The International Sunspot Index R_i

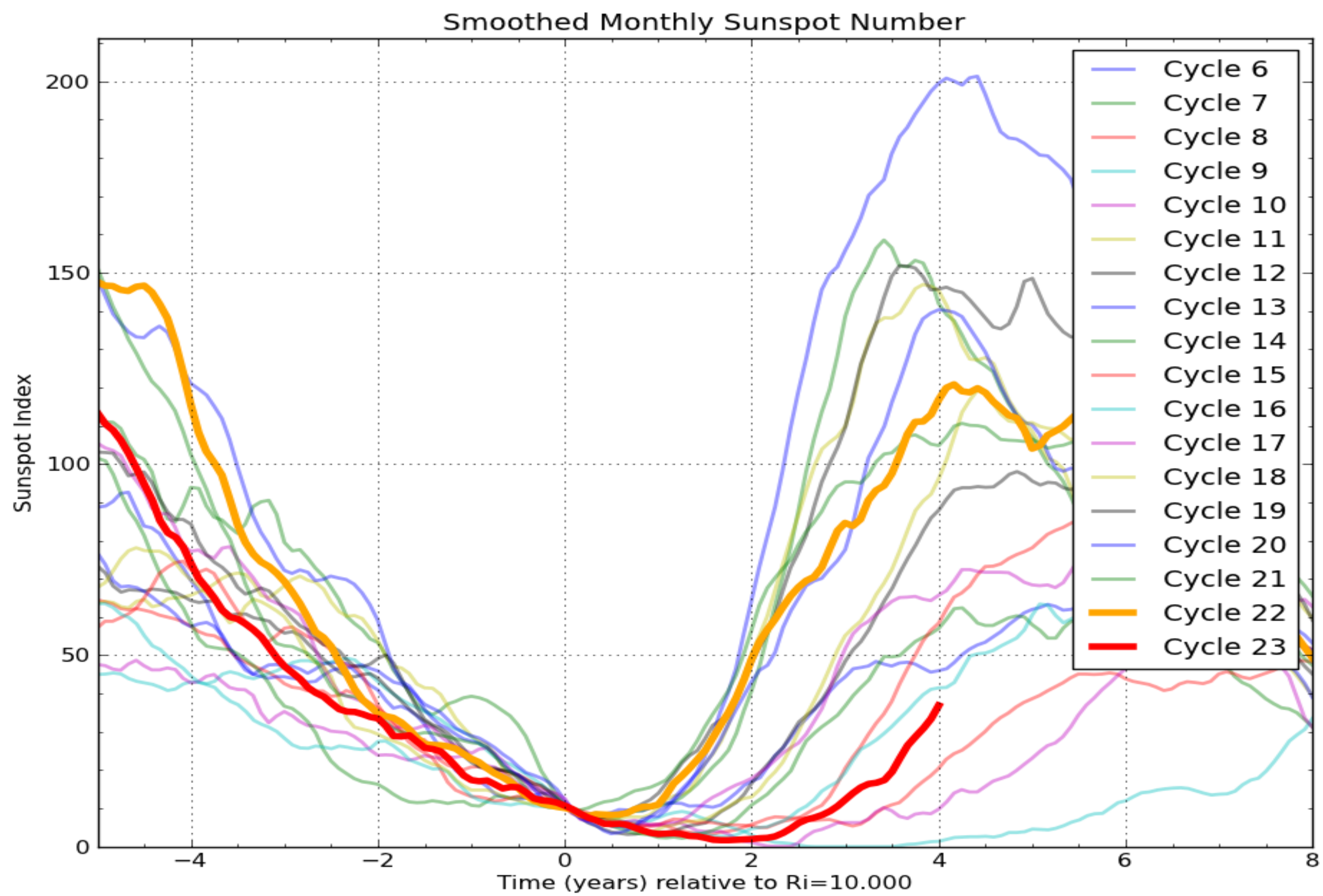
A perspective on the last 50 years

Frédéric Clette

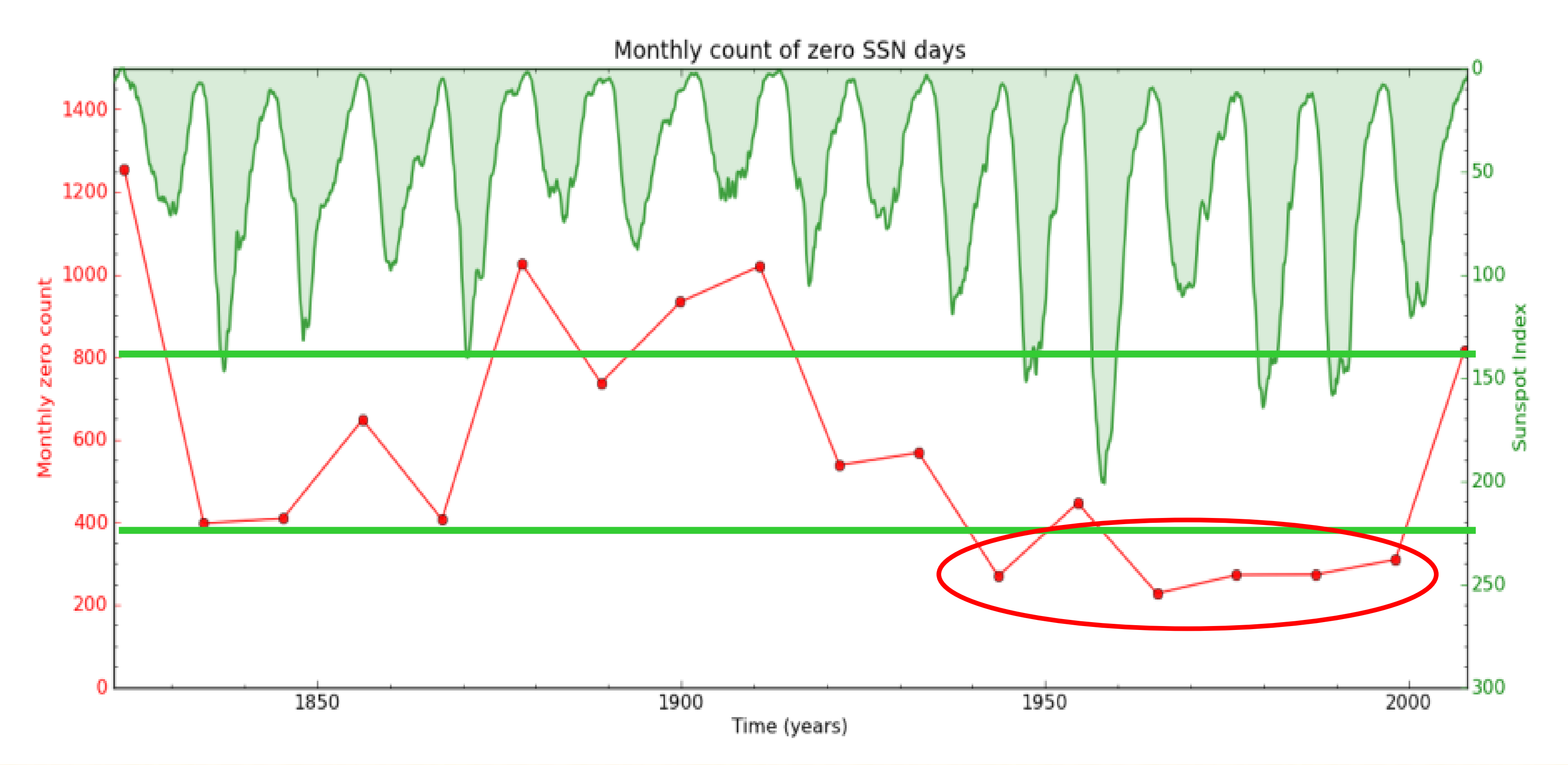
SIDC – WDS “Sunspot Index”

Royal Observatory of Belgium

Cycle 23-24 minimum: long but not extreme



4 short cycle minima (20 to23): unprecedented !



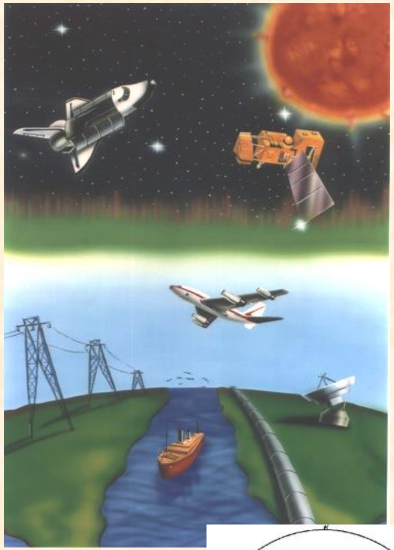
Need to put all recent data and models in a long-term perspective

Sunspot Number:
Primary long-term record of solar activity

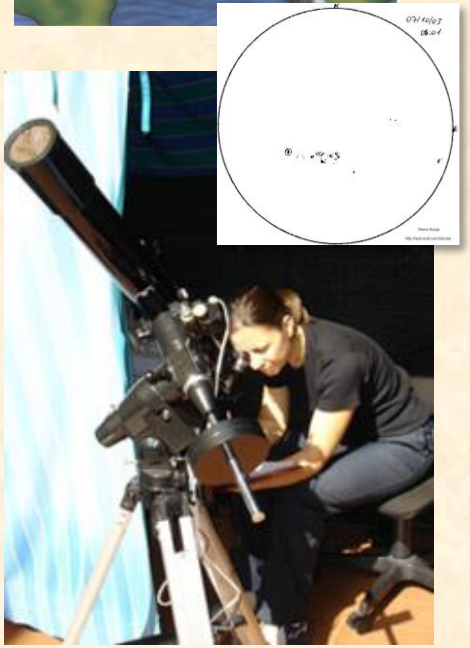
- Multiple uses
- History
- Processing method
- Relation with other indices
- Index anomaly in cycle 23
- Future prospects

R_i: The most widespread solar index

- **> 100 papers/year** based on the sunspot index
  (ADS search, abstract keyword: sunspot number, sunspot index)
- Over **160 000 Web pages** referring to the sunspot index *(Google search, 2012)*
- **Multiple domains of application**:
  - Solar physics
  - Technology (telecom, aviation, space, energy: pipelines, power grid)
  - Climatology
  - Unexpected "fancy" domains: medicine, pigeons, wine production
- **Importance for education and public outreach**:
  - Best way to communicate about solar activity
  - Everybody can observe sunspots
  - For many youngsters, start of a lifelong interest for astronomy.



