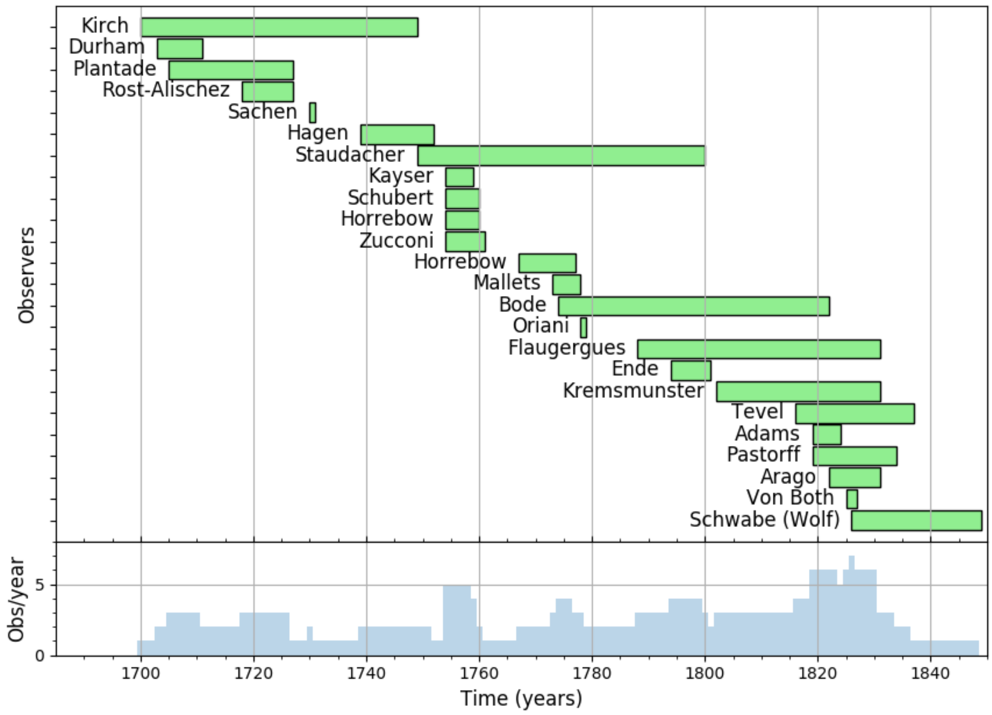


Figure 8: Timeline of the main observers of the 17th century. The bottom plot indicates the number of active observers per year. Note however that observations from many of those observers were sparse, in particular during two data-poor intervals in 1740-1749 and 1790-1800

However, many observers produced sunspot observations much more occasionally, leading to periods when data are very sparse, with even entire months without any observation, most notably in the first half of the 18th century and the last decade of the 18th century, as show in Figure 9. We must point out here that for this application, the recovery of ancient documents did not only aim at recovering qualitative or descriptive material, as in many other historical searches, but was meant to extract a quantitative numbers defining the exact level of solar activity.

Although Wolf was the unique primary observer defining the sunspot number, several changes took place during the initial Wolf period:

- 1861: introduction of additional auxiliary observers at other observatories than Zürich, and introduction of the k normalization coefficients needed to bring the numbers from various observers to the same scale as Wolf's own counts (Wolf 1861).

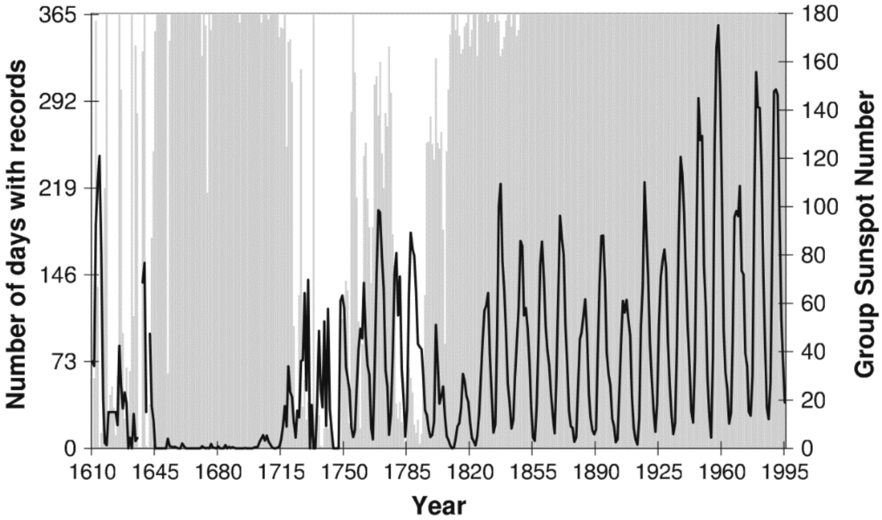


Figure 9: Original sunspot group number by Hoyt & Schatten (1998a-b) (black curve) with the temporal coverage in number of observed days per year (background shading) While the data coverage is close to 100% over the last two centuries, it is much poorer before the 19th century (NB: the high coverage during the interval 1650-1710 is overestimated, as discussed in Section 4.5) (Source: Vaquero 2007).

- 1864: foundation of the Zürich Observatory, of which Wolf becomes first Director. Wolf then hires assistants who carry out part of the observations using the Standard instrument (Figure 10; Wolf 1865]. Wolf also starts to use systematically a smaller portable telescope to make his own observations, given his new duties that imply frequent travels (Clette et al. 2014, Friedli 2016).

Wolf, Mittheilungen über die Sonnenflecken.

194

Sonnenfleckenbeobachtungen im Jahr 1864.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
1	1. 1†	3.15*	5.13*	3. 4*	1. 5*	3. 9*	1. 2*	3.17	3.15	3. 4	5.32	5.17†
2	2. 5w	3.10*	6.13*	1. 1*	1. 3*	5.85w	4.16	2. 7†	3.12	2. 5	4.22†	—
3	2. 3†	3.11*	7.14†	2. 4*	3. 4†	4.17*	4.15	3.13	3.11	2. 3	5.30†	—
4	1. 3*	2.14†	5. 9*	—	3. 7†	5.21*	3. 5*	3.18	4.17	4.16	4.31w	2. 5*
5	1. 1†	2.20†	5.21w	2. 3*	3. 4*	6.23*	4.21	4.17	2. 8	2.11	4.28w	2. 2†
6	2. 8†	1. 7†	4.—w	3. 9*	3. 4*	6.21*	4.22	5.13	2. 8	2. 9	3.23	1. 2
7	3.11†	2.16*	3. 5*	3. 9*	2. 4*	7.26*	3. 6*	7.29	2. 5	2. 3	3.12†	1. 1*
8	3. 6†	2.59*	3. 4*	3. 6*	2. 3*	4.18*	3. 8*	6.53	2. 6	3.10	3.25	1. 1
9	3. 4†	2.10*	5. 8†	3. 6*	2. 3*	7.32†	4.47	6.77	2.14	3.16	3.26	1. 2
10	2. 4*	2.11*	4. 5*	2. 4*	2. 2*	5.16†	4.47	5.28*	2.26	2. 5	4.20†	1. 1
11	2. 3†	3.11†	4. 9*	2. 4*	1. 1*	3. 6†	4.19*	4.27*	2.16	3. 7	4.19†	1. 8†
12	3. 4†	1. 1*	4.27*	2. 5*	3. 5†	2. 5*	4.87	5.93	2. 8†	1. 2	4.27w	1. 4*
13	3. 7†	2.10†	3. 7*	2. 4*	2. 9†	3. 8*	4.21*	6.84	2.18	1. 8	4.15	1. 2w
14	4.21*	1. 3*	3. 7*	2. 3*	1. 4*	3. 22	3.41	4.75	2. 9	1.28	1. 1*	—
15	3. 5*	1. 3*	3. 7*	2. 3*	2. 7*	3.11†	4.75	4.24*	1. 1	1.25	2. 17	1.20
16	4. 9*	2. 4*	3. 7*	1. 1*	2. 7*	3. 8*	3.15*	3.41	2.10	1.11	2.—†	1.29w
17	5.13†	3. 7*	4. 7*	5. 6†	2.10*	2. 7*	3.47	2. 5*	2.10	1. 5	3.21	1.14†
18	5.61w	5.20†	5. 8*	1. 1*	2.10*	5.19	3.10*	3. 8	2. 8†	1. 2	3.15w	1. 9†
19	4.16†	3. 4*	3. 5*	1. 1*	2.10*	1. 4*	2. 5*	1.13	1. 2*	1. 8	3.13	1.17
20	5.21*	5.19w	3. 5*	1. 1*	3.12*	2.14	3.10	1.13	2. 7	1. 7	3.13	—
21	6.19*	3. 4*	3. 5*	1. 1*	4. 9*	2. 9	4.20	1. 9	2. 5	2. 6*	—	1.13w
22	5.19*	2. 3*	4. 5*	1. 1*	4. 9*	1.22	2. 4*	1. 3	1. 1	2. 3	2. 7*	0. 0
23	5.18*	2. 4*	4.10†	1. 1*	3. 5*	1.16	3.10†	1. 2	0. 0	4.34	4.21	1. 7†
24	5.16†	2. 3*	4. 6*	1. 1*	2. 3*	1.13	1. 1*	1. 1†	2. 5	4.19†	5.28	—
25	5.18*	2. 2*	4. 7*	2. 4†	1. 4*	2.15	2. 9	0. 0	4. 6	3.24	—	—
26	5.14*	3. 4*	4. 7*	1. 1†	1. 4*	1. 4*	1. 1*	0. 0	3. 5	3.17	3.—†	2. 3†
27	3.13*	3. 5*	4. 7*	1. 1†	2. 9	2. 4†	2.17	1. 5	3. 8	3.36	2.33	2. 9
28	2.13*	4. 8*	5.10†	0. 0†	3. 5*	1. 1*	2. 5*	2. 7	2. 6	2.12	3.49	—
29	2.10†	6.45*	4. 7*	0. 0†	2. 4*	1. 7	2. 3*	2.15	2. 5	2.31w	3.69w	2.12†
30	2.11*		3.15†	2. 6†	3. 4*	1. 2*	3.12	3.30	2. 3	3.26w	4.52	1. 2
31	2.13*		3. 5*		3. 7*		4.11	3.23		3.15†		1. 2
Mittel	57,5	47,2	67,3	30,0	40,9	58,3	57,2	57,9	30,5	35,5	59,1	24,1

*Figure 10: Reproduction of the yearly table of Zürich sunspot numbers for 1864 (Wolf 1865).For each date, the two numbers give the group and spot counts respectively, while symbols are representing different observers (no symbol for the Zürich Standard refractor, * for Wolf using a small portable refractor). While the * symbols dominate before July 1864, they almost vanish in the second half of the year. This confirms a sharp transition between Wolf and his assistant using the Standard refractor. This first assistant was hired by Wolf in 1864, once the construction of the observatory had been completed.*

- 1871: addition of a helioscope to the standard Fraunhofer refractor (Friedli 2016), which slightly improves the optical quality. This also comes with a change in the processing method, where Wolf combines all numbers from all Zürich observers for every day, instead of taking first his own observations and then filling the few remaining daily gaps with observations from assistants or auxiliary observers. This method is implemented in particular over the period 1878-1893, when Alfred Wolfer becomes the primary assistant until Wolf's death.

This evolution in Wolf's own observing and processing routine clearly opens the possibility of changes in the scale of the resulting sunspot number series, in the form of progressive trends or also abrupt jumps, given the sharp transitions mentioned above.

As new assistant, Alfred Wolfer introduced several innovations. Starting in 1884, he routinely produced sunspot drawings of high quality (disk diameter: 25 cm). He also included in his counts all details that could be observed with the standard refractor (Wolfer 1907):

- All small pores with lifetimes longer than about 1 hour.
- Multiple umbrae in a common penumbra.

This thus included small features that Wolf had ignored in order to be more consistent with early historical observers, and also because he could not see them in the smaller portable refractor that was his prime instrument since 1864. In order to bring his new "modern" counts to the same scale as all Wolf's earlier counts, Wolfer compared his parallel observations with Wolf during a period of 17 years (1878-1893) as shown in Figure 11 (Wolfer 1895). This led to a conventional 0.6 Zürich conversion factor, which was subsequently applied to all sunspot numbers obtained after 1893.

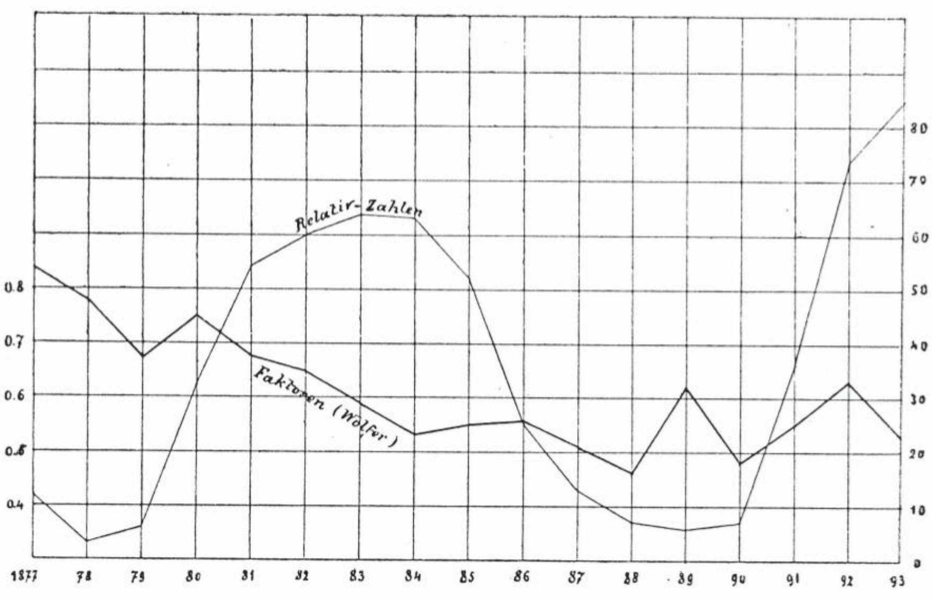


Figure 11: Figure from Wolfer (1895) showing the scaling ratio between Wolfer's numbers and Wolf's number during the 17 years of simultaneous observations 1877-1893. This led to the adoption of a conventional 0.6 factor applied to all numbers obtained after 1893 by Wolfer and all his successors, to bring the recent counts to the scale of Wolf's original counts. Note that the actual ratio drifted over this time interval, shedding doubts about the right choice for this scaling factor.

2.2. The Zürich era (1893-1980)

After Wolf's death, his observing program was continued by the four successive directors, who took over successively the role of primary observer defining the long-term scale of the Zürich sunspot number, namely:

- Alfred Wolfer (1854-1931) from 1894 to 1826
- William Otto Brunner (1878-1958) from 1827 to 1944
- Max Waldmeier (1912-2000) from 1945 to 1980

The corresponding periods are shown in different colors in Figure 12. Figure 13 gives the timeline of the observing periods from the primary observers and all assistants working in Zürich, who produced part of the observations.

