





The new Sunspot and Group Numbers A full recalibration

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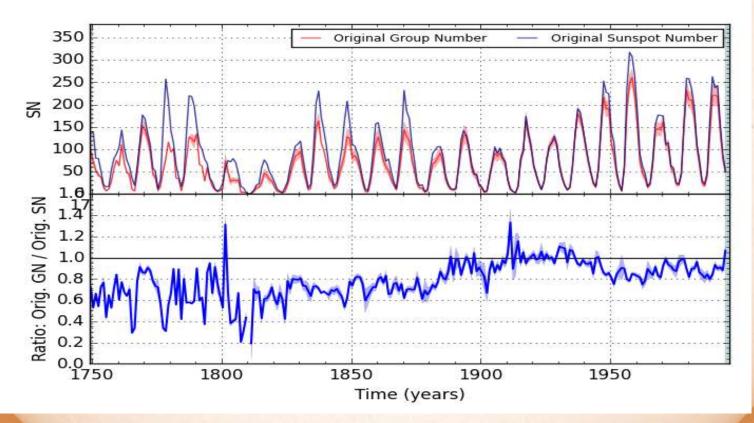
The 400-year sunspot record

- Only direct record of the evolution of the solar cycle over multiple centuries
- Longest scientific experiment still ongoing (B.Owens, Nature, March 2013)
- Multiple applications:
 - Solar dynamo modelling
 - Long-term irradiance reconstructions
 - Calibration of the cosmogenic isotopes (¹⁴C, ¹⁰Be)
 - Earth climate change
 - Infrastructure maintenance (pipelines, electrical power grid)
- > 100 scientific publications / year
- Part of public culture and astronomy education
 - > 150 000 Google hits on "sunspot number":

A necessary revision

- No critical revision of the Sunspot Number series since its creation by R. Wolf in 1849
- Only alternate series: the Group Number (Hoyt & Schatten 1998)

- $R = \frac{1}{N} \sum_{i} k_i (10Ng_i + Ns_i)$ $G_N = \frac{12.08}{N} \sum_{i} k_i Ng_i$
- Large discrepancies between the series (up to 40%)



7/8/2014

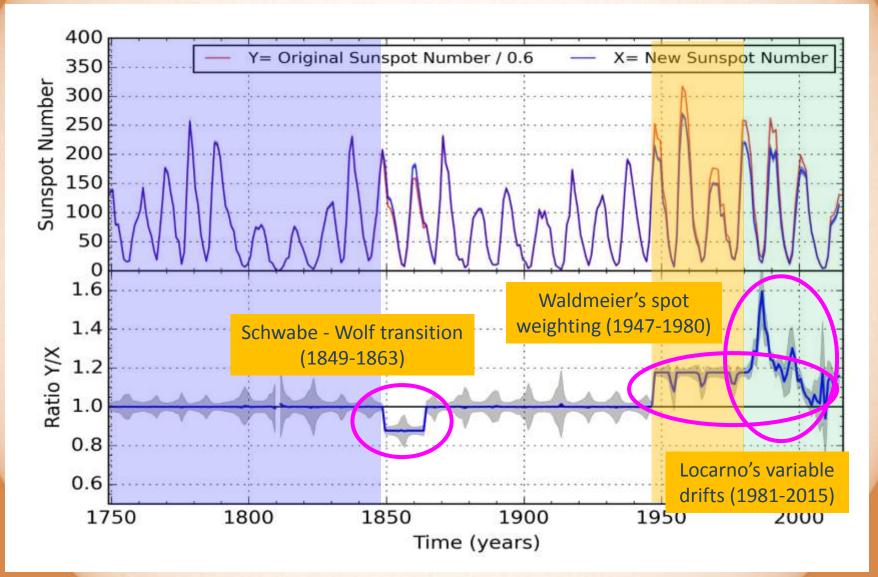
A new impulse: Sunspot Number Workshops

- Community effort started in Sept. 2011:
 - 4 Sunspot Number Workshops: Sac. Peak, Brussels, Tucson, Locarno
 - 40 participants:
 - Core group working on the SN
 - Input concerning other parallel solar tracers: Call-K, magnetograms, TSI, geomagnetic indices



