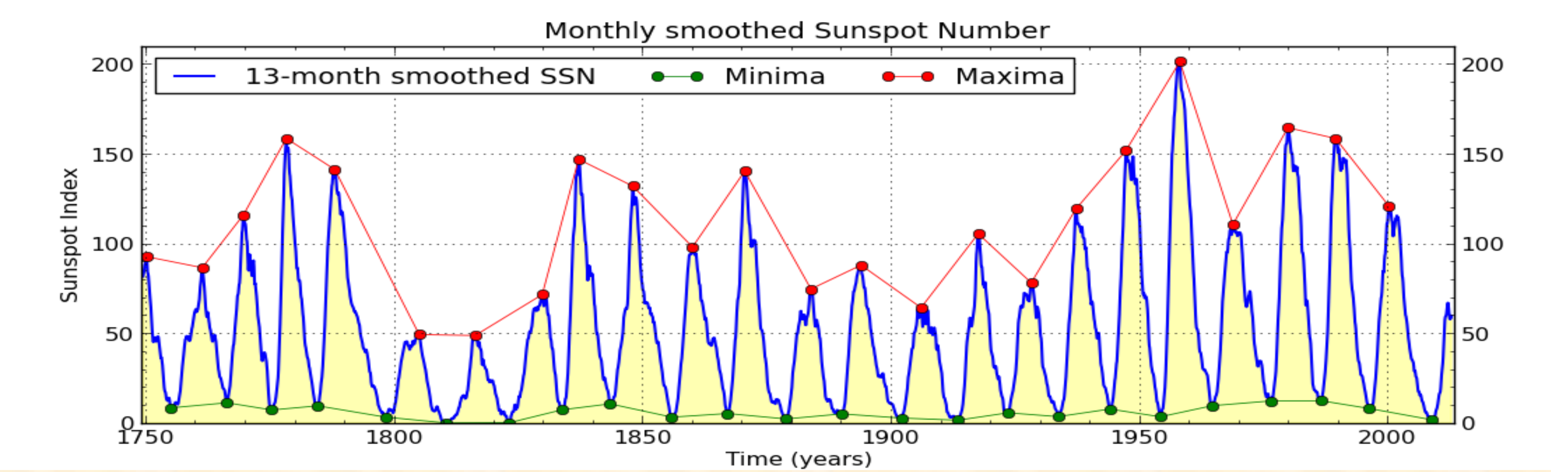
Revisiting the long-term calibration of the International Sunspot Number

Frédéric Clette, Laurence Wauters & Laure Lefèvre

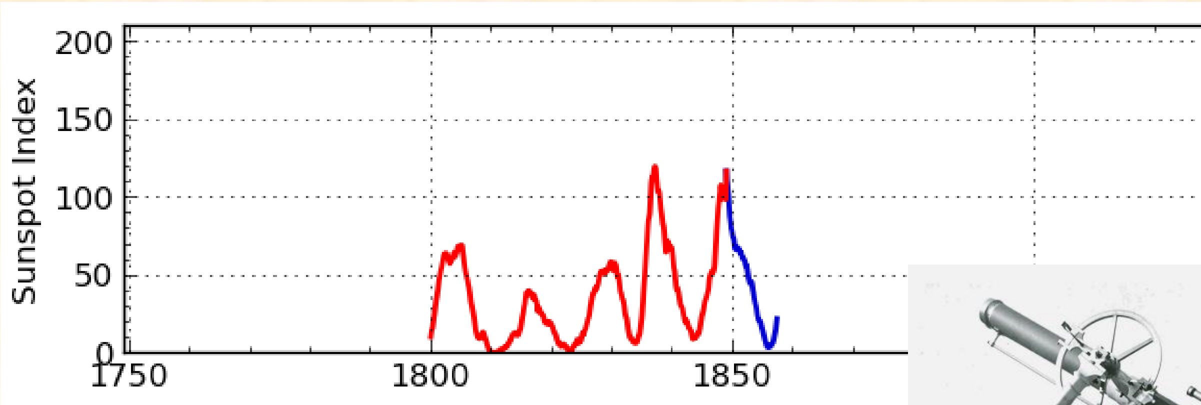
SILSO: World Data Center – Sunspot Index

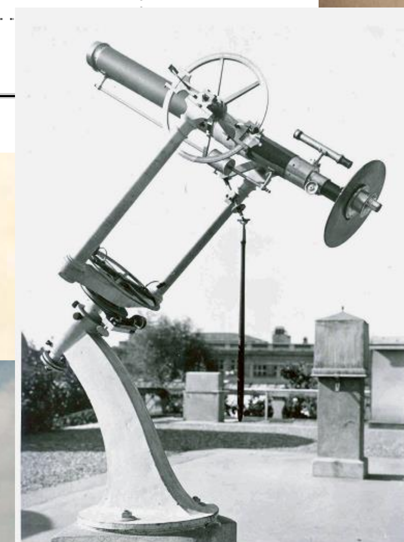
Royal Observatory of Belgium



- A quick chronology of the sunspot number (SSN) construction
- Identified biases in the sunspot series (SSN and group number)
- Recent anomalous trends (cycle 23-24)
- Interpretation: what do the present issues tell us about the early sunspot number ?
- Conclusions and prospects

A brief history of the sunspot number (SSN)





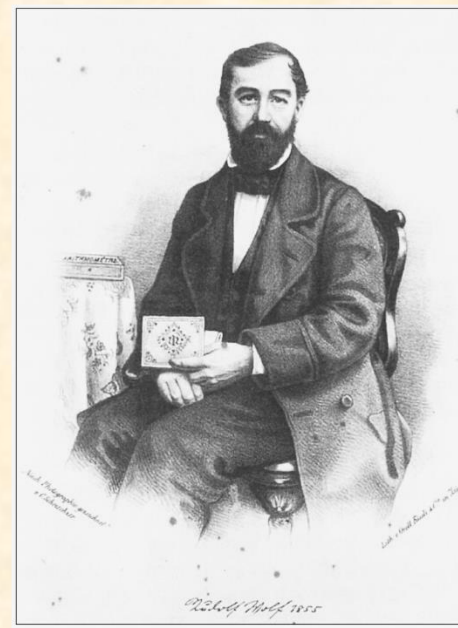
- R. Wolf: invention of the sunspot index [1850]:

W= 10 Ng + Ns

- The 2 standard instruments:
  - **Standard « Fraunhofer » refractor** (fixed, roof of Zürich Observatory)
    D= 83mm, F= 1320mm Mag= 64x
  - **Small travel refractor** (portable, used when travelling):
    D= 43mm, F= 550mm, Mag= 29x
- Still in use now *(Thomas K. Friedli, Rudolf Wolf Society, Zürich)*

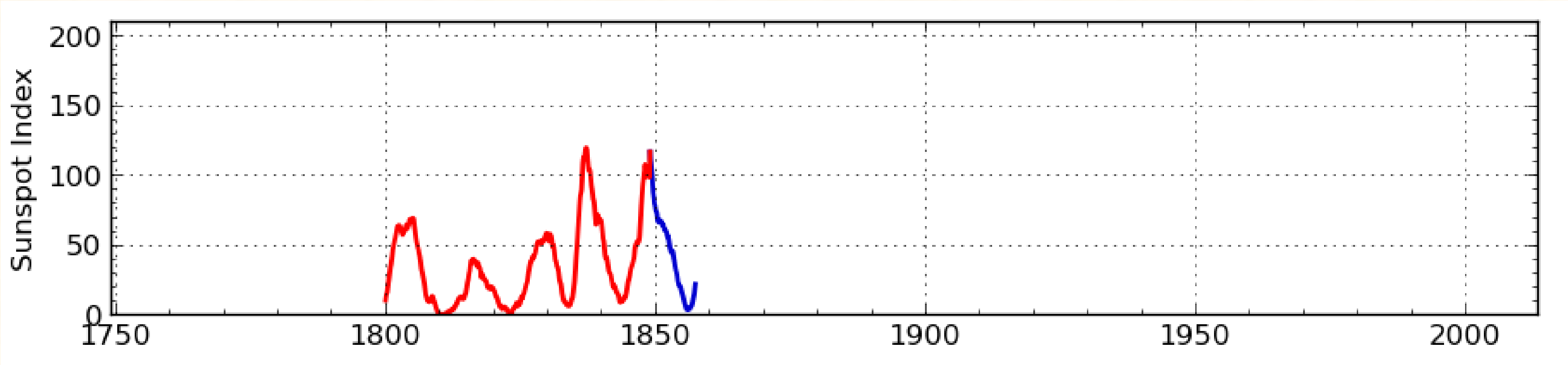
H.U. Keller
and
T. K. Friedli

Mid-1980's



R. Wolf in 1855 (1849-1893)

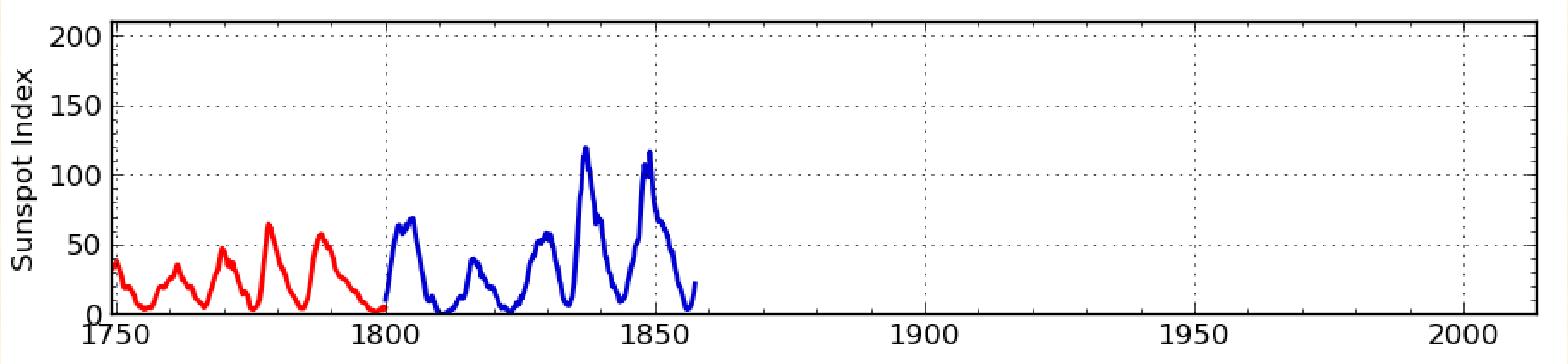
A brief history of the sunspot number (SSN)



- Inclusion of past sunspot observers:
  - Samuel Heinrich Schwabe [1789-1875]:
    - Sunspot observations 1826 - 1867

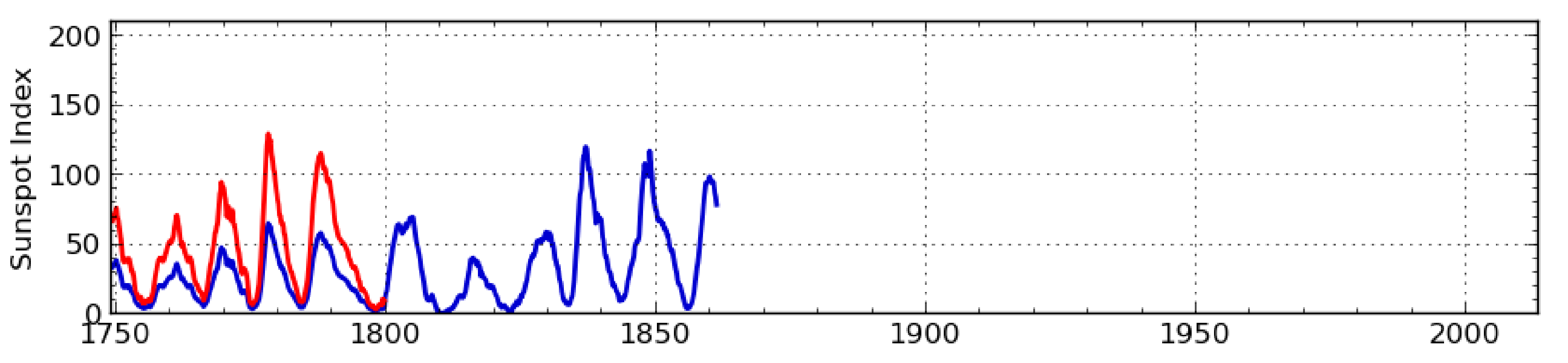
S. H. Schawbe

A brief history of the sunspot number (SSN)



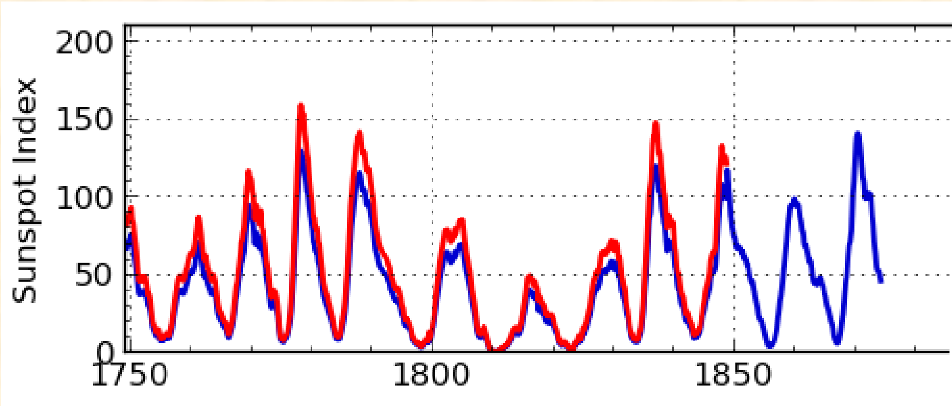
- 1857: adding Staudacher (1749-1799)