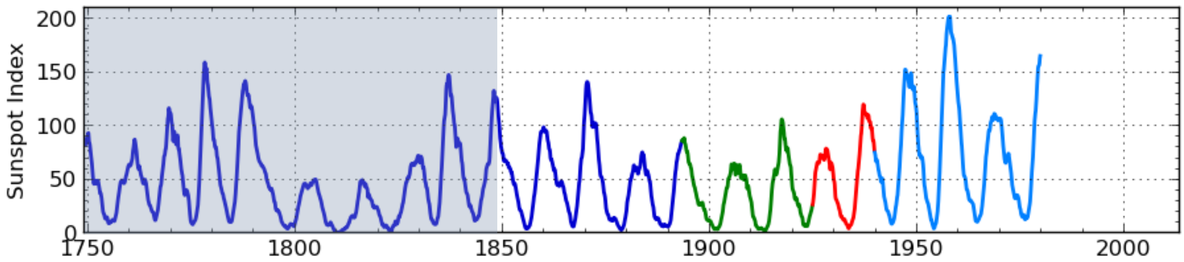


Figure 12: Sunspot number series with the different periods indicated in color: Wolf 1849-1893 (dark blue), Alfred Wolfer 1894-1926 (green), William Brunner 1927-1944 (red) and Max Waldmeier 1945-1980 (light blue). The historical reconstruction by Wolf before 1849 is shaded.

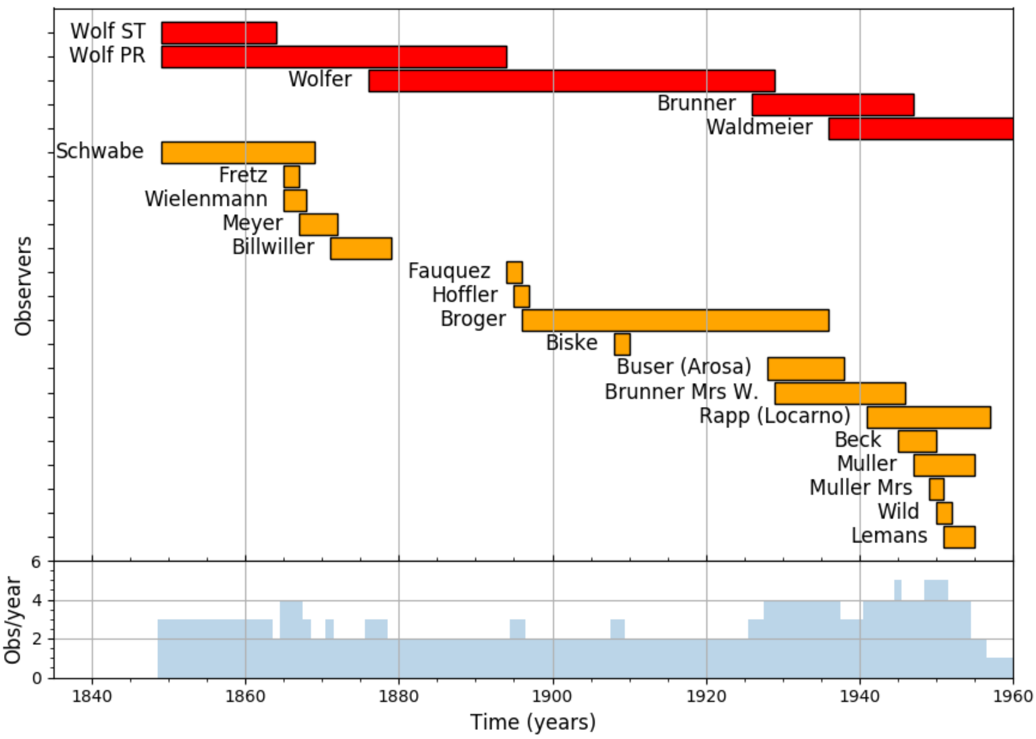


Figure 13: Timeline of the primary observers of the observatory of Zürich (red bars), and of the assistants (orange bars). Wolf ST and PR denote Wolf using the Standard and the small portable telescope, respectively. Note that most primary observers observed during a longer period, overlapping the preceding and following primary observer. The lower plot indicates the number of active Zürich observers for each year. Together, they form the primary base for the scale of the Zürich sunspot number. Note the quick succession of assistants around 1870, 1895 and 1947, as well as the very long observing career of one of the assistants, Max Broger, who was active during 40 years, from 1896 to 1935.

During that era, the base Zürich method remained largely unchanged.

- On most days (about three quarters of the days), the official sunspot number is the Wolf number of the primary observer in Zürich.
- When there is no observation from the primary observer, any observation by an assistant is used. The assistants are trained to count spots like the primary observers and are thus supposed to share his scale.
- When there are no observations at all in Zürich, the sunspot number is derived by an average of all numbers from a network of auxiliary stations.
- In order to bring the Wolf numbers of external stations to the same scale as the primary Zürich numbers, a permanent statistic is maintained in order to derive a yearly mean k ratio between the numbers of the station and the reference number from Zürich on all days with simultaneous observations. This is called the k personal coefficient of the station. On the other hand, the primary observer and his assistants in Zürich have fixed k of 1, as they are considered as the (stable) reference.

For this purpose, a network of auxiliary stations was established, involving both professional observatories and individual amateur astronomers. This network expanded progressively with time from about 12 stations at the end of the 19th century to more than 40 in the mid-20th century. Figure 14 summarizes a survey of the main long-duration stations who started contributing before 1918, when the Zürich observatory ceased to publish tables of all observations contributed by those auxiliary stations. More recently, some prominent long-duration contributors to the sunspot network were the Kanzelhöhe (Austria), Kislovodsk (Russia), Uccle (Belgium) and Catania (Italy) observatories, or dedicated individual observers, in particular in Japan: namely Hisako Koyama (1916-1997; Kahaku Museum, Tokyo), Miyosi Suzuki (still active today) and Kenichi Fujimori (still active today).

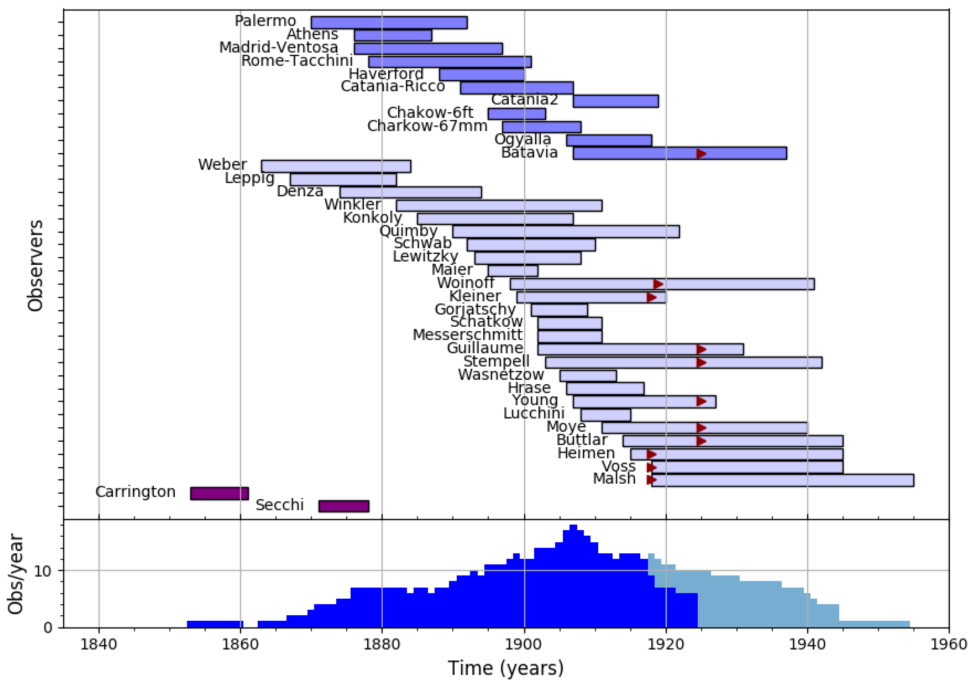


Figure 14: Timelines of the main auxiliary observers who started their observations before 1918, when the printed Zürich records cease to be complete. Professional observatories are in dark blue (top) and individual amateur astronomers in light blue (middle). Carrington and Secchi only provided sunspot areas. The lower panel gives the number of active stations for each year (complete only until 1918).

In order to increase the overall number of observing days for Zürich, in 1957, M. Waldmeier implemented a second station located south of the Swiss Alps, in Locarno: the Specola Solare Ticinese Observatory. A new local assistant, Sergio Cortesi, was hired and was trained to observe exactly according to the principles used at the primary station of Zürich, also with a 80 mm refractor (Cortesi et al. 2016). Thanks to the complementarity of the weather patterns North and South of the Alps, this second observatory increased the production of primary observations beyond 80% of the days.

Although the Zürich system was largely stable, a subtle change in the counting method was progressively introduced. In those alternate counts, large spots get a higher number, above 1 and up to 5 for very large spots with large penumbra (Figure 15). Conversely, in complex sunspot groups with many secondary tiny pores, part of those short-lived spots are ignored in the counts.

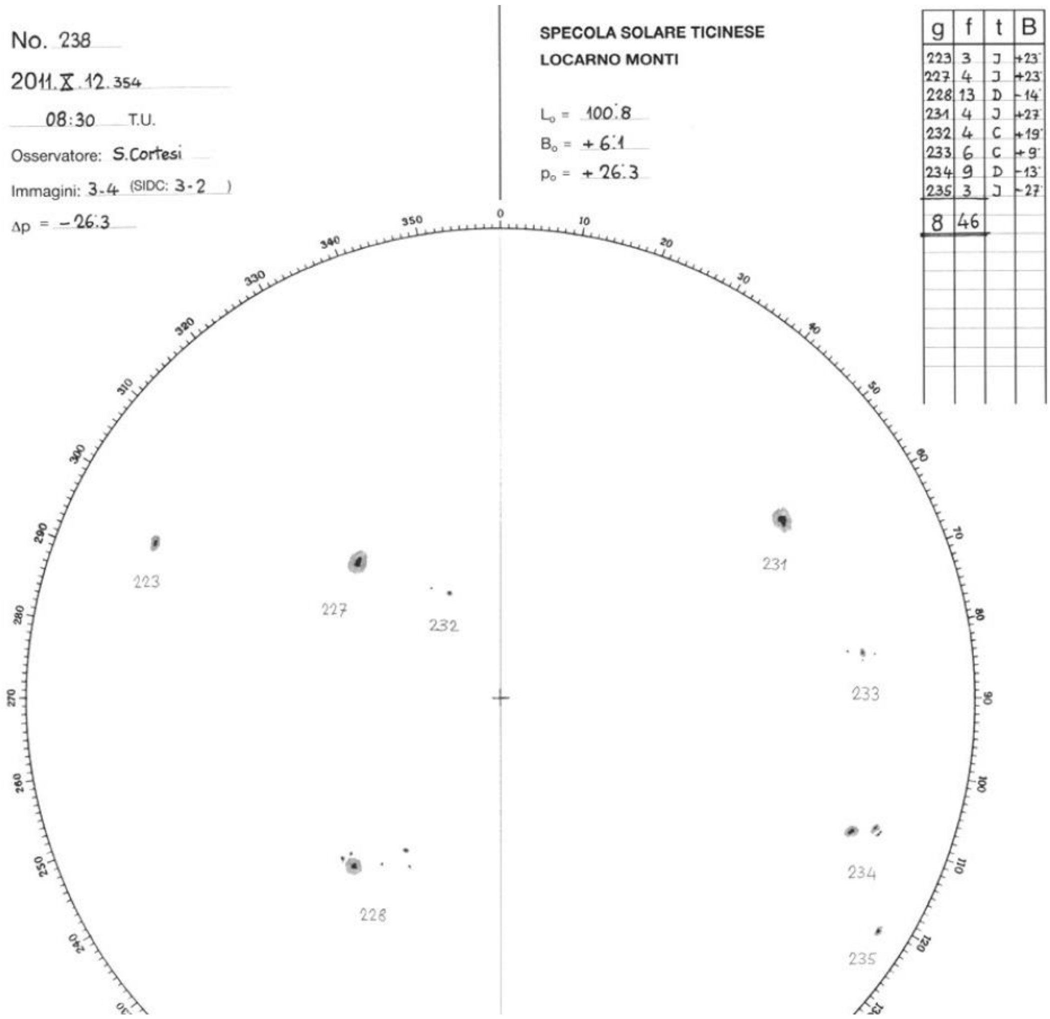


Figure 15: Locarno drawing for October 12, 2011 (Observer: S. Cortesi) illustrating the counts weighted according to sunspot size. For example, the large spots numbered 227 and 231 are counted as 4 instead of 1 in the original Wolf definition. Overall, this leads here to a weighted Wolf number of 126 (10x8+46) instead of 100 (8x10+20), thus a factor 1.26 higher.

Based on original documents (Friedli 2016, private communication, Svalgaard, Cagnotti and Cortesi 2017), we can infer that this alternate method was introduced by Wolfer to help keeping the numbers from his assistants to the same scale as his own primary numbers (k=1 is assumed for assistants). However, after Wolfer, the new primary observers, who worked initially as assistants, continued to use this alternate counting method, but now for the primary counts. This finally became the standard Zürich method, as M. Waldmeier trained the assistant at the newly created "twin" Specola station to use this weighted counting method. The Specola station still uses this alternate counting method nowadays (Figure 15).

As this counting method differs from the primary Wolf formula, where all spots are counted as 1, there is thus a risk of a drift or jump in the overall scale of the Zürich-Locarno sunspot numbers, which can only occur after 1926, i.e. after Wolfer who was still strictly counting according to the Wolf principles that he had learned from Wolf himself during the 17 years of their joint observations. This coherency of Wolfer's counting practices, together with his long overlap with Wolf, makes of Wolfer a very stable reference bridging the initial Wolf era and the numbers produced later on, up to the present.

3. The WDC SILSO

In 1981, with the retirement of Max Waldmeier, the Zürich observatory was closed, bringing the Zürich production of the sunspot number to an end. In order to continue the production of this long-term series, the Uccle station of the Royal Observatory of Belgium took over the role of World Data Center (WDC) for the sunspot number, with international endorsement by a resolution of the International Astronomical Union (IAU General Assembly, 1981, Patras, Greece). The Uccle station was indeed one of the primary long-term contributors to the Zürich sunspot number since 1939. Initially named "Sunspot Index Data Center" (SIDC), the WDC was renamed to "Sunspot-Index and Long-term Observations" (SILSO) recently in 2011. It is supervised by three scientific unions: the IAU, the Union Radio-Scientifique Internationale (International Union of Radio Science, URSI) and the International Union of Geodesy and Geophysics (IUGG). It is also one of the members of the World Data System(WDS) of the ICSU (International Council of Scientific Unions), which supervises the data curation and data dissemination standards and focuses on the preservation of long-term scientific data sets. The WDS currently provides the official accreditation of more than 90 World Data Centers, across all scientific disciplines (https://www.icsu-wds.org/).

As first director of the WDC in Brussels, André Koeckelenbergh focused on three actions:

1. Defining a new pilot station which could replace the Zürich Observatory and ensure the scale stability.
2. Implementing a new computer-based statistical determination of the sunspot number, using preliminary algorithms prepared by A. Zelenka, one of the last assistants of M. Waldmeier (Clette et al. 2007].
3. The extension of the worldwide observing network, in particular outside Europe.

The Specola Observatory in Locarno was chosen as new reference station, as it had been observing in intimate connection with Zürich for more than 20 years and had been directly trained by the former primary station. This would ensure a seamless transition between the Zürich and Brussels numbers in 1981, which proved to be indeed successful as shown by the recent reconstruction of the sunspot number (Clette and Lefèvre 2016).

The new sunspot number calculation is based on the following steps (for more details see Clette et al. 2007):

- Determination of the average monthly k of each station relative to the pilot station for the processed month:

$$k_s = \left(\sum_d W_{LO}(d) / W_s(d)\right) / n_d \qquad \text{Equation 2}$$

Where W_{LO} and W_S are the raw Wolf numbers for the Locarno pilot station and the external station respectively, and n_d is the number of days with common observations.