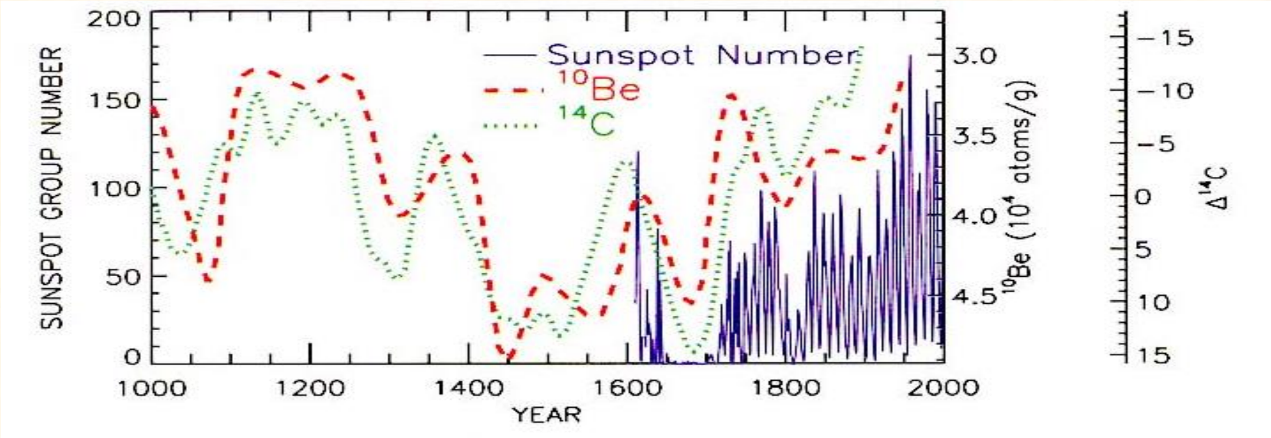
NASA



G. Araujo

A renewed importance

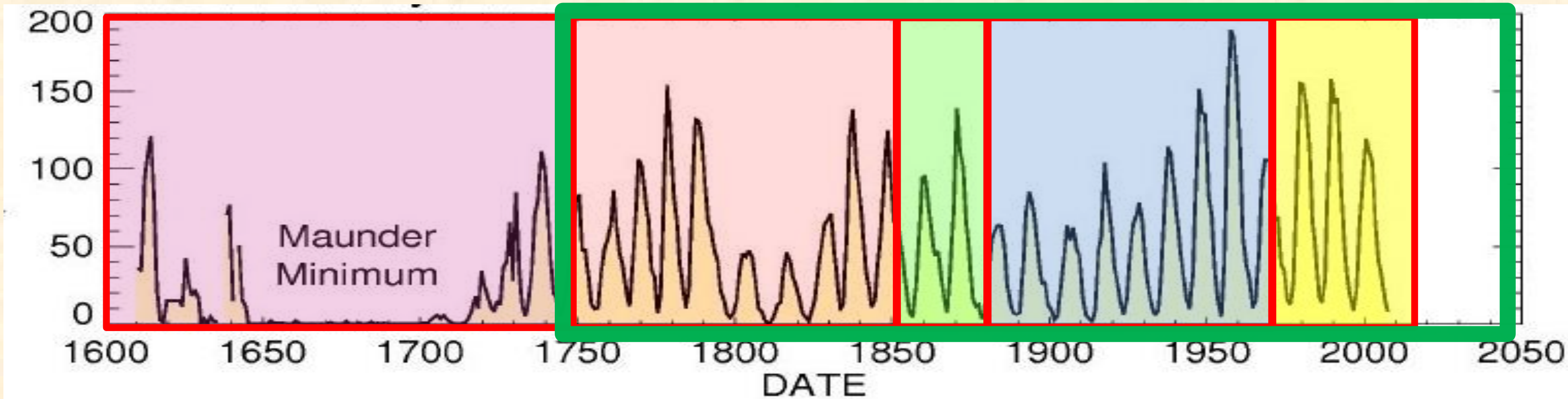
- Regained scientific interest and new importance:
  - **State-of-the-art dynamo models**, solar cycle forecast (main constraint)
  - **Earth climate studies** require multi-century validation of indirect secular proxies (cosmogenic isotopes)



Fröhlich & Lean 2004

- Input to operational space weather predictions and models:
  - Validation and extension of **reference proxies** over long durations (spectral irradiance, SEPs)
  - Assessment of **extreme space weather** (total range of possible activity): Grand Minima and Grand Maxima

The R_z-R_i history in 4 chapters



Historical

- Sparse data (monthly, yearly)
- Reconstructed
- Still topic of research
- Accuracy: ~25%

Galileo

H. Schwabe

R. Wolf (1852-1882)

- **Definition: Wolf number**
- **Primary station: Zürich**
- 10 to 20 auxiliary stations
- Daily values
- R: relative SSN
- Accuracy: < 15%

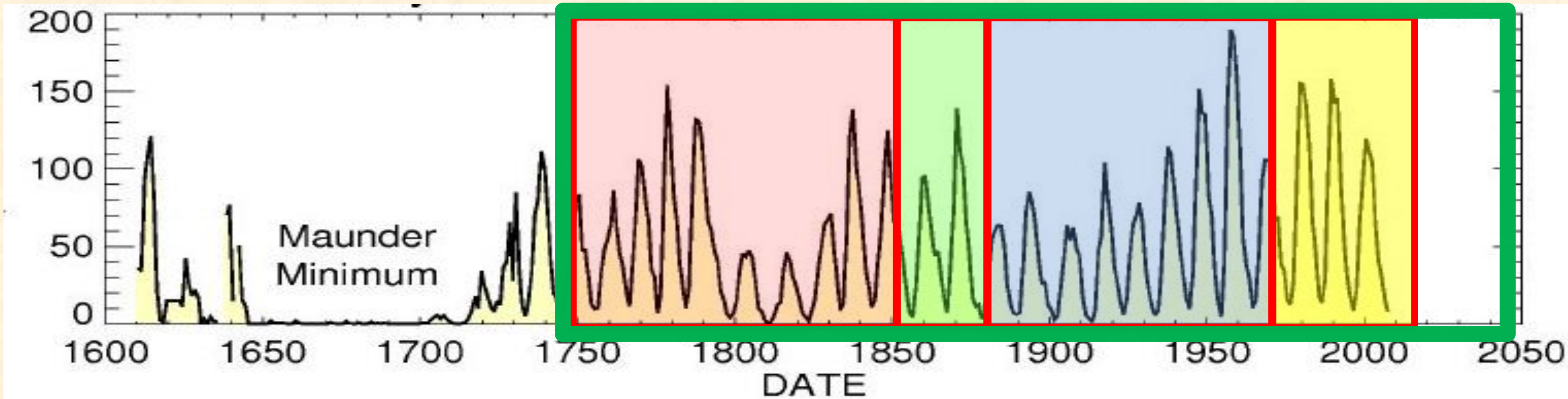
Zürich (1882-1980)

- new counting rules :
  - Small short-lived spots
  - Multiple umbrae
  - **Fixed factor: K=0.6**
- Accuracy: ~5%
- Since 1955, **2nd station: Locarno**

SIDC Brussels (since 1981)

- Extended WW network
- Computerized processing
- **Pilot station: Locarno**
- New products:
  - **Hemispheric SSN**
  - **12-month predictions**
  - **Daily estimated SSN (since 2005)**

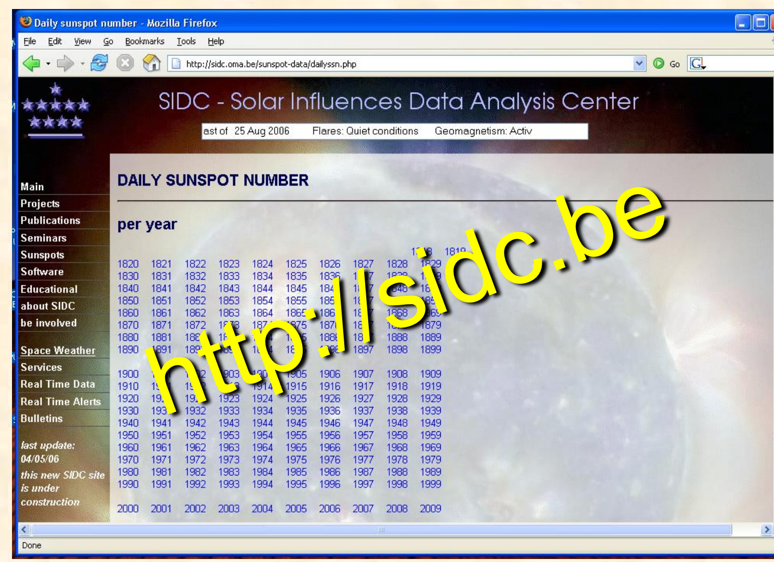
R_z-R_i: the whole series



- **Daily index**: 1818 – now
  (1818 – 1847: some gaps)
- **Monthly average**: 1749 - now
- **Yearly average**: 1700 – now
- **Monthly smoothed**: 1755 - now

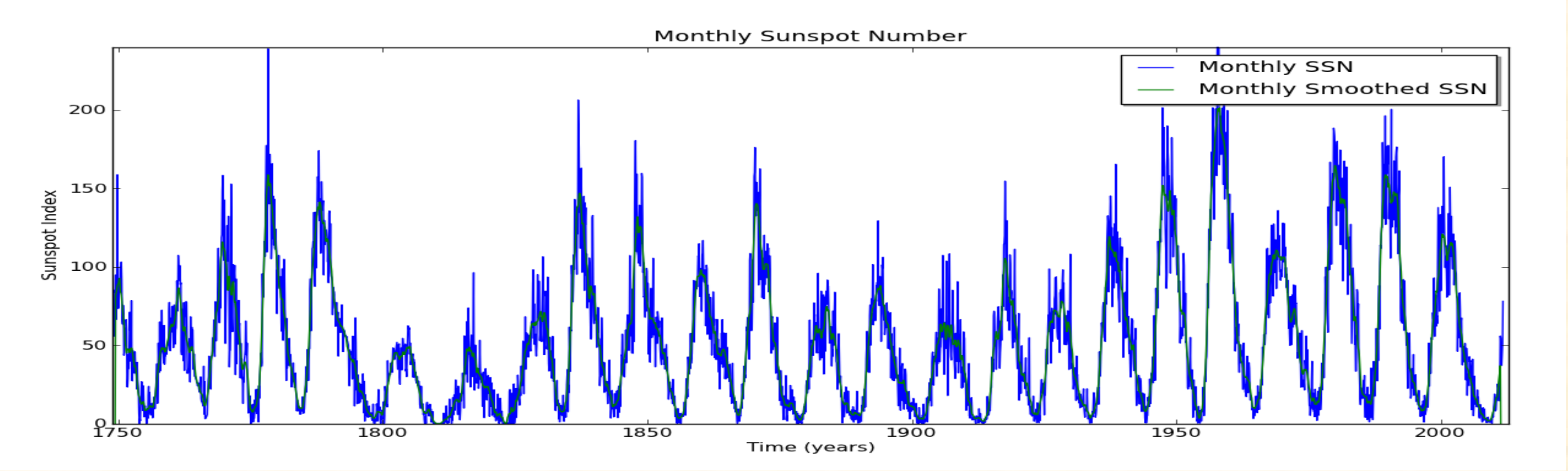
$$\overline{R_i} = \left(\frac{R_{-6}}{2} + \sum_{x=-5}^{+5} R_x + \frac{R_6}{2} \right) \Big/ 12$$

