ROB STCE

ICSU WORLD DATA SYSTEM

Sunspot number, group number and $F_{10.7}$: new insights

Frédéric Clette, Laure Lefèvre, Shreya Bhattasharya

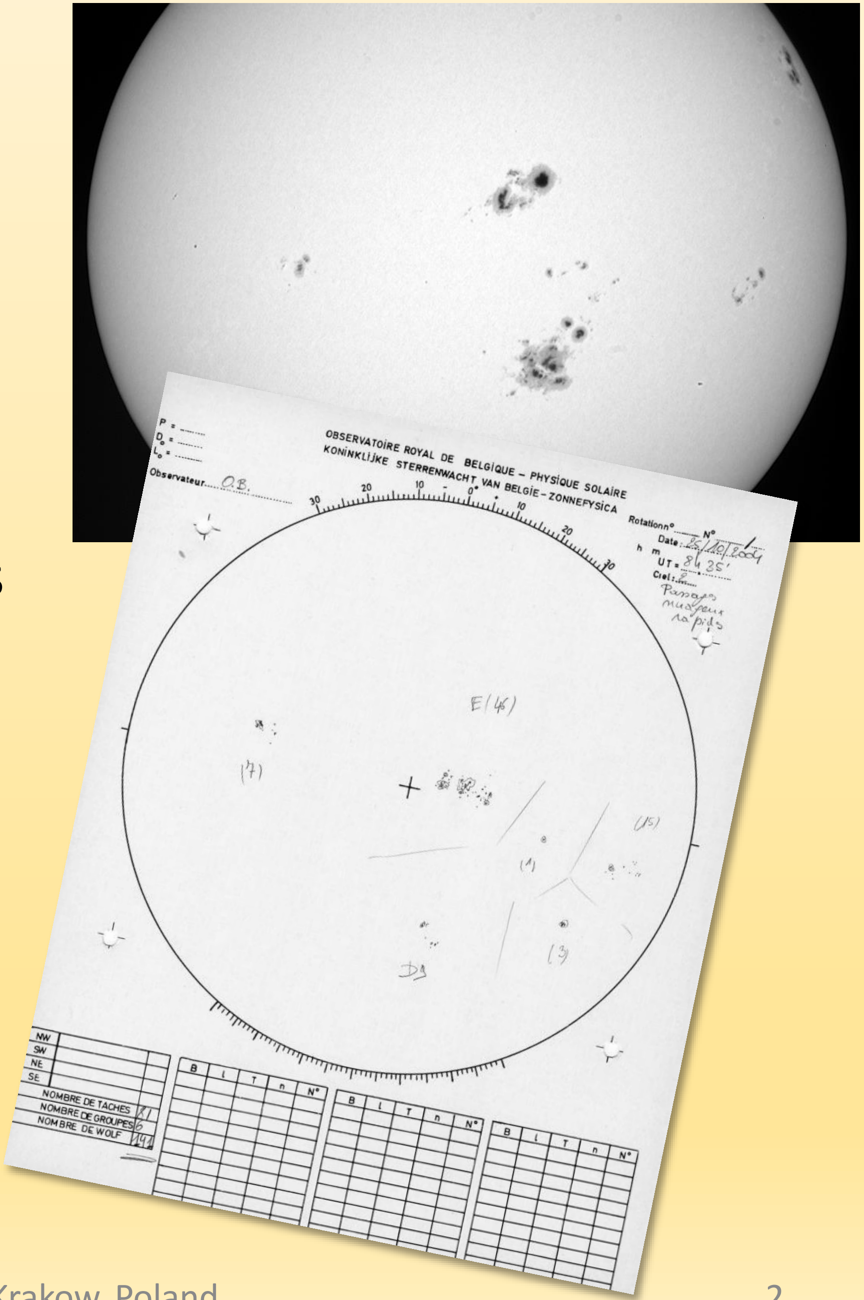
World Data Center SILSO

Royal Observatory of Belgium, Brussels

SILSO

Outline

- Sunspot and Group number:
  the differences
- Sunspot number recalibration
- Group number reconstructions
- Benchmarks and proxies
- A byproduct:
  revisiting the $F_{10.7}$ index
- Conclusions



Introduction: two sunspot number time series

Sunspot Number

$S_N = 10\ Ng + Ns$

- Origin: R. Wolf (1849)
- Start: 1700 (end of Maunder minimum)
- Continuous production to present

- Production in 3 parts:
  - **1700-1849**: reconstruction from historical documents
  - **1849-1980**: Zurich Observatory
  - **1981-now**: World Data Center SILSO, Brussels

- Calibration:
  - **Pilot station: Zurich Observatory**
    - Successive primary observers
    - Specola Observatory **Locarno** (since 1981)
  - Standard telescope, trained observers

Sunspot group number

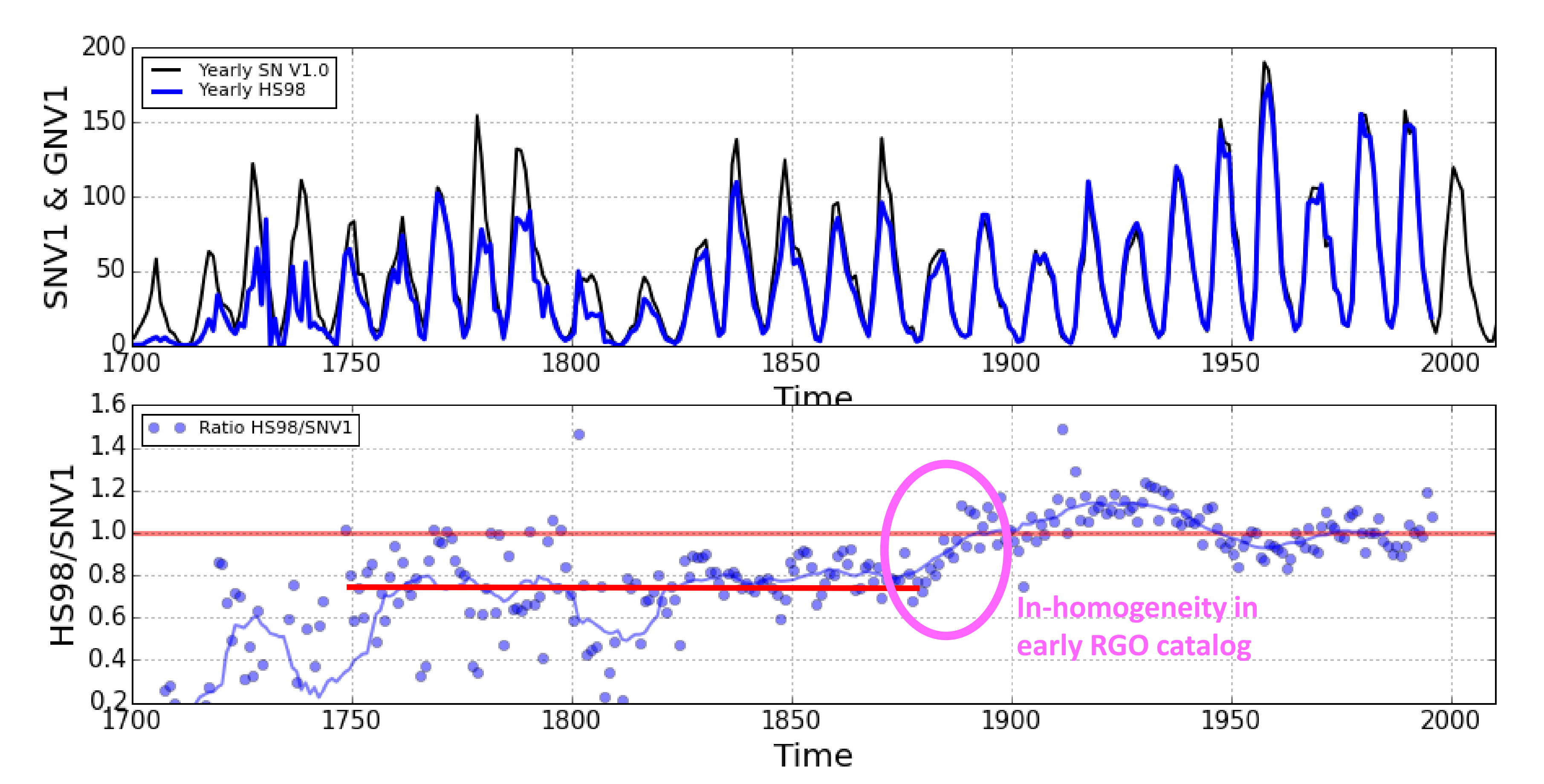
$G_N = 20.13\ Ng$

- Origin: Hoyt and Schatten (1998)
- Start: 1610 (telescope)
- End: 1995 (paper publication)

- Production:
  - Single recent reconstruction
  - Based on an **extended set of raw historical data**

- Calibration:
  - "Daisy-chaining" of observers backwards in time
  - Starting reference: **Royal Greenwich Observatory photographic catalog (1875-1975)**

SN introduction: a primordial disagreement



- **Very good match after 1900**
- **Large disagreement before the 20th century:** G_N lower than S_N by up to 40%

Recalibration effort

- Community effort started in Sept. 2011
- **4 Sunspot Number Workshops**
  - Renewed interest for the S_N
  - Several new reconstructions