- The daily sunspot number is obtained by the statistical average of the numbers from all stations whole network, each normalized by the above k_s personal coefficient.

$$S_N(d) = \left(\sum_s k_s \cdot W_s(d)\right) / n_s \qquad \text{Equation 3}$$

Where n_s is the number of stations providing an observation on that day.

- The elimination of outliers during the two above steps: this includes both the external stations and the reference pilot station, which is compared to the network on a daily basis.

Overall, by the above method, the final sunspot number tracks directly the scale of the primary station, thus staying in conformity with the earlier Zürich number. However, instead of being mostly the Wolf number of the primary station, the daily sunspot number is always the result of a statistical mean over many stations, with filtering of abnormal values. This reduces the random errors and thus the dispersion in daily values, and it avoids any adverse influence of an occasional bad value of the pilot stations, as illustrated in a recent error analysis (see Section 5.2 below, figure 39).

Figure 16 shows the evolution of the worldwide SILSO network, with an initial strong growth, and stabilizing around 90 contributing station nowadays. So far, a total of 282 contributed to the network since 1981, of which about 80 long-duration stations active for more than 15 years.

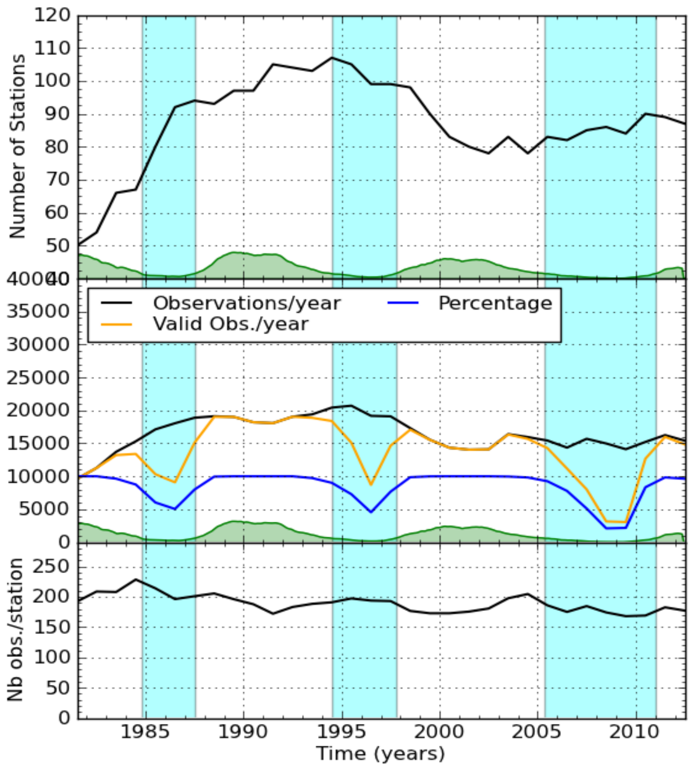


Figure 16: Evolution of the SILSO worldwide observing network since 1981. Top panel: number of stations (the sunspot number is plotted in green for temporal reference. Shaded bands mark the solar cycle minimum periods). Middle panel: Total number of observations per year. Observations valid for the scale determination (days with at least one spot present on the Sun) are plotted in yellow (percentage in blue). Lower panel: Average number of observed days per year and per station for the whole network. Some stations can reach more than 350 days/year, while other are below this global mean (Source: Clette et al. 2014).

The WDC SILSO collects between 15,000 and 20,000 individual observations each year, with an average of 180 observations per year and per station. All those data are now collected in a global database (MySQL), which now gathers more than 520,000 observations. Since 2005, all data contributed by the stations are directly entered by the observers in a Web-based user interface that feeds directly the database. This efficient system includes real-time data error trapping and replaces the former manual import of data sent to the WDC first by postal mail, then fax and more recently by e-mails.

The geographical distribution of stations covers more than 35 countries on all continents, but still with a significant concentration in the European region, by heritage of the past Zürich network (Figure 17). Note that two-thirds of the stations are still individual amateur astronomers (Figure 18). As this dominant contribution of skilled but non-professional amateurs is part of a long tradition associated with the sunspot number, this may be probably considered as one of the very first implementations of scientific crowdsourcing, well before the Internet provided a universal communication network for this growing form of public contribution to science.

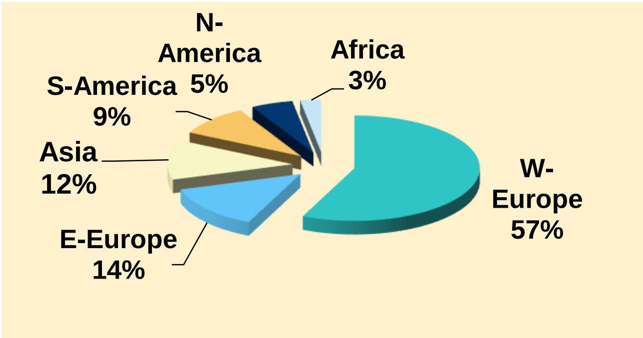


Figure 17: Geographical distribution of SILSO stations by continent, showing the large proportion of Western-European stations, an heritage from the past.

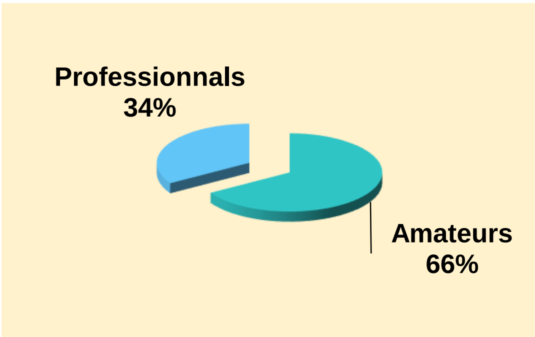


Figure 18: Proportion of amateur astronomers and professional observatories in the SILSO network. Right from the beginnings, skilled amateurs have always been important contributors for sunspot observations.

3.1. SILSO data products

Starting from the base daily sunspot number (total number for the whole solar disk), the WDC SILSO produces a wide range of time series:

- Total sunspot number: daily (1818-now), monthly mean (1749-now), yearly means (1700-now), 13-month smoothed monthly means (1749-now) (Figures 19, 20)
- Hemispheric numbers (1992-present): also as daily, monthly and 13-month smoothed values (Figure 21). Currently, those numbers, based on about 80% of the SILSO stations, is extended back to 1951 by monthly means of the Uccle station.

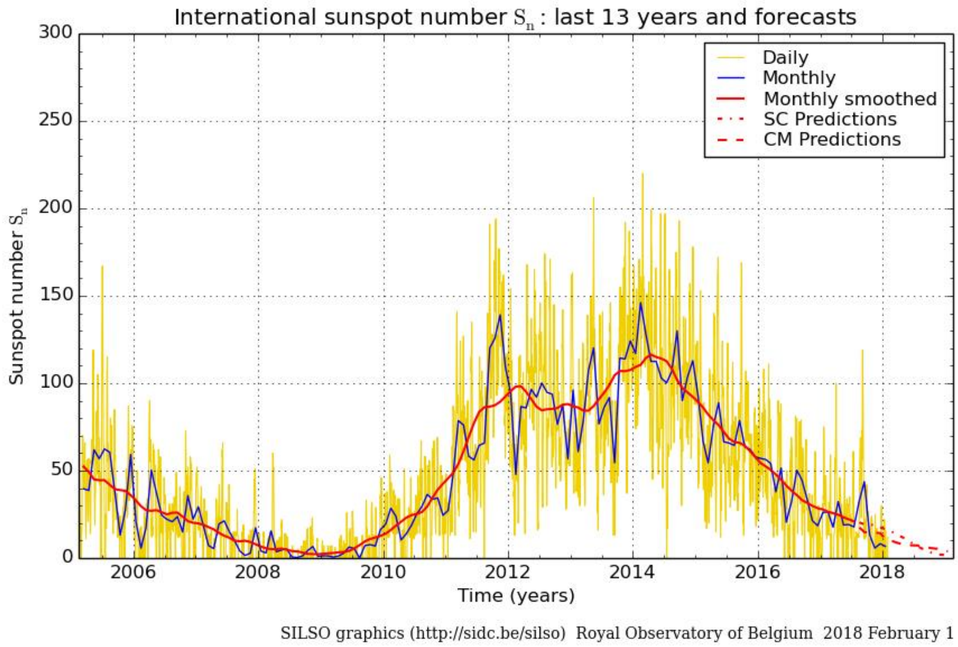


Figure 19: Plot of Daily, monthly and 13-month smoothed sunspot number over the last 13 years, the primary SILSO products

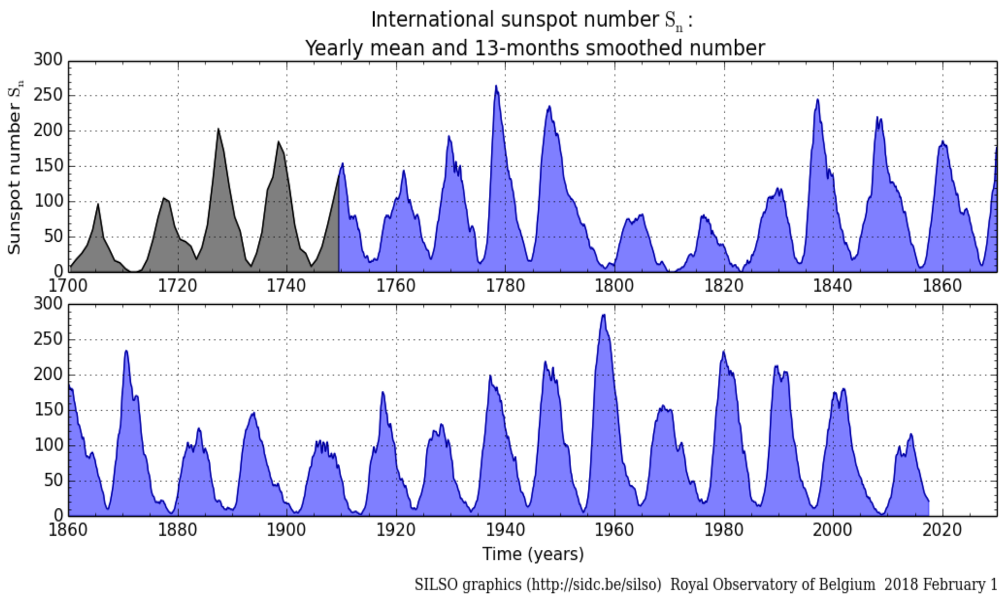


Figure 20: SILSO plot of the yearly mean sunspot number since 1700. From 1750 onwards, the 13-month smoothed number is used.

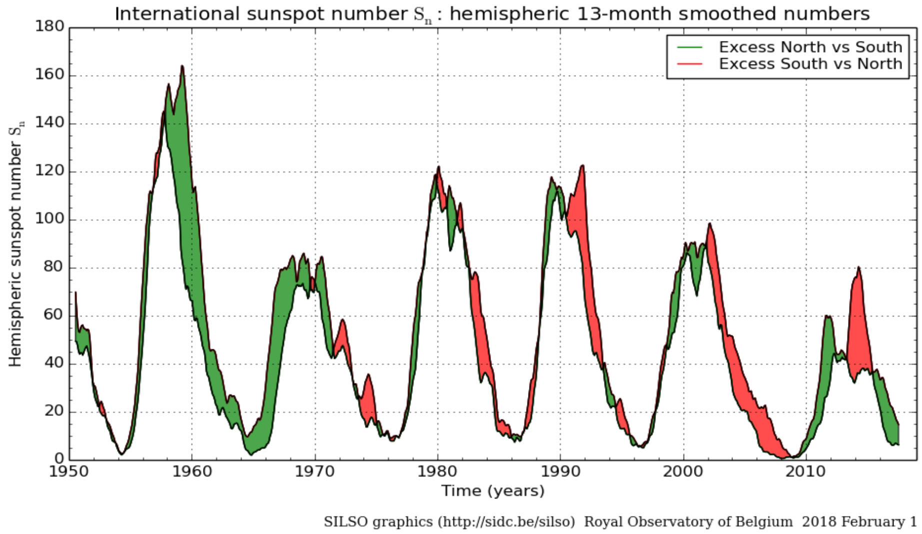


Figure 21: Monthly mean hemispheric sunspot number since 1951, showing the excess of either the North (green) or South hemisphere (red) over the last six solar cycles.

Those primary series are update on the first day of each month. In addition, for short-term space-weather applications, we also produce a near-real time estimated sunspot number (EISN; Figure 22) updated every 5 minutes, as data are fed by the network, and using a simpler calculation (no update of the k personal coefficients).

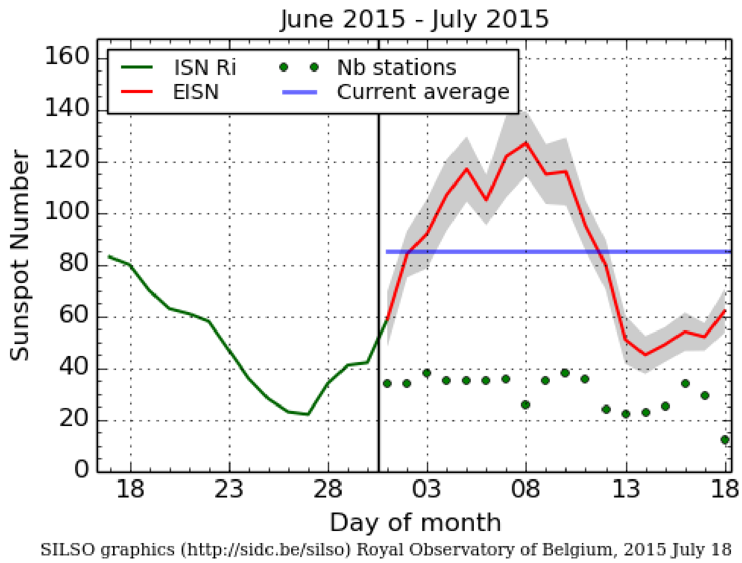


Figure 22: In support to short-term space weather application, the WDC-SILSO also produces the daily near- real-time estimated international sunspot number (EISN). The dots indicate the number of stations included in the calculation.

Beyond the sunspot number itself, the WDC SILSO also produces mid-term predictions of the future trend in solar activity, based on the sunspot time series and using now three different methods (Figure 23):

- McNish and Lincoln method (McNish and Lincoln 1949)
- Standard Curves method (Waldmeier 1935)
- Combined Method (Denkmayr and Cugnon 1997)

While the first two methods are based only on the sunspot number, the third one also uses the aa geomagnetic index as a precursor index for improving the predictions during the transition between the end of one solar cycle and the next one.

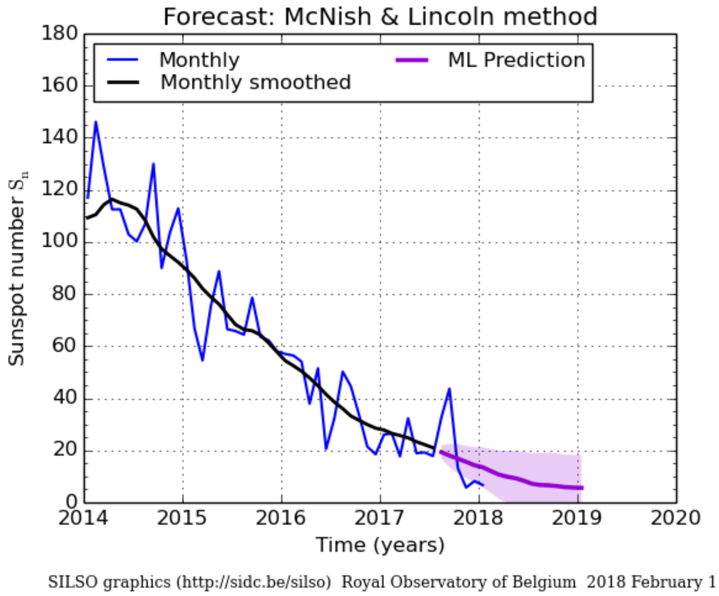


Figure 23: Example of a 18-month prediction of the trend in solar activity by the WDC-SILSO, here using the McNish & Lincoln method, based on the last monthly smoothed values of the sunspot number.