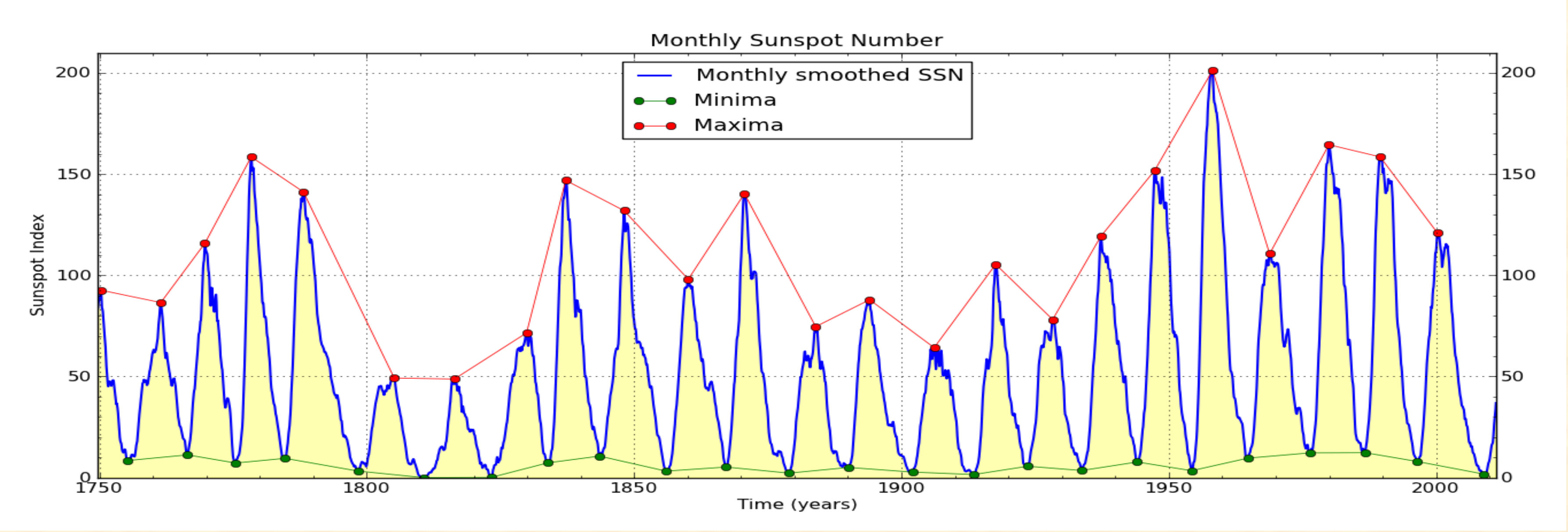
- **Hemispheric:** 1992 - now



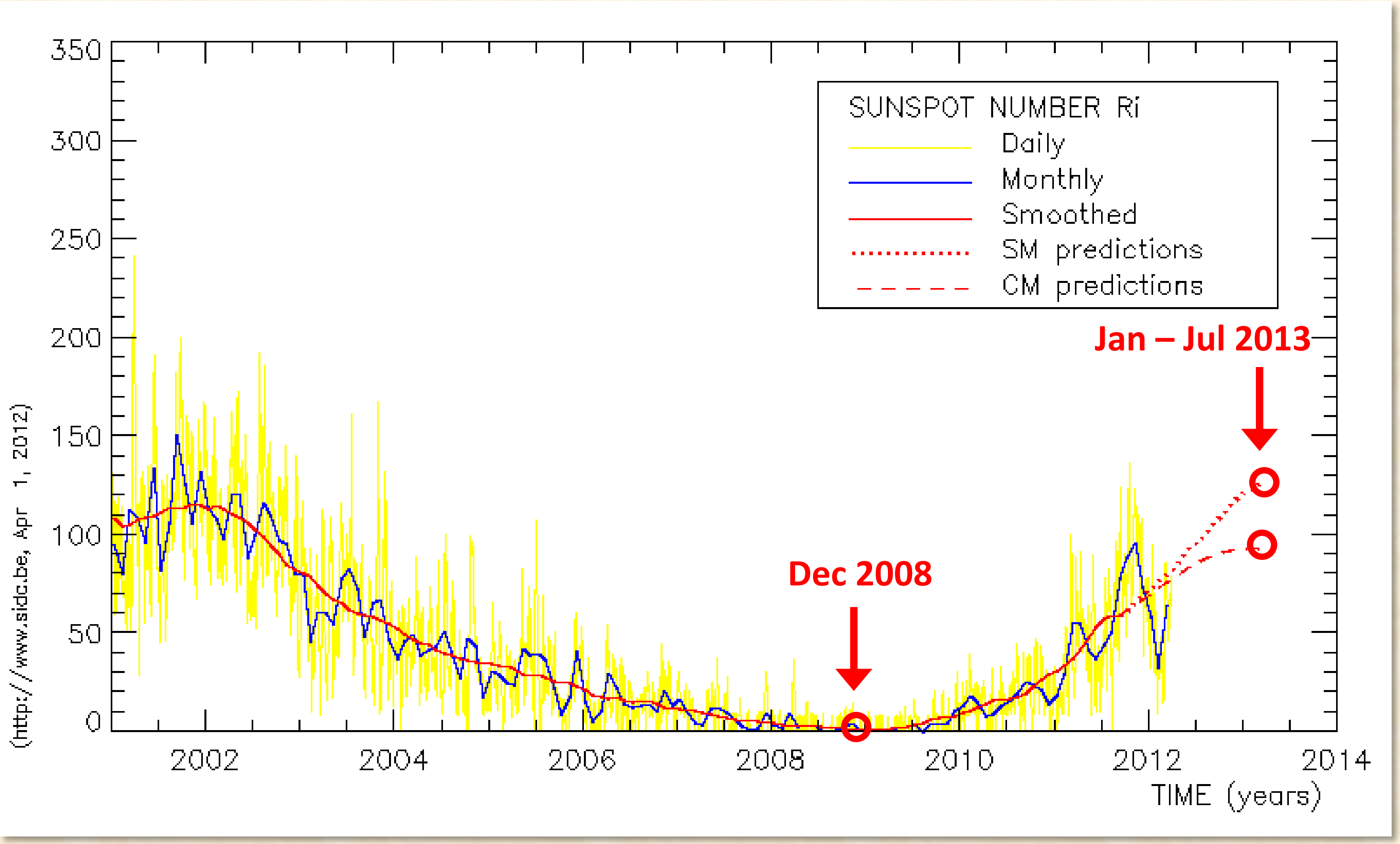
Mirrored at NOAA/NGDC

25 cycles: monthly values and extrema



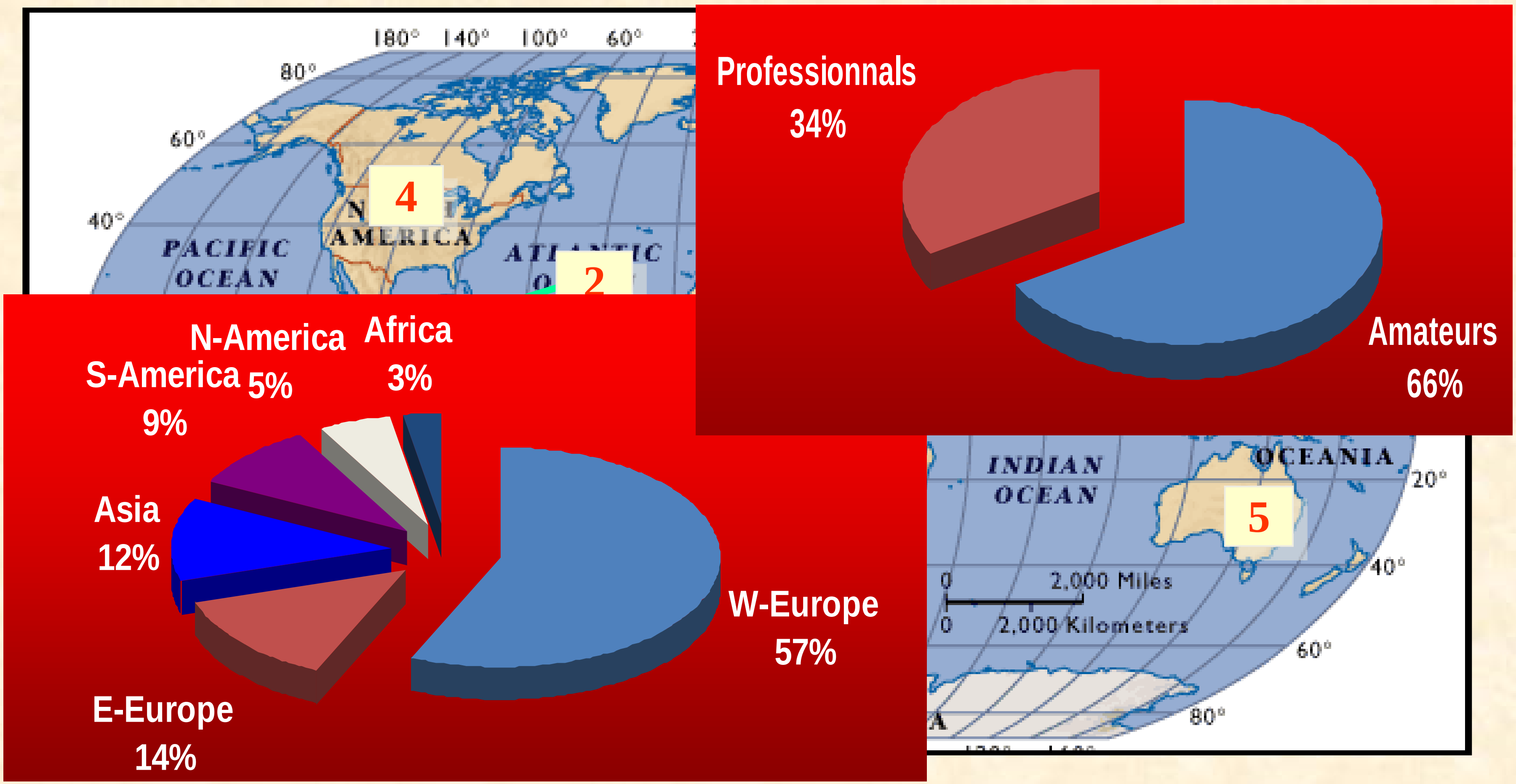


The last 11 years and forecasts

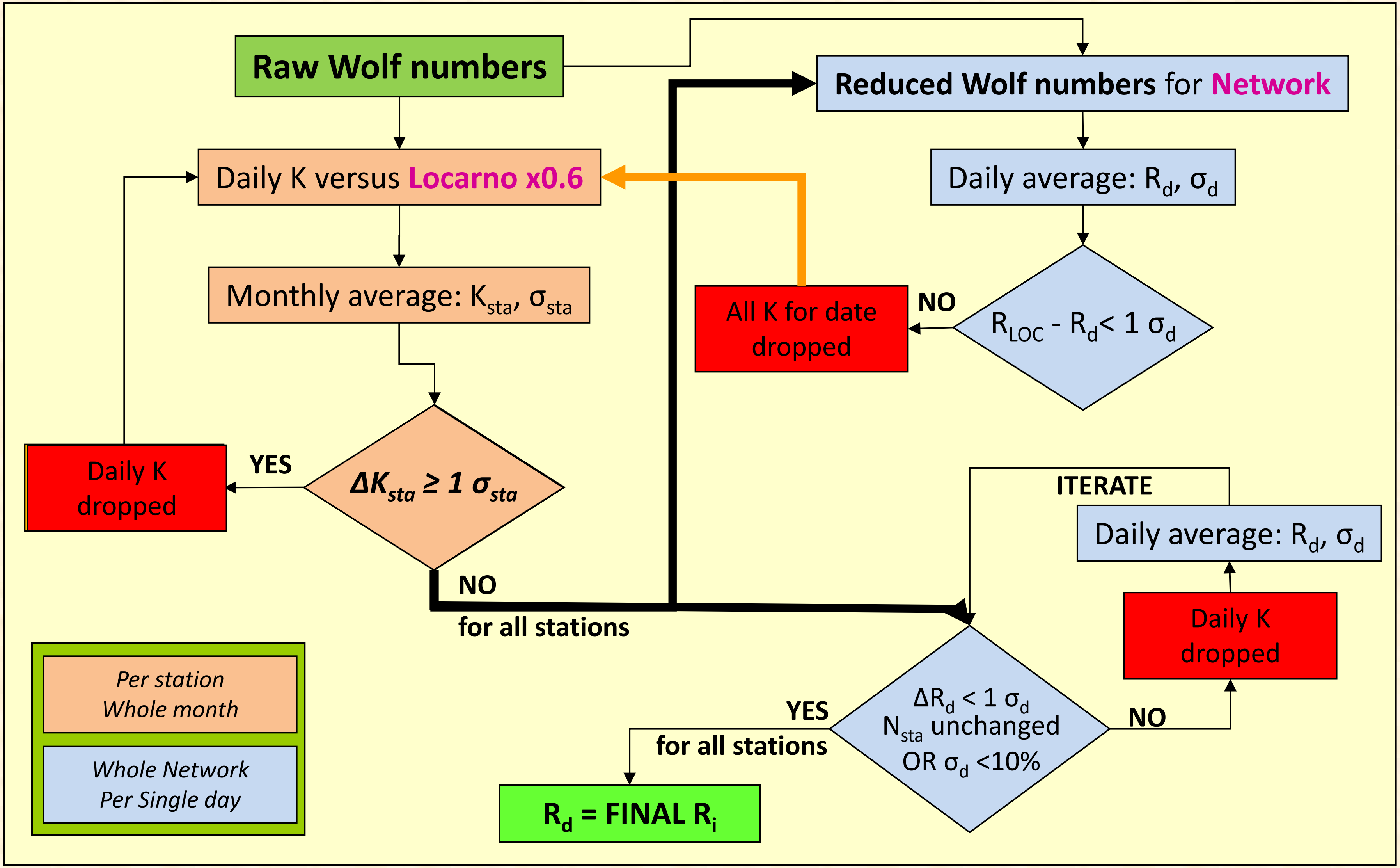


The SIDC worldwide network

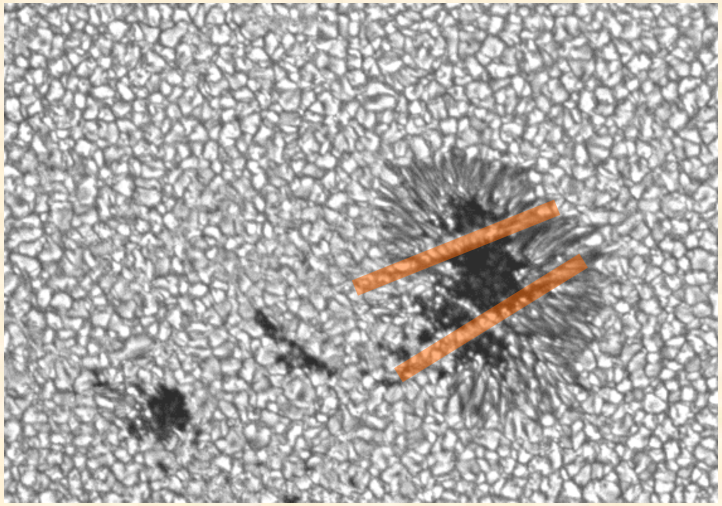
- About 86 stations in 29 countries.
  - Still highly concentrated around Europe
  - Low participation in N-America (AAVSO)