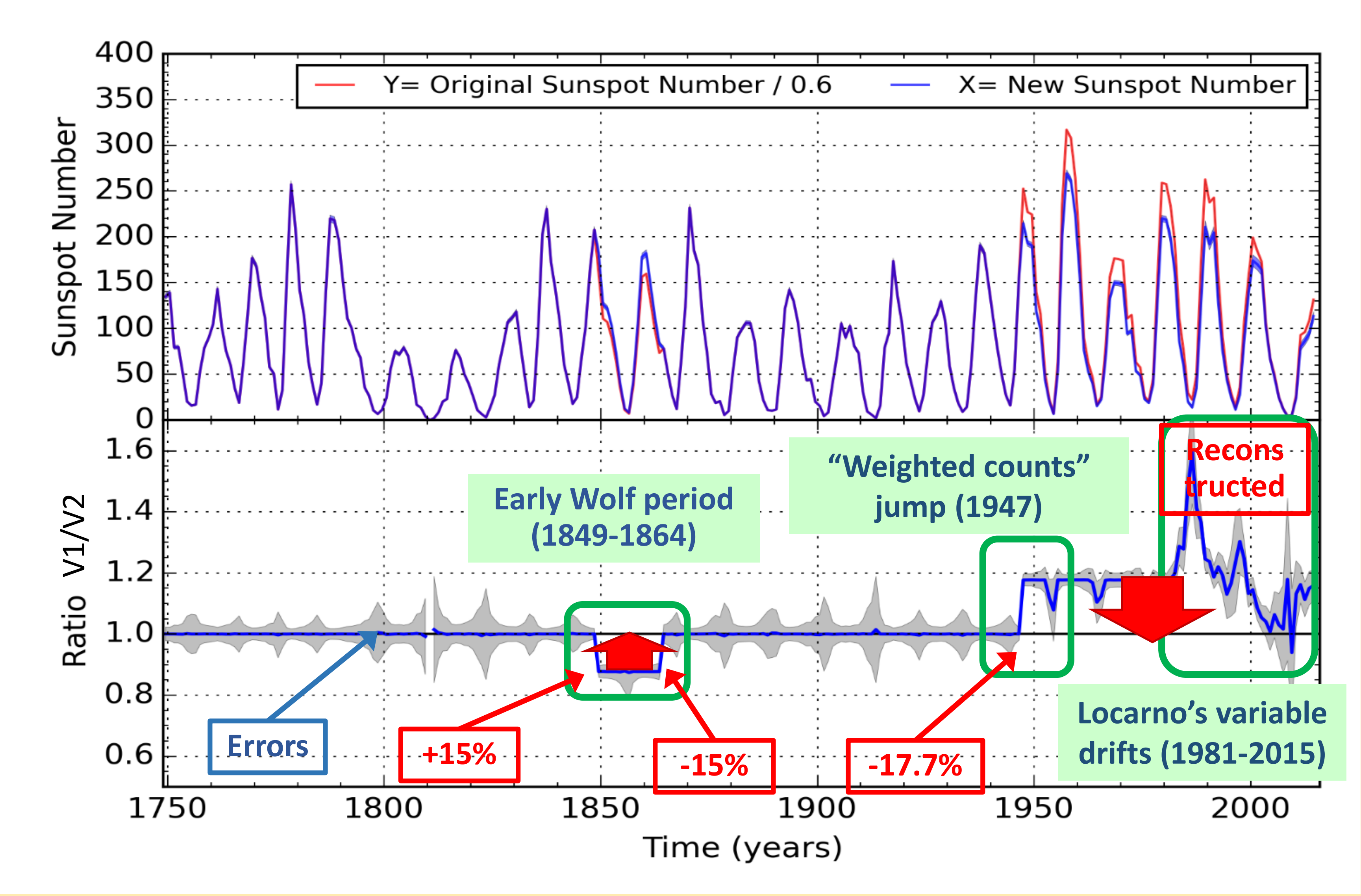

NSO, Sac Peak, USA, Sept. 2011

<u>Synthesis in</u>:
- **Solar Physics:** Topical Issue « Recalibration of the Sunspot Number», **Volume 291 9-10, 2016**, Eds. Clette, Cliver, Lefèvre, Vaquero, Svalgaard, **35 articles**

- **ISSI Team 2018-2022:** *(www.issibern.ch/teams/sunspotnoser/)*
  - Work on new SN version (V3)
  - Steps to a continuous "update – QC – vetting" process (IAU framework)
  - **Focused topical collaborations**

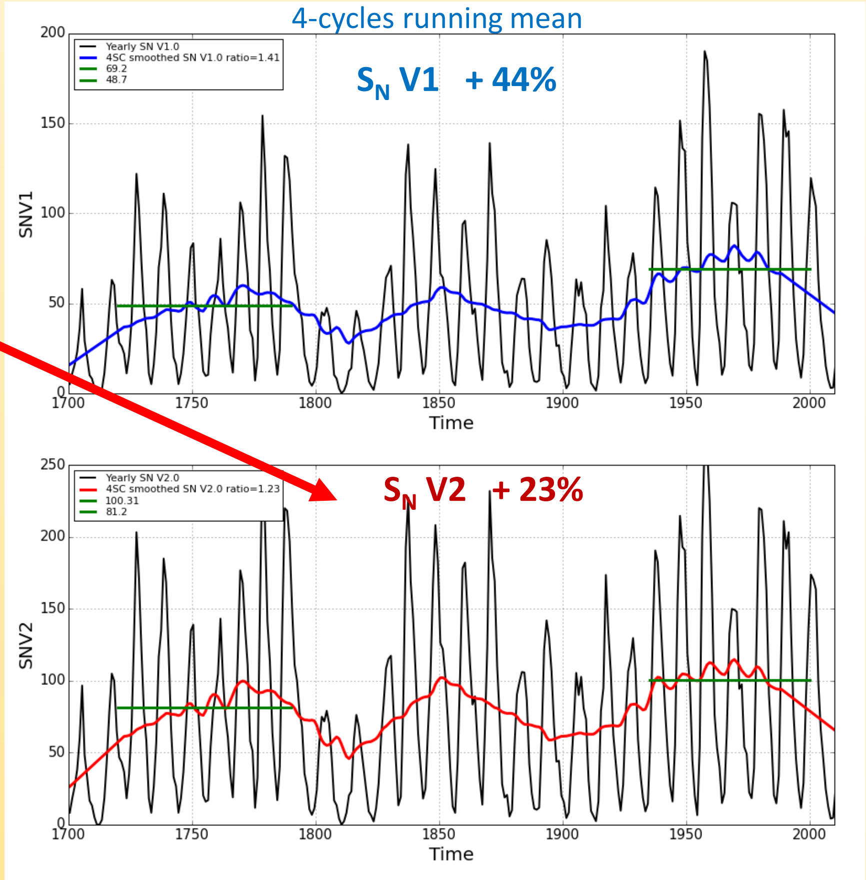

ISSI Bern, Switzerland Jan. 2018

S_N revision: version 2.0 *(release: July 2015)*

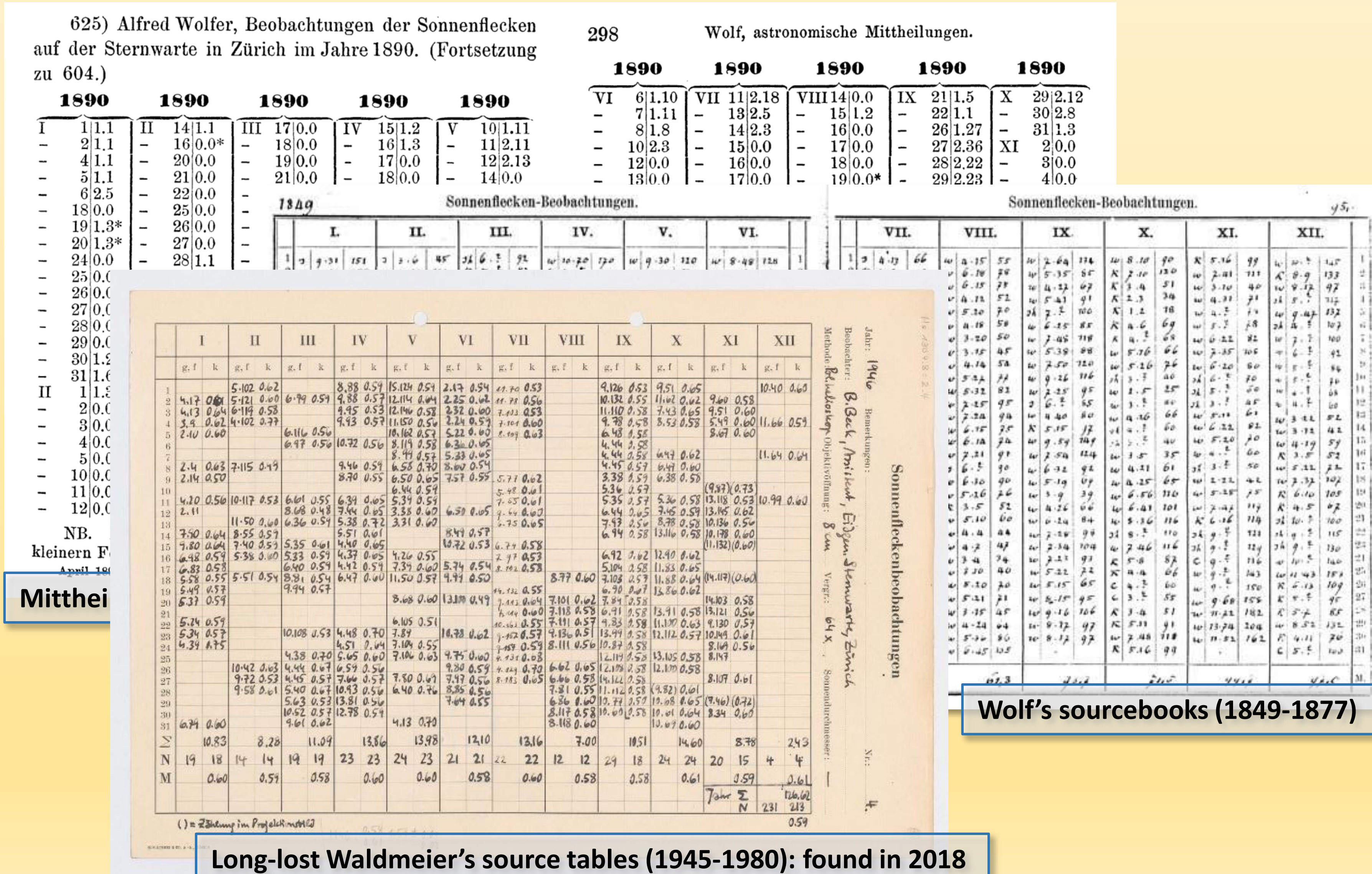


Why does it matter? Diverse impacts

- **Past solar forcing on climate**:
  - Nature of grand minima:
    onset and exit?
  - Nature of grand maxima:
    no higher amplitude, but longer duration of high sequence
- **Constraints on dynamo models**
- **Mid and long-term forecasts**
- **S_N-G_N proxies put recent solar measurements in a long-term context**:
  - Reconstitution of past irradiance, solar wind, etc. (e.g. SATIRE)
- **Calibration reference** for solar, geomagnetic and ionospheric proxies