3.2. The wide sunspot number impact

The SILSO Data Center addresses a wide diversity of users, from individual citizens and the public, to large international civilian or military organizations and private companies. Indeed, the sunspot number has a very wide range of applications. In the domain of solar physics, it is a:

- primary constraint for solar dynamo models (physical models of the solar cycle)
- quantitative reference for solar processes:
  - Solar irradiance and solar wind reconstructions
  - Cosmogenic isotopes (^{10}Be, ^{14}C), which in turn allow indirect reconstructions of solar activity over timescales of millennia (Figure 24)
- time-base for Sun-driven processes (geomagnetism, etc.)

This has also implications in the broader context of astrophysics, as the detailed knowledge of the solar cycle history and sunspot properties is a key to understand distant stars.

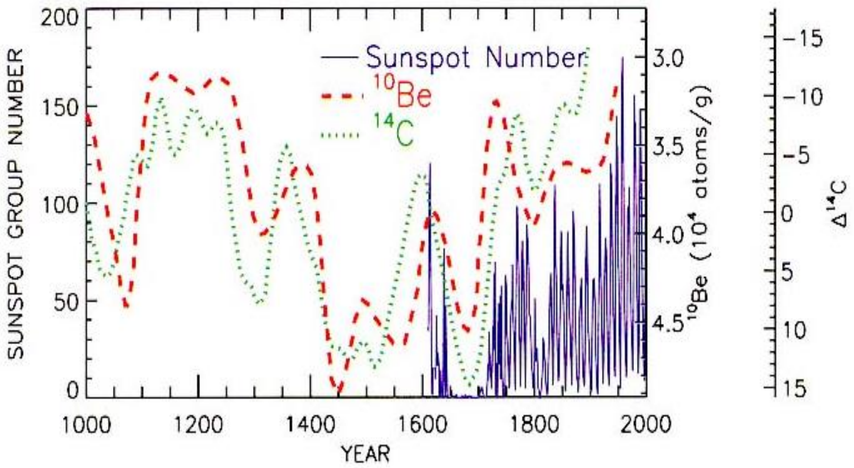


Figure 24: Concentration of the cosmogenic isotopes (^{14}C in dotted green, ^{10}Be in dashed red) over the past millennium, with the group number series (Hoyt and Schatten 1998a-b) as reference for the last 400 years (Source: Fröhlich and Lean 2004). Although the temporal resolution is lower for isotopes, this figure shows how the long term variations of the solar cycle amplitude, including periods of prolonged grand minima, are well tracked by the isotopic concentrations, allowing indirect reconstructions of the solar activity regime over many centuries before the first direct telescopic observations.

Moreover, as the Sun has a direct influence on the Earth environment, the sunspot record is a primary tracer of the long-term solar impact, which thus also leads to direct applications in the domain of geosciences and even current technology developments:

- Climate change, where the Sun acts as the main natural forcing over timescales of centuries
- Atmospheric drag, which conditions the orbital lifetime of low-earth orbit satellites and spacecraft operations
- Cumulative ground-induced currents (GIC) effects on infrastructures like pipelines and electrical power grids, in particular at high latitudes.

This broad impact is materialized by more than 100 scientific publications per year that use the sunspot number, and the 1,600,000 Google links given by the keyword “sunspot number”. The latter also illustrates how sunspots are part of public culture (literature, songs, etc.). Thanks to this popularity and the broad understanding of sunspots by the general public, the sunspot number also proves to be an excellent educational tool to introduce young people, citizens and amateur astronomers to the ever-changing solar activity, and to spawn an appreciation and interest for solar physics and astronomy in general.

4. First end-to-end re-calibration of the historical sunspot number

As was shown in the previous section, the construction of the sunspot number (SN) series was a long progressive process, during which observing and processing practices evolved through a succession of changes in the context of the production, and over multiple generations of observers. Subtle changes in the scale of the resulting sunspot number thus seems almost inevitable, but by how much and when? A first strong indication of such inhomogeneities was brought by the publication of the sunspot group number series (GN, Hoyt and Schatten 1998a, 1998b). This series was specifically created to extend the sunspot number record fully back to 1610 and the first telescopic observations, which allows to include the special episode of the Maunder Minimum (1650-1710) when almost no sunspots were reported. Given the cruder early observations, Hoyt and Schatten defined a simple index that only includes the number of sunspot groups. This is a cruder index, as it does not include any measure of the sizes of the different groups, but as it is based on sunspots, it was expected to be a close equivalent to the SN itself.

However, the comparison immediately revealed that while both series agreed very well over the last century, the two series disagreed by more than 40% before 1900, with the group numbers systematically lower over past centuries (Clette et al. 2014). This signaled the need for a quantitative evaluation of possible biases in either of the series, and was one of the prime motivations for initiating a community effort that was started in Sept. 2011. This collaborative work involved more than 40 scientists and was articulated around five Sunspot Number Workshops (NSO Sacramento Peak, ROB Brussels, NSO Tucson, Specola Observatory Locarno). This work was recently extended for 2018-2019 by new workshops supported by the International Space Sciences Institute (ISSI, Bern; www.issibern.ch/teams/sunspotnoser/) and chaired by Matt Owens (University of Reading) and Frédéric Clette (Royal Observatory of Belgium).

Figure 25: Group picture of the participants of the first Sunspot Number workshop, held at the National Solar Observatory, Sunspot, Sacramento Peak, USA, in September 2011.

Syntheses of the results can be found in a review chapter (Clette et al. 2014), and in a topical issue of Solar Physics entirely dedicated to the recalibration of the sunspot number, which includes 36 articles (Clette et al. 2016a). In this section, we will only summarize the main corrections brought to the original official series, as well as some new recent studies proposing additional or alternate revisions of both series. We will consider separately the SN and then the GN series, as both series were produced differently and thus suffer from distinct problems which require distinct approaches to derive corrections.

4.1. Corrections to the sunspot number

Three intervals were corrected in the new version of the sunspot number series, officially released in July 2015 (Figure 26; Clette and Lefèvre 2016):

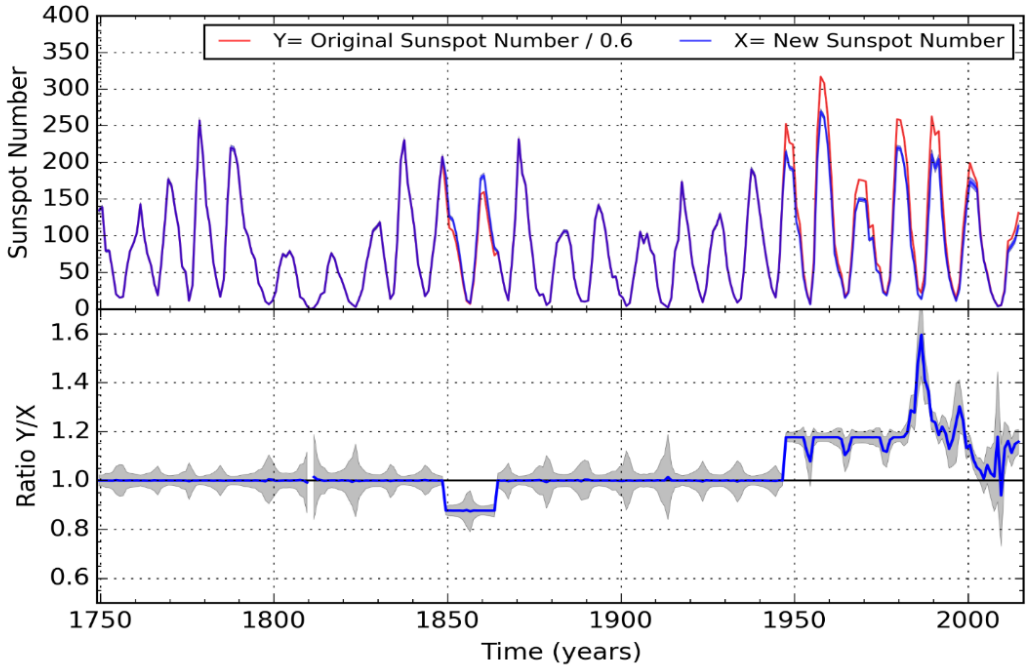


Figure 26: Summary of the changes between the original and new SN series. Top panel: original series (red) and new series (blue). The old 0.6 conventional factor was removed from the original series to bring it to the same scale as the new series over the entire intervals where no corrections were applied. Lower panel: ratio of the original over new series (uncertainties: gray shading), showing clearly the corrections described in the main text.

- 1849-1864: an initial scaling bias affecting the sunspot numbers produced by Wolf, when the system of k personal coefficients was not yet fully implemented, was corrected by raising all values by a factor 1.14 between two sharp transitions. Indeed, the consultation of the original publications allowed to establish the dates of the transitions to the nearest day: transition from Schwabe's observations to Wolf's own observations (January 1st, 1849), transition from Wolf's observations to his first assistant hired in the new Zürich Observatory (July 1st, 1864; see Figure 10).
- 1947: a sharp jump affecting all numbers after that transition, with all numbers about 16% higher on average after that transition. The most probable cause of this overestimate of the sunspot numbers is the introduction of weighted counts, described in Section 2.2 above.
- 1981-2015: a variable drift attributable to the Specola Solare pilot station, which replaced the Zürich observatory in 1981 and which defined the long-term scale of the calculated sunspot number as explained in Section 3 above. The drift actually brought back the scale to the 1981 values over recent years. For this time interval, a multi-station reference was entirely reconstructed using the extensive data available in the SILSO database, giving monthly correction factors, by contrast with the other two periods over which an overall correction factor is applied over the entire interval (Clette et al. 2016b).

Among those corrections, the 1947 jump is of particular importance, as it changes the amplitude of the recent cycles after 1981 relative to all previous cycles, thus changing the long-term trend. Although the cause of this jump is well established, i.e. the introduction of weighted counts according to spot size (cf. Section 2.2), both the time of the transition and the amplitude of the jump were questioned in various publications (Lockwood, Owens and Barnard 2014, Lockwood et al. 2016a,b,c,d). Indeed, the weighting was introduced much earlier than 1947 (Friedli 2016 private communication, Cortesi et al. 2016, Svalgaard, Cagnotti and Cortesi 2017) and Waldmeier became Director and primary observer in 1945, while data indicate that the change only occurred two years later between 1947 and 1948.

Now, by consulting the yearly tables and reports published in the Mittheilungen der Eidgenössischen Sternwarte in Zürich, a deep transition took place in 1947. First, this is when W.Brunner, the former primary observer, stops observing, marking the end of a 20-year series. Moreover, the team of Zürich assistants is entirely renewed as can be seen in Figure 13. With the exception of Karl Rapp, a trained amateur observing from Locarno, no collaborator was observing both before and after the end of 1947. Finally, the list of external contributing stations also reveals a disruption associated with World War II: most stations that contributed before 1940 ceased to observe or to send data to Zürich. Waldmeier recruited new observers during the War, but most of them were ephemeral collaborators. Mostly after the war, Waldmeier managed to again build a durable network, but mostly with new stations. By contrast, the 1926 transition between Wolfer and Brunner benefited from a much better continuity. The observations by Wolfer and Brunner overlap by 3 years (1926-1928) and there was no corresponding change of assistants. In particular, the main assistant, Max Broger, observed between 1896 And 1935, thus broadly bridging the transition. The network of external stations was also largely the same between 1919 and 1940, for Wolfer and Brunner.

We thus argue that the continuity across the 1926 transition ensured the stability of the sunspot number, although Brunner was already applying the weighting, relative directly to Wolfer the last non-weighting observer. On the other hand, the discontinuity of all auxiliary observers around Waldmeier could easily lead to a loss of stability in the scale of the sunspot number. The fact that the jump diagnosed in the data points exactly at the time when an almost completed change of source observers is documented in the Zürich Mittheilungen is a strong evidence that this disruption was the factor that allowed a sudden and persisting bias induced by the methodological change of the weighting.

Regarding the amplitude of the jump, various determinations were derived by comparisons between the sunspot number series and various solar-related indices that existed around the time of the transition, as by then, new observing techniques had emerged (Lockwood, Owens and Barnard 2014). However, they are affected by other uncertainties and errors (Clette and Lefèvre 2016) and provide only a low accuracy. Therefore, for establishing quantitatively the correction, we exploited the fact that the observers at the Specola Solare observatory were trained to use the weighted counts and are still using it nowadays. A blind test was thus initiated by obtaining dual counts from the Specola stations: their usual weighted counts and simultaneous standard counts according to the original Wolf definition. This revealed a variable inflation factor, starting close to one for low sunspot numbers and reaching an asymptotic value of 1.177 ± 0.005 for intermediate and high sunspot numbers, for SNs higher than 50 (Figure 27; Clette and Lefèvre 2016, Svalgaard, Cagnotti and Cortesi 2017).

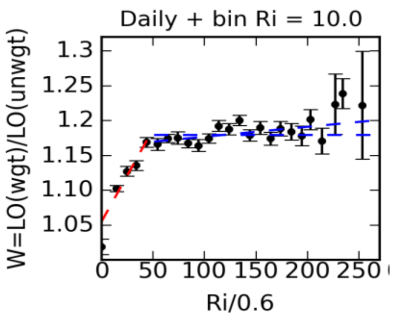


Figure 27: Inflation factor as a function of the sunspot number (vertical bars indicate the uncertainties). This factors starts from about 1.05 then rises sharply up to a sunspot number of 50, when it stabilizes and remains close to constant value of 1.18 for all high levels of solar activity (Source: Clette & Lefèvre 2016).

Over long durations, the mean inflation amounts to about 1.15. This direct determination was used as correction for all numbers after 1947, thereby lowering the amplitude of recent cycles relative to older ones. In addition, the inflation factor obtained with contemporary observations closely matches the estimates of the 1947 jump in the original historical sunspot number. Therefore, as the only difference between the dual counts is the weighting of spots, it gives an additional confirmation that the weighting is indeed the most likely explanation for the 1947 jump.

4.2. Corrections to the sunspot group number

The GN construction relies on completely different principles. The scale of the most modern observations is taken as reference, and earlier observers are compared to this reference to derive their personal scale (k coefficient). Working further backward in time, other earlier observers are compared to recent ones, thus daisy-chaining the successive k coefficients. This is illustrated schematically in Figure 28. This backward-propagation scheme introduces two weaknesses:

- Errors accumulate at each link of the chain, and may lead to a complete inaccurate scale for the oldest data set (Figure 28 top panel).
- Moreover, as the scale of an observer is assumed to be constant over time, any unsuspected drift in one observer will bias the scale of the entire reconstructed series before the affected observer (Figure 28, lower panel).