A brief history of the sunspot number (SSN)



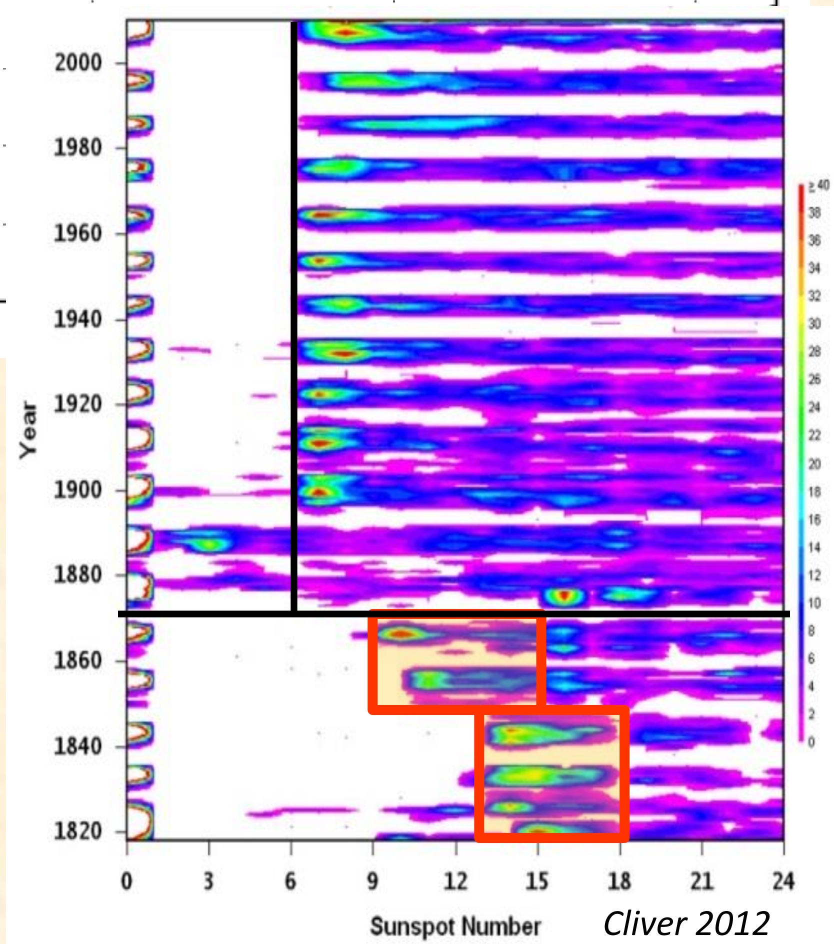
- 1861: magnetic needle corrections **Staudacher data x 2**

A brief history of the sunspot number (SSN)



- 1874: adding new data
  (Flaugergues, etc.)
- 1880: Magnetic needle corrections

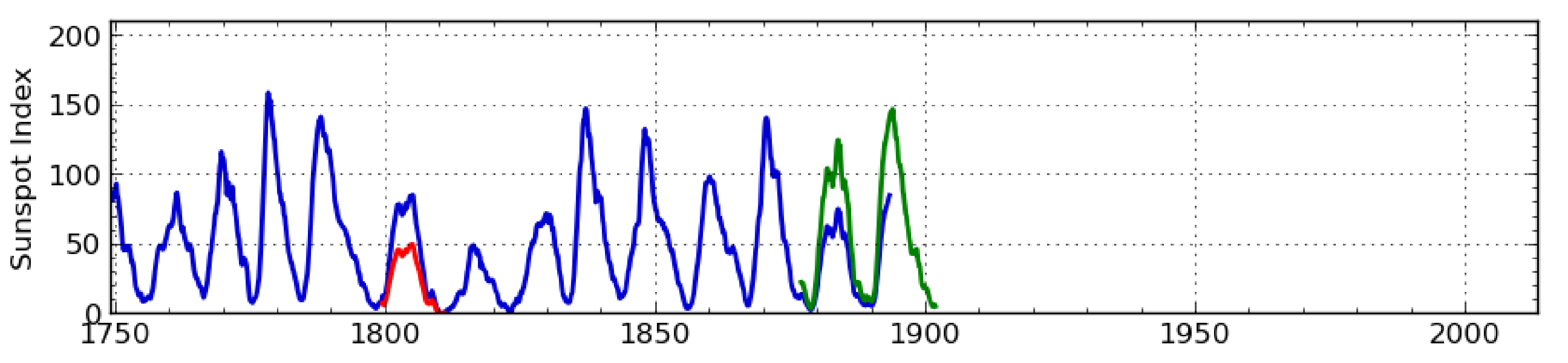
data before 1849 x 1.23



Cliver 2012

Record of these adjustments as seen in the lower end of the histogram of SSN values vs time

A brief history of the sunspot number (SSN)



- 1902: Wolfer correction

  cycle 5 (1799-1810) x 0.58

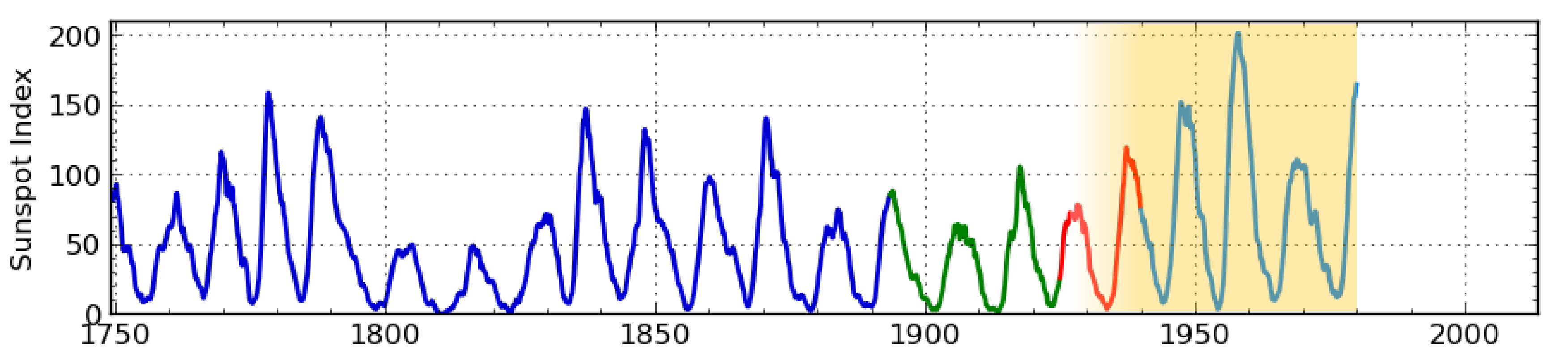
- **Wolf-Wolfer transition** [1877 - 1893]

  New counting method:
  - All small spots included in count
  - Multiple umbrae in common penumbra counted as separate spots
  - 16 years of parallel Wolf-Wolfer counts

$R_Z = 0.6\ W_{ZU}$

Alfred Wolfer (1877-1925)

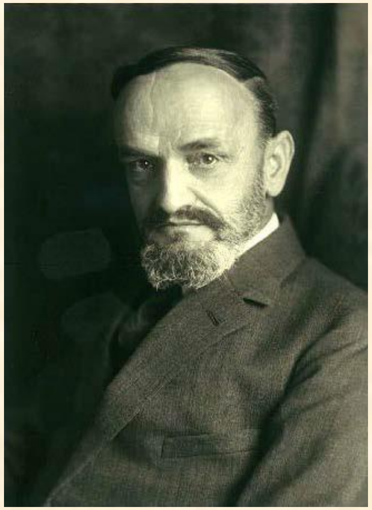
A brief history of the sunspot number (SSN)



- Zürich period:
  - 3 directors

- **Sunspot weighting:**
  - Starting date uncertain: 1930's (W. Brunner) or ~1944 (M. Waldmeier)

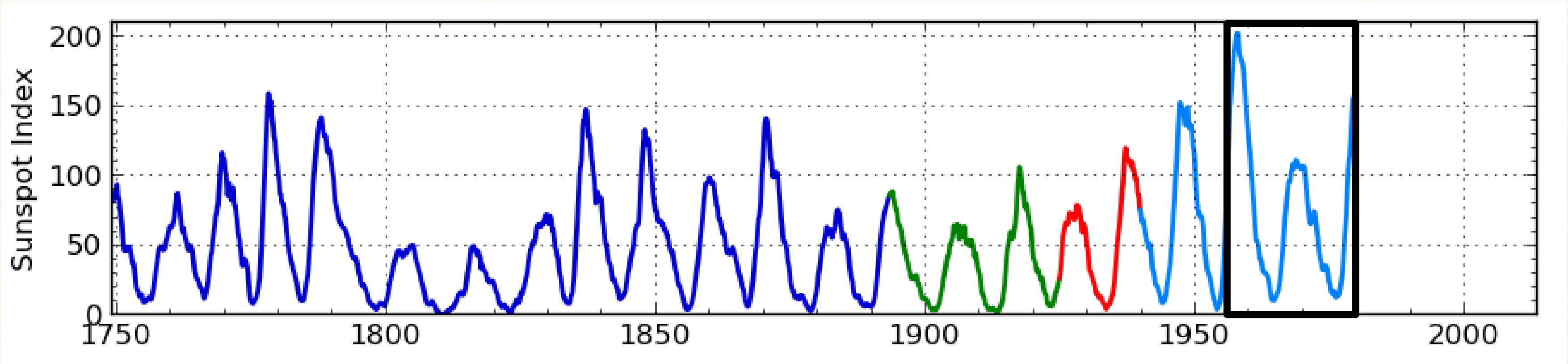
Alfred Wolfer (1877-1925)



William Brunner (1925-1944)

M. Waldmeier [1944 - 1980]

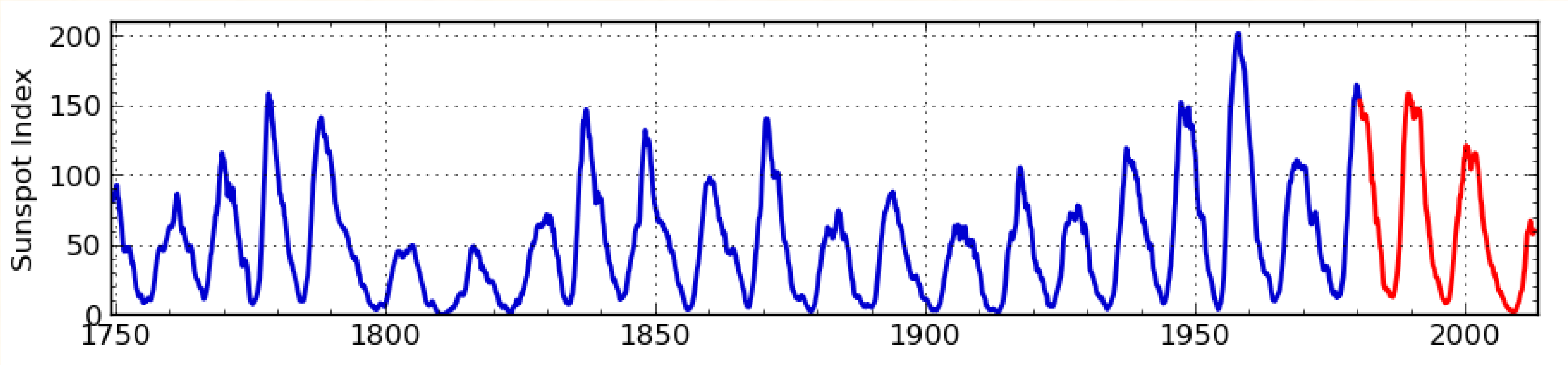
A brief history of the sunspot number (SSN)



- Second base station [1957]: **Specola Solare Locarno** (Ticino, SW)
  - Observer: **S. Cortesi** (still observing today!)
  - Trained to the Zürich method

S. Cortesi and M. Waldmeier circa 1955

A brief history of the sunspot number (SSN)