S_N database: Zurich data recovery

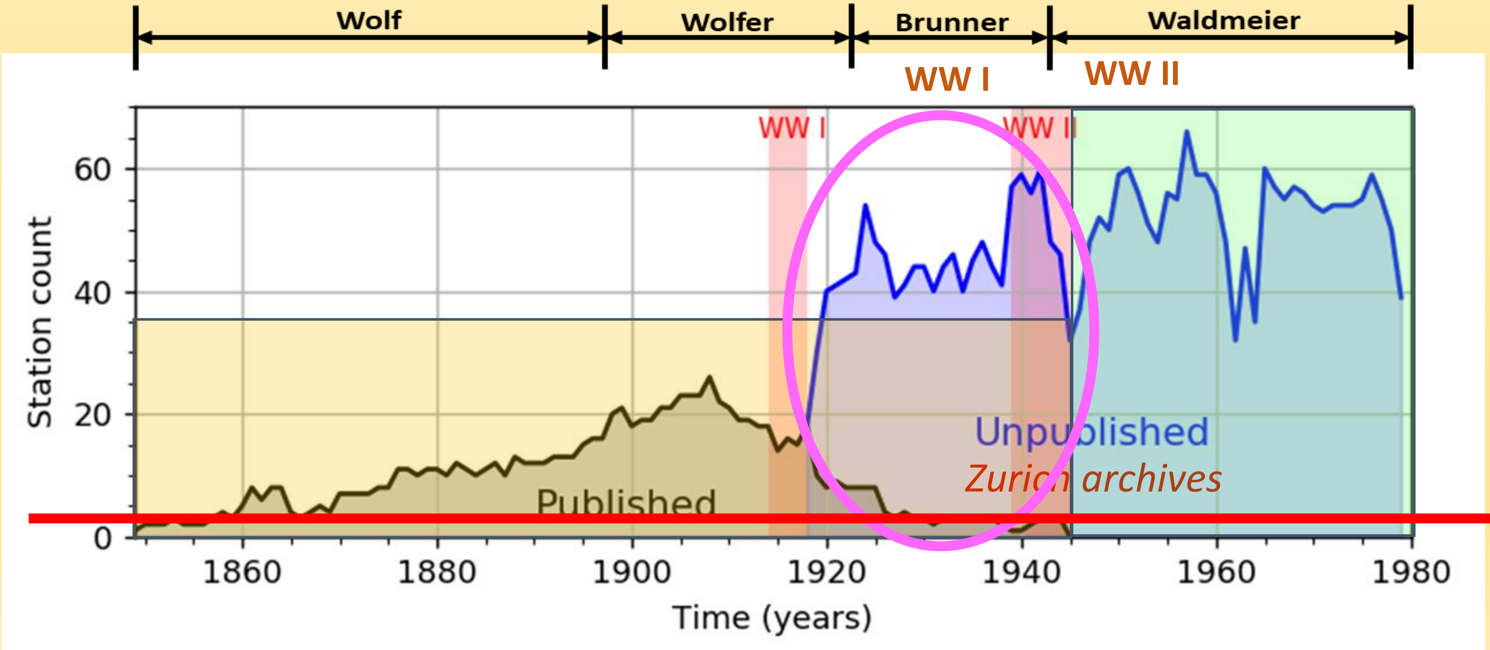


S_N database: major advances *(Clette et al. 2020)*

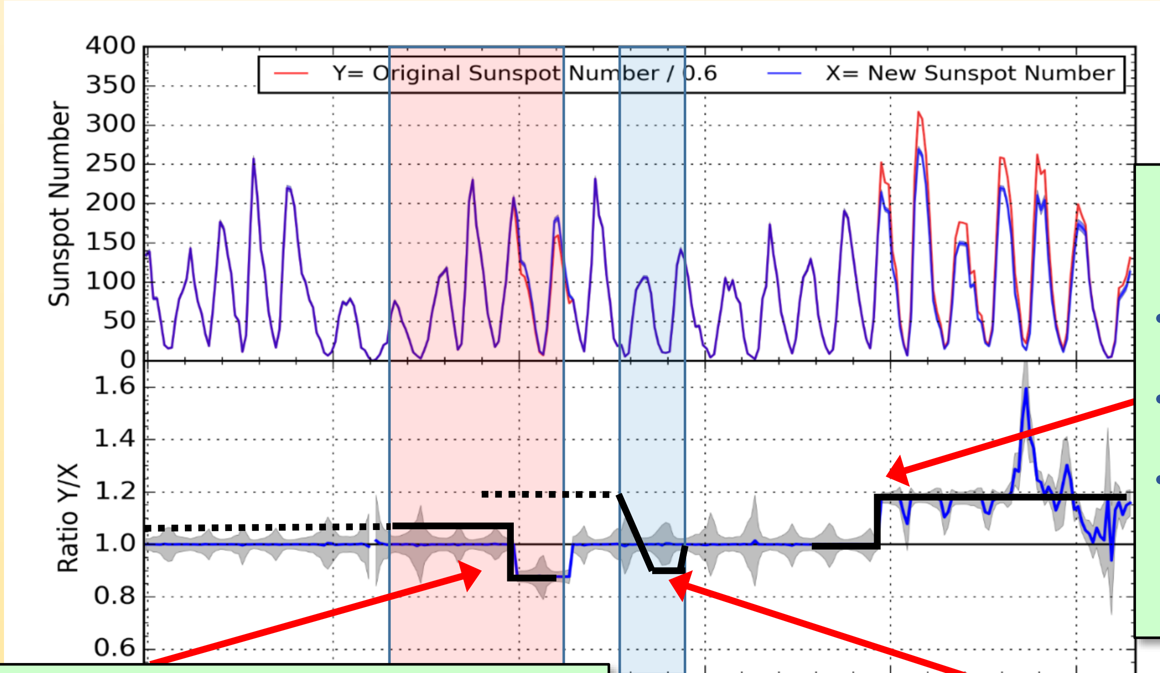
- **All published input data from Zurich** *(Astronomische Mittheilungen der Sternwarte Zurich)*:
  - Fully digitized up to 1944 (internal and auxiliary observers)
- Unpublished data (archives) 1919- 1980:
  - **Original sourcebooks recovered**: **all source data between 1945 and 1970**
    - Scanned by the Library & Archives of ETH Zurich (2019-2021)
    - Extraction of all values (~300.000) in preparation (FARSUN brain.be project, 2023)

➡ **Full continuity up to 1980 (transition to SILSO, Brussels)**

- **Still partly missing: auxiliary data 1919-1944**



S_N ongoing corrections



1947 jump +17.7 %
Clette et al. 2021

- Global agreement on jump amplitude
- Variable inflation factor 1-1.2
- **Timing of jump explained: sharp break in Zurich team and network**

Schwabe - Wolf -20%
Bhattasharya et al. 2022

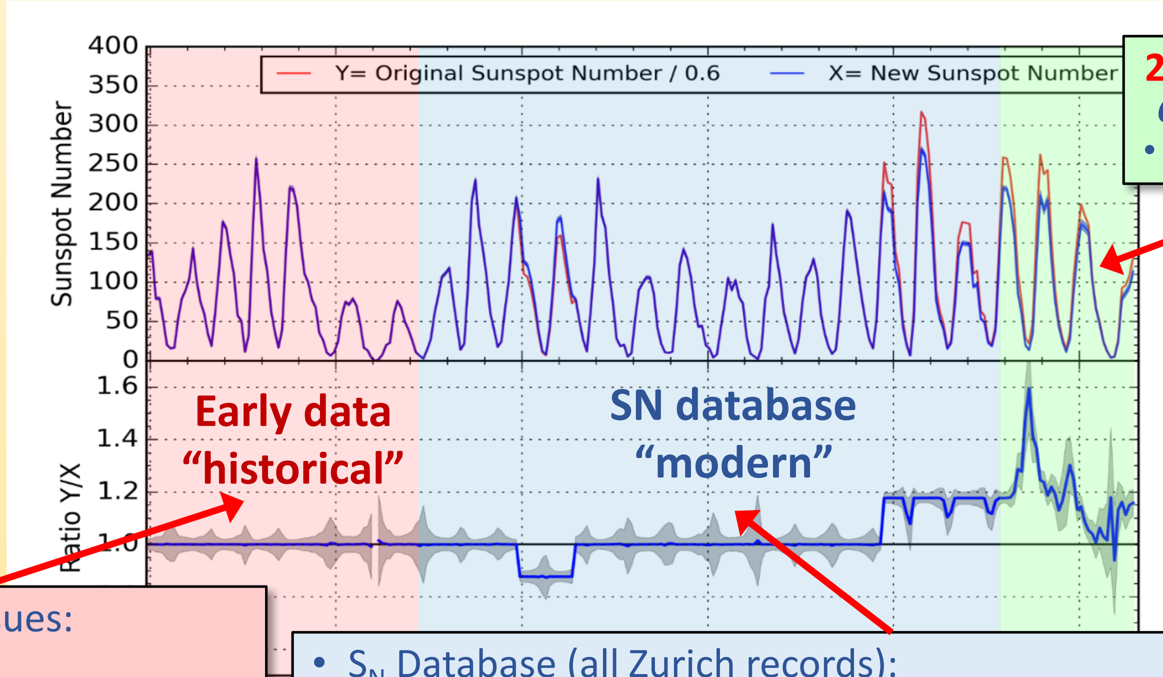
- Past hints: Leussu et al.(2013), Senthamizh et al. (2015)
- Data: Interval 1818-1868
- M
- **W**
be