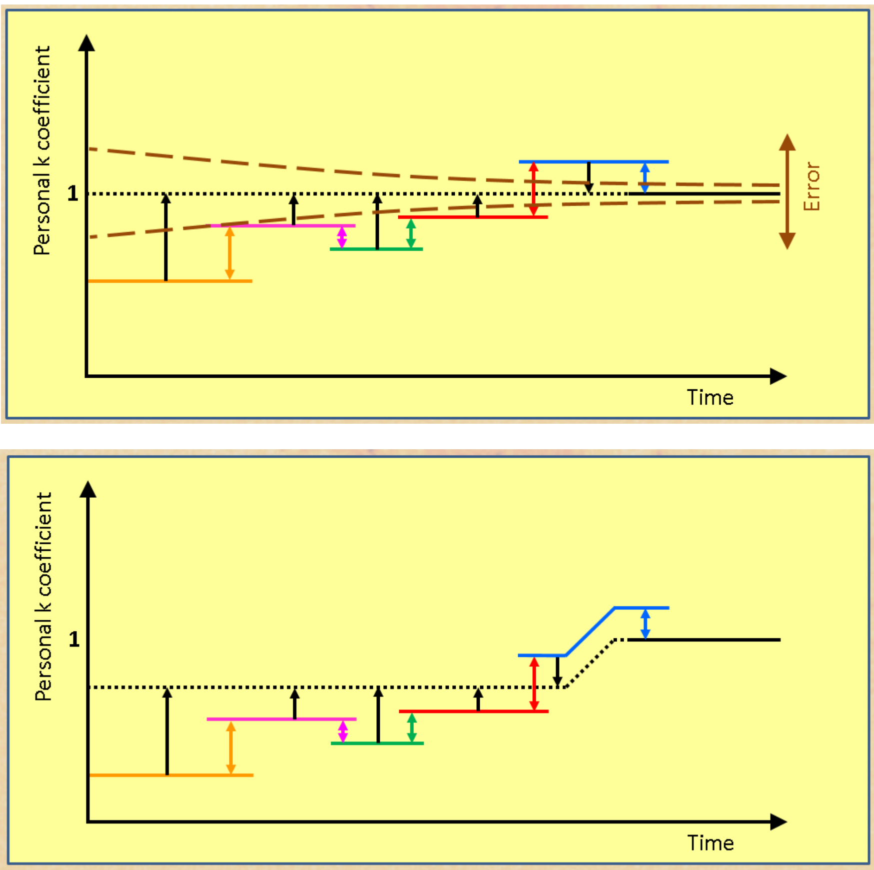
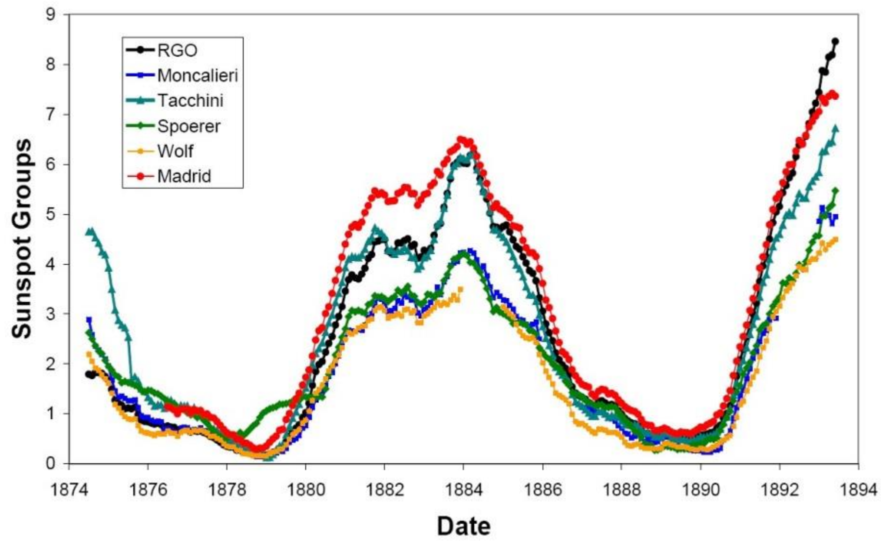


Figure 28: Schematic illustration of the propagation of daisy-chaining errors. Top panel: working backwards, each pair of observer is compared, allowing to bring them to the same scale (k personal coefficient) as a modern observer, taken as the initial reference (dotted black line). In the process, errors accumulate at each step in the chain, leading to large uncertainties for the first observers (dashed brown lines). Bottom panel: If any of the observer suffers from an unidentified progressive trend, a systematic bias is induced, affecting all the other observers preceding the flawed one (here, an upward trend, leading to an underestimate of the entire early series compared to the modern reference).

It turns out that for the first "contemporary" data set, Hoyt and Schatten (1998a-b) chose the catalog derived from the photographic collection of the Royal Greenwich Observatory (RGO; 1875-1975), instead of using multiple visual observers. Therefore, this reconstruction strongly depends on the stability of RGO data over the late-19th and the 20th century. A first comparison between the RGO numbers and several simultaneous visual observers revealed a systematic trend in the ratios, indicating a rise by about 40% of the group numbers in the RGO catalog over 1880-1915 (Figure 29). This was confirmed by a more recent analysis that repeats the Hoyt and Schatten daisy-chaining construction, but replacing the RGO photographic data by all available visual group numbers over the 20th century (Cliver and Ling 2016, Cliver 2017).



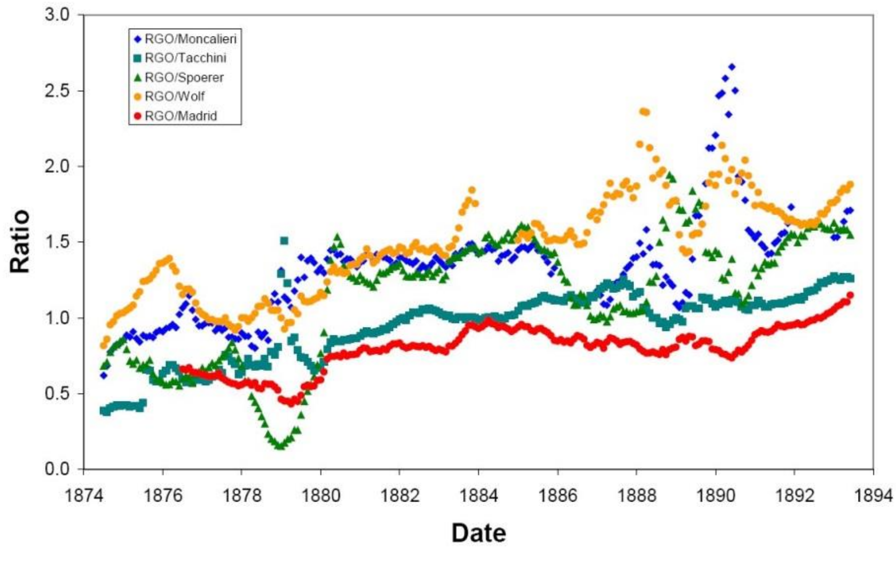


Figure 29: Comparison of the group number from six visual observers with the group number based on the Royal Greenwich Observatory photographic catalog (Source: J. Vaquero, 2nd Sunspot Number workshop, 2013). Top panel: the group number series. Bottom panel: ratios between each visual series and the RGO series. While the individual series show individual random discrepancies, the ratios all show a rising trend of about 40% over the 1875-1893 time interval, indicating an inhomogeneity present only in the RGO series.

The trend in the early RGO group counts could be due to the technical improvement of the photographic plates in those early days of astronomical photography or to improvement in the manual measuring methods. The history of the RGO collection definitely includes methodological changes (Willis et al. 2013, 2016). However, the loss of the early plates during World War II (only paper prints remain) makes this investigation difficult. Still, the above findings definitely question the reliability of the RGO catalog as a proper reference for the homogeneity of the GN series.

4.3. The “backbone” Group Number (1749-2015)

In order to address the above methodological flaws, a new approach was proposed for linking the scale of observers over centuries (Svalgaard 2013, Clette et al. 2014). Five main long-duration observers are used as reference for five time intervals, forming a “backbone” for the reconstruction (Table 1).

Table 1: Table of the primary reference observers in the “backbone” method reconstruction.

Backbone observer	Main interval	Full interval	Nb Obsevers
Staudach	1749 - 1787	1740 - 1822	15
Schwabe	1826 - 1867	1794 - 1883	20
Wolfer	1878 - 1928	1841 - 1944	21
Koyama	1947 - 1993	1920 - 1996	36
Locarno	1957-2015	1950 - 2015	22

Only observers who directly overlap those reference observers are directly compared, forming sub-series (Figure 30). As those series overlap in time, they can then be cross-calibrated, forming the entire series. Moreover, only visual observers are used for the entire length of the series up to 2015, partly by using the SILSO data for the second half of the 20th century, and thus avoid any bias associated with the RGO series.

Figure 31 shows the comparison between the original and the new so-called “backbone” GN numbers (Clette et al. 2014, Svalgaard and Schatten 2016). While both series match closely after 1900, the new groups numbers are essentially 40% higher over the entire interval 1715-1880, bringing the amplitude of solar cycles in the 18th and 19th century to the same level as recent cycles in the 20th century, while the original GN suggested that all cycles of the 20th century were stronger than any cycle in preceding centuries. The ratio deviates even more from unity over the Maunder Minimum, but the activity was extremely low during that interval (1650-1715). This special episode is discussed in Section 4.5 below.

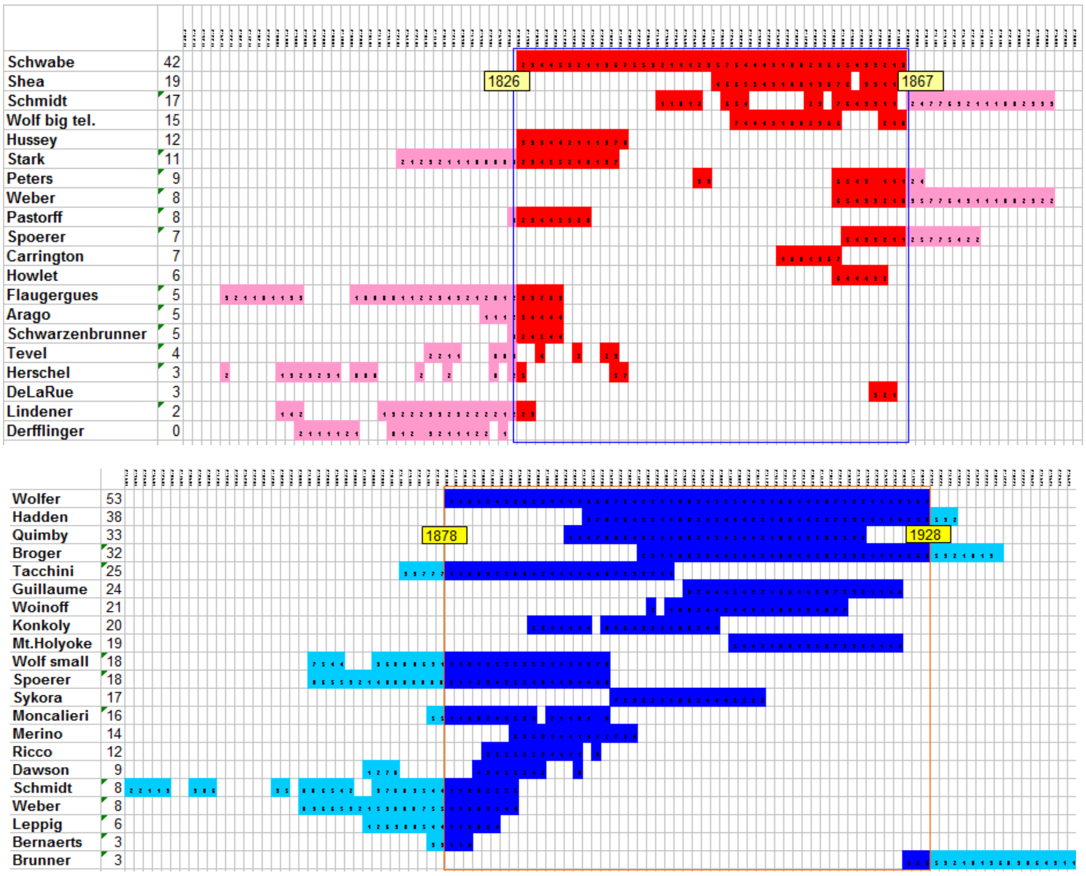


Figure 30: Timelines of all observers linked to one primary observer, for the Schwabe interval (top), and the Wolfer interval (bottom). Note that the time intervals spanned by each backbone segment are overlapping with each other, allowing to assemble them into a single global GN series (Source: Svalgaard and Schatten 2016).

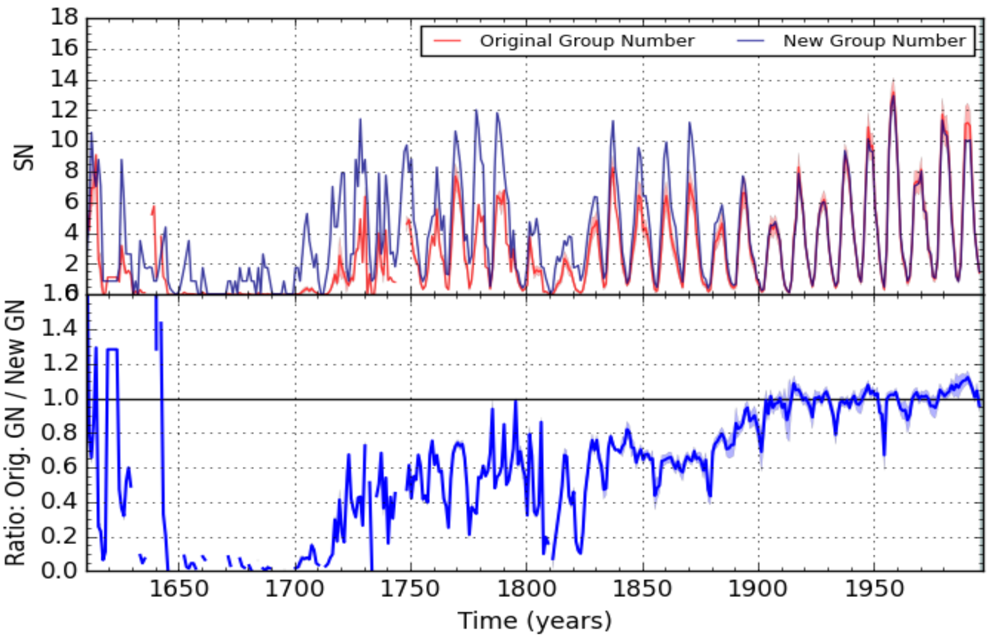


Figure 31: Summary of the corrections between the original GN series and the reconstructed "backbone" GN series. The two series are plotted in the top panel, while the ratio of the original over new series is shown in the bottom panel. Note that while both series agree closely over the 20th century, the entire early part was raised by about 40%. The very low ratios over the Maunder minimum simply reflect the very low, almost null, values in the original group number series. The new values differ only by 1 or 2 units, but are definitely higher, suggesting the persistence of a weak solar cycle.

Keeping the same principles, Chatzistergos et al. (2017) improved some aspects of the “backbone” method by increasing the number of backbone observers in such a way that their reference observers are all directly overlapping, instead of just the secondary observers attached to one of the references. He also replaced the k scaling factor by a non-parametric comparison between observers. This alternate backbone reconstruction falls between the low original GN series and the new high “backbone” GN series, confirming the underestimate in the original Hoyt and Schatten GN series but questioning the magnitude of the upward correction.

4.4. An Alternate approach: active-day fraction

As the use of k factors linking observers is questioned in general, a completely different approach was proposed to derive the personal scales of individual observers without requiring mutual comparisons: the active-day-fraction (ADF) method (Usoskin et al. 2016). By assuming that the number of spots reported by an observer depends entirely on his capacity to distinguish the smallest spots (acuity), this method establishes a relation between the number of reported spotless days (group number = 0) and the average scale of the GN when spots are reported. A base index is used, the active-day-fraction (ADF), which is the monthly ratio between the number of days with reported sunspot groups and without any spot. Then, in order to simulate observers of different acuity, the RGO photographic catalog is used between 1990 and 1975 (in order to avoid any possible pre-1900 inhomogeneity). The full unaltered catalog is supposed to represent a perfect observer, while imperfect observers of lower acuity are simulated by excluding spots with areas below chosen thresholds in the group counts.