R_i processing flowchart



The R_i human factor: statistical treatment



- Human factors for individual observers:
  - – **Visibility of the smallest spots (sky quality)**
  - – **Splitting of large complex groups**
  - – **Splitting of multiple umbrae in common penumbra**
- **Random "noise"** (timescales < 1 month):
- **Systematic personal differences** (timescales > 1 month)

➡ **Tracked by K coefficient system:**

- Uncorrelated differences between many independent observers

- **Remaining causes of global scaling biases:**
  - **Stability of the processing method:**
    - Problem common to all indices !
  - **Stability of the pilot station:**
    - Internal tests and monitoring

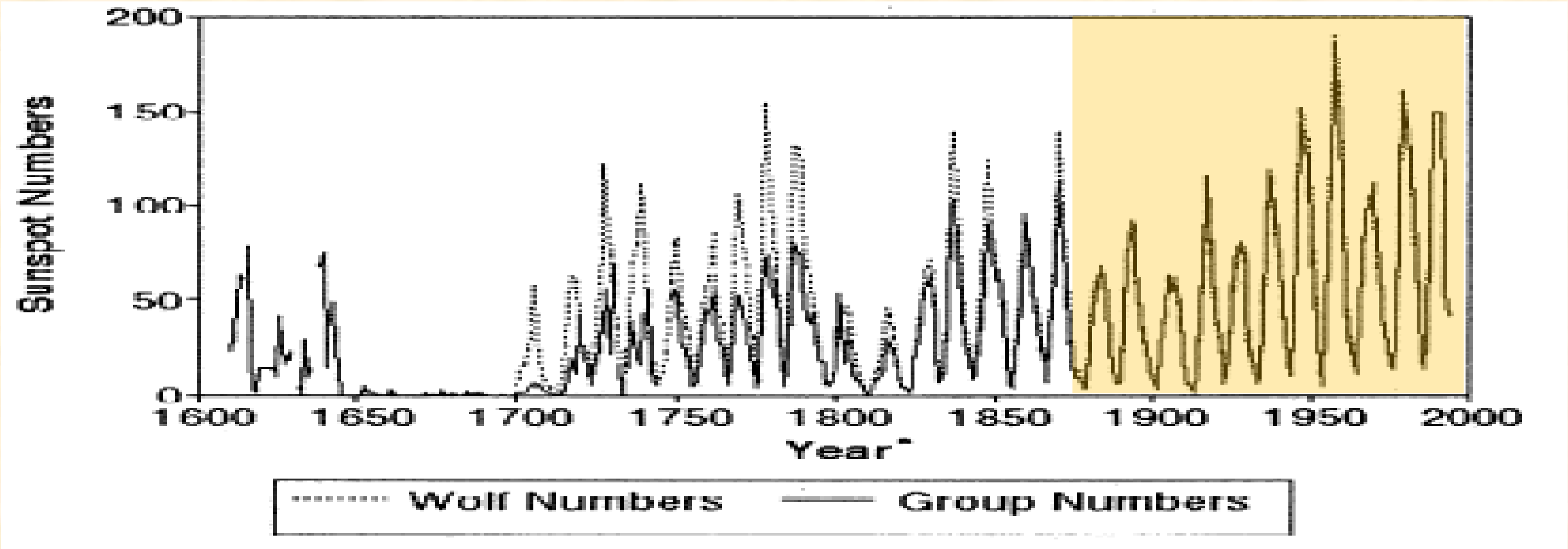
R_G: Group sunspot number

(Hoyt & Schatten, 1998)

- Only group counts
- **Assumption: on average, always the same average number of spots per group**

$$R_G = \frac{1}{N}\sum_{i=1}^{N} k_i 12.08\, g_i$$

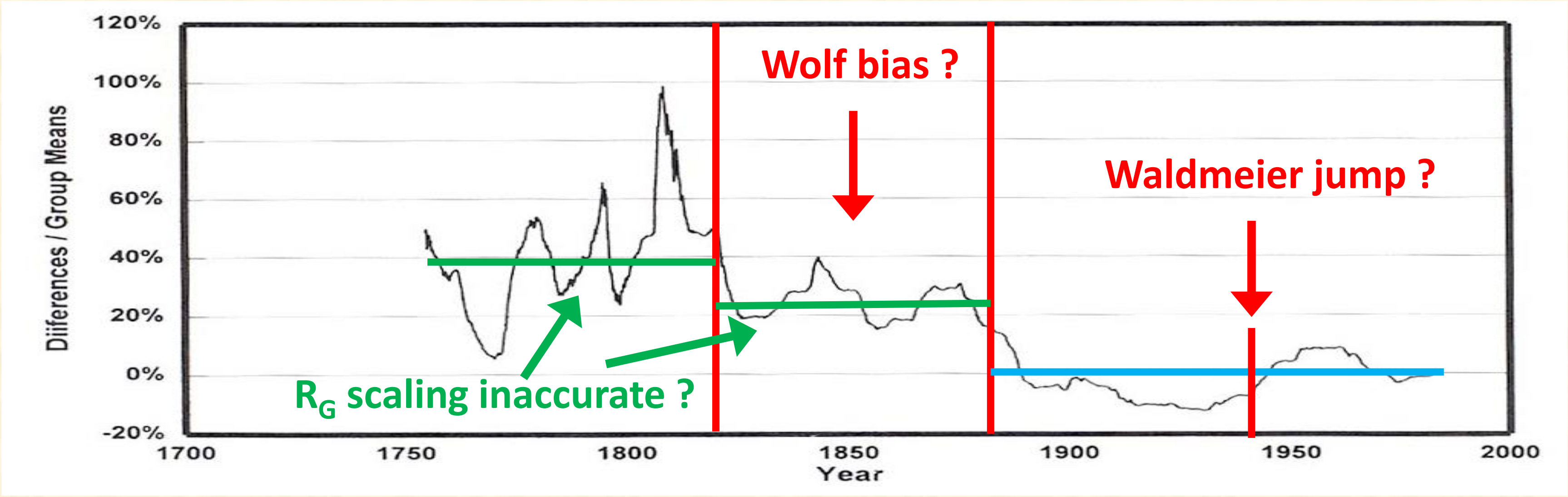
- Reference: RGO photographic catalog (1874-1976)
- After ~1880: R_i and R_G agree within ~5% rms



R_G: Group sunspot number

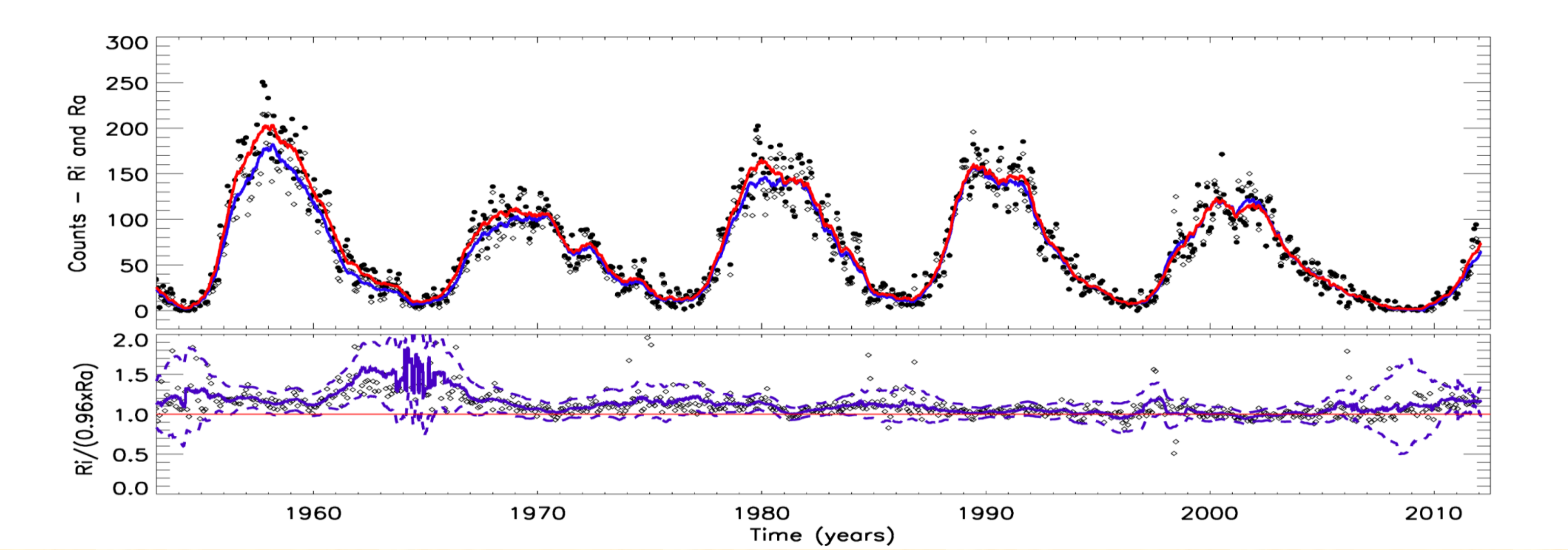
- **Wolf numbers about 25% higher than R_G before ~1880**
  - Raw R_Z values adjusted according to magnetic needle readings
  - R_G based on chained backward extrapolation of K personal coefficients.
- Jump around 1945: sunspot weighting according to size introduced at that time ? (Waldmeier)

➡ **Topic of SSN Workshop series** (NSO, Sept. 2011; ROB, May 2012)



The American sunspot index R_A

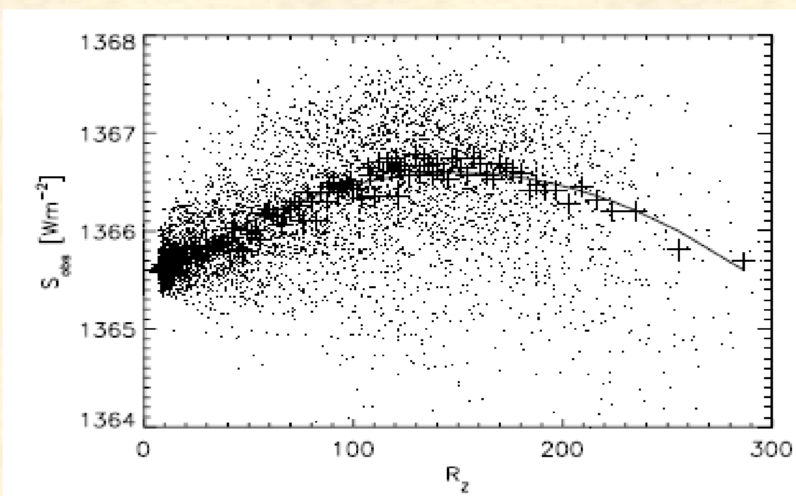
- Since 1944, produced by the **AAVSO** (A.H.Shapley, 1949).
- Network and processing completely independent from the international index R_i
- **Before 1990, discrepancies due to processing flaws in R_A**
  (Hossfield 2001)
- Currently: R_A-R_i **correlation coefficient = 0.983, no trend**
  (*Coffey et al. 1999)*