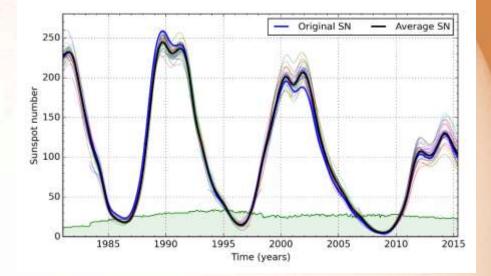
Synthesis in: Clette, F., Svalgaard, L., Vaquero, J.M., Cliver, E.W.: 2014, *Revisiting the Sunspot Number. A 400-Year Perspective on the Solar Cycle.* Space Sci. Rev. 186, 35-103 DOI: 10.1007/s11214-014-0074-2

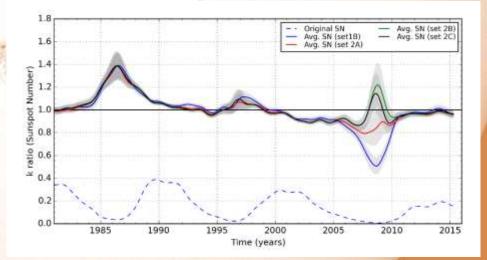
Sunspot Number corrections: overview



Locarno's variable drift (1981-2015)

- After the 1981 Zürich-Brussels transition: changing trends found in the SN from the Locarno pilot station (Clette et al. 2014)
- Direct reconstruction of the SN from a subset of 42 longduration and stable stations in the WDC – SILSO database:
 - Correction factor: monthly mean k ratio with the original SN series
- Causes
 - Loss of the Zürich Observatory as reference : initial overestimate over 1983-1995
 - Slow aging of primary observer (S. Cortesi)
 - Recovery with arrival of a new observer (M. Cagnotti, 2005)
 - Minor role by the sunspot weighting factor

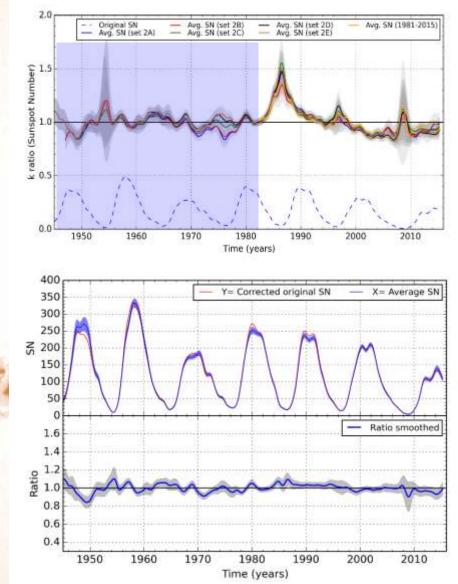




Locarno's variable drift (1981-2015)

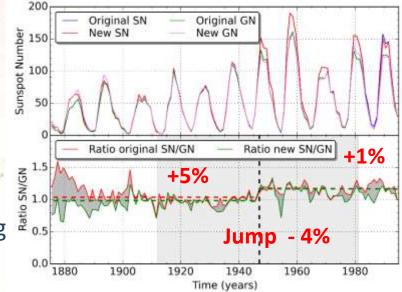
 Long reconstruction 1945-2015: 17 long-duration series covering the 1981 transition

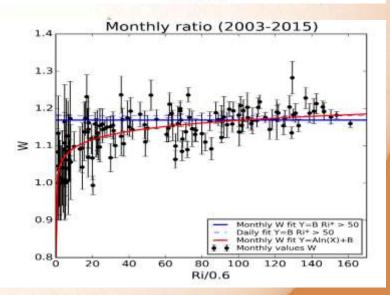
- After correction by the k factor over 1981-2015:
 - Constant ratio between the reconstructed series and the corrected original series
 - Average ratio before and after 1981 are equal:
 - Scale factor = 1.00 +/- 0.012