By varying the chosen minimum-area threshold, one then matches the cumulative distribution function of the simulated ADF with the corresponding ADF of the actual observer. Once the threshold is determined, the RGO data are used to build a correspondence matrix of the full unfiltered counts (perfect observer) and the filtered counts when the threshold is applied to the catalog (simulated lower acuity), as shown in Figure 32. This is an interesting approach as this matrix allows a non-parametric conversion between the input numbers from the actual observers (abscises) and the corresponding estimated counts for a perfect observer (ordinates). No least-square fit to the distribution is used and the output gives a probability distribution (Figure 32, panel b) instead of a simple mean.

The main advantage of this method is that it allows to derive a correction and normalization of individual observers without requiring any comparison between observers. Therefore, isolated observers without any time overlap with any other observers could be calibrated and the error-propagation issues of the k coefficient are avoided.

However, several weaknesses have been identified in this innovative approach:

- First, the ADF reconstruction is only possible when the ADF is below 80%. This means that the method is applicable only to periods of low solar activity near the minima of the solar cycles. However, the equivalence matrix is applied to the whole range of group numbers up to the largest group numbers (cycle maxima). Therefore, the conversion is used outside the domain of determination, thus a form of extrapolation, which questions the validity of the scale corrections found for a large part of the solar cycles (Svalgaard and Schatten 2017).
- For its modeling of imperfect observers, the method assumes that the only factor influencing the group counts is the acuity of observers. However, the number of groups also depends on the way each observer is splitting the groups, deciding when a cluster of spots is actually a big group or two neighboring groups, a non-trivial decision (cf. Section 5.1 below). This factor is particularly important near cycle maxima, when the solar disc is tightly crowded by many sunspot groups, precisely when the ADF is beyond 80% and thus not applicable.

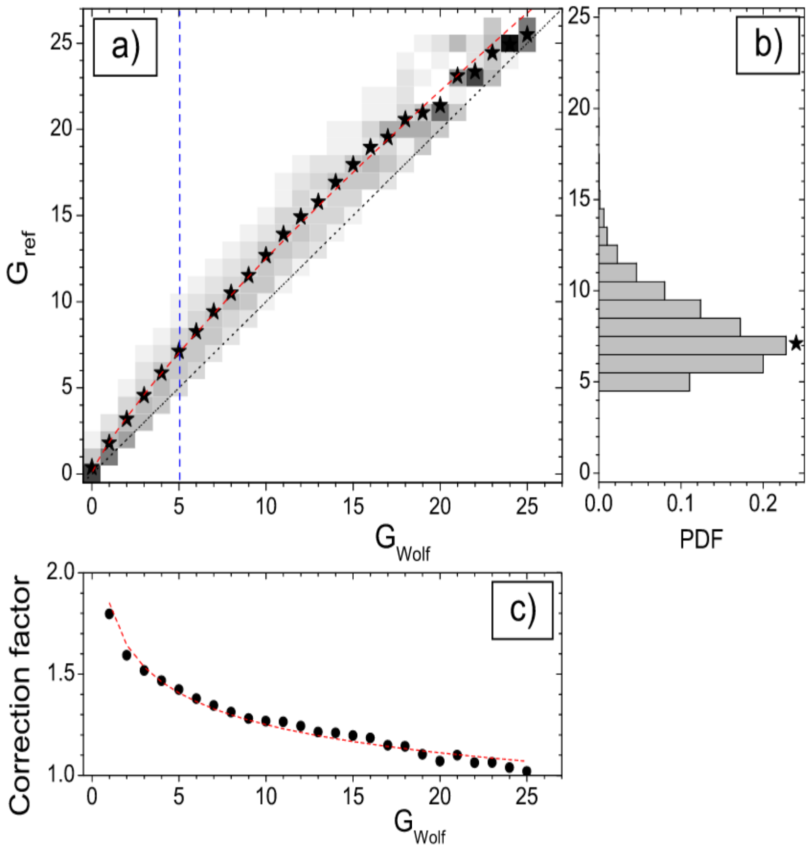


Figure 32: Example of a correspondence matrix synthesized for one observer (R. Wolf). Panel a: density distribution of group numbers from the raw unfiltered RGO catalog, simulating a perfect observer (vertical axis) and from the filtered RGO catalog (low-area thresholding) based on the ADF derived from Wolf's observations (horizontal axis). For any given observed number (vertical dashed line in panel a, the matrix provides the non-parametric probability distribution of corrected values (panel b). A parametric fit to the matrix (stars in panel a) gives the average correction factor as a function of the raw observed group number (panel c). (Source: Usoskin et al. 2016)

- Finally, as the ADF is entirely based on the absolute group counts, it also assumes that the sampling is random and uniformly distributed over time. In order to verify this assumption, we checked the number of observed days per month of all observers used in the ADF reconstruction. In many cases, we found significant non-random variations and in certain cases a solar-cycle modulation, with a lower number of observed days around the times of cycle minima [Figure 33: statistics for G. Spörer]. This clearly indicates that observers may tend to neglect reporting their observations (or making drawings) when no spots are present on the Sun. As a consequence, this artificially increases their ADF fraction, which thus simulates a better observer with higher acuity in the model assumptions. Therefore, a lower factor will be used to raise the values to the level of a perfect observer, leading to a global underestimate of the reconstructed GN.

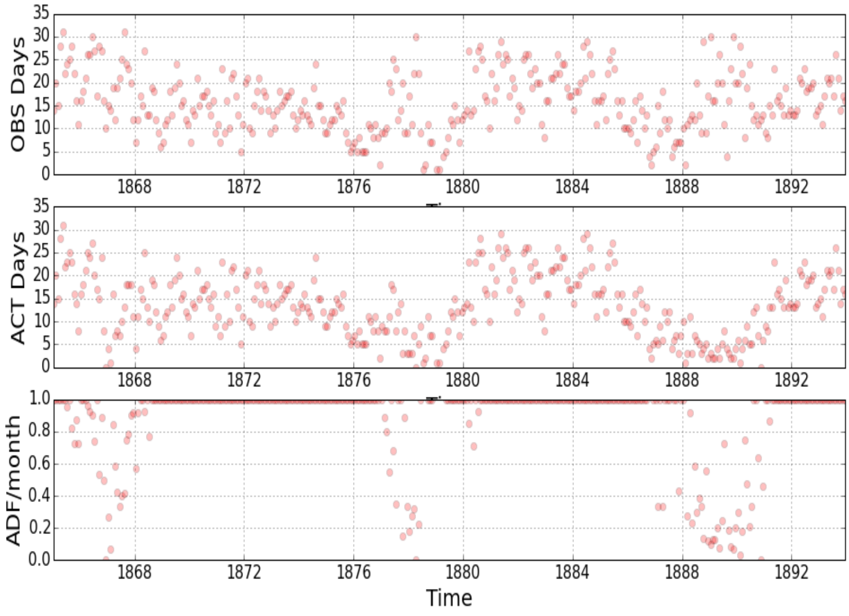


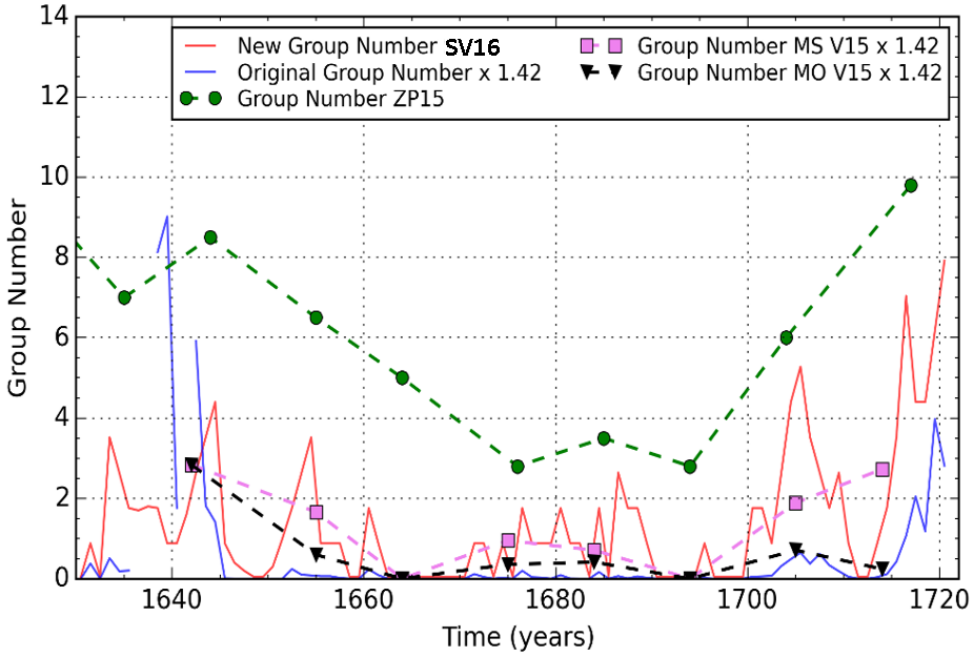
Figure 33: Active-day-fraction statistics for Gustav Spörer: number of observed days per month (top), number of active days per month (middle), active-day fraction ADF (bottom). The ADF clearly shows the solar cycle modulation, dropping to low values at each minimum, around 1867, 1879 and 1890. The top plot also shows a solar cycle modulation, indicating that the observing rate is not entirely random (weather conditions, etc.) but also follows the level of activity: Spörer clearly neglected to report when there were few or no sunspots on the Sun, violating a base hypothesis of the ADF method.

Indeed, the published ADF group number gives rather low values before the 19Th century, close to the original Hoyt and Schatten group number, and like the latter, with a marked upward trend towards the 20th century. However, given the downward-bias mechanism illustrated here, there is a good chance that such low values are an artifact of the method.

Moreover, one of the hopes brought by the ADF method, namely the possibility to calibrate isolated observers when data are very sparse like in the early historical part of the sunspot data, did not prove statistically possible. Therefore, neither the k-coefficient chaining approach nor the ADF approach can help to tackle the difficult issue of early sunspot data, mainly before 1750.

4.5. The 17th century and the Maunder minimum

In the early part of the group number series, special efforts were made to improve our reconstruction of the near-spotless period of the Maunder Minimum (1650-1715). The main progress resulted from a full revision of the original GN archive of original historical observations, often revisiting the original historical documents (Vaquero et al. 2016). Besides various corrections and the addition of some newly recovered observations, the main change was the elimination of many null values that had been unduly interpolated by Hoyt and Schatten (1998), across intervals of several days between two spotless observations. As in low activity, most spots are small, with short lifetimes of a few hours to only a few days, such interpolations can thus artificially extend the duration of entirely spotless periods. Using this new cleaned catalog, Vaquero et al. (2015) indeed obtain higher activity levels during the Maunder minimum (Figure 34). Depending on different requirement levels on the data, the amplitudes change but remain low (Figure 34: pink squares and black triangles). Still, contrary to the original group number which indicated a totally inactive Sun (Figure 34: blue curve), the improved data show the persistence of a very weak solar cycle throughout this quiescent period. Svalgaard and Schatten (2016) obtain such slightly enhanced activity when extending the backbone group number construction, by applying the scale derived for the second half of the 18th century to all early group number values (a debatable extrapolation; Figure 34 red curve).



Original Group Number (Hoyt & Schatten 1998)
SV16: « Backbone », Svalgaard & Schatten 2016
ZP15: Zolotova & Ponyavin 2015
V15: Vaquero et al. 2015
MS « Strict » model;
MO: « Optimum » model

Figure 34: Comparison of different reconstructions of the group number during the Maunder Minimum. The dashed curves connect points corresponding to the maxima of solar cycles for the Vaquero et al. (2015) and Zolotova & Ponyavin (2015) studies. All the new reconstructions suggest higher, though still weak, solar activity during this special interval, instead of a fully spotless period.

Another interpretation of historical data by Zolotova and Ponyavin (2015, 2016) introduces the bold hypothesis that all observers in the 17th century were looking for planetary transits and thus only selectively reported sunspots with a smooth circular shape, ignoring most spots which have more distorted shapes. Assuming such a global censorship, they obtain much higher group numbers and mid-amplitude solar cycles (Figure 34, green points), even questioning the reality of this long fully quiescent grand minimum. This gives the highest reconstruction to date. However, subsequent studies re-checked the existing reports and drawings of that epoch, showing that many accurate renditions of irregular sunspots are present just like at other epochs (Usoskin et al. 2015, Carrasco, Vaquero and Gallego 2018). Therefore, the invoked selective observational bias and the corresponding high activity levels are considered as unrealistic.

4.6. External validation: geomagnetic record

Over more restricted times periods, some alternate time series retracing solar activity are available, mainly cosmogenic isotopes and geomagnetic indices or indicators (reports of aurora borealis). However, as these indices involve indirect responses of the Earth environment to solar activity, they include other sources of errors and trends. Therefore, they cannot be used as a reference to calibrate the sunspot number series. This is why all the diagnostics and corrections described above are entirely based on direct sunspot data. Still, after the series has been revised, a comparison with those parallel series can provide an additional validation of the correctness of the modification, if the alternate series independently retraces the same evolution of solar activity.

Recently, a full joint revision was carried out for the solar open magnetic flux in the interplanetary medium, which is based on long-term geomagnetic indices (Owens et al. 2016). This state-of-the-art series that extends back to 1845 indicates similar solar activity levels between the mid-19th century and the present. By comparing the geomagnetic reconstruction with equivalent reconstructions based on the different published sunspot and group number series (Figure 35), this study concludes that the best match is now obtained with version 2.0 of the SN and the recent part of the "backbone" GN.

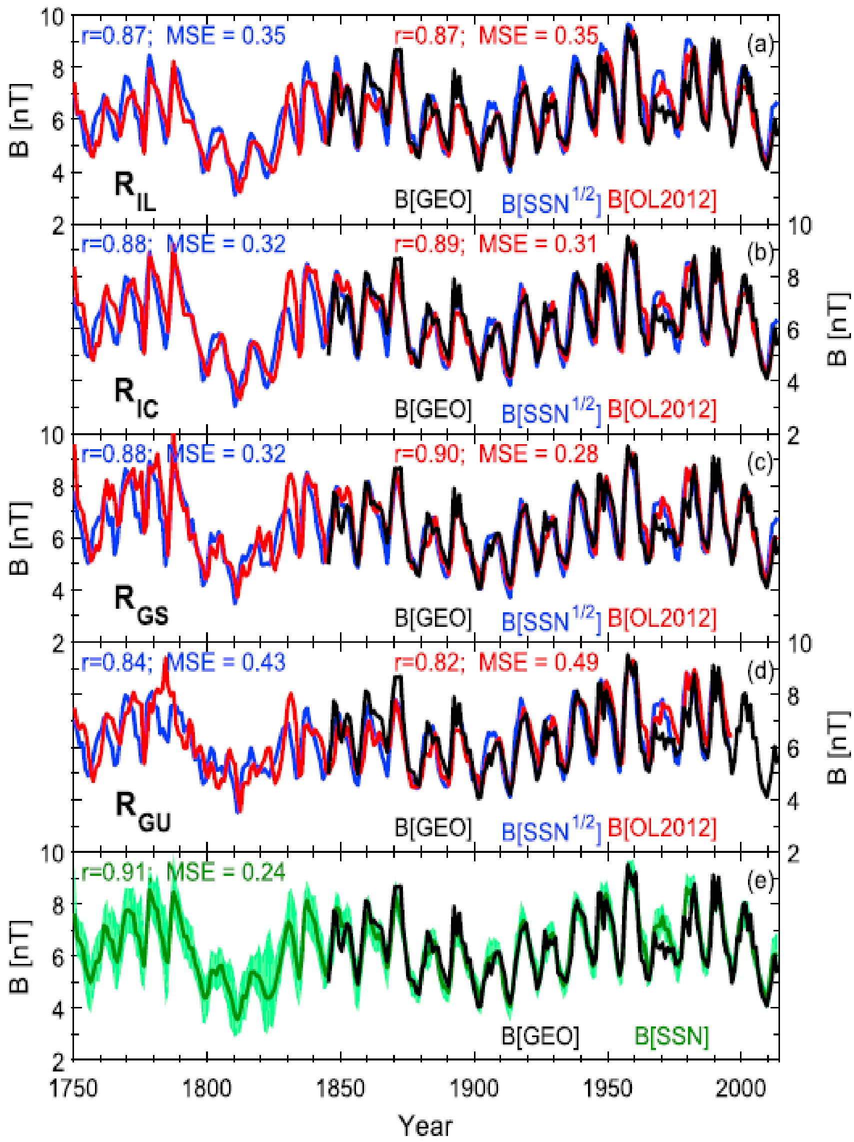


Figure 35: Reconstructions of the solar open magnetic flux over the past centuries, based on different versions of the sunspot or group number series, compared to the reconstruction from the geomagnetic record (black curve in all panels). In each panel, the red and blue lines correspond to two reconstructions methods, r is the correlation coefficient and MSE is the mean square residual error. From panel a to d, the base sunspot series are respectively, the sunspot number by Lockwood et al. (2014), the new international sunspot number by the WDC-SILSO, the "backbone" group number and the ADF group number. Panel e is a weighted composite of the above estimated series. (Source: Owens et al. 2016). The best match with the geomagnetic record is obtained by the new international sunspot number and the "backbone" group number.