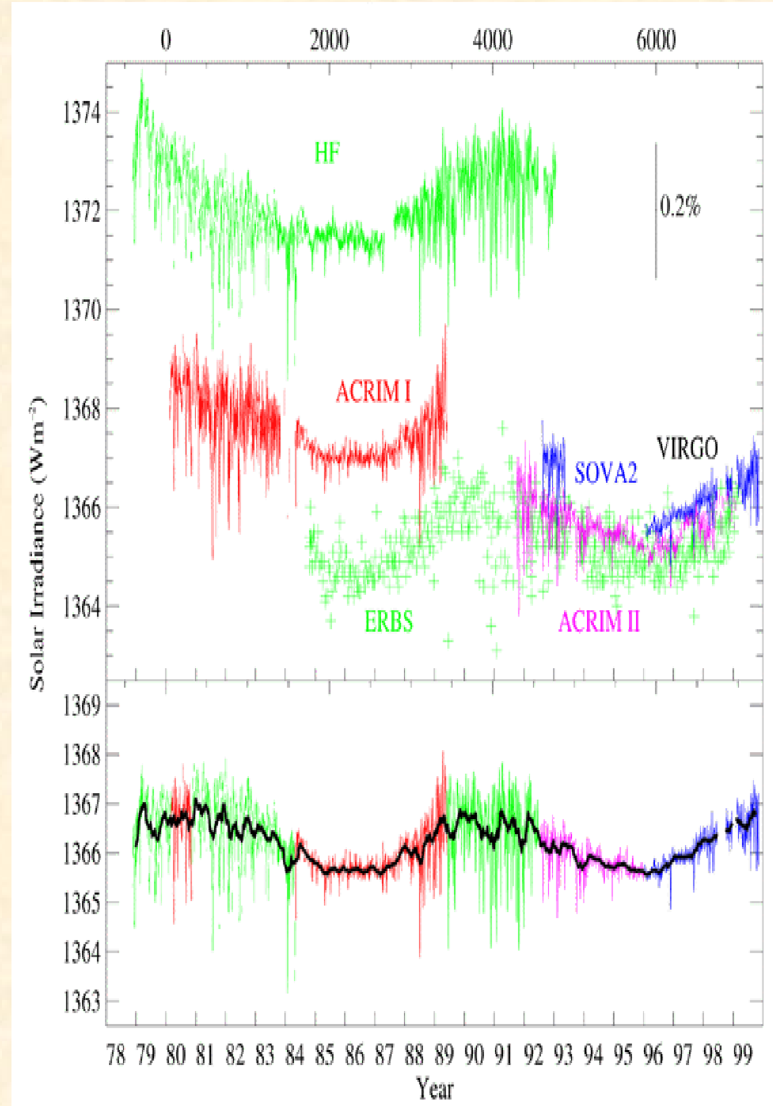


Total Solar Irradiance

- 0.96 linear correlation *(Wang,Y-M. et al. 2005)*
- Accuracy issues:
  - Disagreements between different radiometers: 0.6% (instrument models)
  - **4 x the solar cycle amplitude** (0.15%) !
- **Non-linear relation for R_i > 150**
  (Solanki & Fligge 1999)

  Other non-sunspot contributions (faculae, near-UV plages)

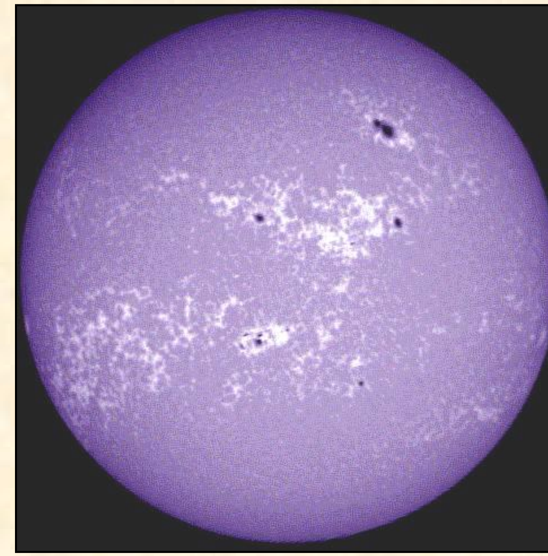




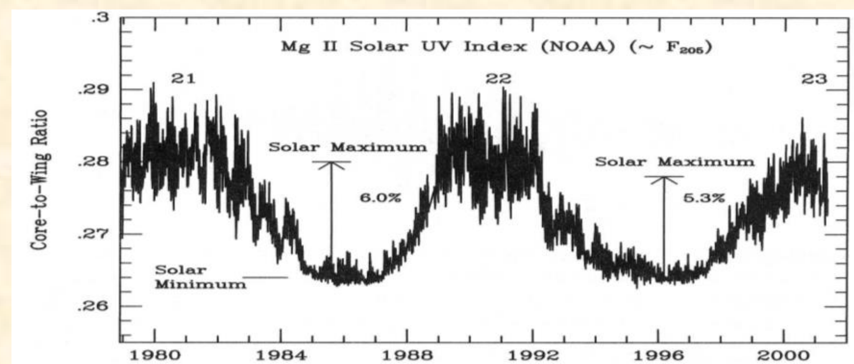
Complementary indices

- **R_i closely related to magnetic flux emergence**:
  - High threshold on magnetic field (> 1500 G)
  - Spots disappear early in the magnetic decay of an active region

- **Chromospheric and coronal indices (F10.7, CaII, MgII) contain a strong contribution from weak decaying fields** (flux dispersion): plages, faculae, ephemeral regions, quiet Sun/ coronal hole relative area.
  - **Non-linear relation**
  - **Time delays versus R_i**



CaII K, Kitt Peak Obs.



Mg II

➡ Discrepancies do not mean disagreements and flaws !

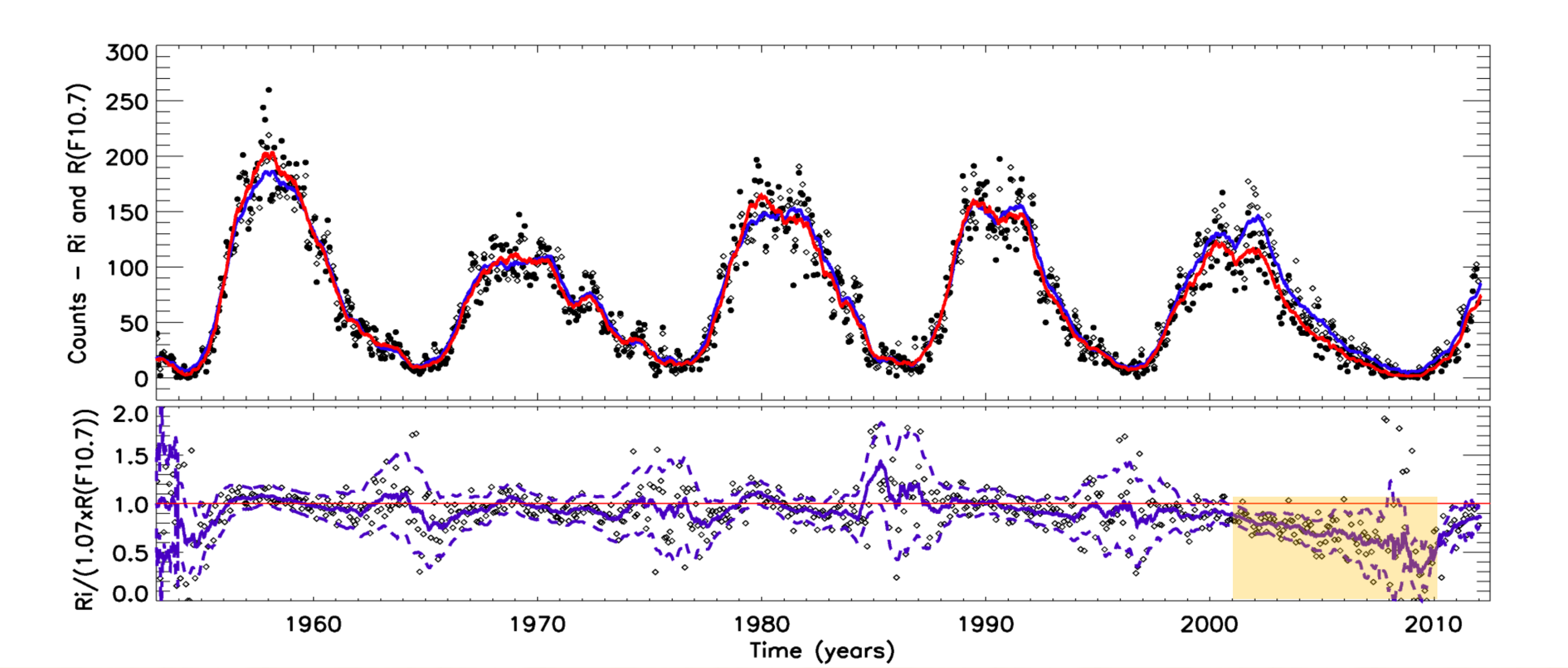
Index differences = solar information

A recent R_i – $F_{10.7}$ disagreement

- 1950 – 2000: stable quasi-linear relation
  (Lin. Corr.=0.98)

R_i= 1.14 $F_{10.7}$ – 73.21
(Tapping, K.F. 1999)

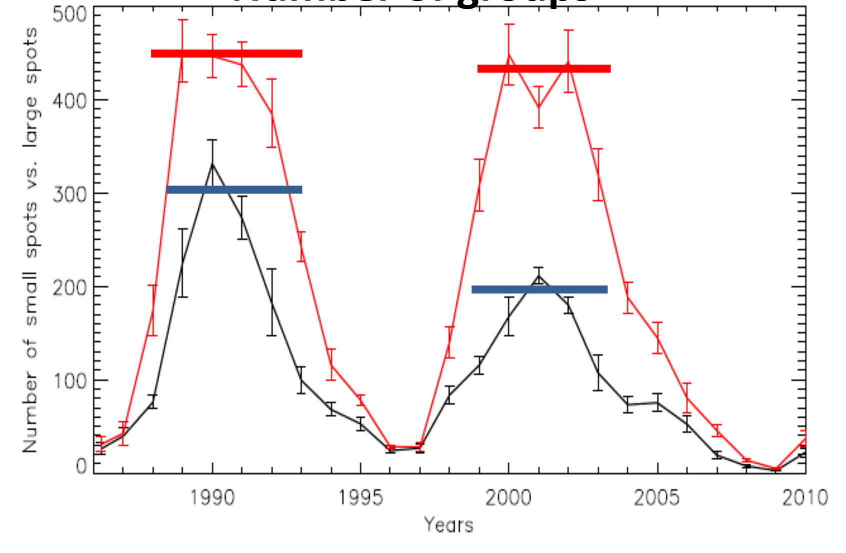
- Since 2000: **R_i ~15% below its $F_{10.7}$ proxy** *(Svalgaard & Hudson 2010, Lukianova & Mursula 2011)* (+ other chromospheric indices)



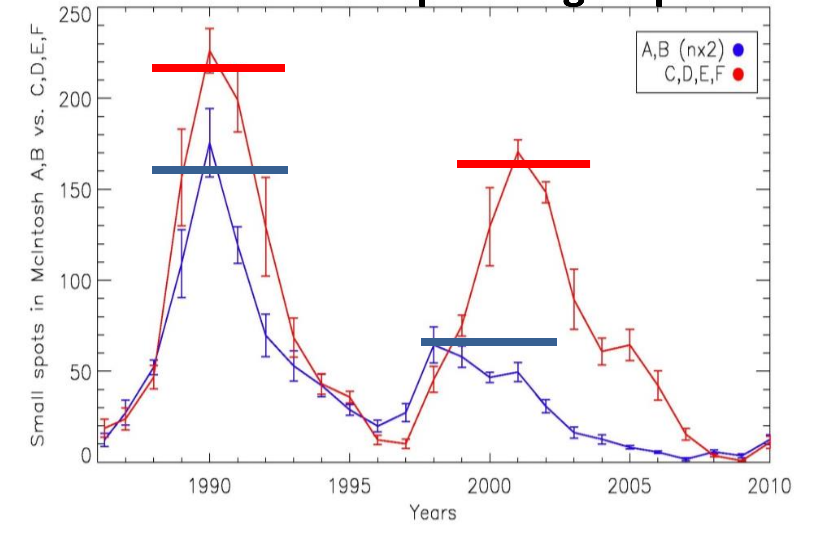
A scale-dependant sunspot deficit

- Study based on 2 detailed sunspot catalogs (DPD, NSO/SOON)
  - Small A & B type groups: deficit by factor 2-3
    (Lefèvre & Clette 2011, Kilcik et al. 2011)
  - Small spots in all groups: deficit by factor 1.4 (large groups) to 3 (small groups)