Waldmeier's weighted number (1947-1980)

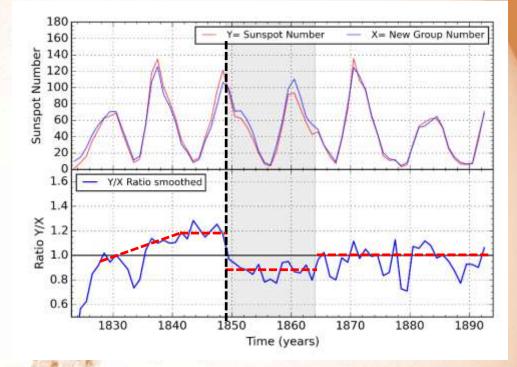
- 1947: new counting practice: large spots counted as >1 (2 to 5) according to penumbral size
- Inflation factor range: 1.15 to 1.25
- One low value: 1.126 (Lockwood (2014), but improper data:
 - Original series SN and GN containing other uncorrected biases (before 1915 and after 1980)
- Most robust determination: double counts, weighted and standard, done at the Locarno station:
 - Mean ratio in cycle 24:
 1.165 +/- 0.035
 - Existence of a maximum asymptotic mean value: 1.177 +/- 0.005
 - See also Svalgaard 2015, Sol. Phys.





The Schwabe- Wolf transition (1849-1863)

- **1849: 20% downward jump** in the SN relative to the original Schwabe numbers (*Leussu et al. 2013*)
- By comparison with the Group Number over a wider time interval:
 - Schwabe upward trend 1826-1840
 - 14% upward jump in 1863
- Equal scale before 1826 and after 1863
- A probable cause:



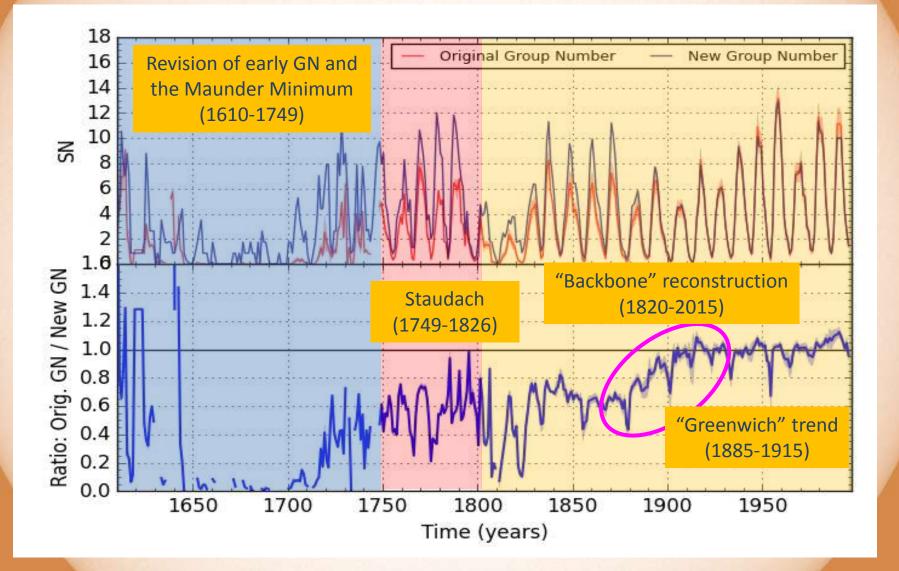
- Wolf initially mixed the raw Schwabe numbers with his own observations (small portable refractors).
 - Distinct markers only appear in published tables by 1863
 - Standard 80mm Zürich refractor delivered in 1864

Time-limited correction: SN increased by 1.14 (+/- 0.02) over 1849-1863

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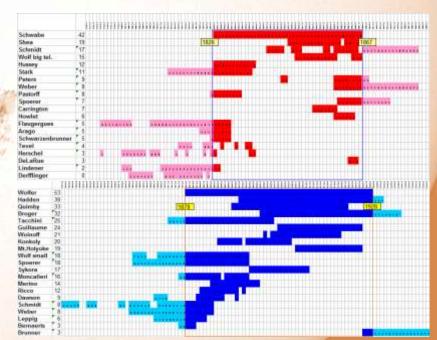
Group Number correction: overview