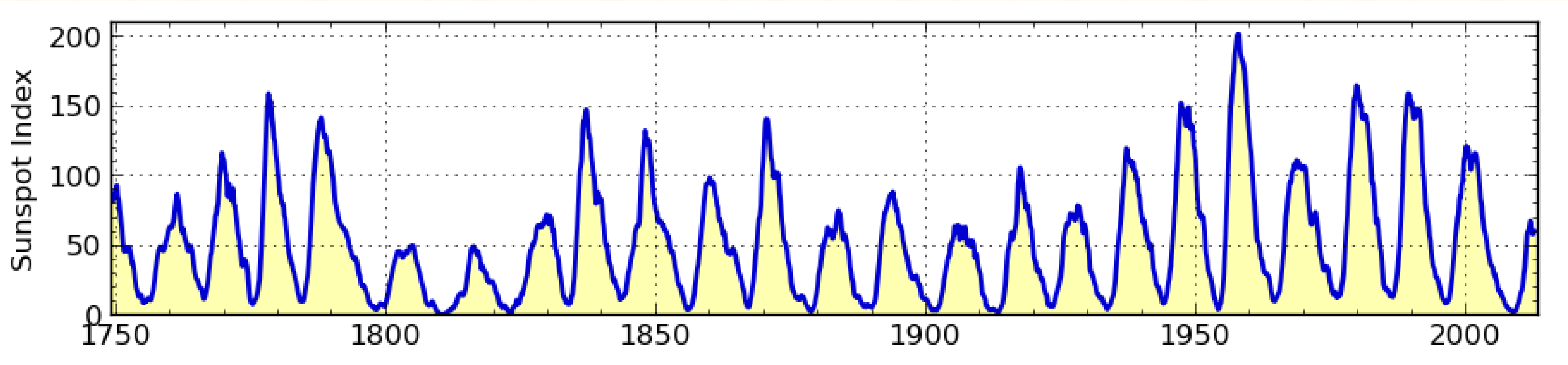


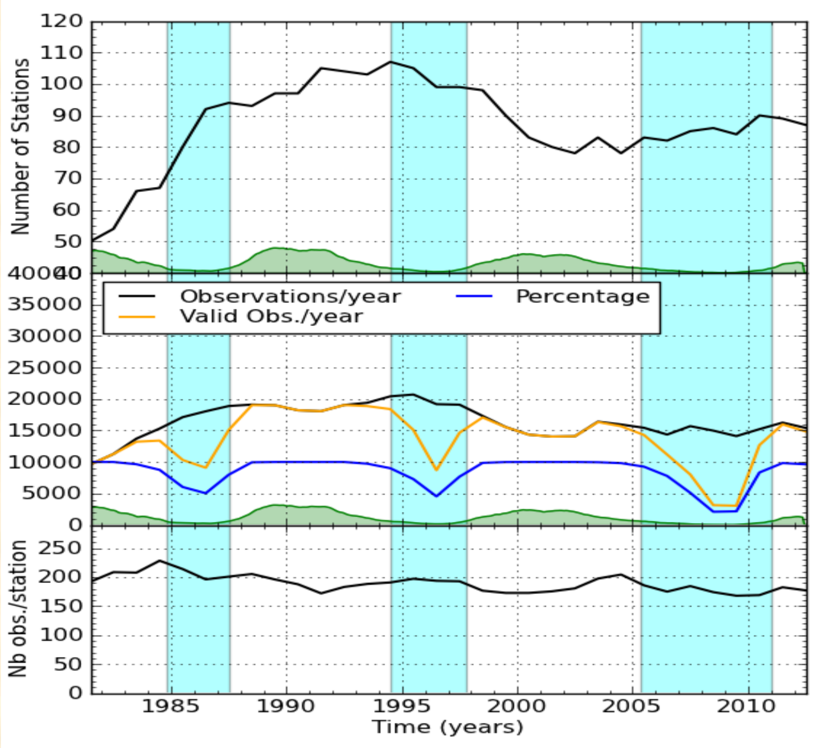
The Zürich SSN computation

- **SSN = Wolf number of the Zürich station**
- Daily gaps filled with average of auxiliary stations (10 to 40 stations)
- Scaling: yearly average k personal coefficients

- 1981: transfer of the WDC – Sunspot to Brussels (SIDC)
  - New pilot station:
    Specola Solare Ticinese, Locarno
    (Main observers: S. Cortesi, M. Cagnotti)
  - New global statistical determination of SSN using the full network
  - Extension of the worldwide observing network:
    from ~30 to ~80 stations

A brief history of the sunspot number (SSN)





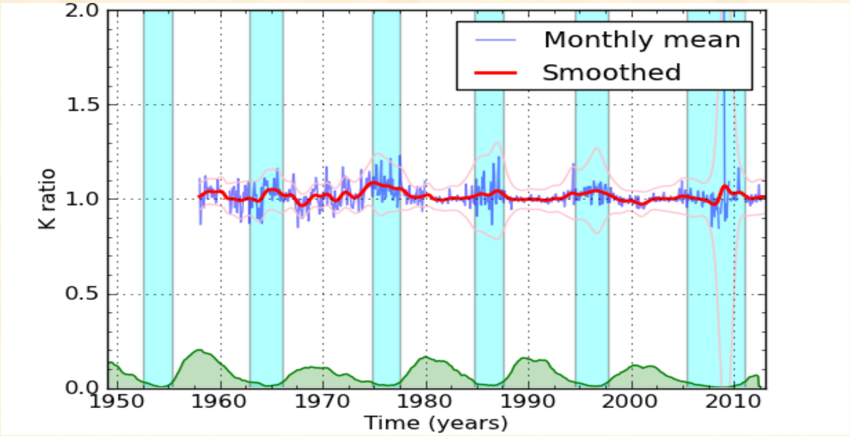
Statistics over the last 31 years

- 267 contributing stations
- 30 countries
- 80 long-duration stations (> 15 years)
- At any time, ~ 80 - 100 stations
- ~180 observations/year/obs.
- 450,000 observations

The Brussels International Sunspot Index R_i (1981-now)

SSN calculation method

- Scaling: average monthly k relative to pilot station:
$$k_s = \sum_d W_{LO}(d)/W_s(d)$$
- Daily SSN: statistics over whole network: $R_i = \sum_s k_s \cdot W_s$
- Elimination of anomalous daily Locarno values



- W_{LO}/R_i monthly rms variation: ~3 %

Data elimination: outliers at 2 σ_k
Monthly mean station k_s: first approximation (k_s, σ_k)

Daily average SSN R: first approximation (R, σ_R)
W_{LO} data elimination at 1 σ_R

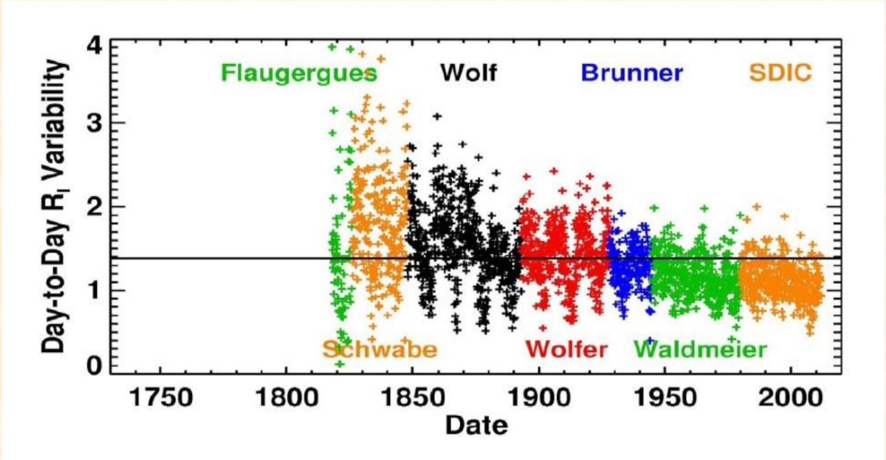
Data elimination: outliers at 1 σ_k
Monthly mean k: final (k_s, σ_k)

Iteration: elimination at 1 σ_R
Daily average SSN R_i: final value (R_i, σ_{Ri})

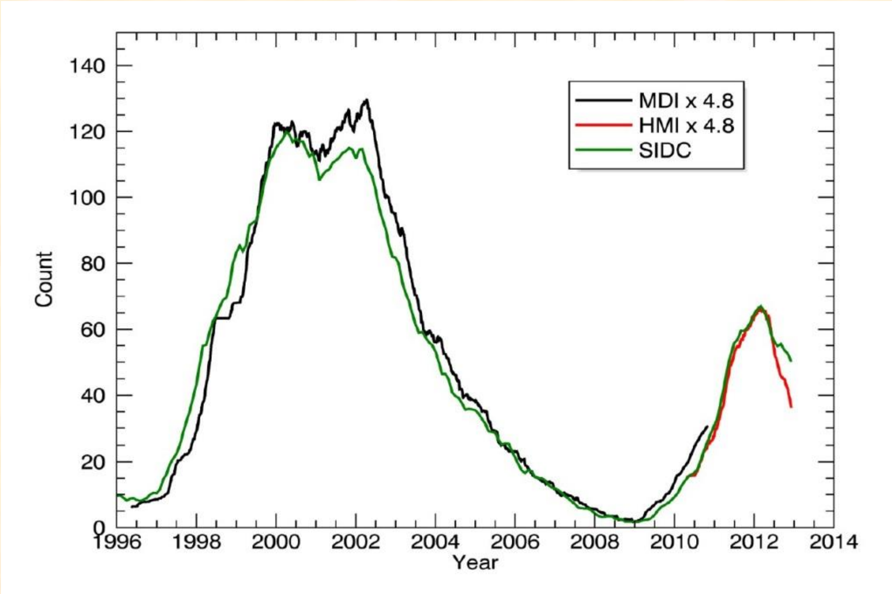
On timescales > 1 month, R_i is largely tracking the pilot station W_{LO}

SSN accuracy vs other indices

- Current rms dispersion of raw individual W_s values:
  - Daily: 8%
  - Monthly: 1.5%
- Photospheric indices:
  - R_G, R_A, $R_{Boulder}$, Area, Mx, $F_{10.7cm}$
  - High linear correlations (R>95%):
- Quantitative index:
  - magnetic flux emergence
- Chromospheric and mixed indices:
  - TSI, CaII-K, MgII
  - Good correlations:
    - Non-linear relation
    - Time lags
  - Different physics !



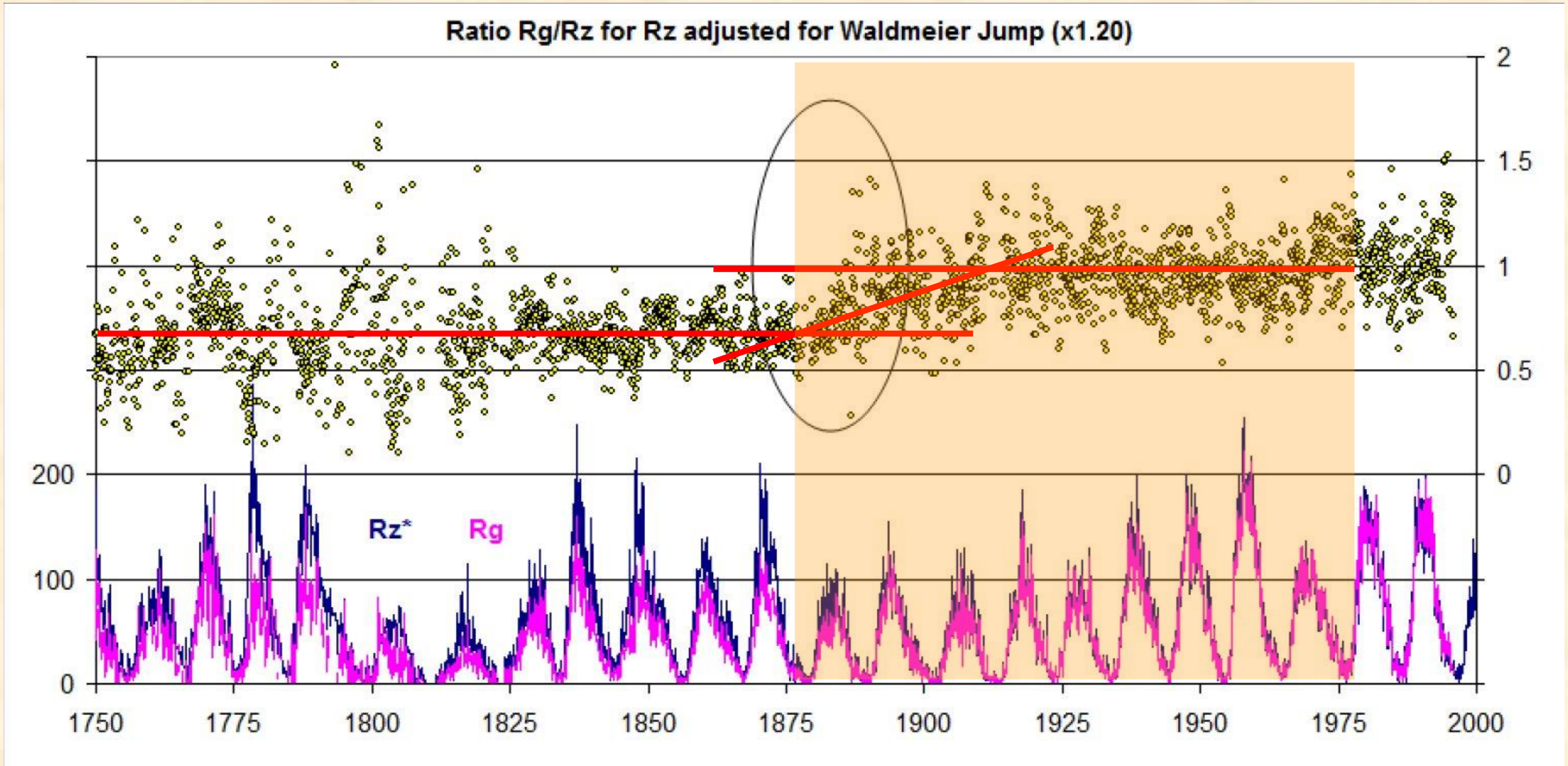
D. Hathaway, SSN workshop 2012



STARA catalog; F. Watson, 2012

The 1885 drift: R_Z versus R_G

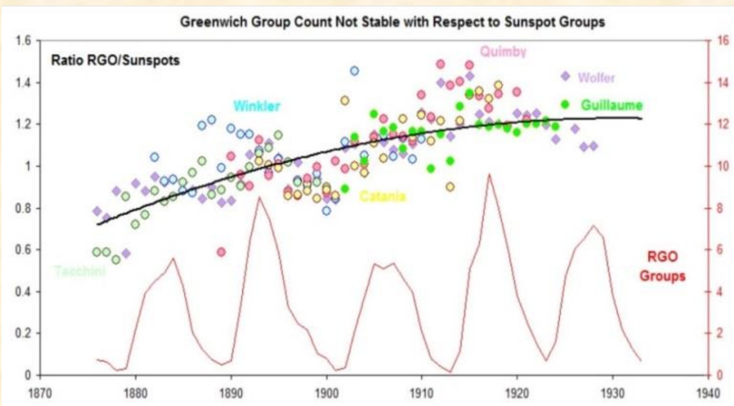
- Main alternate index: group sunspot number R_G *(Hoyt & Schatten 1998)*
- R_G 40% below R_Z before 1880 !
- Progressive ramp: 1875 – 1910 (~35 years)