Number of groups



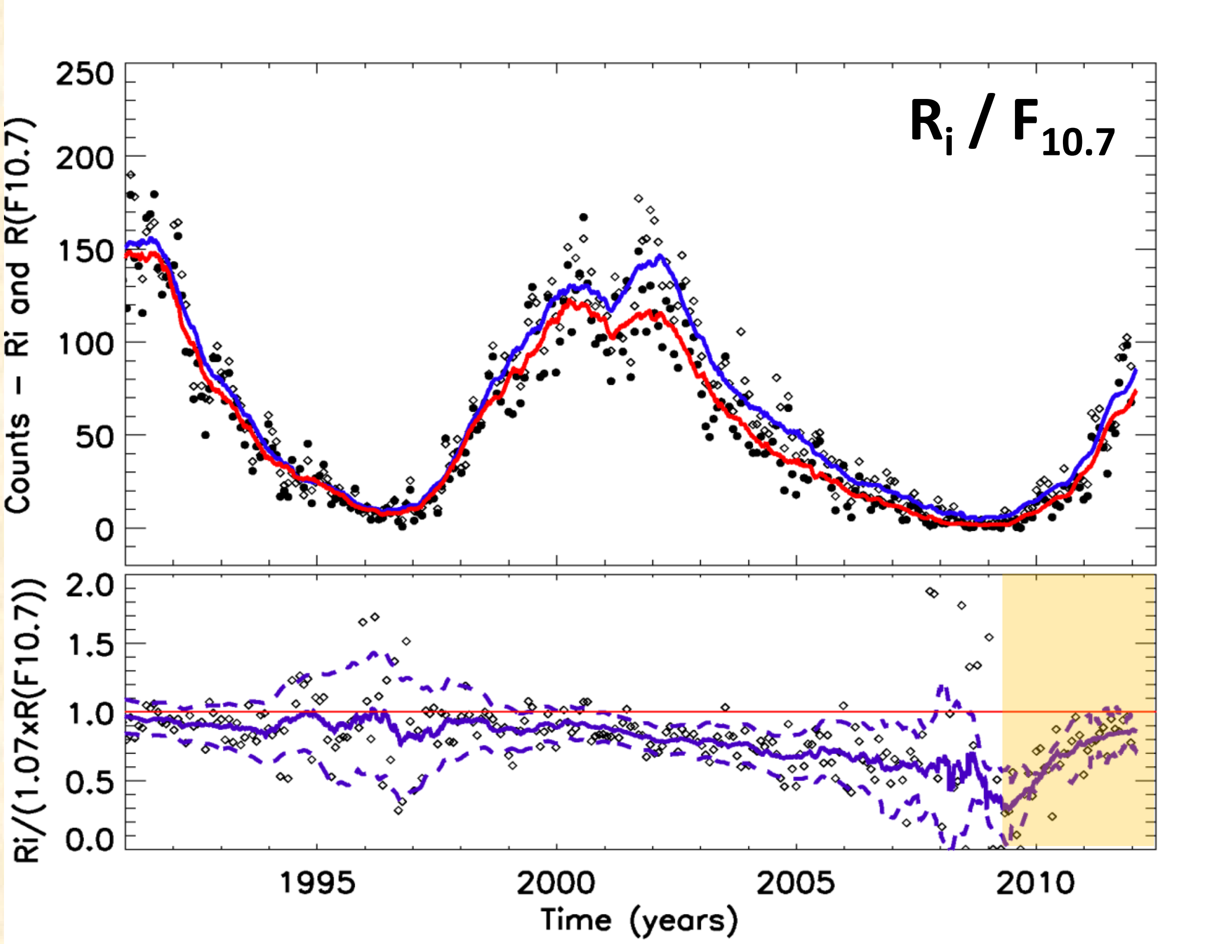
Number of spots in groups



- Possible connection with the **parallel decline of the average core field in sunspots** *(Penn & Livingston 2010)*

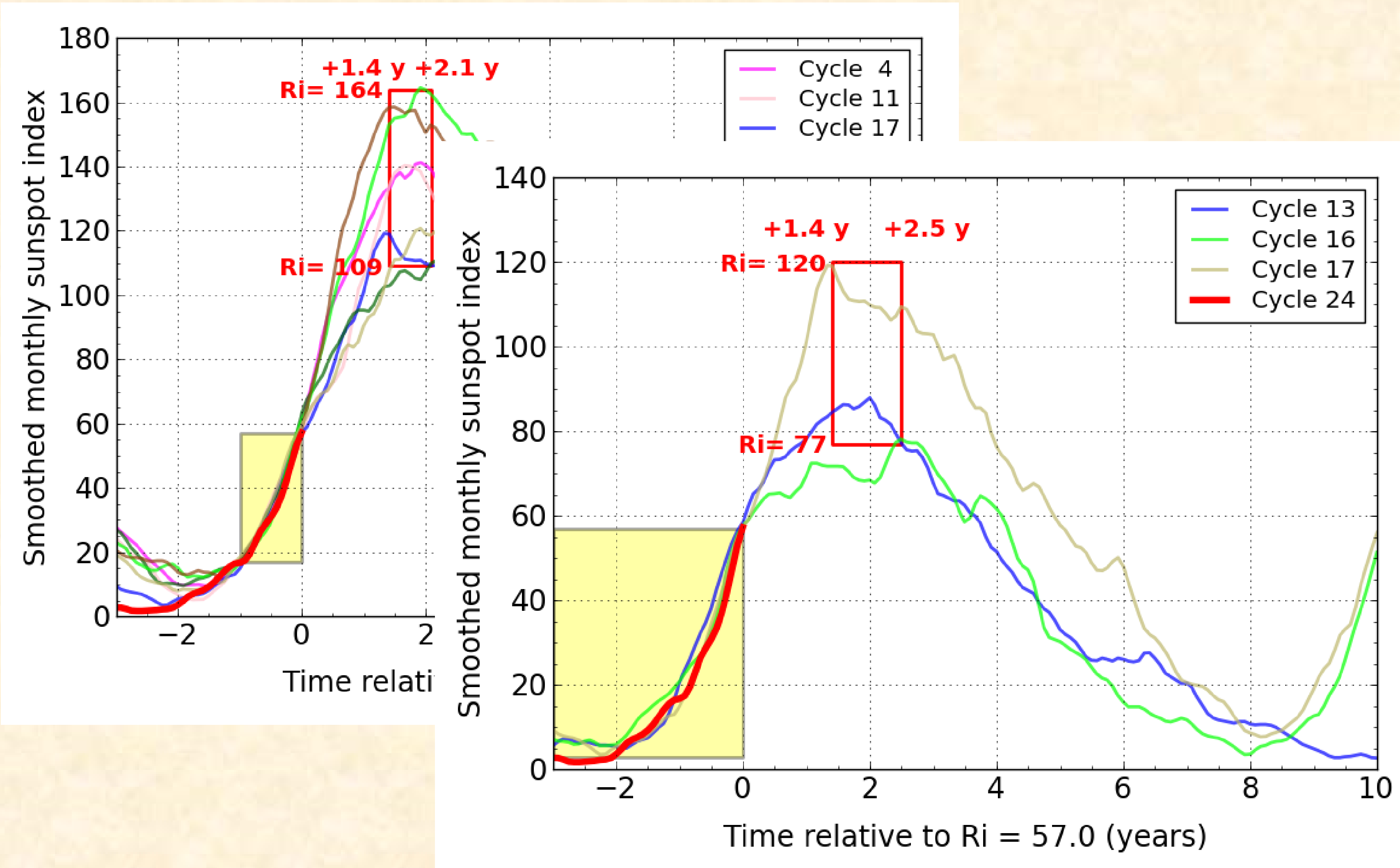
Cycle 24: a return to normal ?

- R_i index :
  - Uniform sunspot weighting
  - **Significant contribution from smalls spots**
- Other indices and fluxes:
  - Dominated by large magnetic structures
  - **“Blind” to small-scale changes**
- Implications for dynamo models:
  - **Second sub-surface dynamo ?**



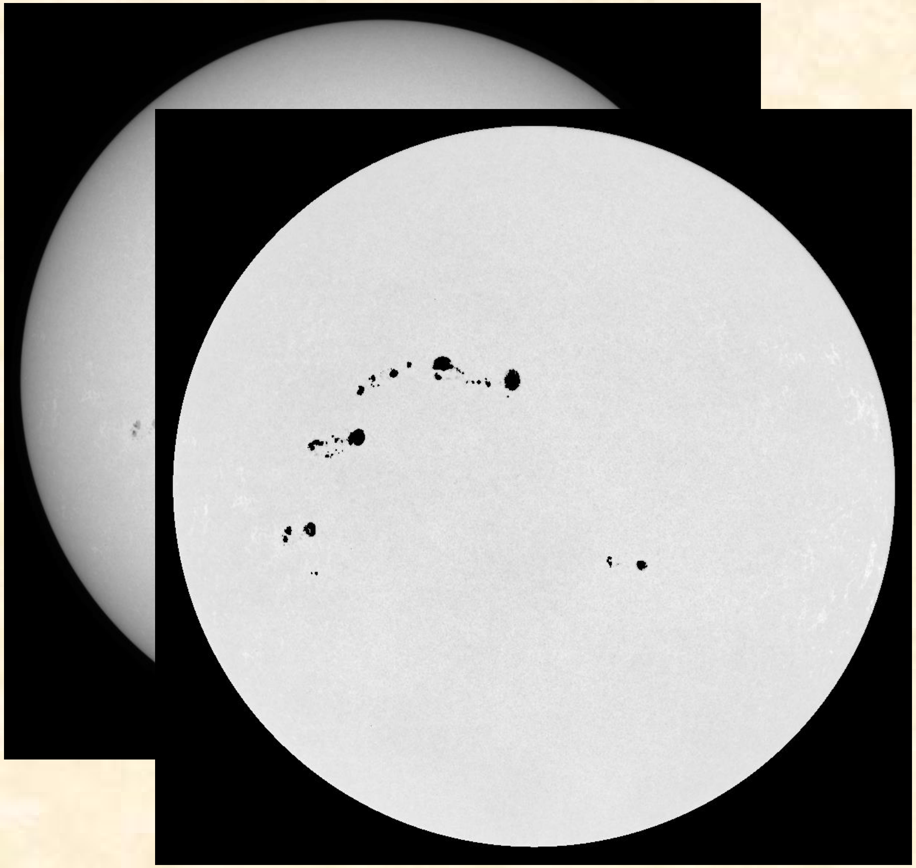
Since 2010, return to pre-2000 values

Cycle 24: what the SSN tells us …



The future: looking ahead

- An **image-based index** (CCD, ground-based and space)
- Feature extraction (image segmentation)
- Currently in development:
  - SIDC, Belgium
  - Kanzelhöhe, Austria
  - Coimbra-UNINOVA, Portugal
  - OSPAN/ISOON, USA
  - Bradford, UK
- Different properties:
  - detectability of smallest spots
  - sunspot grouping



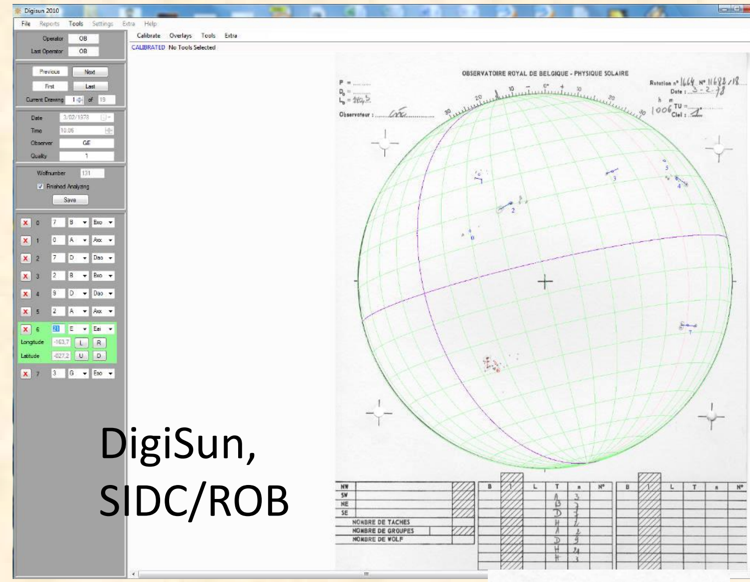
(Zharkova et al. EGSO, 2003)

➡ Different parallel indices **= R_i proxy** (or even multiple targeted proxies)