Wolf - Wolfer -20% ?
Friedli 2020

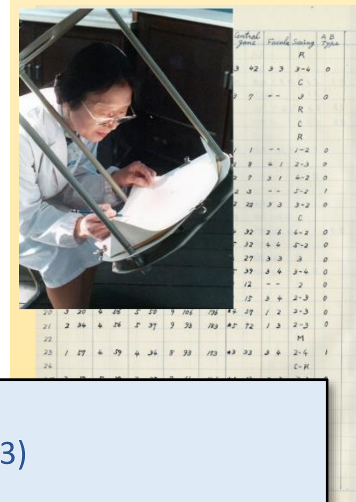
- Work by E.Frenkel (1913) revisited

- **All recent papers: productive COVID period !**
- **Most corrections = abrupt transitions**
  - Are corrections applicable to all earlier data?
  - No slow drifts between jump? (stability of primary reference observers)

S_N : towards a full end-to-end S_N reconstruction



2015 reconstruction
Clette & Lefèvre 2016
- Already in SN V2.0



- Challenging issues:
  - Sparse data
  - No clear distinction between spots and groups
- **Role of sunspot drawings!**
  - Allows recounting
  - Statistics of individual
- **Ove**
  dat

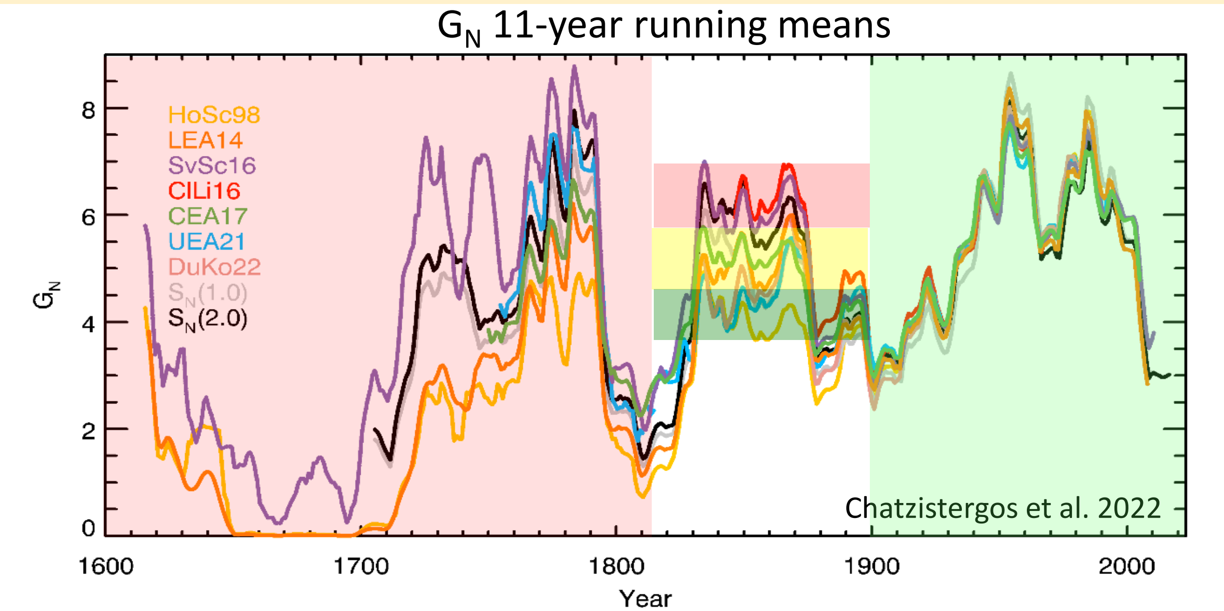
- S_N Database (all Zurich records):
  - Waldmeier archives (FARSUN project, SILSO, late 2023)
- Adding new and revised data sets:
  - Carrington 1853-1861 *(Bhattasharya, Teague, 2022)*
  - Madrid 1935-1986 *(Aparicio et al. 2018, 20222)*
  - I. Koyama 1945-1986 *(Hayakawa et al. 2020)*
  - + recovery of still-missing Zurich archives 1919-1944?
- Inclusion of uncertainties: data mining techniques

19)

Time consuming part: data encoding (> 300 000 values)
V2.1/2.2 (Schwabe-Wolf-Wolfer corrections) **> 2023** (Bhattasharya PhD)
V3.0 (full reconstruction back to 1818) **> 2024- 2025** (FARSUN)

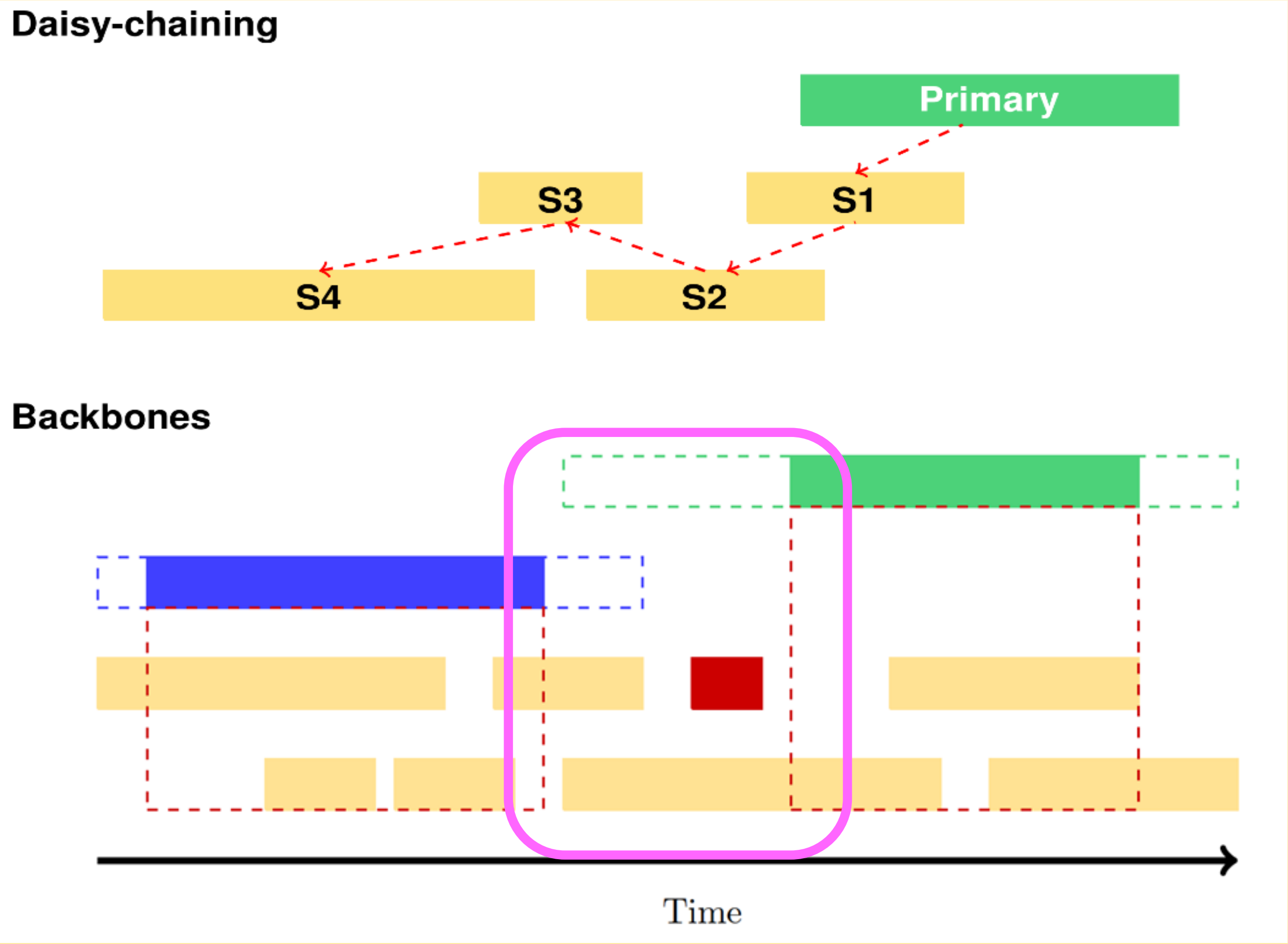
G_N revision: multiple series

- 10-year smoothed series *(Chatzistergos)*
- 7 G_N series:
  - Range (19th century): 40%
  - 3 rough classes: high, medium, low
- Before the 19th century:
  - Large uncertainties
  - Simple propagation of 19th century scaling