Cliver, Clette & Svalgaard 2013

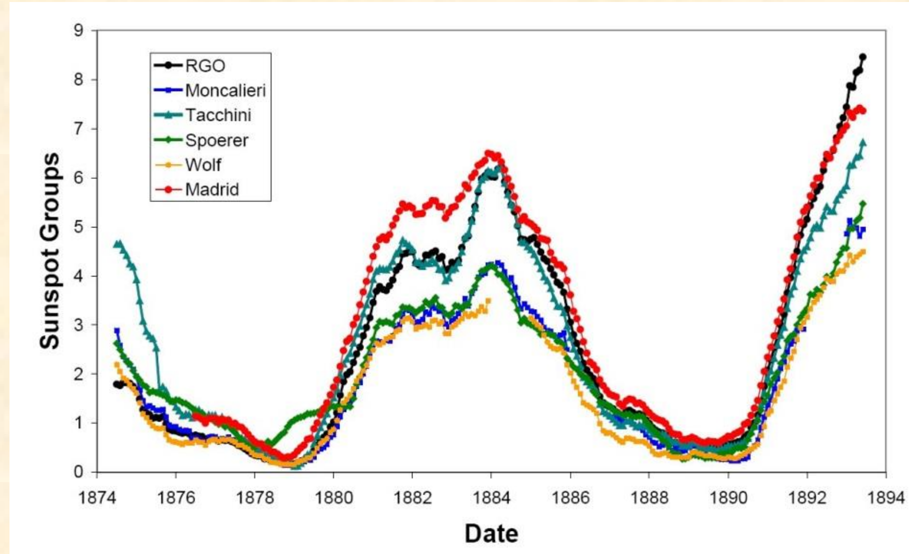
The 1885 drift diagnostics: reference sunspot series

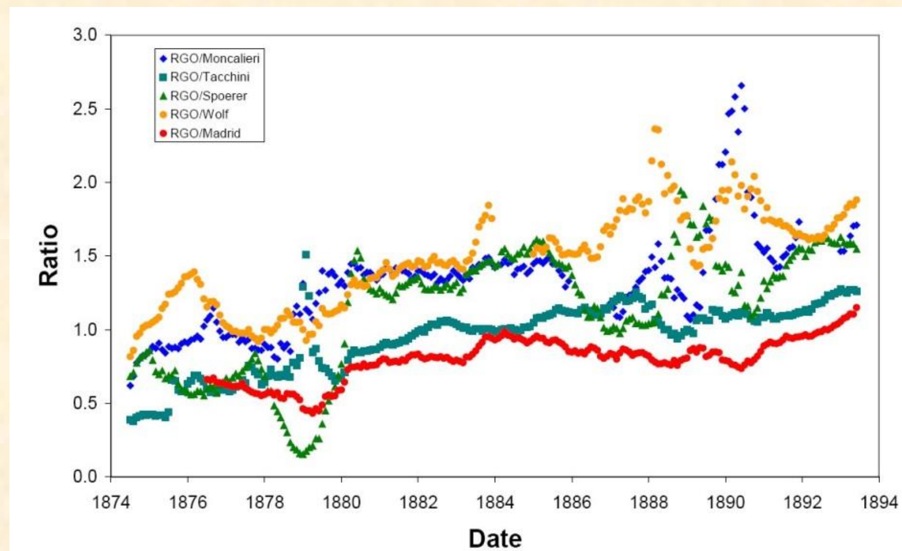
- Progressive increase of the RGO sunspot number and group count relative to all parallel stations
  - Reference: multiple long-duration observers spanning the 1874 – 1910 interval *(Svalgaard 2012 ,Vaquero 2013)*
  - ⇨ **Ratio increases by ~40% over 1875 - 1893** *(J. Vaquero 2012)*



Svalgaard, 2012

- Indications of changes in the early RGO data set *(Willis et al, 2013)*:
  - Photographic plate type
  - Measuring method



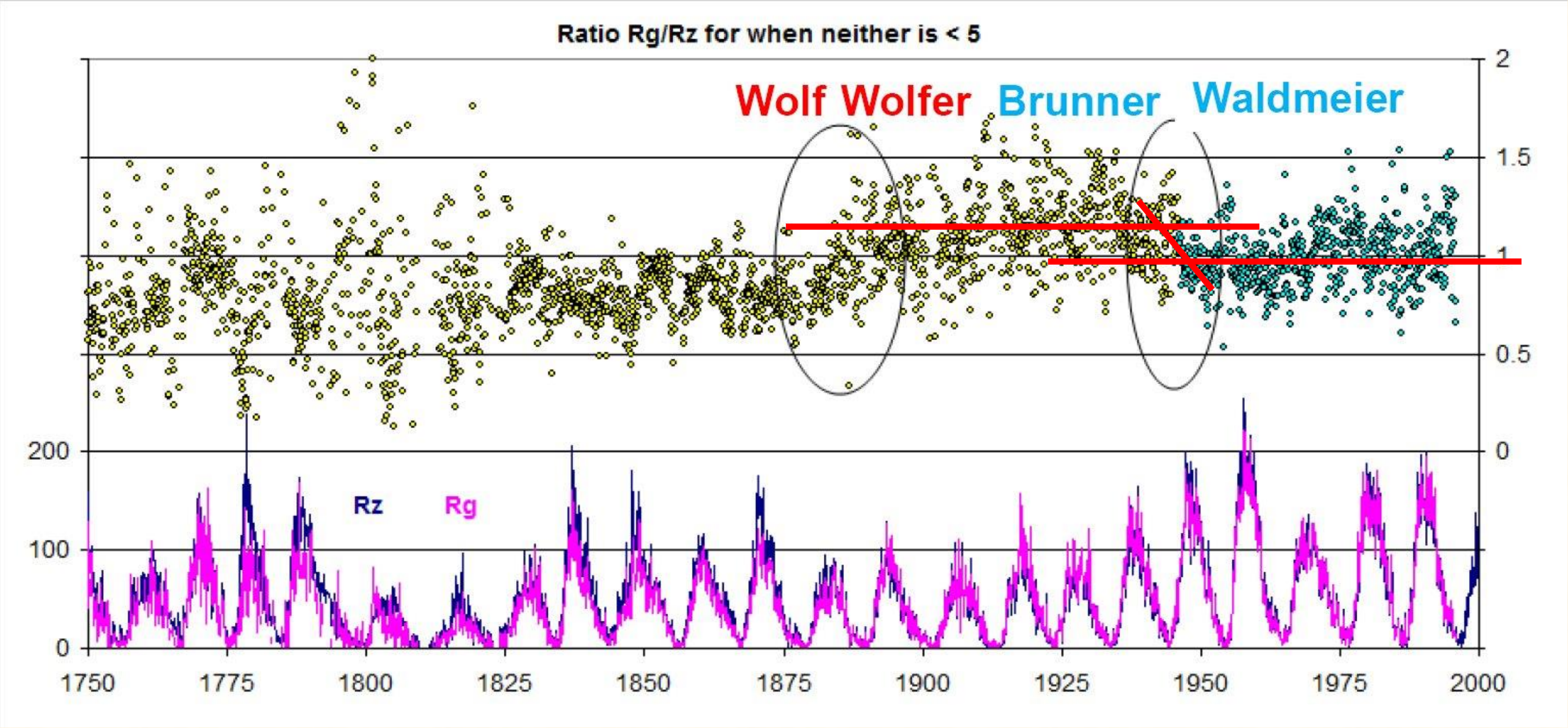


Vaquero, SSN Workshop, 2013

⇨ **the R_Z-R_G discrepancy is mostly due to an R_G underestimate**

The Waldmeier jump

- Rather sharp jump around 1945
- Ratio R_G/R_Z: decrease by ~15-20%



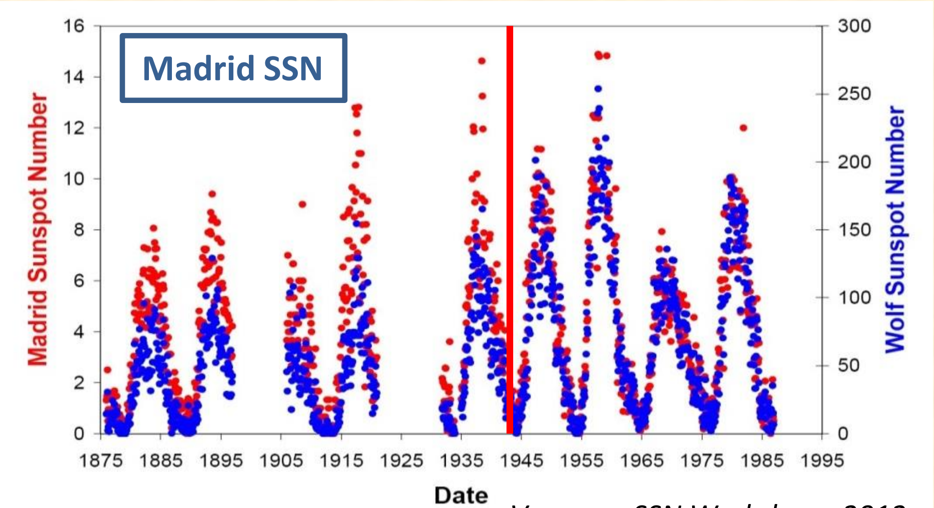
Cliver, Clette & Svalgaard 2013

The Waldmeier jump diagnostics

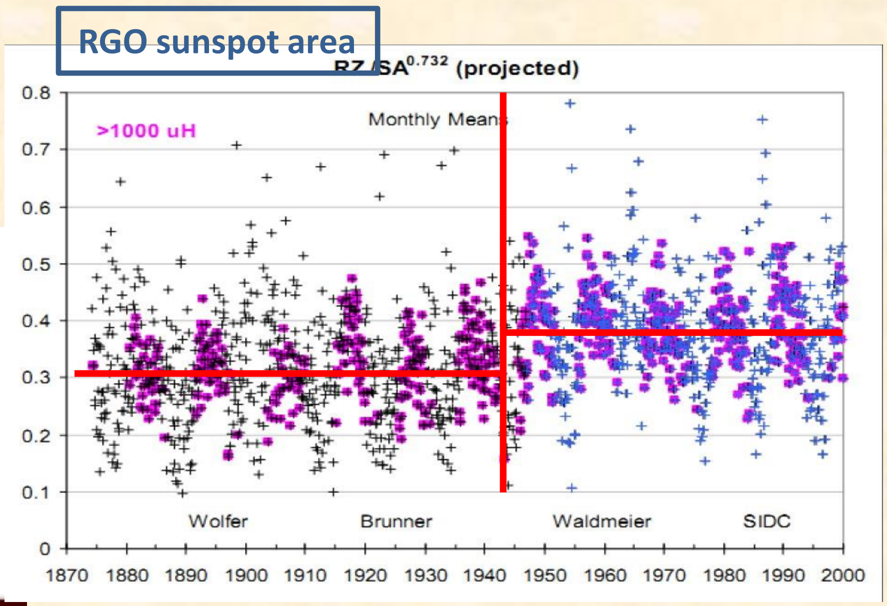
- Jump in SSN confirmed by different analyses:
  - Comparison with long-duration stations (e.g. Madrid) *(Vaquero 2012)*
  - Ratio SSN / sunspot area (RGO) *(Svalgaard 2012)*
  - Bayesian separation of group and spot contributions in SSN: *(Dudok de Wit 2012)*
    - 2 break points in R_Z - R_G relative statistical properties