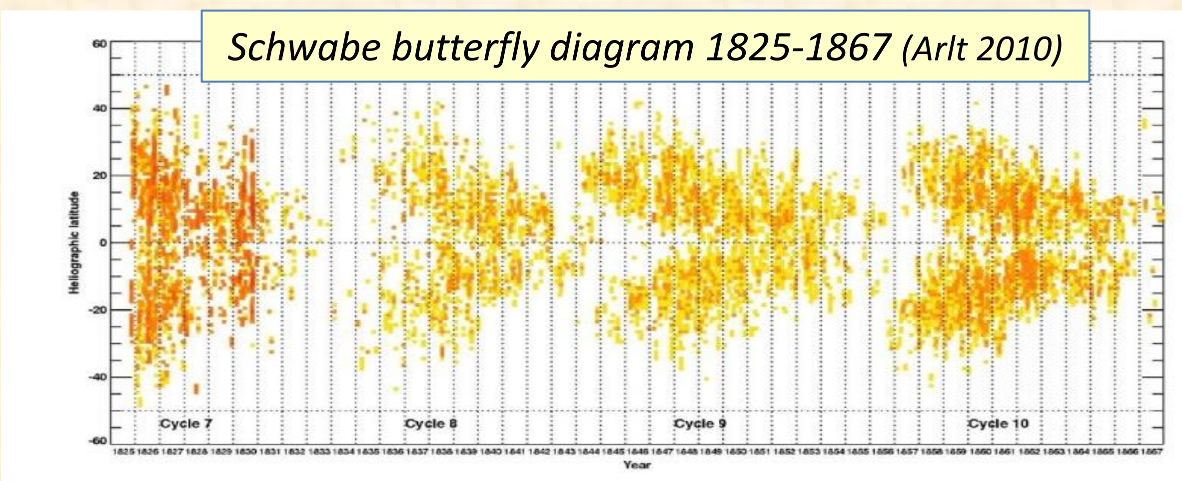
➡ ***If purely sunspot-based : link to distant past***

The future: looking back

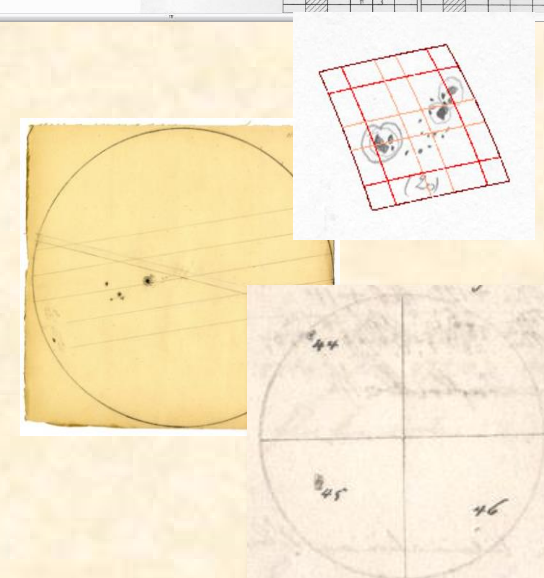
- **Exploitation of historical sunspot drawings**:
  - Digitization
  - Measurements >> catalogs, databases
- 1-D scalar information expanded to:
  - Count, area, position, morphology, dipole size & orientation, evolution, growth, decay, rotation rate, global distributions in latitude and longitude.
- **New long-term <u>direct</u> proxies** by multiple sunspot parameter combinations



DigiSun, SIDC/ROB

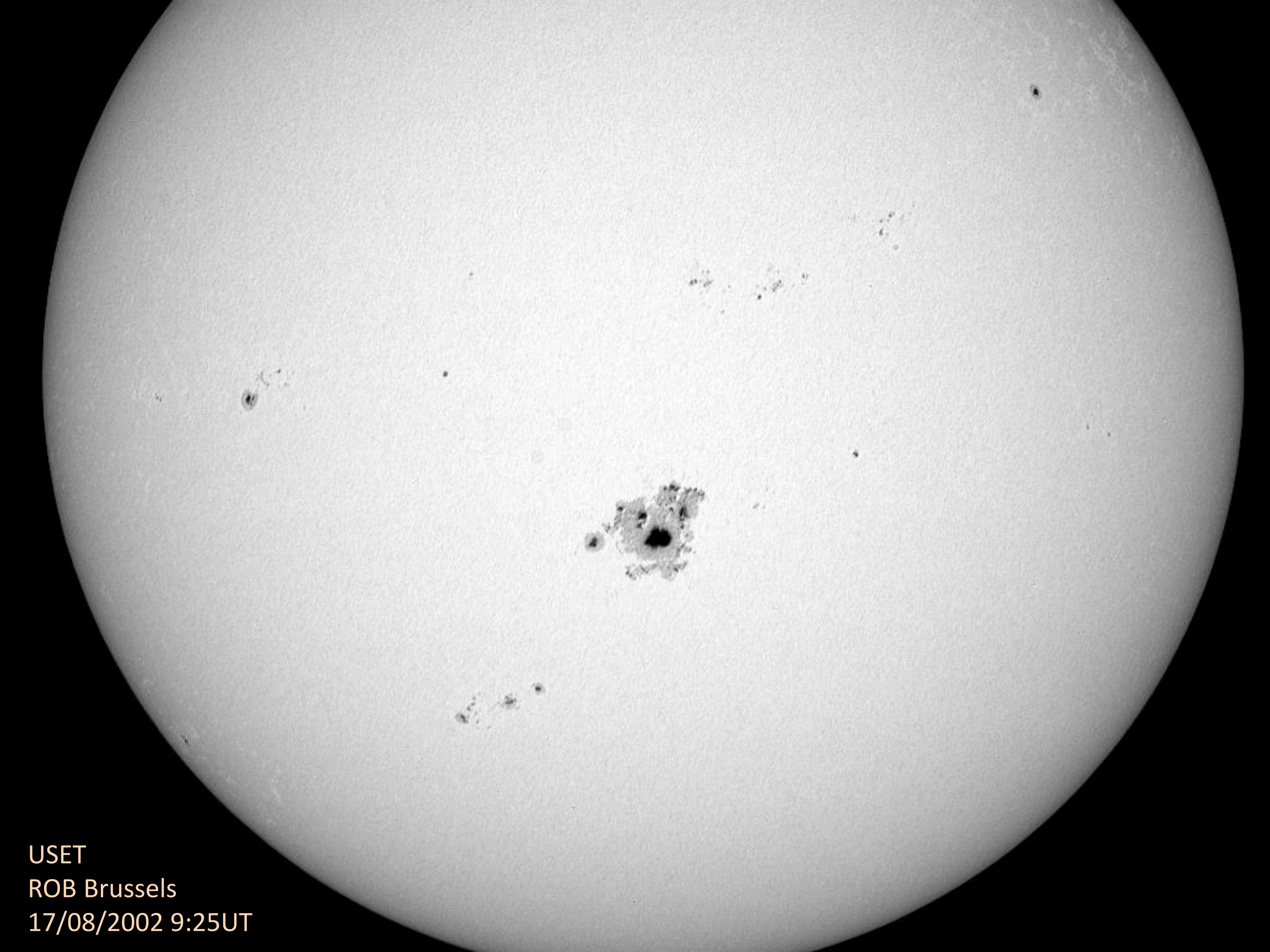


Schwabe butterfly diagram 1825-1867 (Arlt 2010)



Conclusions

- R_i remains a **key tool for all solar cycle studies**
- R_i: **"best ambassador" for communicating about solar activity**
- R_i nowadays at SIDC: **a mature index**
  - Fully standardized processing
  - Upgraded with new tools and methods (database, quality control)
  - Introduction of new products (user demands)
- **Some remaining issues in the early part of the R_Z series**:
  - New ongoing efforts (geomagnetic, cosmogenic proxies): SSN workshops
- Future prospects: **Awareness of the potential is still missing**:
  - New investments required to go beyond the simple SSN heritage
  - **Low-cost science vs unique return** but require long-duration support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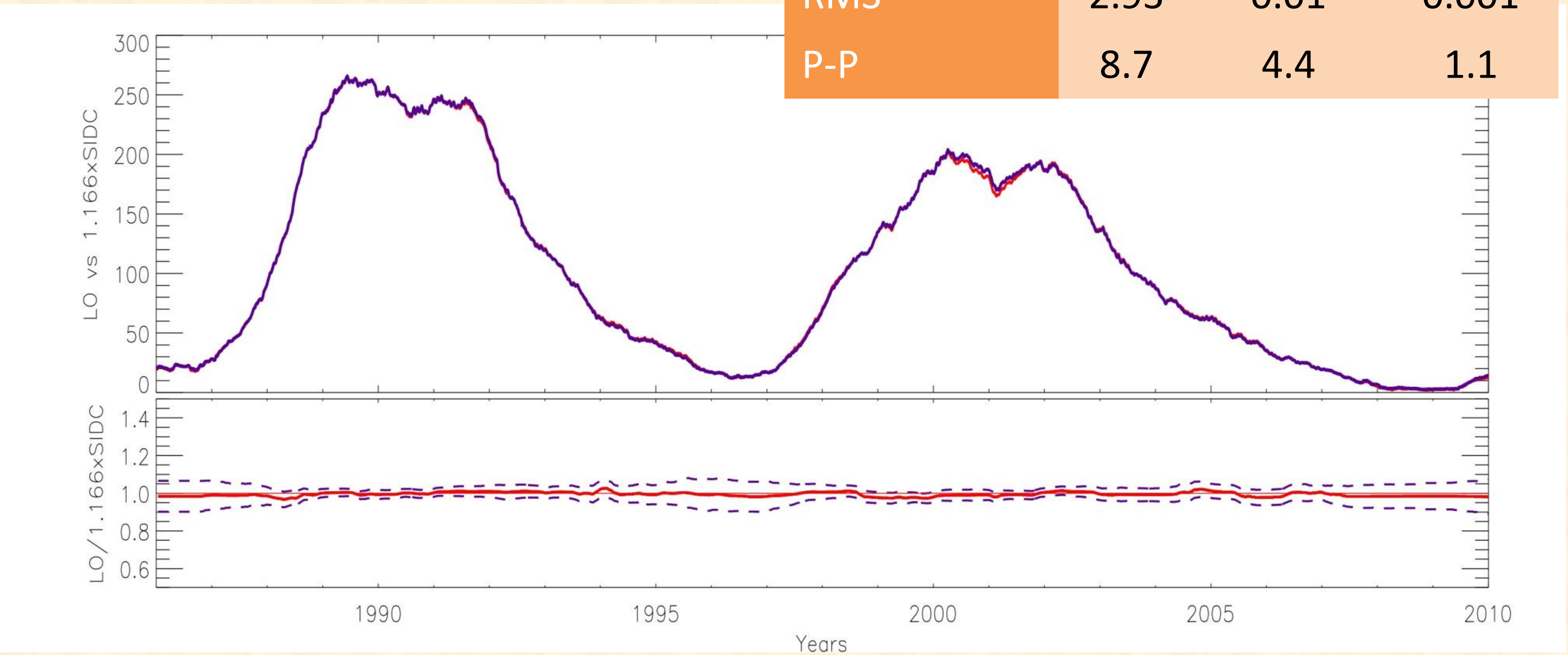
The R_i pilot station: Specola Solare in Locarno

- **"Specola Solare Ticinese"** station at Locarno Monti (Altitude: 370 m)
- Instrument: **Zeiss coudé refractor**: D=15cm, F=2.25m
- Main observer: **Sergio Cortesi** since 1955 … still observing!