The "backbone" Group Number (1749-2015)

- Original method (Hoyt& Schatten 1998):
 - daisy chaining of k coefficients between parallel observers, working backwards in time
 - Non-visual reference after 1875: photographic catalog from the Royal Greenwich Observatory
 - Includes a 42% trend (1885-1915) (Clette et al. 2014)
- New approach for linking the scale of observers over centuries (Svalgaard 2012, Clette et al. 2014, Svalgaard & Schatten 2015):
 - "Backbone" provided by 5 longduration observers to which other observers are normalized.
 - Overlapping backbones are crosscalibrated
 - Only visual sunspot observers are used, including in the 20th century

	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
1.00	Koyama	1947 - 1993	1920 - 1996	36
	Locarno	1957-2015	1950 - 2015	22



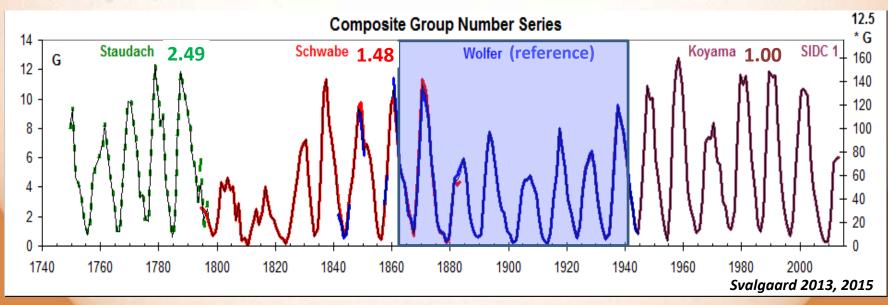
The "backbone" Group Number (1749-2015)

- First Staudach backbone (1749-1787):
 - Insufficient group splitting: unrealistically large groups
 - Full recounting from original drawings (Svalgaard 2015)
- GN increased by 1.68 relative to Schwabe



Staudach, Feb. 13 and 15 1760

- Final 1749-2015 composite backbone:
 - Base reference: A. Wolfer (standard counts, standard refractor)

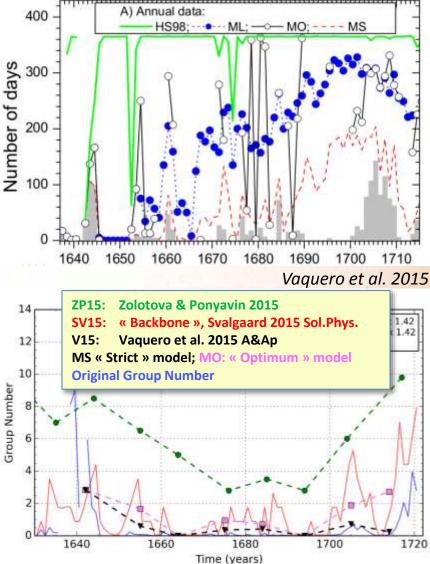


Revisiting the Maunder Minimum

- Elimination of many interpolated null GNs in meridian transit observations (Vaquero & Gallego 2014, Clette et al. 2014, Vaquero et al. 2015 in press):
- Reduction of the actual coverage from ~100% down to ~60%
- A new hypothesis (Zolotova & Ponyavin 2015): spots that did not look like round transiting planets were systematically ignored.
 - Only non-null observations are used
 - Contradicted by several alternate approaches like the "active days" method (Vaquero et al. 2015, Usoskin et al. 2015)