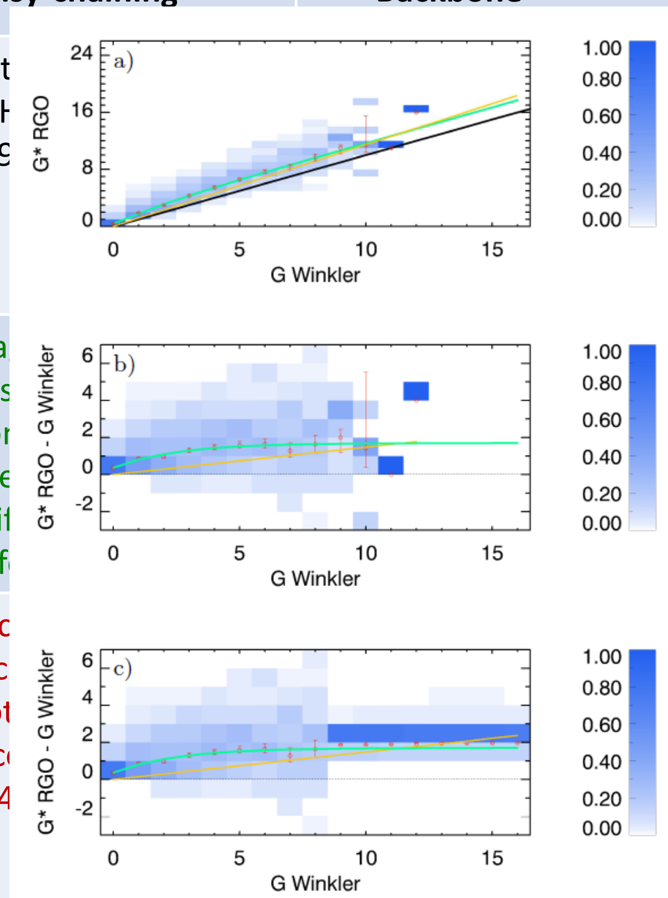
ID	Publication	Method	Scale
SN(1.0)	*Zurich (original)*	*SN, pilot station*	*High*
HoSc98	Hoyt & Schatten 1998	GN orig., daisy-chain	Low
LEA14	Lockwood et al. 2014	H&S GN-based SN correction	Med-Low
SN(2.0)	*Clette et al. 2016*	*SN(1.0) corrected, pilot station*	*High*
SvSc16	Svalgaard & Schatten 2016	Backbone 1	High
ClLi16	Cliver & Ling 2016	HoSc98 correction, daisy-chain	High
CEA17	Chatzistergos et al. 2017	Backbone 2	Med-High
UEA21	Usoskin et al. 2016, 2021	Active-day fraction	Med-Low
DoKo22	Dudok de Wit 2022	Tied ranking	Med-Low

G_N methods: daisy-chaining versus backbones



G_N methods: Observer-pair comparison

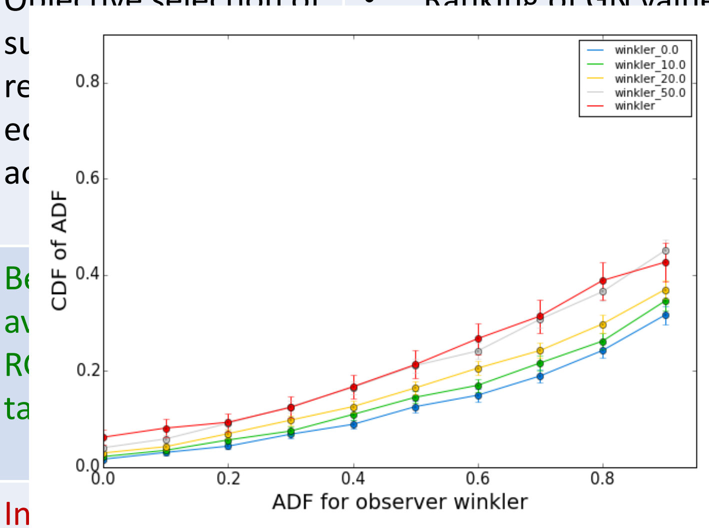
	Cliver & Ling 2016	Svalgaard & Schatten 2016	Chatzistergos et al. 2017
Method	• **Daisy-chaining**	• **Backbone**	• **Advanced backbone**
Innovations	• Crit of H 199	imary s) only	• More primary observers • No temporal averaging (daily values) • Corrections through cross-probability distributions (non-parametric CPD)
Assets	• Dia • Mis fror tele • Drif befo	bias few	• Direct overlap between primary observers • Allows non-linear relations between observer pairs • Error estimate
Issues	• Bac acc • Not rec 184	ondary eraging mple	• Lack of data at high G_N values (Monte-Carlo simulation) • Observers assumed to be [illegible] global CPD)
Result	• **High**	• **Highest**	• **Intermediate**



Most mature G_N reconstruction !

G_N methods: Observer-pair comparison

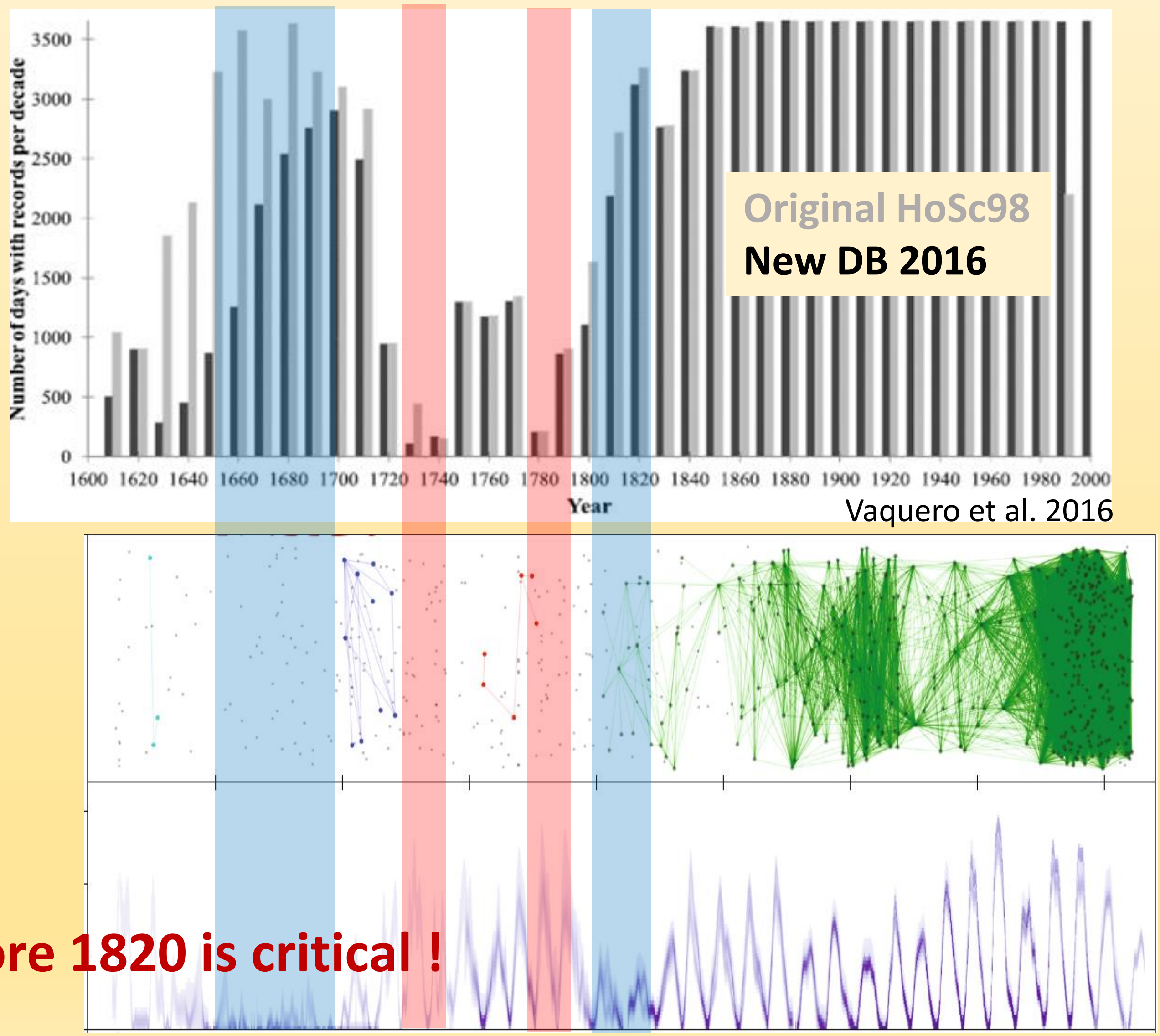
	Usoskin et al. 2016, 2021 Willamo et al. 2017, 2018	Muñoz-Jaramillo (preliminary)	Dudok de Wit & Kopp (2022, in preparation)
Method	• **Active-day fraction (ADF)**	• **Segmented ADF**	• **Tied ranking**
Innovations	• Statistics of days with G_N=0 and G_N > 0 • Single "perfect" observer (RGO 1900-1976) • Degraded data: S_S minimum area threshold (acuity)	• Objective selection of su re ec ac	• Ranking of GN values
Assets	• No observer-pair comparisons • Non-parametric correction (RGO-based) via cross-probability distribution (CPD) • Error estimate	• Be av R(ta	data
Issues	• Bias when different activity levels between RGO and observer *(Willamo et al. 2018)* • Unreported spotless days • Effect of group splitting (beyond acuity factor) • Works only when ADF< 0.8	• In values next to pure ADF	gaps • No understanding (yet) of the mutual influence of gap-filling and ranking steps.
Result	• Medium-low	• No series yet	• Medium-low



Not yet fully validated!

G_N reconstruction: archive of source data

- Updated G_N database *(Vaquero et al. 2016)*:
  - Additions
  - Corrections
  - Eliminations
- Main gaps in 18th century:
  - 1740-1750
  - 1780 – 1800
- Major spotless periods:
  - 1650 – 1715 (Maunder)
  - 1800-1820 (Dalton)



Vaquero et al. 2016

Muñoz-Jaramillo, Vaquero 2018

⇨ **Adding data before 1820 is critical !**

GN-SN data: intensive recoveries !