➡ No indications of changes in the RGO data around 1940-50

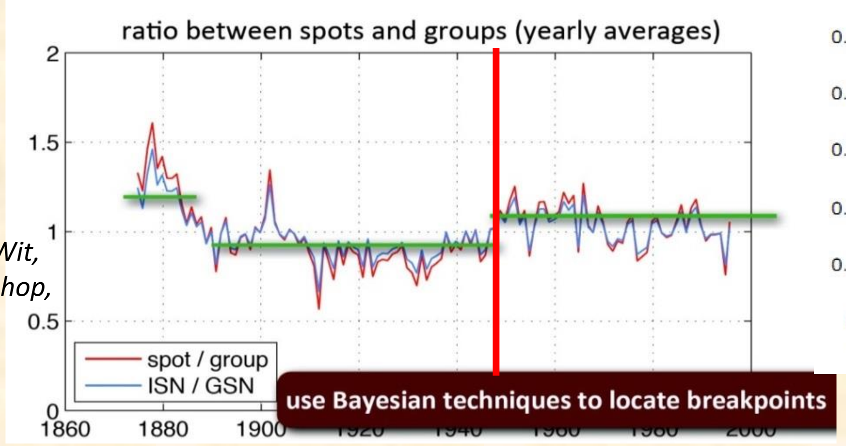
➡ Change in the SSN scaling



Vaquero, SSN Workshop, 2012



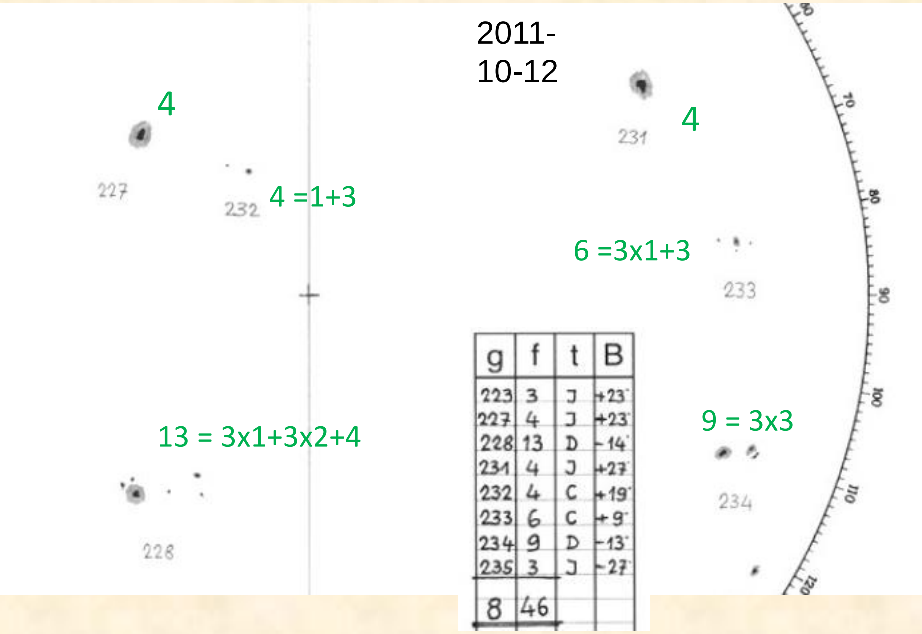
Svalgaard, 2012



Dudok de Wit, SSN Workshop, 2012

The Waldmeier jump: probable cause

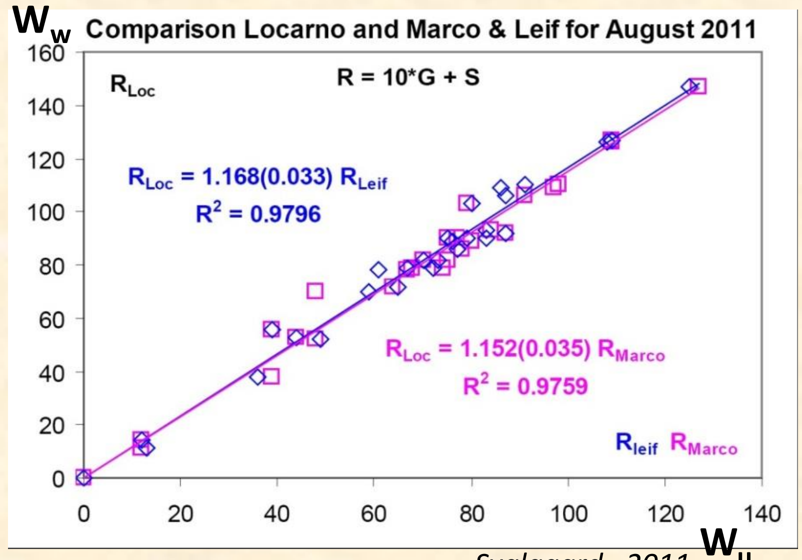
- **Sunspot weighting**:
  - Large spots are counted >1 (up to 5)
- Uncertain date of introduction:
  - Brunner in 1932 *(Cagnotti, 2012)*
  - Waldmeier, director from 1940 *(Waldmeier, 1968, Astr. Mitt. N°285)*



g	f	t	B
223	3	J	+23
227	4	J	+23
228	13	D	-14
231	4	J	+27
232	4	C	+19
233	6	C	+9
234	9	D	-13
235	3	J	-27
8	46		

- Locarno trained to the method (1955): still in use !
- Blind test (2003 – 2011): double counting by M. Cagnotti

⇨ **Ratio W_w / W_u = ~1.16**

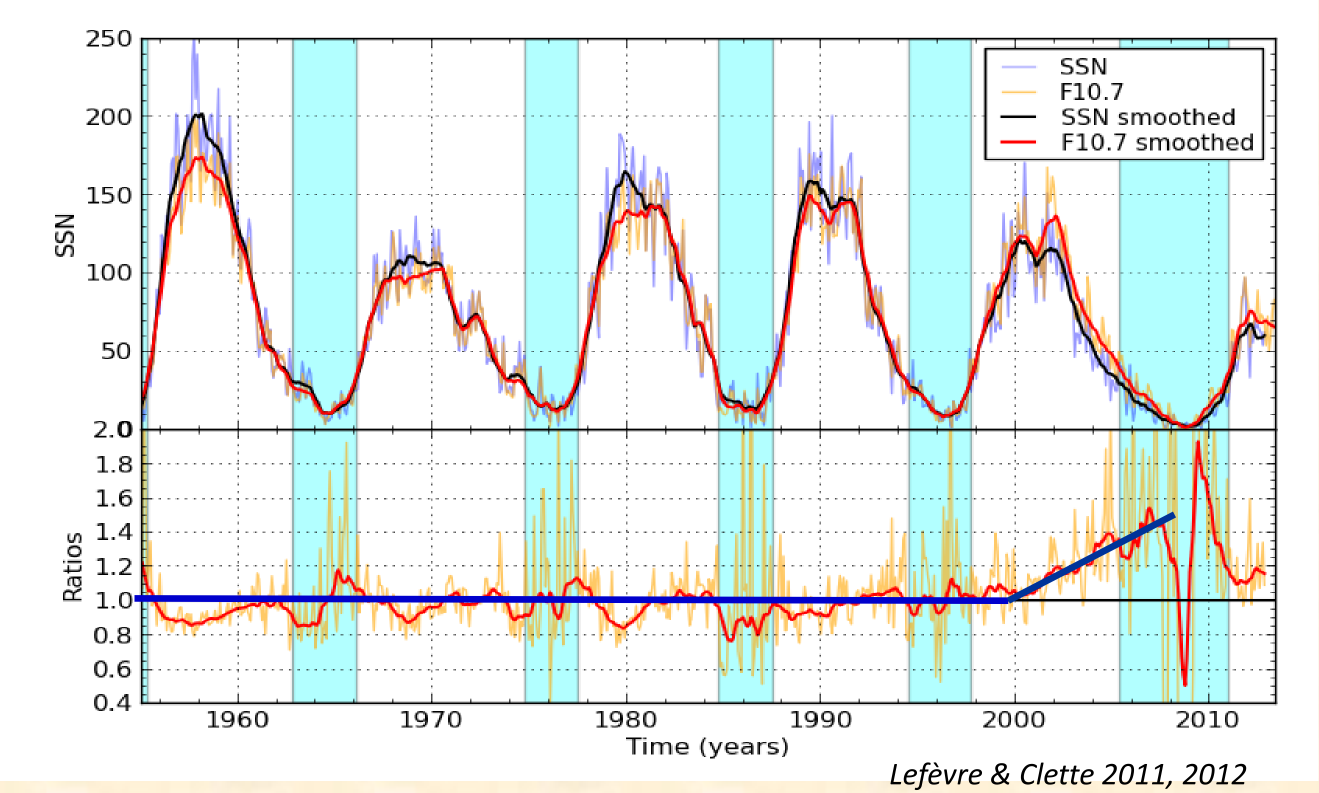


Svalgaard, 2011

Anomalies in the long cycle 23

Long cycle 23-24 minimum: Were there precursor signs during cycle 23 ?

- Break in the relation between SSN and other solar activity indices
- **The $F_{10.7}$ example** *(Svalgaard & Hudson 2010, Lukianova & Mursula 2011, Lefèvre & Clette 2011)*:
  - Divergence from a constant ratio starting in 2000
  - SSN ~15% lower than the $F_{10.7}$ proxy *(Johnson 2010)*
  - Apparent return to normal ratio in cycle 24



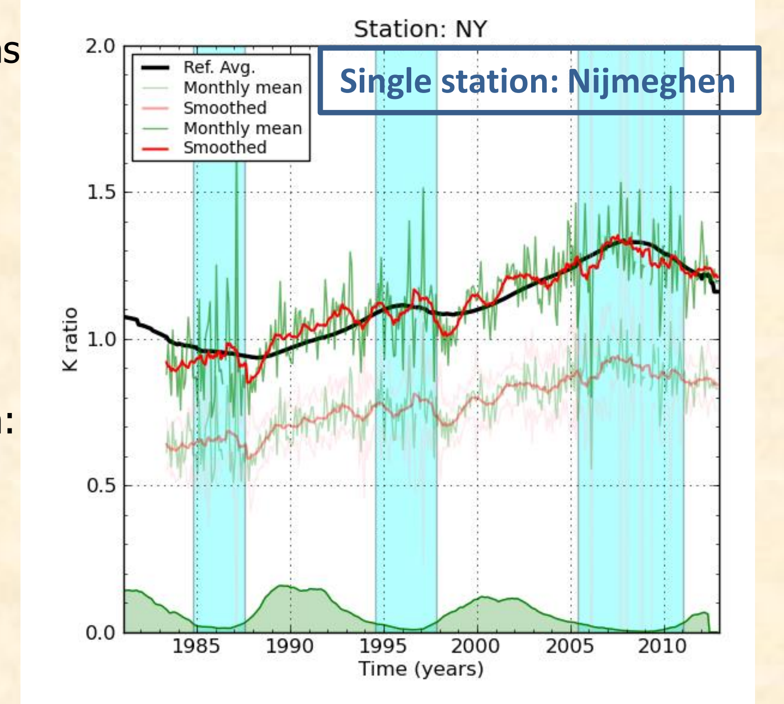
Lefèvre & Clette 2011, 2012

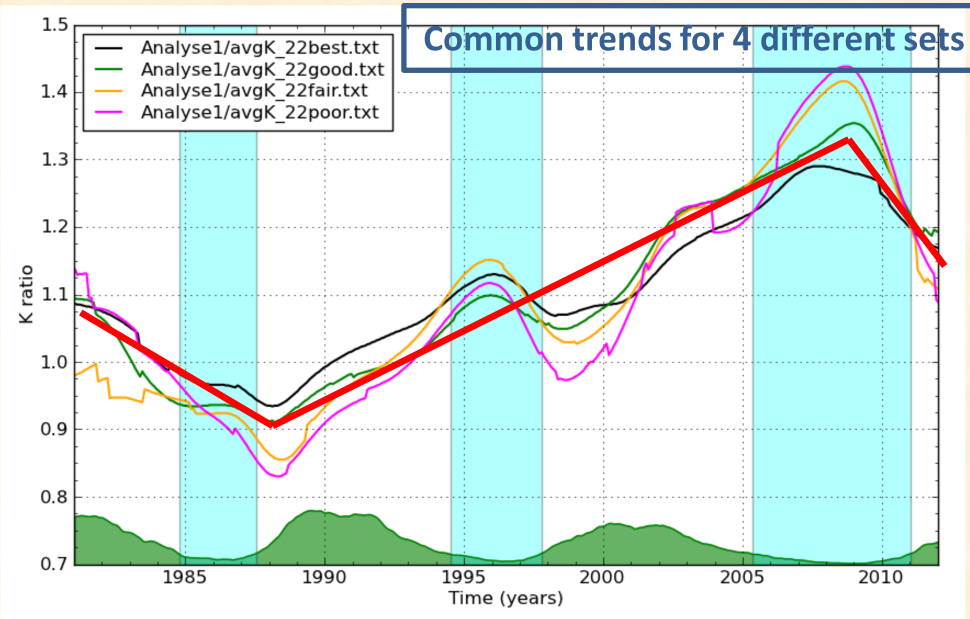
Cycle 23 and vanishing spots: recent drifts in R_i

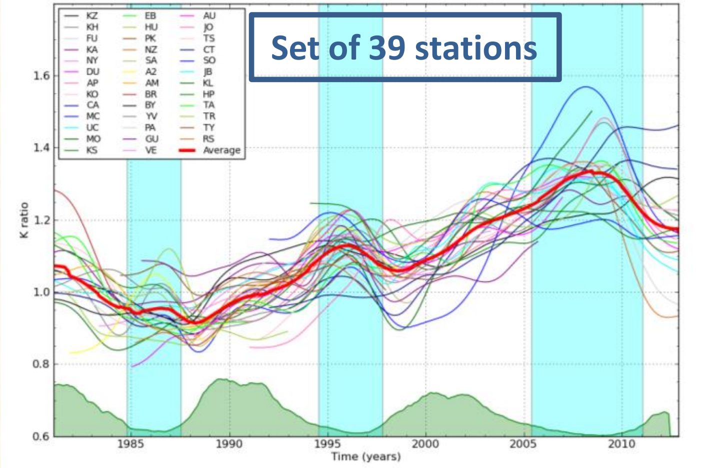
- Global analysis of raw sunspot counts from all 267 stations
  - ~80 valid stations with duration > 15 years (> 200,000 observations)
  - Multi-station average of the ratio W_S/R_i (~ W_S/W_{LO})

- Consistent trend for different « mixes » of stations (according to duration, rms dispersion)

- « S » pattern drift attributable to the Locarno pilot station:
  - Peak-peak amplitude (including minima): 30%
  - Effective impact on SSN: 20%