All this brings a new picture of the secular evolution of solar activity over the last three centuries (Figure 36). Both the original SN and GN series showed marked rising trends. However, the trends did not match and was much stronger in the original GN series (40 %/century) than in the SN series (15 %/century). After independent re-calibration, the SN V2.0 and the "backbone" GN series now match much more closely, and show the same low trend of less than 5 %/century. This fundamentally new scenario, where solar activity remained in the same range over past centuries instead of reaching an unprecedented maximum in the 20th century, can lead to deep changes in the interpretation and in conclusions regarding various solar-driven processes, including of course the role of the Sun on the recent evolution of the Earth climate.

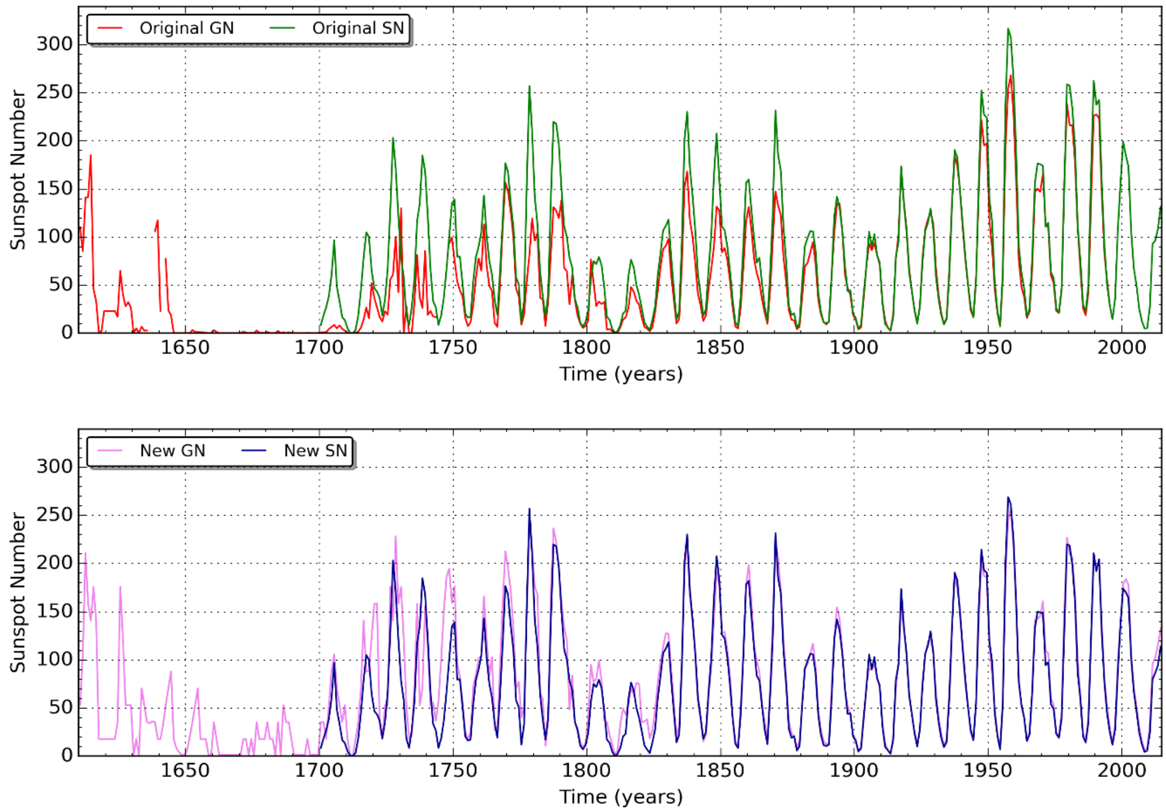


Figure 36: Comparison of the original sunspot and group numbers (top panel) and the new corrected sunspot number and "backbone" group number (lower panel). In both cases, the group number has been scaled to the sunspot number over the 20th century. The original series show a rising trend in cycle amplitudes over the last three centuries, different for the group and sunspot number, while both new series indicate similar amplitudes over the entire period.

5. Determining uncertainties

In order to interpret more quantitatively the above changes, it has become essential to determine the uncertainty of the sunspot numbers, while the original series did not provide any error estimate or very rough ones. In the previous sections, we have seen how the technical quality and the number of observations increased over time. Therefore, we may expect that the uncertainties vary with time and are larger in the early historical period than nowadays. Let us consider the sources of errors and of systematic biases that may affect the sunspot record.

5.1. Main sources of errors

The detector used to count spots, i.e. the human eye, did not evolve at the scale of the past few centuries. This absence of change in the primary detector is one of the key factors that ensured a high stability to the visual sunspot record over such long durations. By contrast, more recent techniques like photography or electronic imaging experienced much faster evolution, over timescales of a just few years.

Of course, the most likely factor of evolution is the technical improvement of the optical telescope since its invention. The optical resolution will indeed determine the visibility of the smallest spots. However, another lucky combination of factors also reduces the influence of this optical factor over past centuries. Indeed, the minimum physical sunspot size is about 2500 km, a minimum diameter that is defined by the scale of the solar granules (convection pattern). This diameter corresponds to an angular dimension of about 3.5 arcsec as seen from the Earth, which corresponds to the angular resolution of a rather small telescope with an aperture of 70mm. It turns out that telescopes already reached such apertures during the 18th century. Therefore, the degrading influence of small telescopes mainly affects the first sunspot observations before the mid-18th century. Since then, even when telescopes with even larger aperture were used, they could not reveal more sunspots as all sunspots are already resolved by smaller apertures. Moreover, in practice, larger apertures are more affected by the atmospheric turbulence, which anyway limits the gain in resolution relative to more modest telescopes.

Another important but often overlooked source of discrepancies between group counts from different observers are the group-splitting rules and practices. This requires defining the boundaries between clusters of spots. Much more than counting spots, this involves an interpretation based on existing knowledge: e.g. sunspot groups are formed by a magnetic dipole, thus often featuring two main spots. This dipole has a maximum possible size and the chronology of the evolution of each sunspot group can only follow specific evolutionary tacks. In this respect, the introduction of sunspot group classification schemes, like the Zürich, McIntosh or Mount Wilson classifications, may influence the observer in a different way at different epochs. Visual effects can also play a role, like a small drawing size favoring the grouping into larger groups, as was found in the case of Staudacher (Svalgaard 2017; Figure 37), although this was not verified in a systematic way for many observers yet. Still, this effect is playing a role mainly around the phases of cycle maxima, when the solar disk is filled with many groups, while at most other times, the groups are widely separated and the splitting is non-ambiguous. So, again here, solar properties naturally limit the range of the possible biases induced by this other source of error.

We also note that when original drawings exist and are preserved, it is possible to re-count the group in a modern and uniform way, thus correcting any mistake by the original observer, as was done in the case of Staudacher (Svalgaard 2017), leading to a 25% increase in the average number of groups.

Figure 37: Sunspot drawings by C. Staudacher for February 13 and 15, 1760 (Source: Svalgaard 2017), from which R. Wolf reported a single large group. Based on current knowledge of the maximum possible size and the normal bipolar morphology of sunspot groups, three distinct groups must actually be counted (circled)

One last factor helps to limit the influence of personal biases on the reconstructed global index. At most epochs, there are several parallel observers, who in almost all cases do not communicate among themselves and thus count completely independently. Therefore, the personal errors are uncorrelated and cancel out over many spots counts and many group splittings. This error-reducing effect of multiple observers confirms the importance of a multi-station network, with as many stations as possible, as it is the case nowadays with the large worldwide SILSO network.

By contrast, the processing method used to compile all the counts to produce the global sunspot index plays a critical role in the accuracy and stability of the resulting numbers. This dominant role of the processing in the homogeneity of the series was illustrated by the recent corrections described above, where most problems can be traced to flaws or changes in the base method, rather than to the source data.

5.2. Global statistics based on the SILSO database (1981-now, > 550.000 data)

Another way to analyze the error statistics in the main sunspot series is to exploit the mass of recent data available in the SILSO database. A first exploration was carried out by Dudok de Wit, Lefèvre and Clette (2016), and showed that the errors in the daily Wolf numbers of individual observers includes two components (Figure 38):

- Dispersion errors that vary linearly with the sunspot number and correspond to the human errors in the individual counts reported by the observers (disagreement between simultaneous observations).
- Time-domain errors that vary as the square root of the sunspot number and is associated primarily with the randomness of solar activity itself and also partly with long-term drifts in the scale of observers. This component has thus a Poisson distribution, equivalent to thermal noise and photon shot noise in an electronic detector.

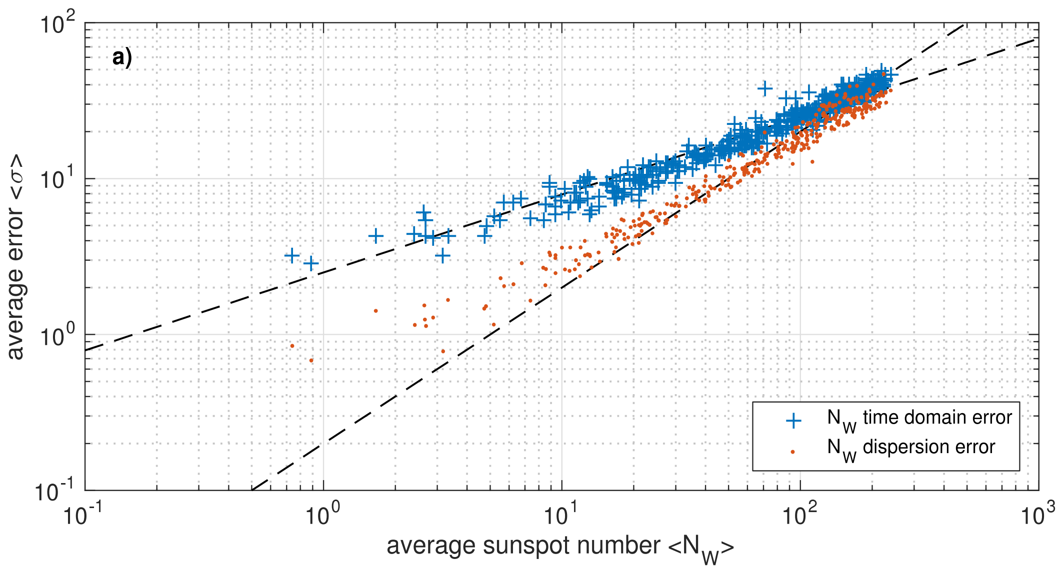


Figure 38: Dependence of the average time-domain (blue) and dispersion error (red) on the sunspot number (log-log scale). While the dispersion error is directly proportional to the sunspot number, the time-domain error scales as the square root of the sunspot number (dashed lines with slopes = 1 and 0.5). Dispersion errors only become important for the high levels of activity (S_N > 100)

The second source of errors is dominant over the whole low and mid-range of the sunspot numbers, while the second source only becomes important near solar cycle maxima. Therefore, most of the time, the errors are dominated by solar random variability, while different observers agree comparatively well. Over long durations, we expect that the quality of observations increases over time and thus that the errors tend to decrease. This is exactly what is found, after re-normalization of the sunspot numbers by the Anscombe transform, which suppresses the solar cycle modulation in the errors and stabilizes the variance by a variable gain α (Dudok de Wit, Lefèvre and Clette 2016]. This gain then allows to track the changes in the error amplitudes over time. This is shown in Figure 39 where jumps and trend-transitions in the gain α match well-known transitions between successive primary observers and between processing methods in Zürich and Brussels, as described in Sections 2 and 3.

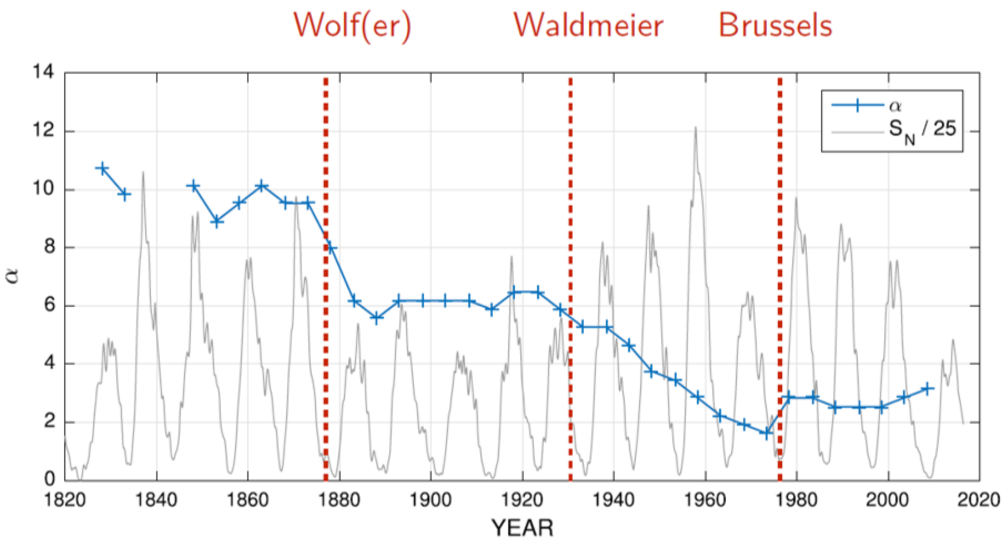


Figure 39: Evolution of the gain factor α tracing the changes in the variance of the sunspot number errors over the last two centuries. Important known transitions in the production of the sunspot number are indicated (vertical dashed lines). They clearly led to matching jumps and trend changes in the error variance, which progressively decreased over the entire time interval, as expected from the successive improvements brought to the statistical determination of the sunspot number..

By showing how the errors evolve over past centuries, this quantitative determination indicates that in any application using the sunspot number, this variable error should be taken into account to correctly translate the varying degree of uncertainty applicable to different epochs.