THE ASTROPHYSICAL JOURNAL, 890:98 (10pp), 2020 February 20 https://doi

Thaddäus Derfflinger's Sunspot Observations during 1802–1824: A P

THE ASTROPHYSICAL JOURNAL, 909:194 (7pp), 2021 March 10 https://doi.org/10.3847/1538-4357/abdd34

1610 -1699	1700-1799	1800-1899	1900 - 1999
T.Harriot 1610-1613	Plantade 1705-1726	T. Derfflinger 1802-1824	Madrid 1876-1986
C. Scheiner 1611-1631	P. Becker 1708-1710	Prantner 1804-1844	Stonyhurst Coll. 1886-1940
J. Tardé 1615-1617	J-H. Müller 1709	F. Hallaschka 1814-1816	M. Aguilar 1914-1920
C. Malapert 1618-1626	J-C Müller 1719-1720	H. Schwabe 1825-1867	Coimbra Obs 1929-1941
C. Scheiner ~1620	J.F. Weidler 1728-1729	A. Colla 1830-1843	R. Carrasco 1931-1933
Derham ~1620	P. Wargentin 1747	Kunitomo 1835-1836	H. Koyama 1945-1996
J. Smogulecki 1621-1625	J.C. Staudacher 1749-1796	W.C. Bond 1847-1849	E. Strach 1969-2008
D. Mögling 1626-1629	C. Horrebow 1761-1776	R. Carrington 1853-1861	
P. Gassendi ~1630	Japan 1749-1750	G. Spoerer 1861-1894	
G. Marcgraf 1636-1642	B. Oriani 1778-1779	A. Secchi 1871-1875	
Rheita 1642	Toaldo 1779		
Hevelius 1642-1645	Comparetti 1779		
M. Fogelius 1650-1700	I. Zenbei 1793		
H. Siverus 1650-1700	Armagh Obs. 1795-1797		
Cassini 1671			
J-C. Gallet 1677			
G. Kirch 1680-1709			
Eimmart Obs. 1681-1718			
J. Flamsteed 1672-1703			

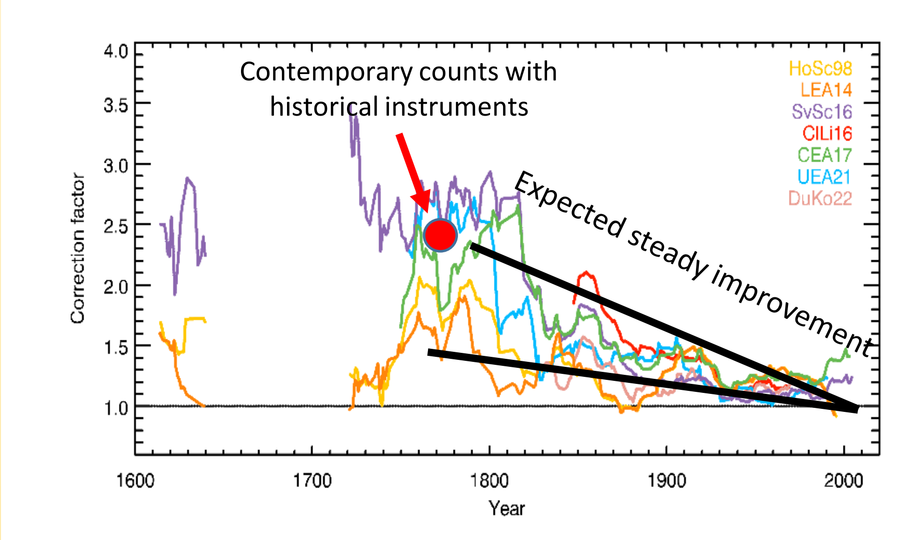
H. Hayakawa[5,6,7,8]
r M.S. Carrasco[7] · Bruno P. Besser[8,9] · Shoma Uneme[2] · Shinsuke Imada[2]

Received: 5 March 2021 / Accepted: 23 September 2021 / Published online: 22 November 2021

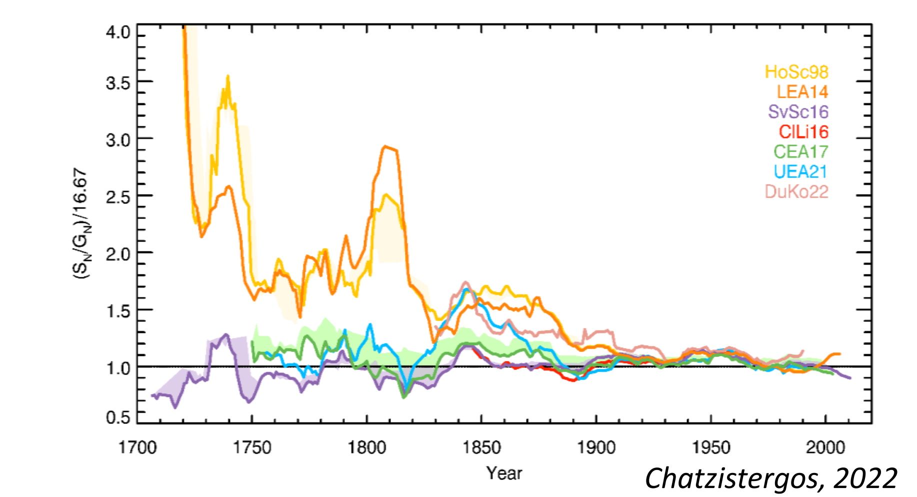
ed: 8 June 2021 / Accepted: 9 August 2021 / Published online: 28 October 2021

Benchmarks

- **Progress in telescope optics**:
  - Ratios between reconstructed and raw uncorrected series
  - Historical optics *(Svalgaard)*
  - Mathematically degraded images *(Karachik, Pevtsov, Nagovitsyn, 2019)*



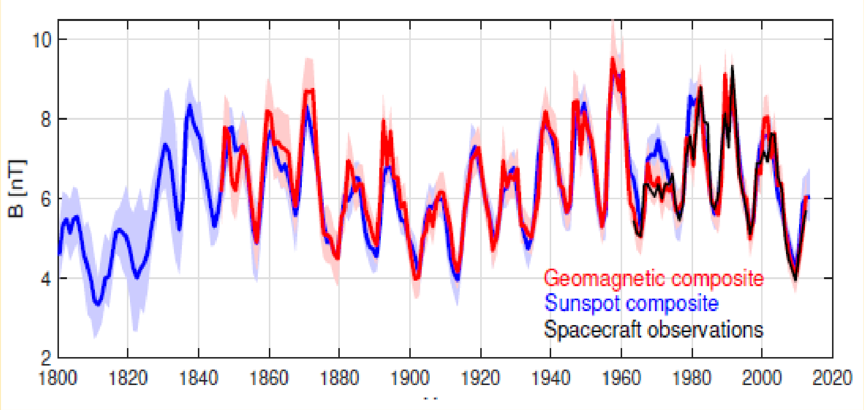
- **Equivalence G_N <-> S_N**:
  - Same underlying process (magnetic flux emergence)
  - S_N construction is completely independent (pilot station back to 1849)



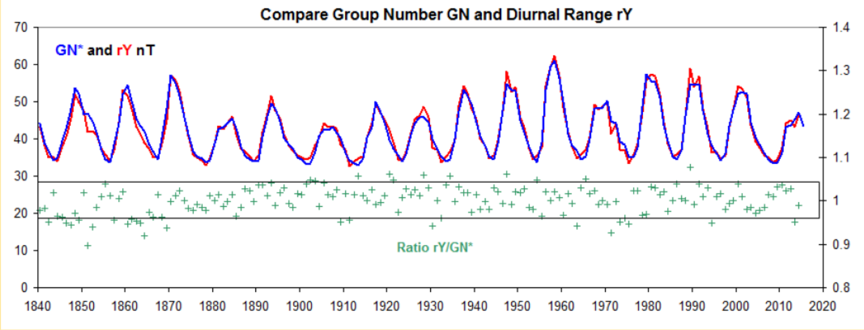
Chatzistergos, 2022

Solar activity proxies

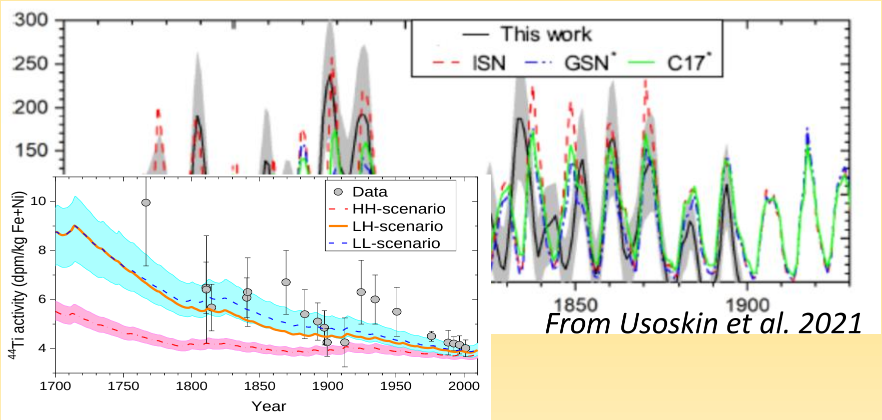
- **Geomagnetic indices**:
    - Open magnetic flux in solar wind
    - Recent re-calibration (ISSI team) *(Owens et al. 2016)*



- **Diurnal modulation of the geomagnetic East component rY**:
    - Proxy of solar UV irradiance
    - Yearly means 1840-present *(Svalgaard, 2015)*



- **Cosmogenic isotopes (^{10}Be, ^{14}C,^{44}Ti)**:
    - Proxy of solar wind (modulation potential)
    - ^{14}C from trees (*Usoskin et al. 2021)*
    - ^{44}Ti from meteorites (Asvestari et al. 2017)