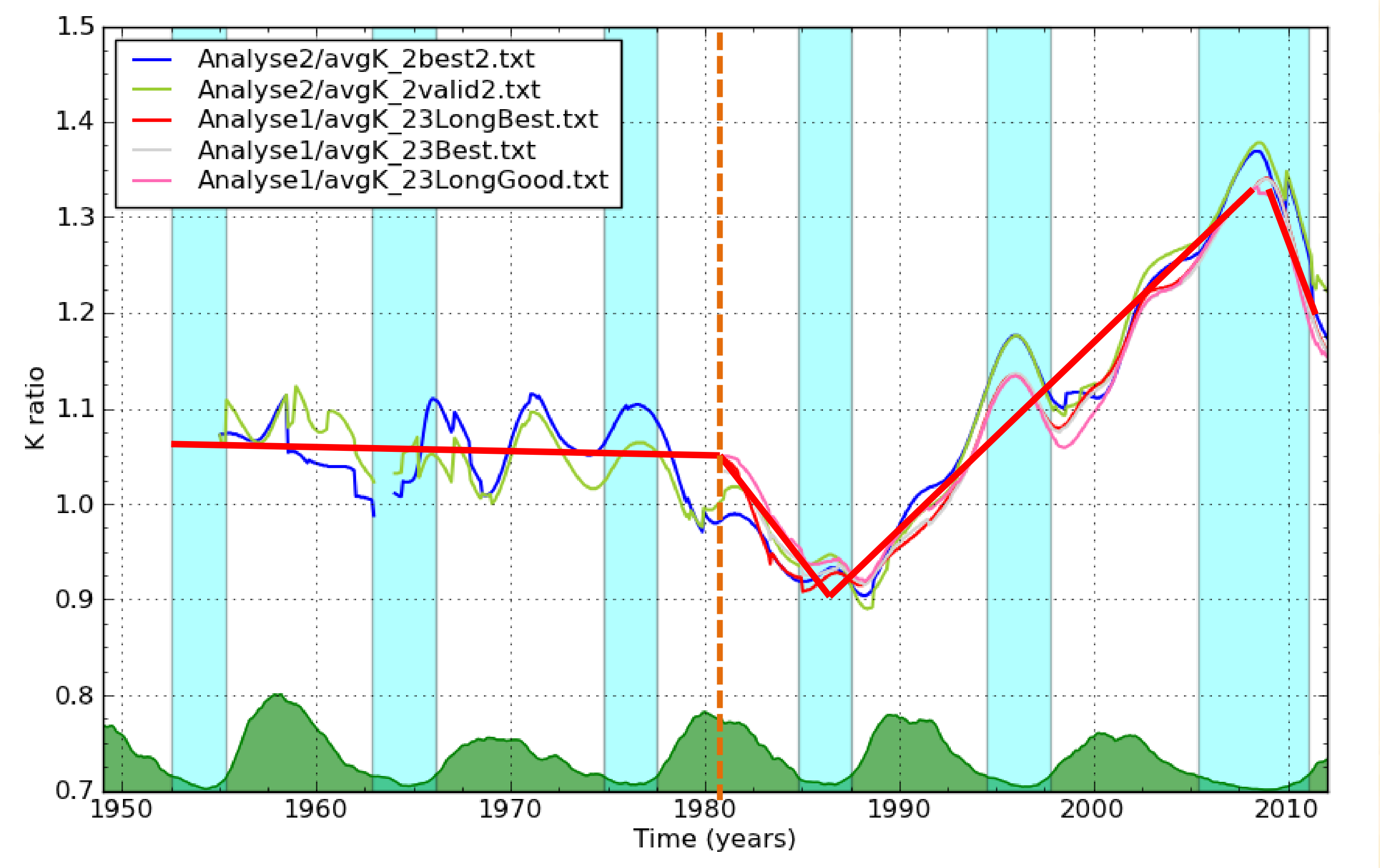


Recent drifts in R_i (1981-2013)

- Adding raw records from Zürich: 20 stations, 1955-1980

- No trend before 1981 (Pilot station: Zürich)

- Drifts start with the transition to Locarno

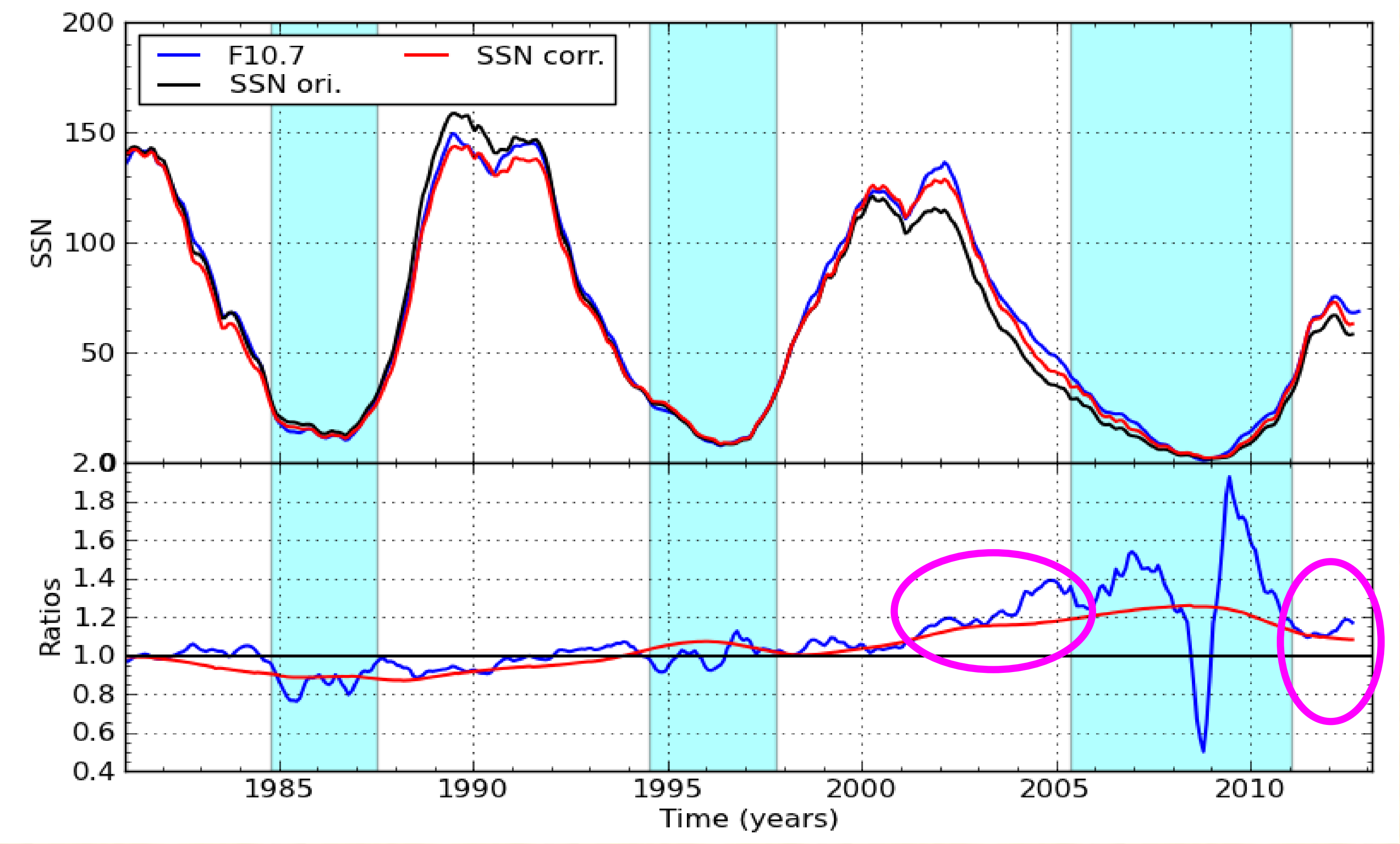


- All raw observations available in the SILSO database
- Good alternate pilot stations can be identified

⇨ **The R_i drift can be fully corrected !** (recomputation planned in 2013)

Recent drifts in R_i : consequences for cycle 23 anomalies

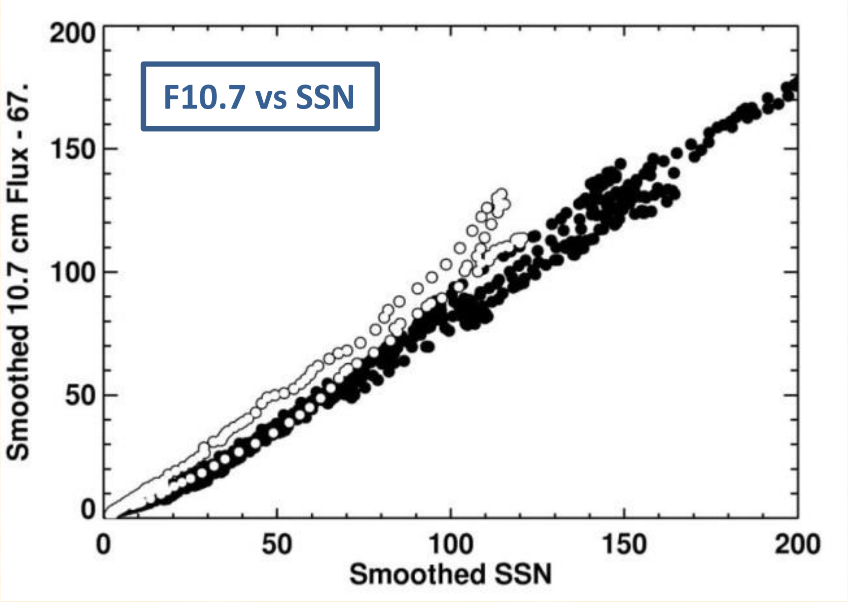
- Discrepancies with other indices (R_A, $F_{10.7}$) are partly eliminated

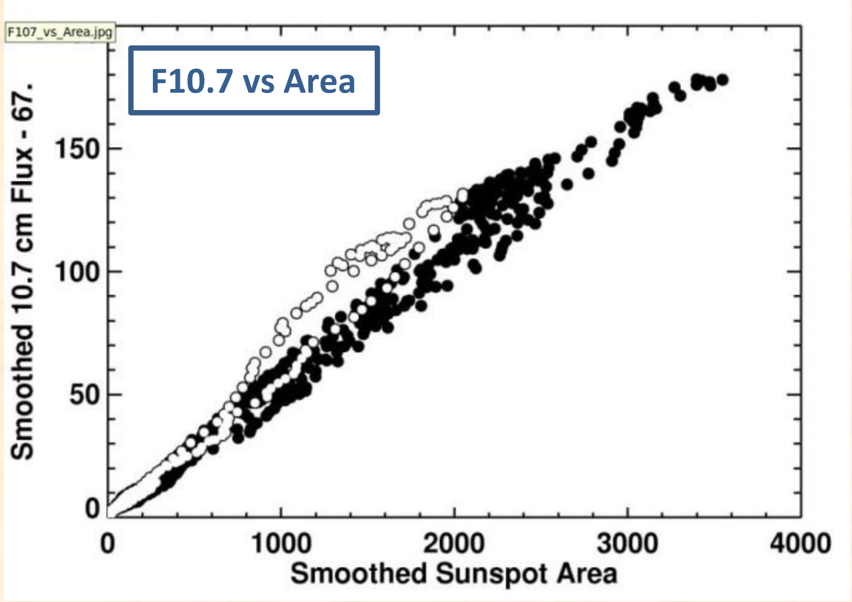


- **$F_{10.7}$ still deviates significantly after 2002 !**

Cycle 23 and vanishing sunspots

- Same drift of $F_{10.7}$relative to SOON sunspot areas *(Hathaway 2010)*





Hathaway 2010, 2013

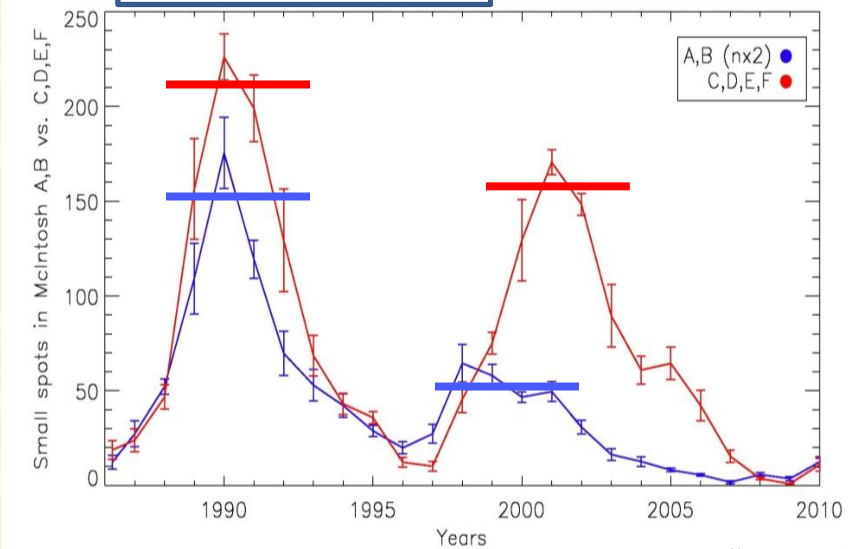
Problem in $F_{10.7}$? in SSN ?

Or true physical change in the Sun ?