 Slight increase in the sunspot numbers during the MM:
 Short 9-year solar cycles





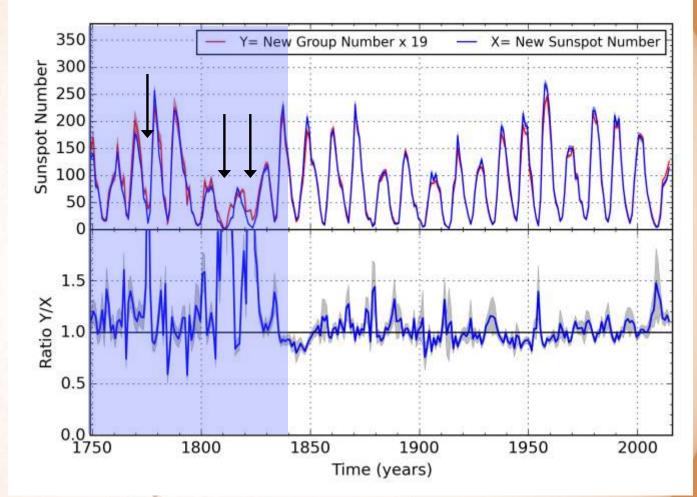
Combining all corrections: matching SN and GN

Original 350 Y= Original Group Number x 19 X= Original Sunspot Number / 0.6 series: 300 Sunspot Number 250 SN / 0.6 200 GN x 19. 150 100 50 0 1.5 Ratio Y/X 1.0 0.5 0.0 1750 1800 1950 1850 1900 2000 Time (years)

Combining all corrections: matching SN and GN

Close agreement over the entire interval 1826-2015

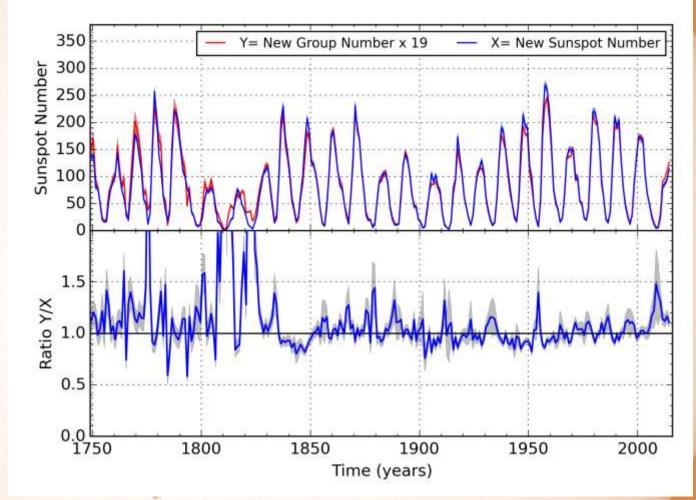
Still significant differences before 1826: more work is needed !



Combining all corrections: matching SN and GN

Close agreement over the entire interval 1826-2015

Still significant differences before 1826: more work is needed !



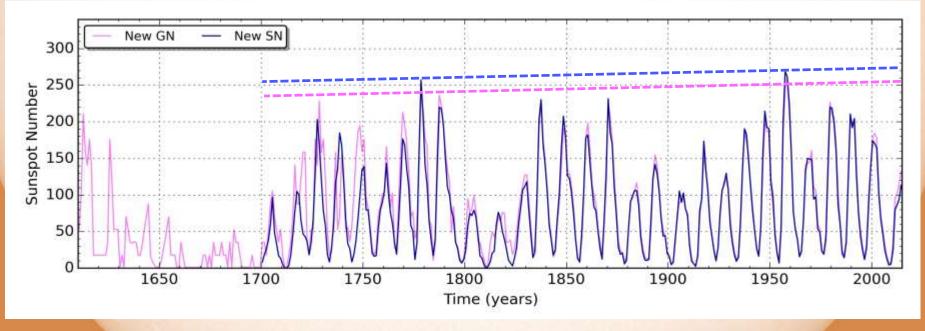
The improved agreement gives a strong final confirmation of the validity of the corrections

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Uniform peak cycle amplitudes over last 3 centuries

- Original series: strong upward secular trend from the end of the Maunder Minimum to the mid 20th century ("Modern maximum", *Solanki et al. 2004, Usoskin 2013*):
 - GN: + 40% / century (red) SN : + 15% / century (green)
- New SN and GN= similar very weak upward trend < 5 %/century