From Usoskin et al. 2021

GN benchmark & proxies: overview

	Recons. G_N	Optical progress	S_N V2.0	Geomag. Open B	Diurnal rY	Isotopes ^{14}C, ^{44}Ti
HIGH	SvSc2016 ClLI16 *SN V1/2*	**BEST**	**BEST**	**BEST**	**BEST**	**NO**
MEDIUM	CEA17 DuKo22 UEA21	**FAIR LOW**	**FAIR LOW**	**FAIR LOW**	**FAIR LOW**	**FAIR HIGH**
LOW	HoSc88 LEA14	**NO**	**NO**	**NO**	**NO**	**BEST**

- **Low reconstructions are excluded by most benchmarks & proxies**
- **Intermediate reconstructions are mostly compatible but never optimal**
- **Still contradictory diagnostics: subject to revision !**

G_N reconstruction: prospects

- Further **development of the advanced backbone**
- Single **common data set for testing/benchmarking** all methods
- Benchmarks: tracking the **progresses in solar activity proxies**
  - *e.g. single solar cycles resolved in ^{14}C isotope records* (Usoskin et al. 2021, A&A)

- **When everything breaks down!** *All methods are inapplicable during grand minima and when data are too sparse*
  - **Sunspot drawings**= ground truth: e.g. statistics of group types
  - **Local use of proxies (**geomagnetism) to bridge gaps < 10-20 years

- **Remaining problems common to all methods**:
  1. Hypothesis of **scale uniformity** of individual observers
  2. Effect of **random temporal distribution of sparse data**

     (cf. Usoskin, Mursula & Kovaltsov 2003, ESAsp)

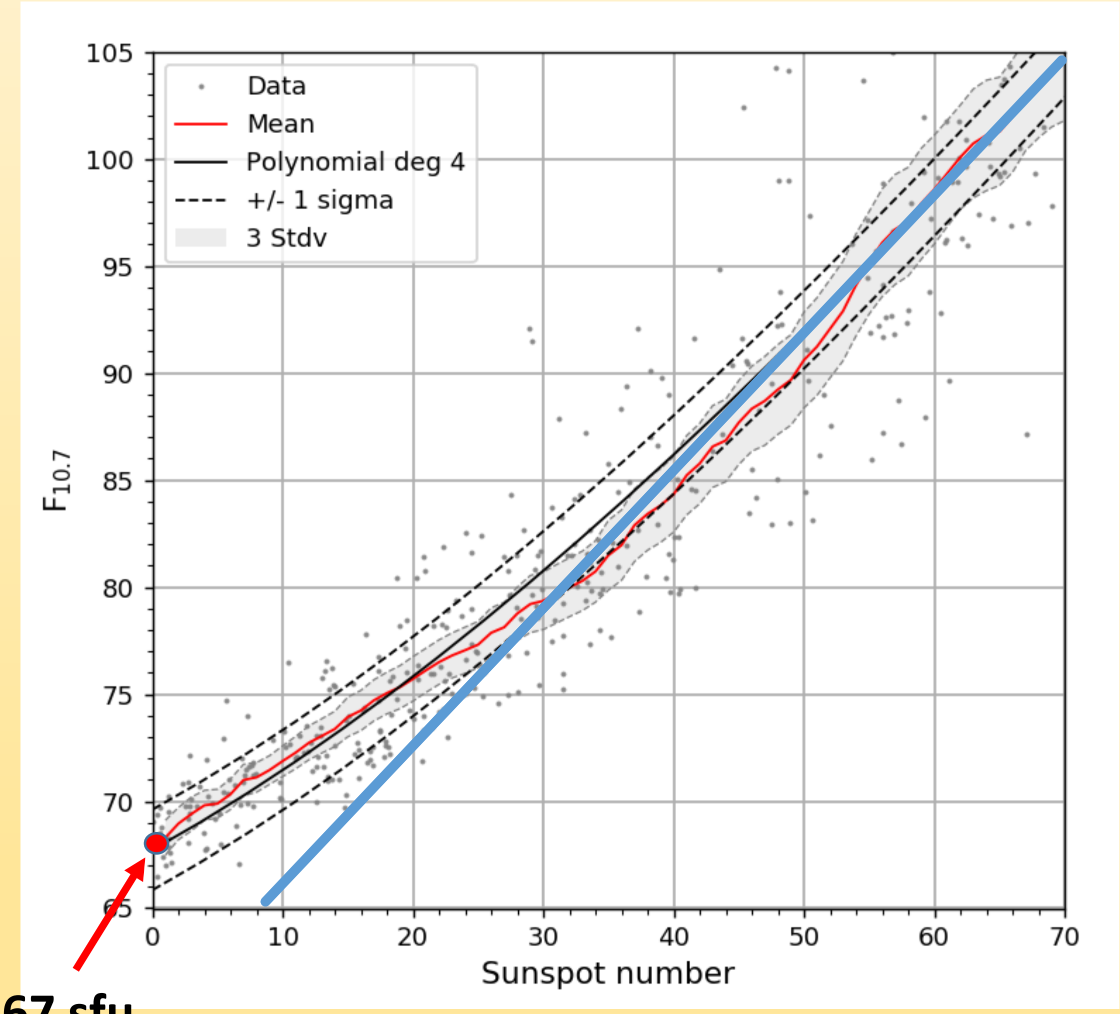
- **Addressed by S_N uncertainty quantification** *(Mathieu et al. 2019)*

Next step: mutual adaptation of methods for S_N <> G_N

$F_{10.7}$ background radio flux: relation with S_N

- Past results:
  - Many disagreeing S_N - $F_{10.7}$ relations
  - No error range
- **4th degree polynomial**:
  - Needed for good fit in the low range
  - Polyn. values + errors
- **Linear for S_N > 35**

$$\widehat{F}_{10.7} = 67.73\ (\pm 1.13) + 0.337(0.056)\ S_N + 3.69\ (\pm 0.77.).10^{-3}\ S_N^2 - 1.52(\pm 0.38).10^{-5}\ S_N^3 + 1.33(\pm 0.62).10^{-8}\ S_N^4$$



Mean "all-quiet" $F_{10.7}(0)$ = 67 sfu

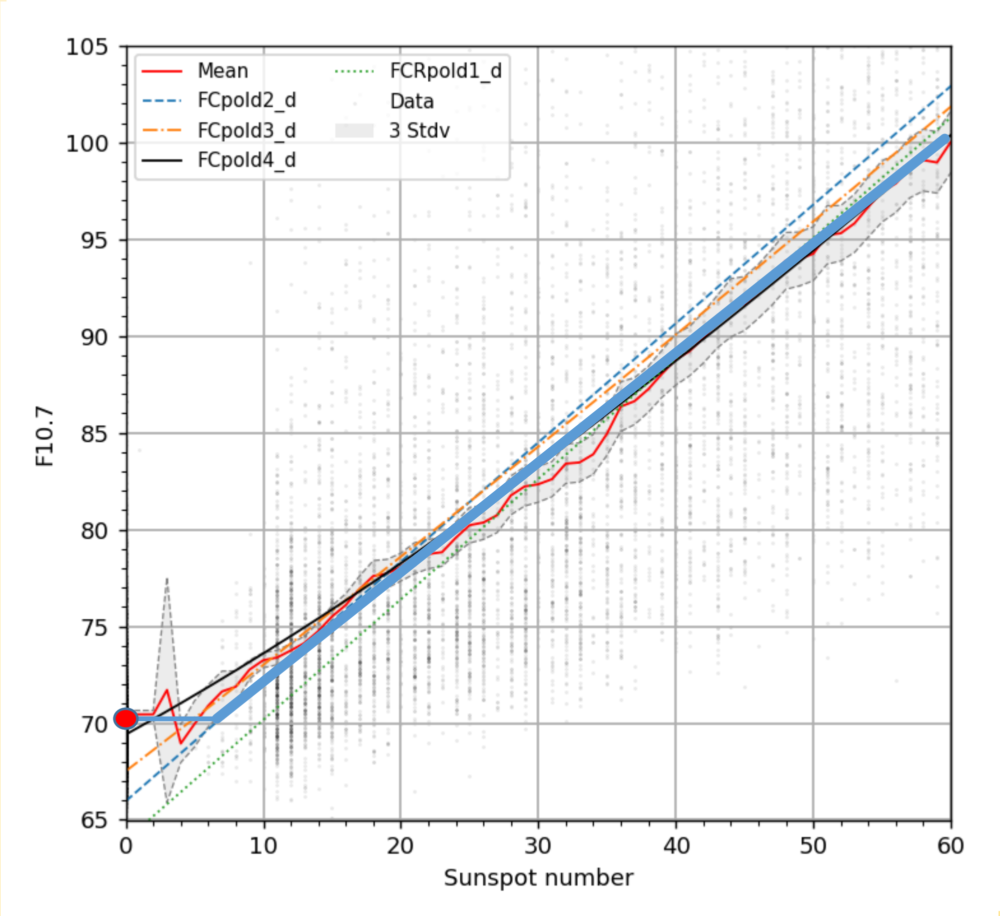
Function of the duration of spotless interval: lowest for ~30 day averages

Model: pure temporal averaging effect

- Raw daily data:
  - **Fully linear down to first spot**
  - S_N=0 is offset (0-11 jump)

$$S_N = 10\ N_G + N_S$$

- **Synthetic $F_{10.7}$ series**:
  - Linear conversion of actual daily S_N series to $F_{10.7}$
  - Monthly averaging