Cycle 23 and vanishing sunspots: small-spot deficit

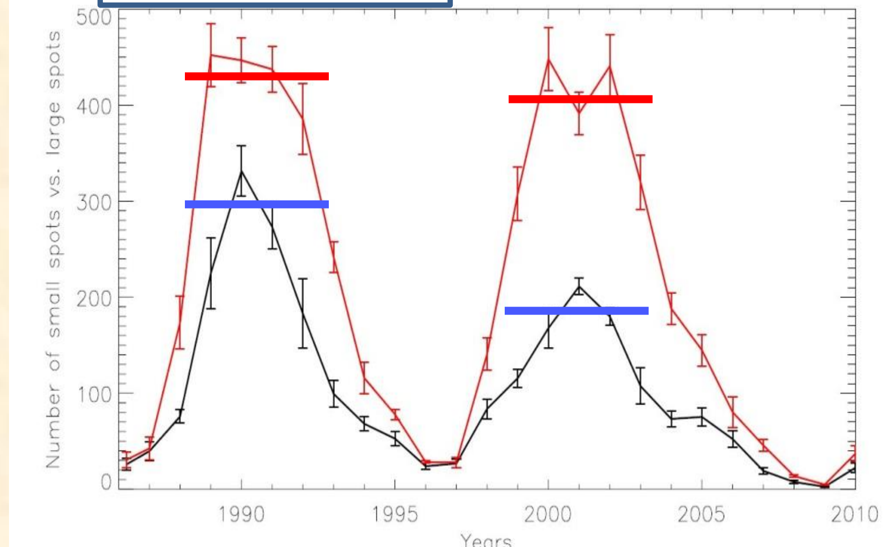
- Exploitation of detailed sunspot catalogs (DPD, Debrecen; NOAA/SOON)
- Scale dependant small-spot deficit in cycle 23:
  - Deficit of small groups (A & B: spots without penumbra):
    - Ratio cycle 23 / cycle 22 ~ 50% *(Lefèvre & Clette 2011 2012, Kilcik et al. 2011)*
  - Deficit of small spots also in larger groups:
    - Ratio cycle 23 / cycle 22 < 75% *(Lefèvre & Clette 2012)*
- Starts in 1998
- Significant only after 2000 (first peak in cycle 23 maximum)

Small vs Large groups



Lefèvre & Clette 2011

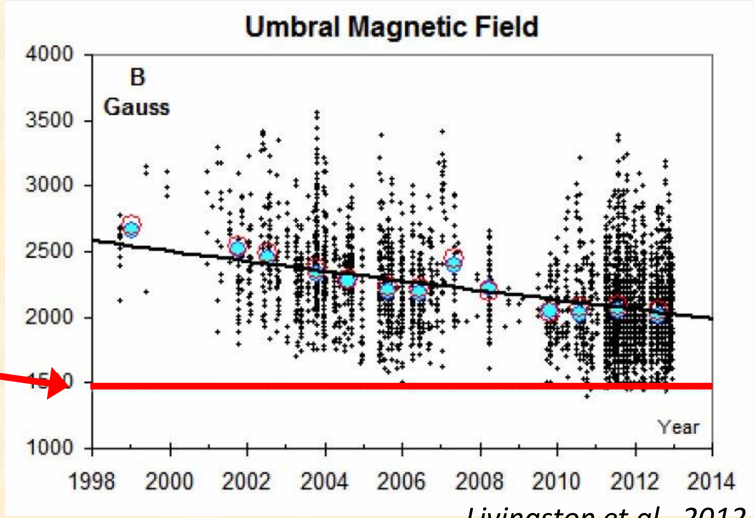
Small vs Large spots



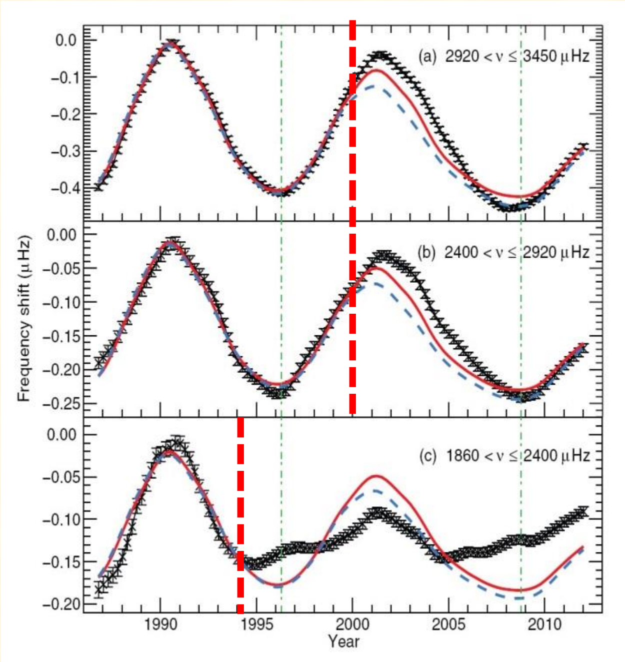
Lefèvre & Clette 2011

Cycle 23 and vanishing spots: declining field strength

- Livingston-Penn effect *(Livingston & Penn 2009, 2012; Penn & Livingston 2006,)*:
  - Average core magnetic field in umbra (FeI line: 1565 nm)
  - **Steady decline since 2000**: Magnetic field: -40 G/year
- Existence of a **lower threshold: 1500 G**
- Decline of the small-**sunpot formation fraction**
- BISON helioseismic sounding 1978- 2012 *(Basu et al. 2013)*:
  - Solar-cycle induced modulation of p-mode frequencies in the near-surface layers
- Top layers (high-frequency modes): discrepancy starting in 1998
- Deeper layer ($r < 0.997\ r_{\odot}$) *(low frequency modes)*: deviation during entire cycle 23
- **Thinning of the subsurface magnetic field layer** (< 20000 km)



Livingston et al. 2012



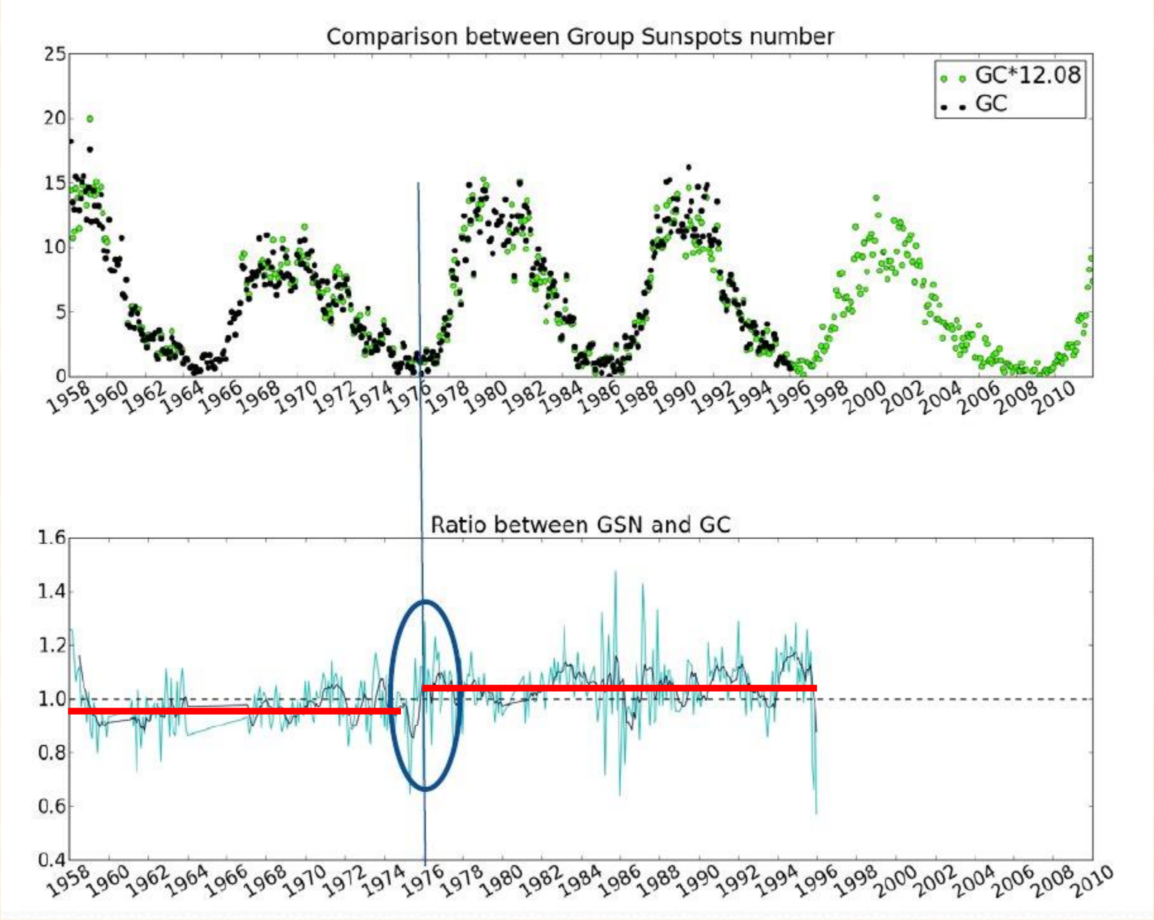
Basu et al. 2013

Cycle 23 and vanishing spots: variable SSN / R_G ratio

Any corresponding trend in the sunspot/group ratio ?

- Reconstruction and extension of the Group Number R_G up to 2012 (WDC – Sunspot database):
  - **Both indices calculated from the same data set**
- Good overall match with R_G from Hoyt & Schatten:
  - Ratio near 1.0 and constant

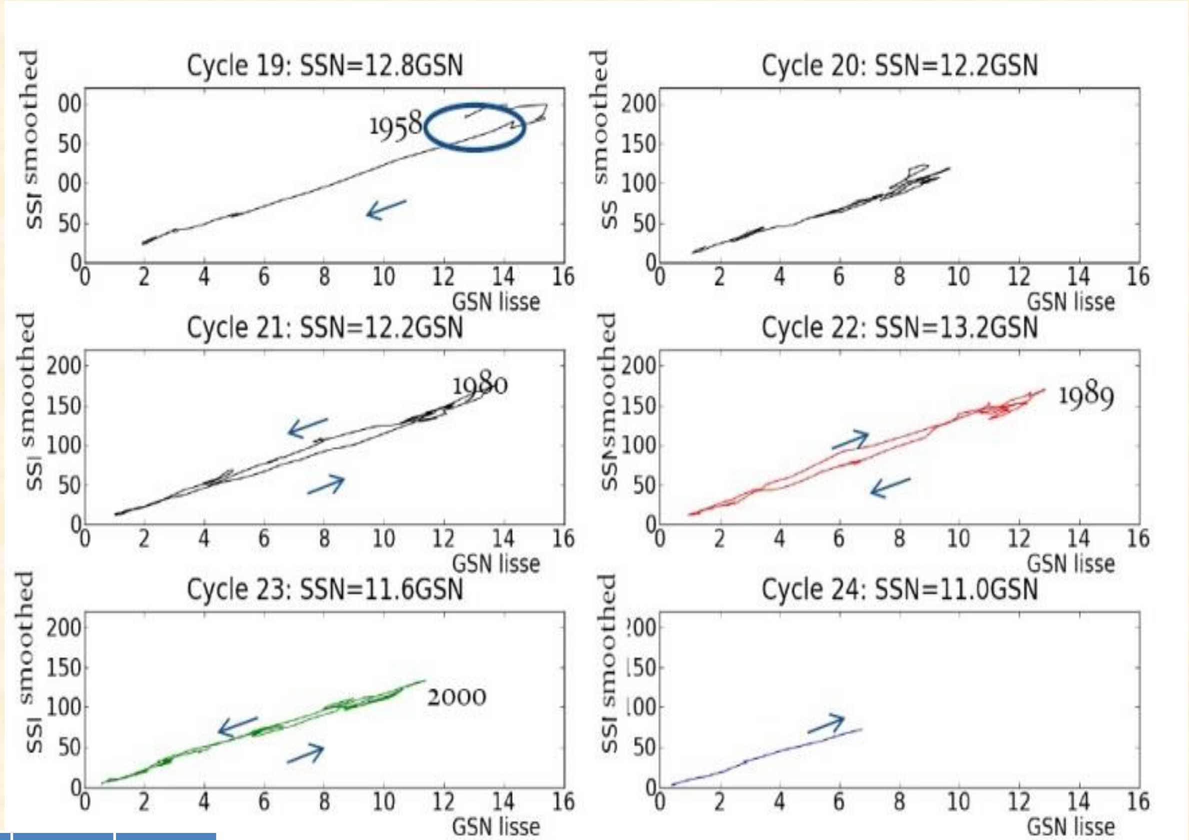
    except for
  - Jump around 1975 (transition from RGO to SOON data)
  - **R_G scale increased by ~10% after 1975**



Wauters & Clette, SSN Workshop 2013

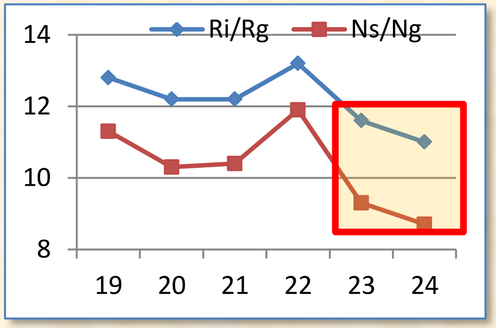
Cycle 23 and vanishing spots : variable SSN / R_G ratio

- Changing R_i/R_G ratio:
  - Stable over cycles 19 to 22
  - Decline in cycle 23 and early part of cycle 24
- Decrease of the average number of spots per group by ~30%



Wauters & Clette, SSN Workshop 2013

Cycle	Ns/Ng	North	South	R_i/R_G	North	South
19	11.3			12.8		
20	10.3			12.2		
21	10.4			12.2		
22	11.9	12.5	10.7	13.2	13.5	12.5
23	*9.3*	*9.5*	*8.7*	*11.6*	*11.5*	*11.9*
24	*8.5*	*8.7*	*6.4*	*11.0*	*11.2*	*10.3*

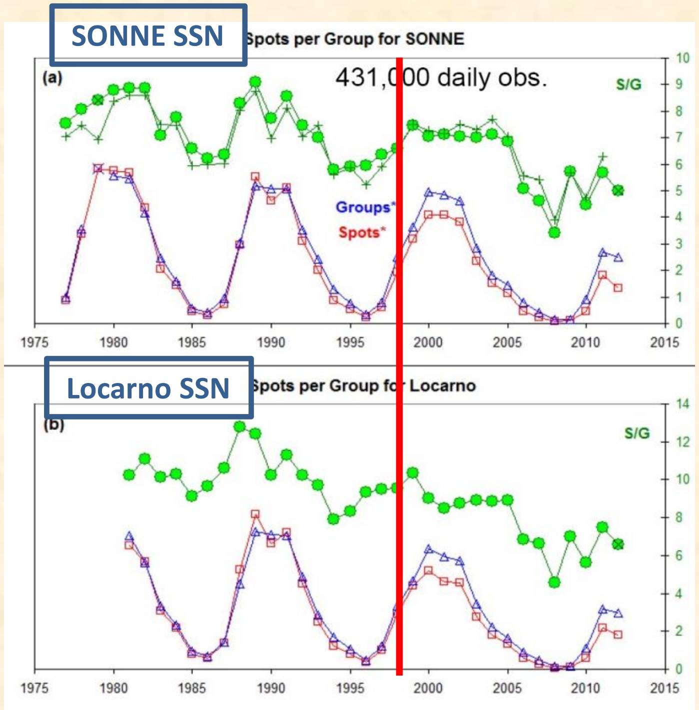


Cycle 23 and vanishing sunspots: spots per group

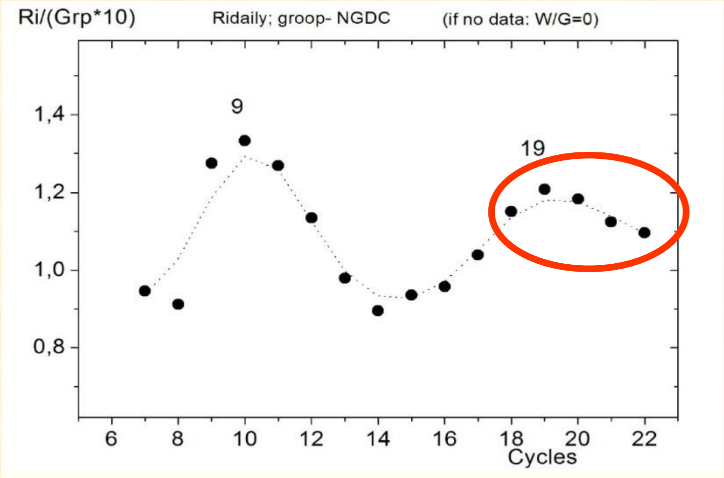
- Same trend deduced for different stations and data sets
- Apparent secular variations of the number of spots per group:
  - Increase for stronger cycles
    (Tlatov 2013, Nagovitsyn et al. 2012)
  - *Caveat: Ratio of distinct series based on different sets of raw observations.*

➡ SSN and group number are two distinct physical quantities.