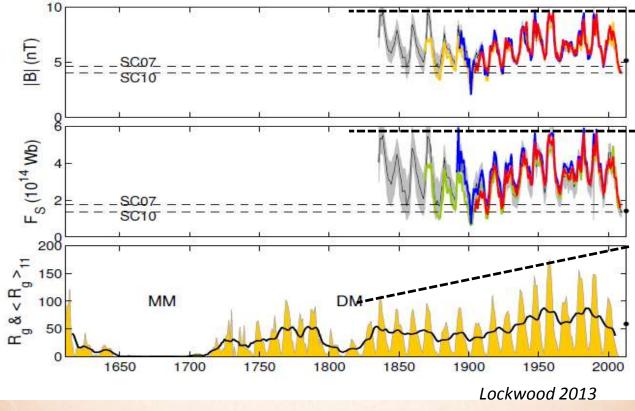
Soon after the Maunder Minimum , solar activity returned to high levels equivalent to recent cycles of the 20th century



(blue, purple)

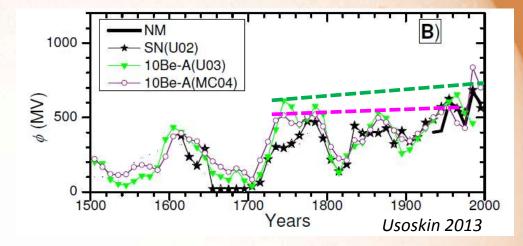
Comparison with indirect indices of solar activity

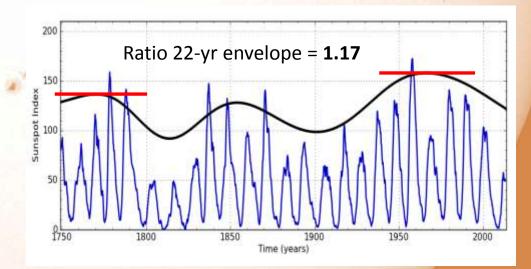
- Geomagnetic indices: reconstructed open magnetic flux over the last 180 years (Lockwood et al, 2013)
 - Recent reconstructions show identical cycle amplitudes between the mid-19th century and the 20th century



Comparison with indirect indices of solar activity

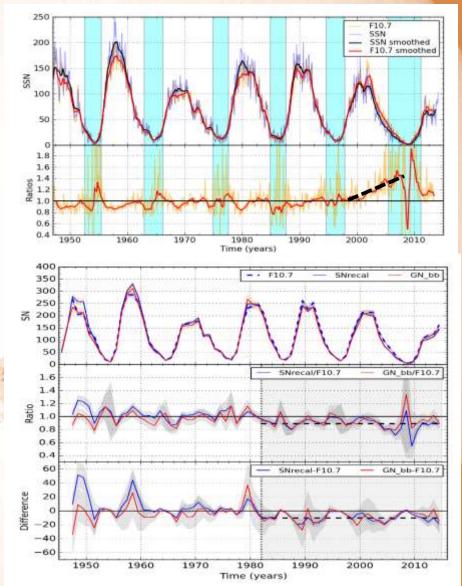
- Cosmogenic isotopes (¹⁰Be, ¹⁴C):
 - contradictory results between different samples and models (modulation potential φ):
 - Upward trend (Usoskin et al. 2002, Solanki et al. 2004)
 - No trend (Muscheler 2007, Usoskin et al. 2015)
 - Limitations: complex deposition processes, evolution of Earth magnetic field
- Time integration of φ (20 to 40 years)
 - Low-pass filtering of SN series (22 years):
- Upward trend but weaker
- The longer sequence of strong cycles in the 20th century gives a higher solar signal without stronger solar cycles





Better agreement with modern solar indices

- Original SN too low versus the F_{10.7} radio flux after 2000 (Svalgaard & Hudson 2010, Lukianova & Mursula 2011, Clette & Lefèvre 2012)
- Using the reconstructed SN and the "backbone" GN over 1945-2015
 - no more anomaly after
 2000
 - F_{10.7} is too high by 10% after
 1983 !