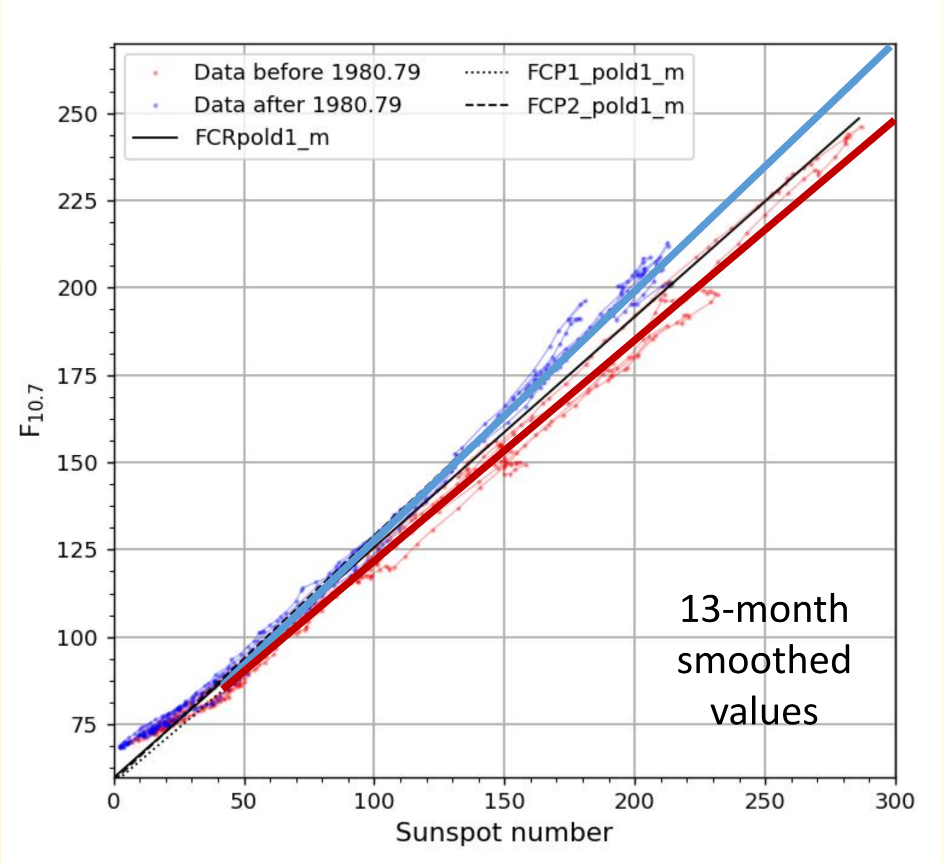


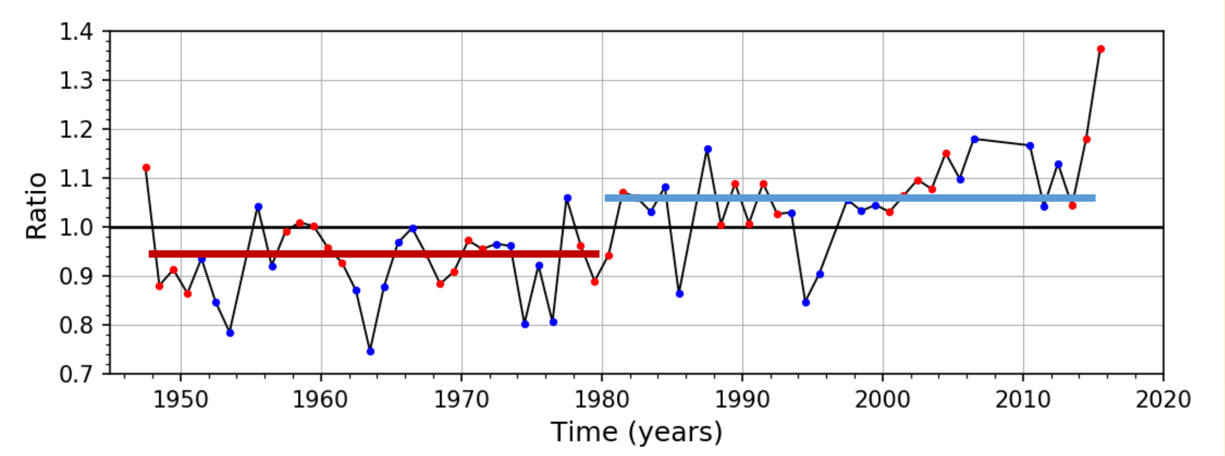
⇨ Matches the observed low-range non-linearity (also for yearly means)

⇨ **Non-linearity due to the S_N=0 offset point temporally convolved with the frequency of spotless days.**

A sharp jump in 1980

- **Abrupt upward jump in 1980**:
  - Before 1980: S= 0.6345 (±0.0066)
  - After 1980:   S= 0.7020 (±0.0089)
  - Ratio: **1.106 ± 0.017 (10.6 %)**
  - **Time: Dec. 1980 – Jan 1981**
- **Good global homogeneity of both series before and after the jump**
  - Very high linear correlation (V2 better than V1)
- Validation of both series





Separate proxies needed for each half-series !

1947-1980

$$\hat{F}_{10.7} = 66.64\ (\pm 1.48) + 0.366(0.067)\ S_N + 2.59\ (\pm 0.86).10^{-3}\ S_N^2 - 0.99(\pm 0.40).10^{-5}\ S_N^3 + 1.33(\pm 0.62).10^{-8}\ S_N^4$$

1981-present

$$\hat{F}_{10.7} = 67.84\ (\pm 1.06) + 0.386(0.044)\ S_N + 2.86\ (\pm 0.45).10^{-3}\ S_N^2 - 0.73(\pm 0.13).10^{-5}\ S_N^3$$

Whole series

$$\hat{F}_{10.7} = 67.73\ (\pm 1.13) + 0.337(0.056)\ S_N + 3.69\ (\pm 0.77.).10^{-3}\ S_N^2 - 1.52(\pm 0.38).10^{-5}\ S_N^3 + 1.97(\pm 0.60).10^{-8}\ S_N^4$$

1980 jump: retracing the historical cause

- Two main $F_{10.7}$ construction eras *(non-overlapping)*:

Covington (1947-1979)
- Manual measuring from paper recorder rolls

Tapping (1982-now)
- Computer processing of digital measurements

Transition team (1979-1981)
- Development of computerized processing
- No clear stable method

- **Processing issue:** unique change of people and method
- **No instrument calibration problem**

Clette, F. (2021), J. Space Weather and Space Climate, Vol. 11, id.2, 25 pp.
DOI: 10.1051/swsc/2020071

Conclusions

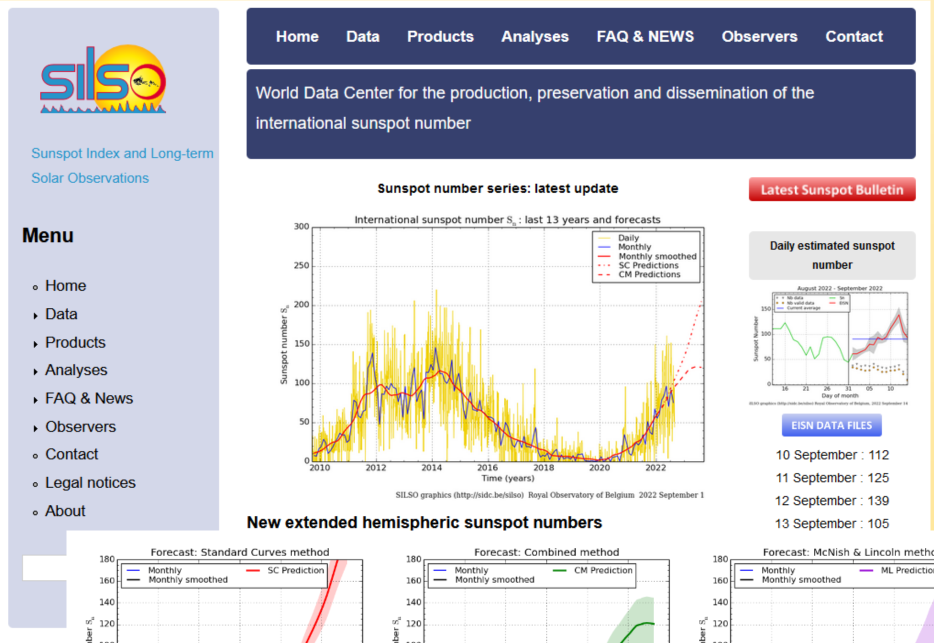
- Multiple topic-focused partnerships: **welcome to join in !**
- Way forward:
  - **Combining methods, apply** (only) **where they work**
  - **Data uncertainties** become central
- **Next major S_N update**: release **2024**
- Reconstruction of S_N & G_N series now a **continuous process**
- Steps towards a formal **version-adoption framework** (IAU):
  - Base community (ISSI Team) > In progress …
- **A new generation of young sunspot researchers !**
  - Theo, Hisashi, Shreya, Sophie, Victor, etc.

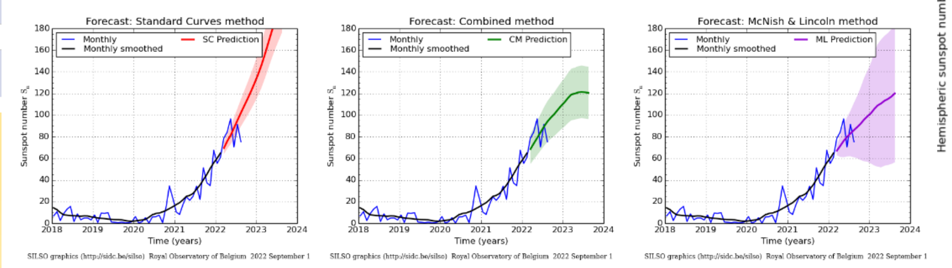
Stay tuned ….

World Data Center – SILSO

Sunspot Index and Long-term Solar Observations

http://sidc.be/silso





Standard Curves method (SC) | Combined method (CM) | McNish&Lincoln method (ML)