6. Managing future upgrades

Beyond the recent upgrade of the sunspot data series itself, new research conducted recently also marks a deeper transition from an heritage “archive” series to a modern data set open to continuous improvements. The emerging data-correction scheme actually forms the base a more permanent quality control process. This is summarized by Table 2 which highlights three main dimensions along which this transition has taken place.

While the first end-to-end revision was undertaken in 2011-2015 more than 150 years after the initiation of the sunspot time series by R. Wolf, a new version (Version 3) is now already in preparation. For the sunspot number, it will mark a new methodological step. Indeed, the current official revision was obtained by deriving corrections of diagnosed defects and applying them to the original sunspot number series built until 2015. Now, the new version will be entirely re-built from the raw numbers of single observers, and by processing all the data as much as possible in the same way as the current data of the modern SILSO network, thus ensuring a seamless connection between the early numbers and future numbers.

Table 2: Main conceptual transitions between the production of the original "heritage" sunspot number and the new sunspot number construction

Past status	New status
Static "definitive" series, with only a monthly extension	Entire series open to revisions, using new recovered data and state-of-the-art methods.
No error bars	Focus on the determination of observer precision (repeatability) and accuracy (absolute scale, long-term trends)
Isolated production and proliferation of parallel series, leading to confusion and the repetition of known errors	Collaborative work through workshops with topical working groups leading to a synthesis of all inputs into a common "best" series

This will involve adaptation of the current production software, by importing the knowledge acquired by correcting past flaws in the original series into new more robust methods. This will include in particular the use of a multi-station reference in place of a single pilot station and other refinements that we won't detail here. On the other hand, this full re-determination will entirely rest on the full recovery of all historical sunspot data usable for this recalculation. Of course, a prime source will be the original logbooks of the Zürich observers themselves, starting with R. Wolf. It turns out that Wolf's original handwritten sourcebooks archived at the library of the University of Zürich were recently scanned and digitized by the Rudolf Wolf Gesellschaft (http://www.wolfinstitute.ch, Friedli 2016). Those logbooks include raw numbers by Wolf and other early contributing observers (e.g. H. Schwabe) that never appeared in printed form, thus giving more insights into Wolf's processing practices.

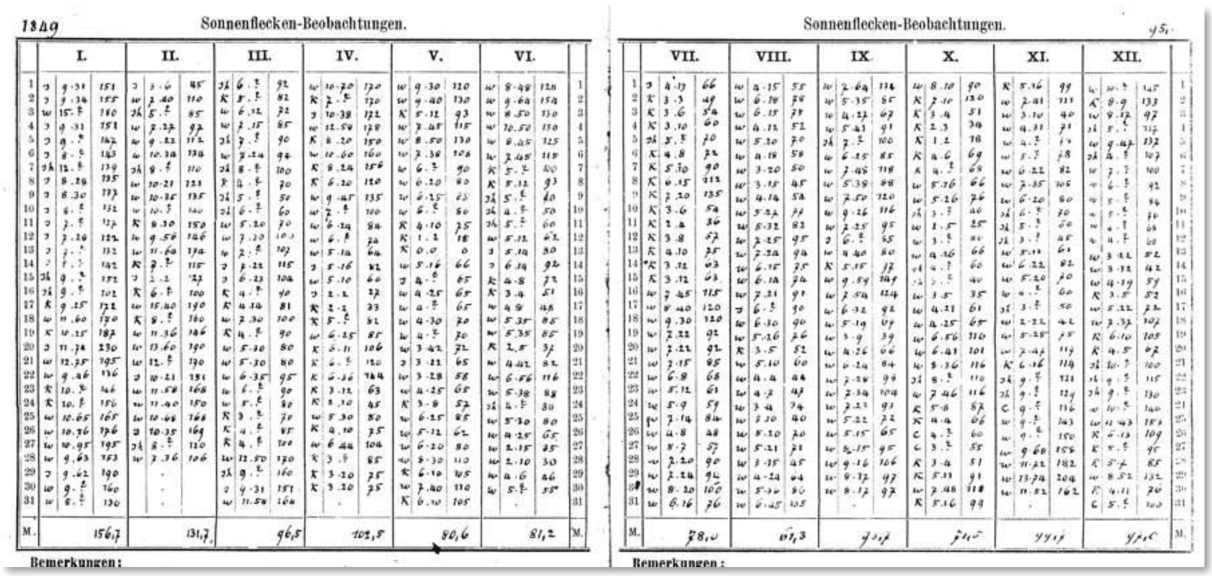


Figure 40: Wolf's handwritten sourcebook (1849-1875): page for the year 1849 (Source: ETH-Bibliothek, Hochschularchiv: Hs 368:46)

Of course, another core source are all the observations by the Wolf's successors at the Zürich Observatory. A recent survey showed that those data were entirely published from 1871 to 1945 in the Astronomische Mittheilungen der Eidgenössischen Sternwarte in Zurich. Likewise, the raw counts from the auxiliary stations that were collected by the Zürich Observatory are also entirely published in the Mittheilungen but only until 1919. As illustrated in Figure 41, the network was strongly expanded but only a few stations were still published until 1926, when Brunner stopped their publication entirely, mentioning that they were preserved and available in the archives of the Observatory. Unfortunately, recent searches did not allow to recover any of those documents (Svalgaard 2016 and R.Ramelli 2017, private communication). A large part of the original reports from auxiliary stations from 1957 to 1980 were archived at the Specola Solare Observatory in Locarno and are already largely included in the SILSO database.

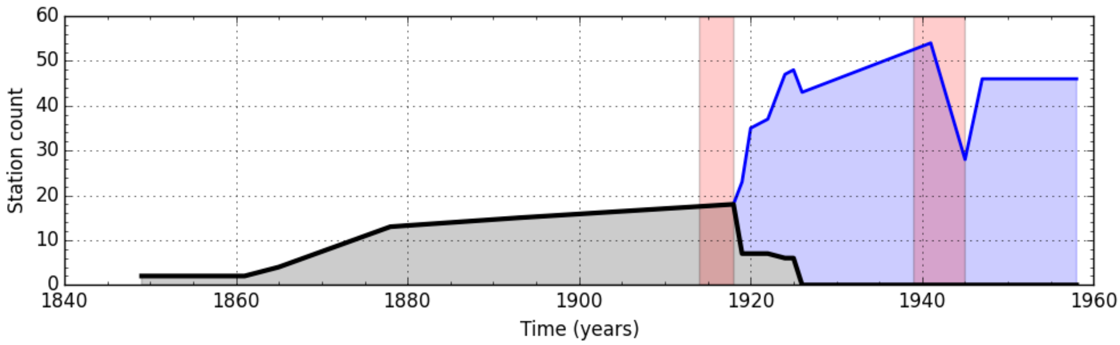


Figure 41:: Number of contributing stations with data published in the Mittheilungen of the Zürich Observatory (grey) and stations with unpublished after 1919 (blue). The pink shaded bands mark World Wars I and II. A steep growth of the observing network after World War I led to the end of the full publication of the data from auxiliary stations. A temporary drop in the number of stations, as well as a significant re-composition of the network occurred during World War II.

Therefore, one of the main challenges for the coming months and years will be to recover the missing observations and to encode all the number founds in those sources. The authors have already started this work, and all data published in the Mittheilungen are already encoded into a database up to 1908. Future work will concentrate on the recovery of the data for the period 1919-1957 and on data preceding the Zürich era, before 1849. This will require recovering original drawings, logbooks and publications from individual observers and professional observatories, often at the source itself. A good starting point for the early historical data will be the already-completed GN archive of raw group-number observations (Vaquero et al. 2016), recovering the counts of individual spots that were not taken into account for the construction of the first version of this archive by Hoyt and Schatten.

This ongoing work thus nicely illustrates how important the recovery of original historical still is for the advancement of our knowledge of the solar cycle. Our current advanced mathematical methods and computational capabilities are definitely a key to the ongoing progress, by better addressing unavoidable issues like large temporal gaps and sparse or irregular data. However, even those advanced tools entirely rest on the unique base information provided by past observers. The patient recovery and critical verification of any available sunspot data will be central for future work.

Beyond the sunspot number as reference indicator of the global solar activity, our current ability of manage large amounts of data allows us exploiting more detailed information about individual sunspot groups and sunspots. This can be derived from sunspot catalogs and sunspot drawing series, which span shorter durations than the sunspot number series but often cover many decades, back to the 19th century (Figure 42). Over recent years, several drawing collections were scanned and made available on line (e.g. Kanzelhöhe, Austria; Catania, Italy; Kandilli, Turkey). The digitization of the Zürich drawing collection itself, starting in 1882, is currently in progress. Drawings from some early observers, like Staudacher and Schwabe were also exploited (Arlt 2008, 2011). Such early drawings can bring more insight on observing practices and limitations.

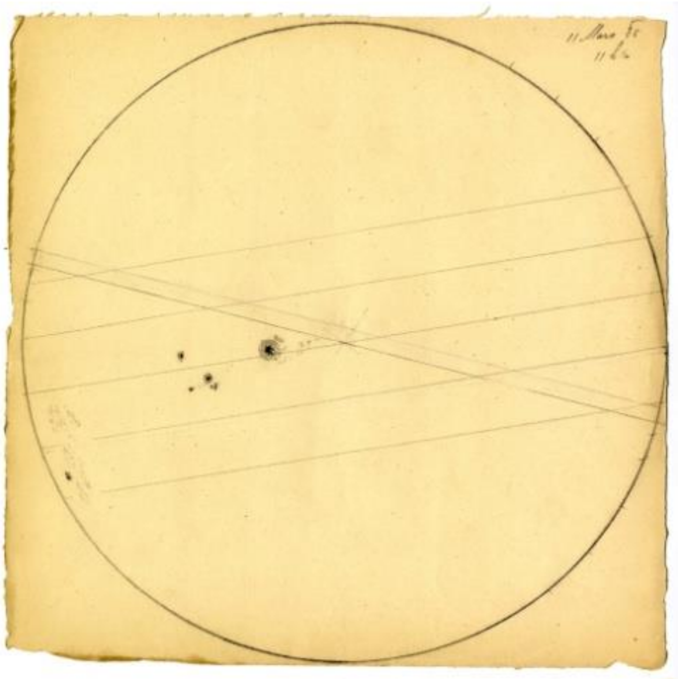


Figure 42: Example of a still unexploited drawing series: high quality sunspot drawing by Eugène Spée for March 11, 1886, with a disk diameter of 25 cm, taken from a set of about 200 drawings (Source: Royal Observatory of Belgium)

Drawing series and catalogues primarily bring information about spatial patterns of solar activity, like latitudinal distributions (Butterfly diagram), active longitudes, populations of sunspot groups of different morphological classes. The most time-consuming step for recovering this information is the extraction of sunspot characteristics, positions, etc. from the scanned drawings. This requires the development of specific measuring software, like the DigiSun application developed at the Royal Observatory of Belgium (Figure 43). This advanced tool was used to build the Uccle sunspot catalog, which spans more than 70 years, starting in 1940 (based on more than 20,000 drawings from the Uccle station: original scans accessible from http://www.sidc.be/uset/searchFormDrawing.php). Such applications allow extracting all the information contained in those documents, often well beyond what was possible at the epoch of the observation (e.g. sunspot area measurement).

Of course, over recent years, many observatories have been routinely producing digital images of the solar photosphere using CCD cameras. One could thus wonder why not creating a new global sunspot index that would be entirely based on such imaging data? Indeed, many sunspot parameters can be extracted automatically, impersonally and with a slightly higher precision.

However, switching to this entirely different technique requires deeper reflection:

- Using images is a different technique, with different sensitivities to parameters like atmospheric turbulence, diffusion, etc. Just regarding the atmospheric seeing, the camera grabs an instantaneous snapshot, with different non-optimal image sharpness over different parts of the solar disk, while a visual observer chooses the moments of best sharpness for each solar feature over several minutes or seconds.
- Imaging techniques experienced large and fast evolution from photography to the recent CCD and CMOS sensors, with quickly increasing pixel counts in just a few years. This makes it

difficult to compare images made only a few years apart, when the human eye hardly evolved over centuries.

- Although counting spots proves rather easy for a computer, the splitting of groups and their classification from images is still at the limits of even the most advanced artificial-intelligence techniques, with only a 80% reliability level (e.g. Colak and Qahwaji 2008)

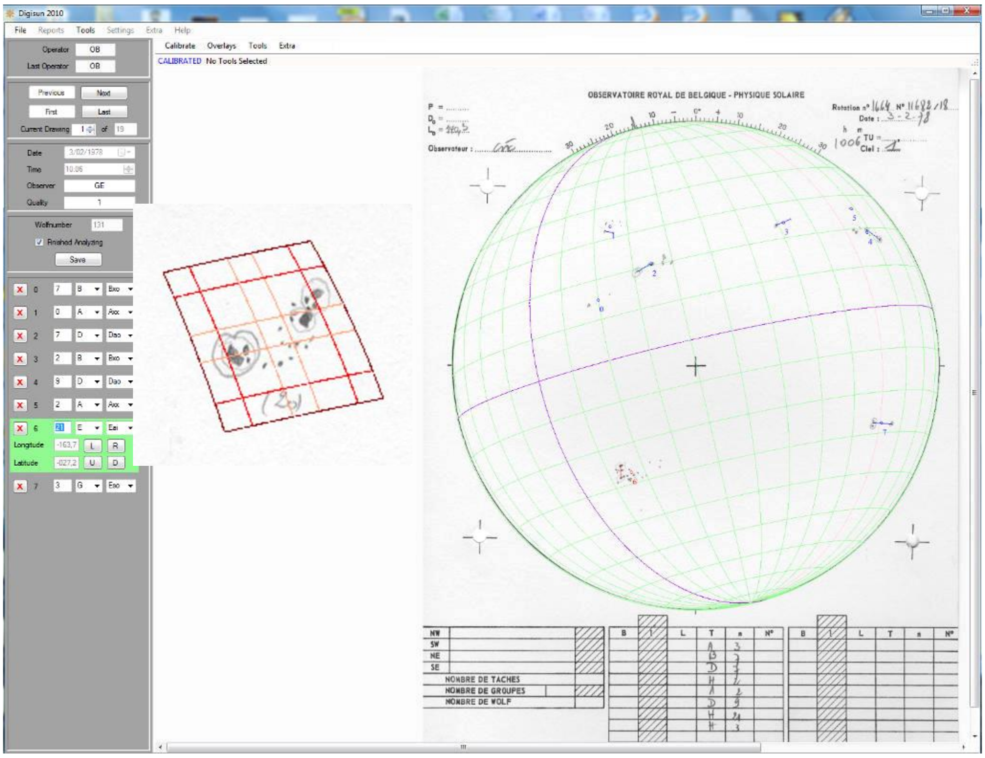


Figure 43: Example of a computer-based drawing digitization tool, the DigiSun software developed at the Royal Observatory of Belgium. This application allows on-screen measurements of sunspot group positions, numbers and areas and direct conversion into heliospheric coordinates. All measurements are immediately stored in a relational database, from which a 70-year long catalog of individual active regions is currently constructed (expected completion in 2019)

Therefore, even if further efforts must definitely be pursued to create a modern image-based sunspot index, the visual sunspot number still needs to be continued for many years in the future. Indeed, the time overlap with any new solar index should be long enough to cover all phases of a solar cycle and the whole range of possible activity levels. This is required to fully calibrate the new index versus the classical sunspot number and to fully understand the differences in properties between the two measures of sunspot activity.

Without this important cross-analysis, we would break our only link between the abundant and detailed but time-limited solar observations collected nowadays from the ground and in space, and the past history of solar activity, preventing to understand newly discovered solar processes in the perspective of the solar evolution as a whole. This is why the historical heritage of the sunspot number, in a modernized form, has still a key role to play in the 21st century.

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