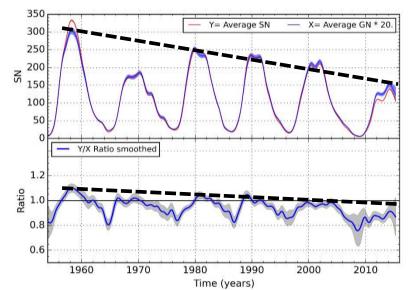
A sunspot deficit in recent solar cycles?

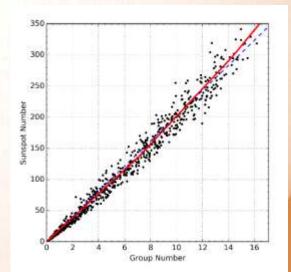
- Decline in the average number of spots per group over past cycles, enhanced after after the maximum of solar cycle 23: (*Tlatov 2012, Clette, Lefèvre 2012, Svalgaard 2013, Clette et al.* 2014)
- Reconstruction of SN and GN from the same base set of stations (SILSO network) over 1945-2045 (Clette et al. 2015):
 - Cycle modulation in the ratio
 - Trend in the ratio follows the maxima of successive cycles

Constant non-linear relation

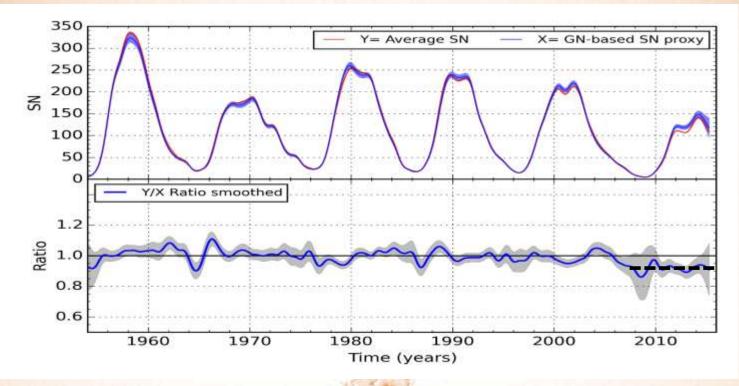
(degree 2 polynomial):

 $S_N = 17.8(\pm 0.4) \times G_N + 0.21 (\pm 0.03) \times G_N^2$





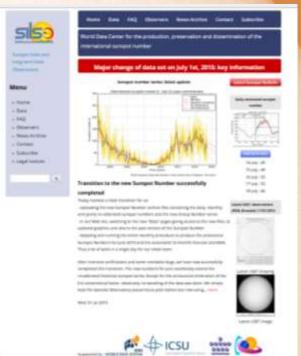
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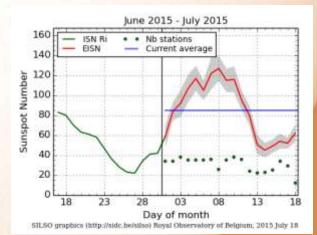


- GN-based proxy of the SN :
 - No more cycle modulation: constant ratio over 1945 2008
- The average number of spots per group obeys a constant relation
 - The recent spot deficit is a natural consequence of the activity decline
 10% deficit only starts in cycle 24

Upgraded data distribution and production

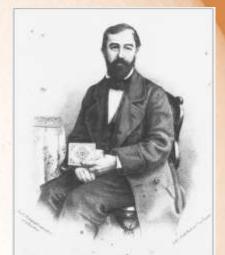
- New SILSO Web site: portal for all SN products on-line since early 2014:
 - Ready for future extensions (versions, info)
- Operational transition to the new SN: July 1st, 2015
 - Archive: Version 1 files replaced by Version 2.0
 - Adaptation of entire software for all SILSO products: hemispheric numbers, daily estimated SN (EISN), 12-month predictions
 - Unchanged base method for the total SN but:
 - Pilot station: Specola, Locarno un-weighted counts (original Wolf formula)
 - Factor 0.6 set to 1.0