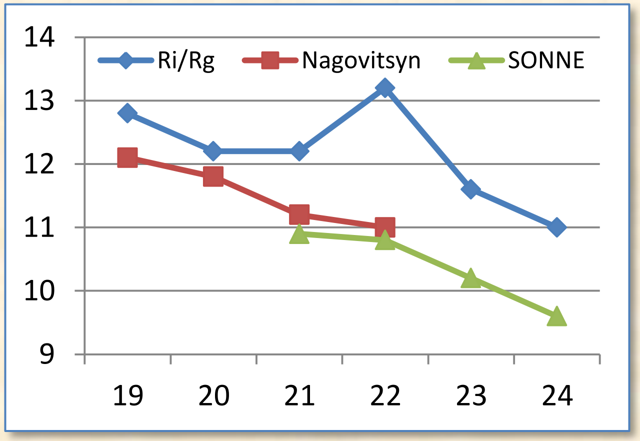
➡ **Varying R_Z-R_G relation** = physical information



SONNE, A. Bulling, L. Svalgaard 2013



Tlatov 2013



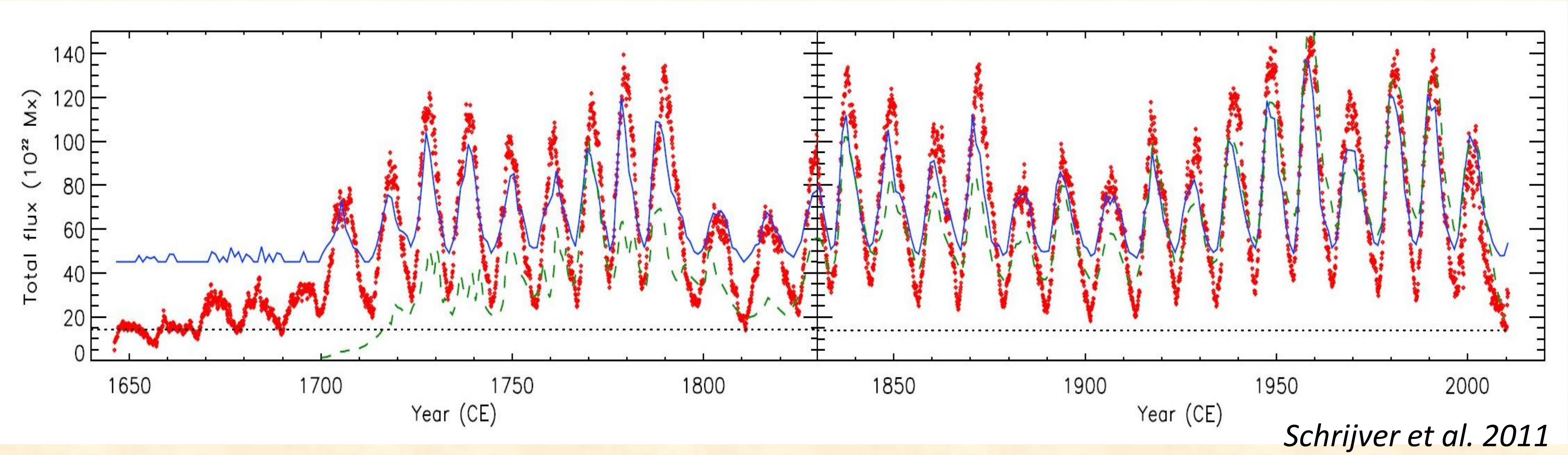
Vanishing spots: theoretical implications

- Dynamo models:

  Existence of two dynamo components, deep and shallow ?
  - Babcock-Leighton near-surface flux diffusion mechanism *(Muñoz-Jaramillo et al. 2010, 2011)*
  - Role of a shear layer just below the surface *(A. Brandeburg 2005)*
  - Near-surface magnetic flux aggregation mechanism *(K. Schatten 2009 , Rempel, et al 2009)*

- TSI and spectral irradiance reconstruction:
  - Lower sunspot blocking (magnetic fields falling below 1500G threshold)
  - Higher excess in network and plages (near-UV, microwaves, solar wind ?)
  - **Reduction of the effective range of irradiance variations in low activity ?**

    *(cf. existence of **base level in solar flux**, Schrijver et al. 2011)*



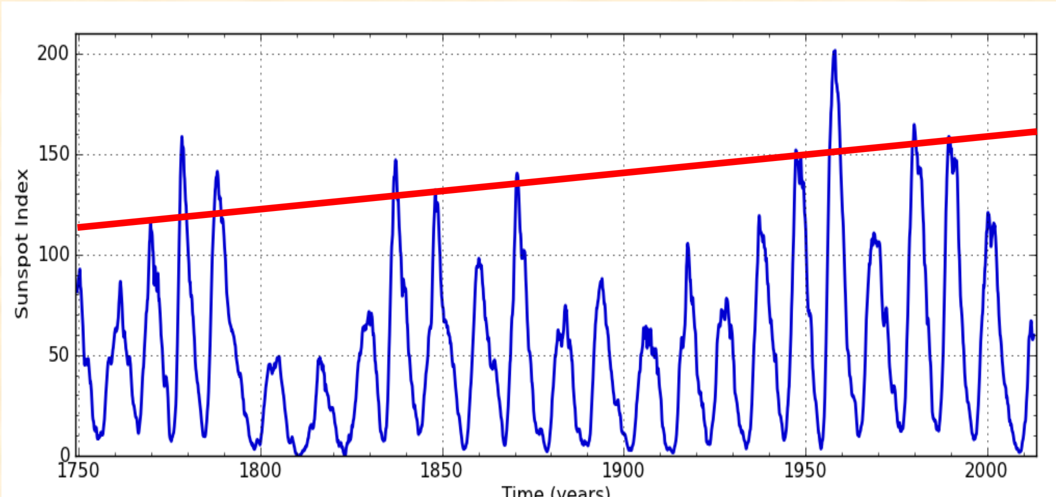
Schrijver et al. 2011

Future prospects: fully corrected SSN series

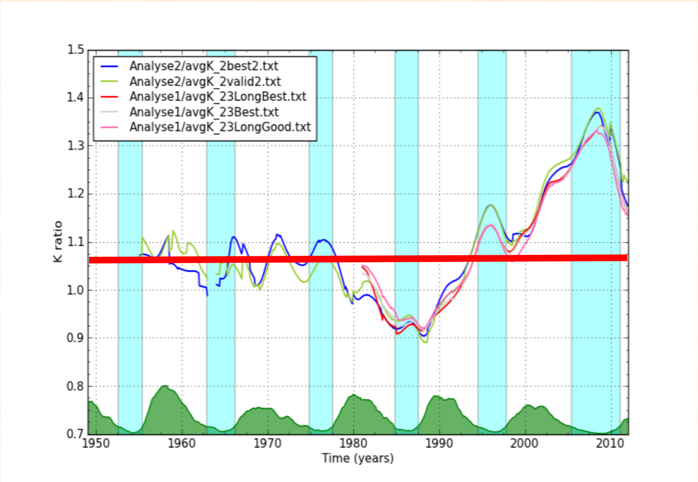
- **SSN workshops**: full revision and validation of the SSN series
- 3 past workshops: Sac. Peak Sept. 2011, Brussels May 2012, NSO-Tucson Jan. 2013
- 2 future workshops: AIP Potsdam Oct 2013, USA? Spring 2014
- Output:
  - Special journal issue gathering all results (~ 40 contributors, early 2014)
  - Release of a fully revised SSN series (WDC – SILSO, Brussels)

Two main corrections (in 20th century!)

SSN R_Z / 1.2 after 1944 | SSN Ri detrended over 1981-2013



Cliver, Clette & Svalgaard 2013

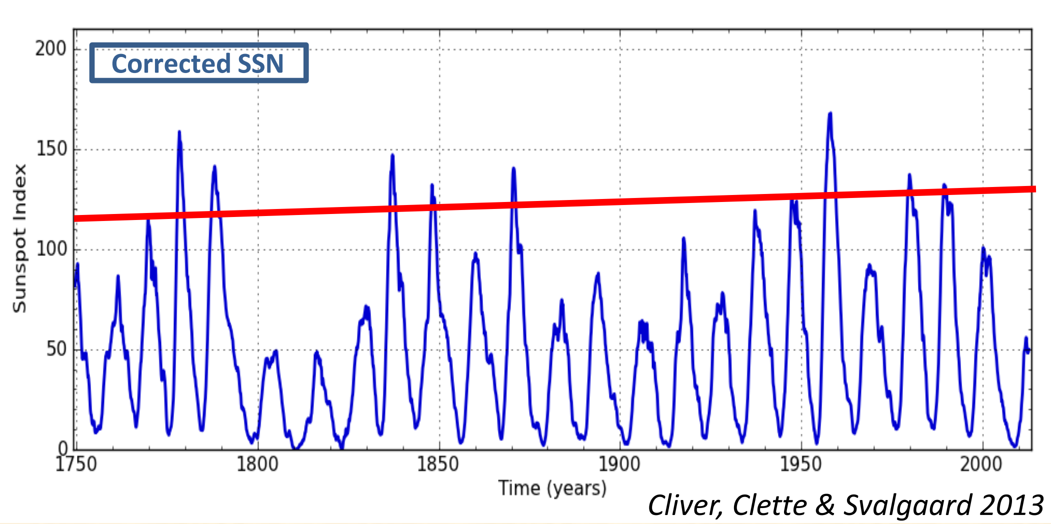


Future prospects: fully corrected SSN series

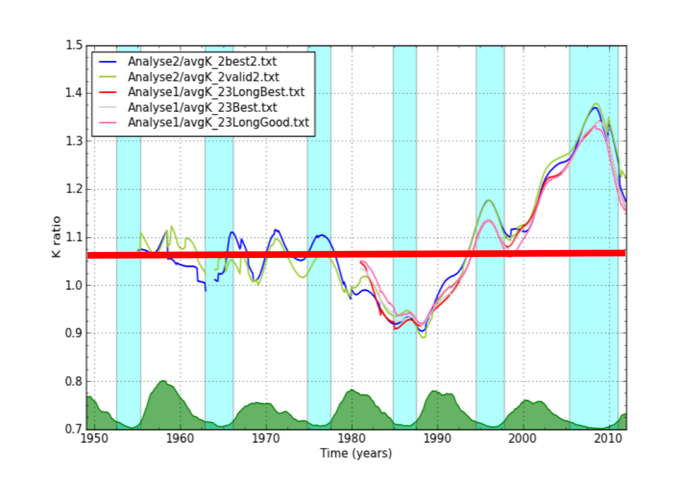
- **SSN workshops**: full revision and validation of the SSN series
- 3 past workshops: Sac. Peak Sept. 2011, Brussels May 2012, NSO-Tucson Jan. 2013
- 2 future workshops: AIP Potsdam Oct 2013, USA? Spring 2014
- Output:
  - Special journal issue gathering all results (~ 40 contributors, early 2014)
  - Release of a fully revised SSN series (WDC – SILSO, Brussels)

Two main corrections (in 20th century!)

SSN R_Z / 1.2 after 1944 | SSN Ri detrended over 1981-2013



Cliver, Clette & Svalgaard 2013



- Reduction of the upward trend in solar activity since the Maunder Minimum
- Closer agreement between R_i and modern solar indices after 1980 (except cycle 23?)

Conclusions:

- Revival of the SSN and sunspot science
- Biases and trends now largely identified:
  - Fairly recent (late 19th century – now): many original data accessible
  - Recent errors are propagated backwards over the entire series.

- The ratio between the sunspot number R_i and group number R_g is intrinsically variable (e.g. vanishing small-spots)
  - Manifestation of small and large-scale process in the solar dynamo
- Corrected SSN > small secular rise from last Maunder Minimum to 20th century
  - Limited range of secular trends in amplitudes of cycle-induced modulations
  - Variation in the clustering of high or low cycles (recurrence)

⇨ **Epochal step: first end-to-end revision of SSN since 1849 !**

Release in 2014

Sunspots remain the only long-term direct information on solar activity.

WDC – SILSO: international sunspot number data

http://sidc.be ("Sunspot" tab)

New dedicated Web site coming up soon (mid-2013)

WDC – SILSO Sunspot Index
and Long-term Solar Observations

SSN Workshop wiki *(incl. all PDF presentations)*

http://ssnworkshop.wikia.com/wiki/Home