New conventions

- Elimination of the 0.6 Wolf-Wolfer correction factor:
 - Based on 17 years of parallel observations by Wolf and Wolfer (1876-1893)
 - New modern counts set to Wolf's scale (small 40mm refractor)
 - Does not make sense after 123 years of modern SN
 - Source of confusion: SN was always too low
 - compared to raw counts of current observers
 - New reference: A. Wolfer (1893-1926)
- New symbols: S_N and G_N
 - Coexistence of several denominations: R, R_z, R_i
 - Clear distinction with the original "heritage" series
- Elimination of the 0-11 jump rule
 - emulation of a single-station Wolf number
 - New file formats: standard errors



R. Wolf in 1855 (1849-1<mark>893)</mark>



Alfred Wolfer (1876-1925)

New version management

- Objectives:
 - Structured scheme for future additions and improvements to the SN series
 - Past versions remain available for reanalyses of past published studies
 - Complete incremental documentation

Implementation:

- "Archive" section in SILSO Web site
- Filenames with a 2-digit version number: Vn.i
 - n: for each major change to the SN values
 - i: for minor changes (e.g. isolated typos) or side modifications (e.g. error estimates, file format).
- Links to info files + publications
- Supervision:
 - Data curation: World data System (ICSU)
 - Scientific: creation of an advisory committee (IAU, Division E)
 - Solar physicists and data processing specialists

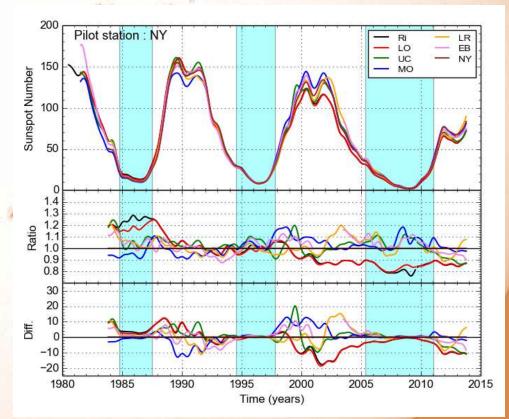
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The future

Development of a new operational method

 Implementation of a multi-station reference
 Full re-calculation of the SN since 1981
 Routine production of the Group Number

- Application of more advanced statistical methods:
 - sparse data with gaps and null values (ARMA)
 - station assessment and classification (Bayesian PCA, total linear regression)



Conclusions

- Major corrections to the SN and GN series
 - The new SN and GN now largely agree
- From a static heritage to a living data series: long overdue!
 - "Cultural" shock for the scientific community
- Multiple implications:
 - Same levels of solar activity from Maunder Minimum to 21st century

and the state of

- Variable average number of spots per group: decline in cycle 24
- Opening new research paths
- Renewed interest for the long-term sunspot record:
 - Recent wave of new publications
 - Topical issue of Solar Physics (> 40 papers)
- Base for a new Sunspot Number production:
 - open to future additions and improvements
 - new digital archive for historical sunspot observations HASO
 - (J. Vaquero, Univ. Extremadura, Merida)

For the latest information, please visit ...

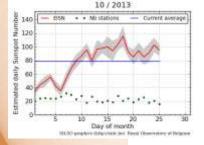


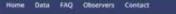
WDC – SILSO Sunspot Index and Long-term Solar Observations

Forecast: Standard Curves method

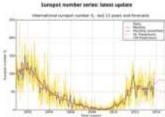
SC Prediction







Abrid Data Center for the production, preservation and disse nation of the



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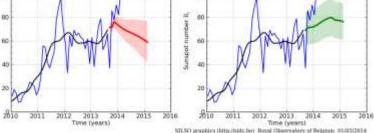
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Forecast: Combined Method

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http://ssnworkshop.wikia.com/wiki/Home Sunspot Workshops http://haso.unex.es/ Historical Archive of Sunspot Observations 7/8/2014

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