The key role of the Locarno station

- R_i has accurately tracked the Locarno pilot station
- Trends fully removed for timescales > 1 month

Dispersion %	Daily	Monthly	Yearly
RMS	2.93	0.01	0.001
P-P	8.7	4.4	1.1



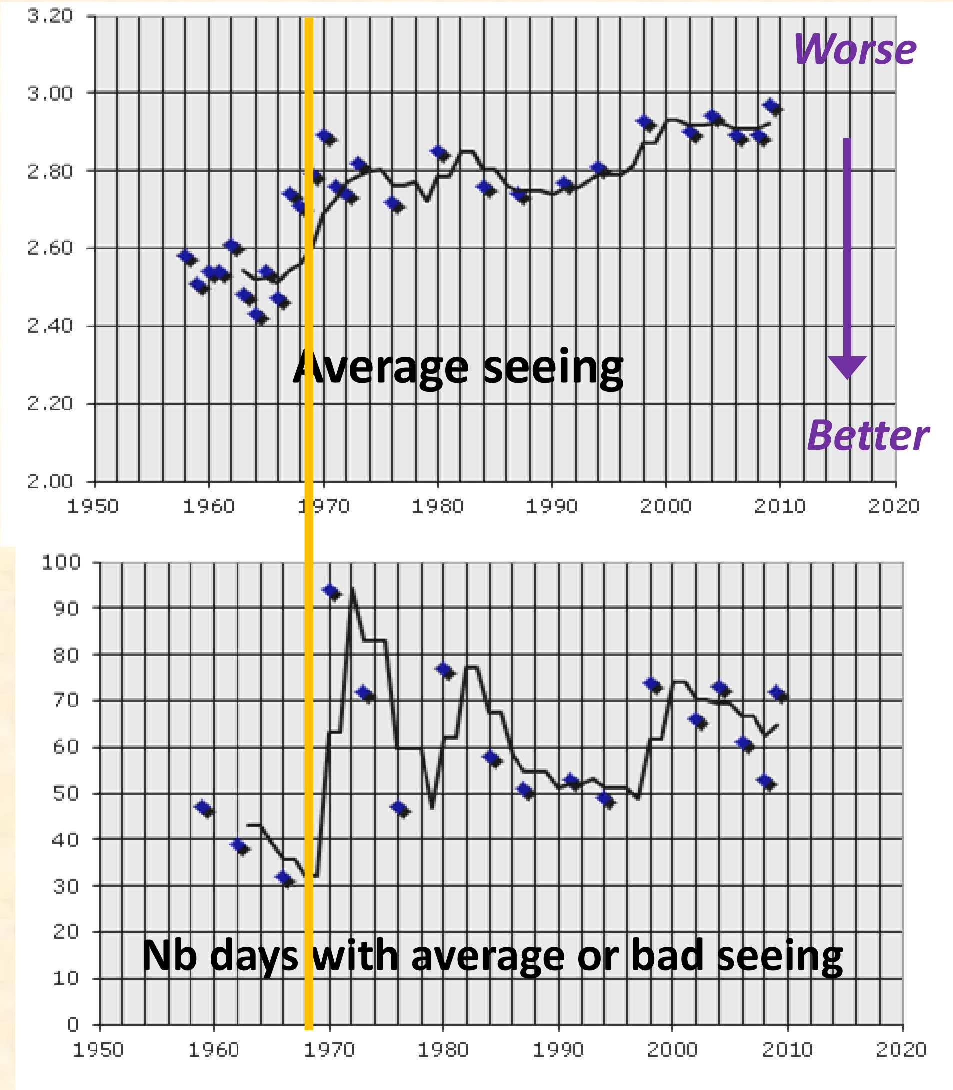
→ R_i and $W_{Locarno}$ are almost equivalent

Internal Locarno diagnostics

- **R_i = absolute index (cf. TSI)**

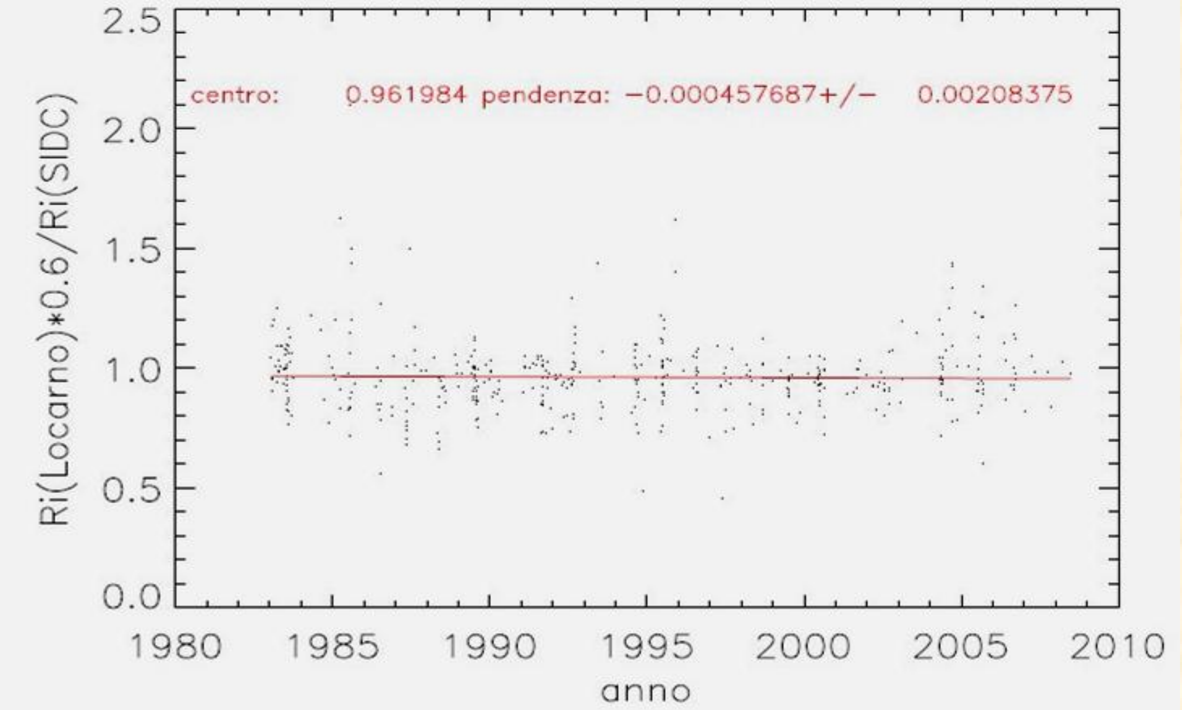
Validation rests primarily on the understanding and validation of the different elements involved in the measurements

- **No change in the instrument** (instrument transformation and component ageing)
- **Limited degradation in the observing conditions (seeing):**
  - One step around 1970 (new construction next to the observatory
  - 2.5 to 2.9 (scale: 0 -5)



Internal Locarno diagnostics

- **Evolution of the observer** (S. Cortesi: 90% of all observations)**:**
  - No health or eyesight problems.
  - Tracking of internal **K coefficient of 4 alternate observers:**
    - **No trend**
    - **Always close to 1 : 0.961 to 1.037 (i.e. +/- 4 %)**



- Obs.: M. Bianda
  - 25 years
  - K= 0.961
  - Trend=   0.0 +/- 0.002

Meeting at the ROB: February 2011

The R_i human factor: optical factors

- ***No specific aperture required for SIDC contributing observers***
- *How is the detection of the smallest spots influenced by the resolution?*
- Two factors:
- **Theoretical optical resolution** (unobstructed aperture):
  - Rayleigh criterion: $\theta = 138 / D(mm)$
  - Dawes criterion: $\theta = 116 / D(mm)$
- **Seeing:**
  - variable with time, daytime range similar for all low-altitude sites:
    1.5 to 3, typ. 2 arcsec (equiv. D= 45 – 90 mm, typ. 70 mm)
  - Large apertures more affected (size of turbulent eddies ~8 -12 cm):

➡ **Reduces the difference of effective resolution between small and large apertures (> 10 cm)**

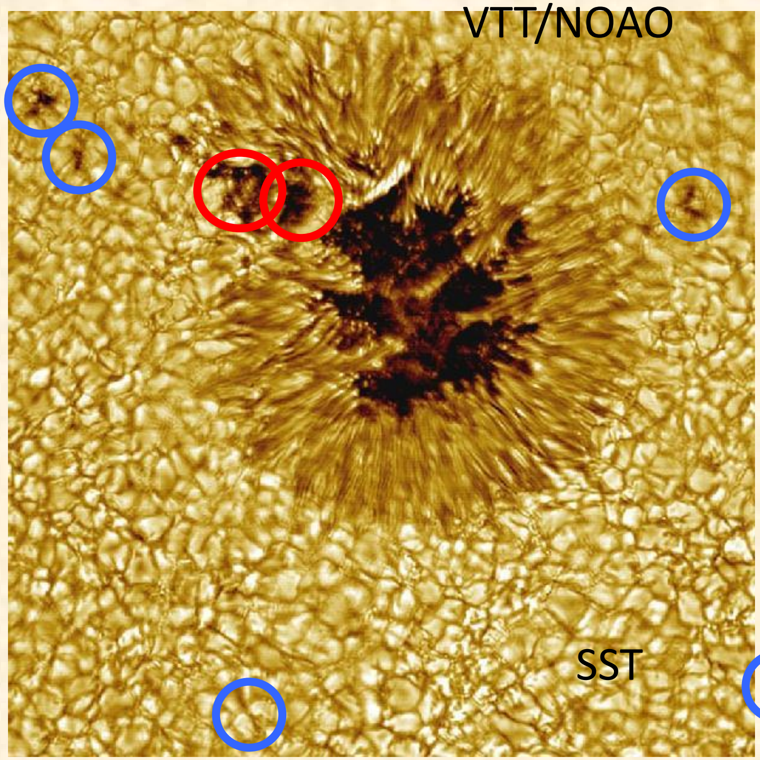
What is the smallest possible sunspot ?

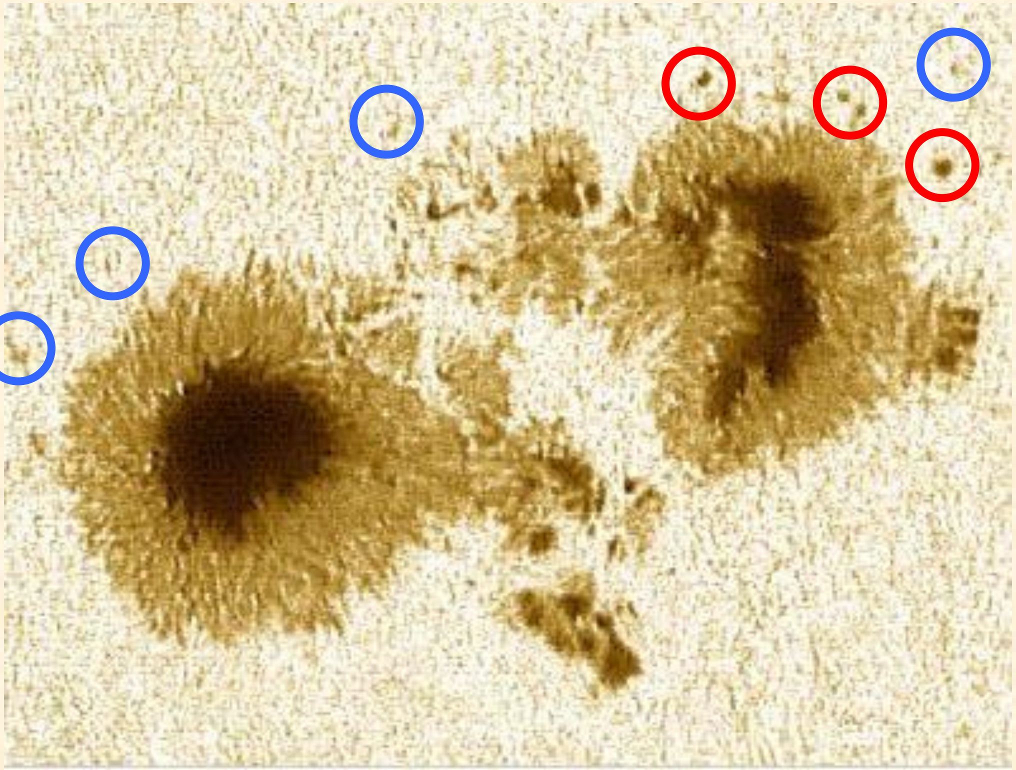
- Various definitions:
  - Semantic problem “pore” vs “sunspot”:
    - Pore = small spot without penumbra
    - Pore = random intergranular blemishes that are not real sunspots

Source	Spot diameter	Spot lifetime	Pore diameter	Pore lifetime
Bray & Laughhead 1964	With penumbra		Without penumbra	
Waldmeier *(Husar 1967)*	**>3” (2000km) = 1 granule**	**> 30 min**	< 3”	< 30min
Bruzec & Durrant 1977	>10” (6000km)	> 1 day	< 5”	< 1 day
McIntosh 1981	**> 4” (2500km) = 1 granule**		< 4”	

- Overall agreement: lowest spot size near 2000 km (3 arcsec)
  - Dictated by granulation dynamics rather than spots (cancellation of convective motion): lifetime: avg. 10 min (up to 30 min)

Sunspots and "pores"





○ (red)	**Sunspot**
○ (blue)	**Pore**

What is the smallest possible sunspot ?

- Best "observational" definition:

	Diameter	**Lifetime**	**Outline**	**Contrast**	Penumbra
Granulation (pore)	< 3" < 2500km	**< 30 min**	**Fuzzy** **Irregular**	**low**	none
Sunspot	> 3" > 2500 km	**> 30 min**	**Sharp** **~ round**	**High** **Dark core**	none

- Simple criteria naturally adopted by all observers
  - No major discrepancies due to personal subjective interpretation

➡ Match of the smallest real-spot angular size with usual seeing (3 arcsec) and telescope aperture D= 50 mm:

  - Limited gain in small spot counts at apertures > 50 - 80 mm

(cf. Svalgaard, private communication)

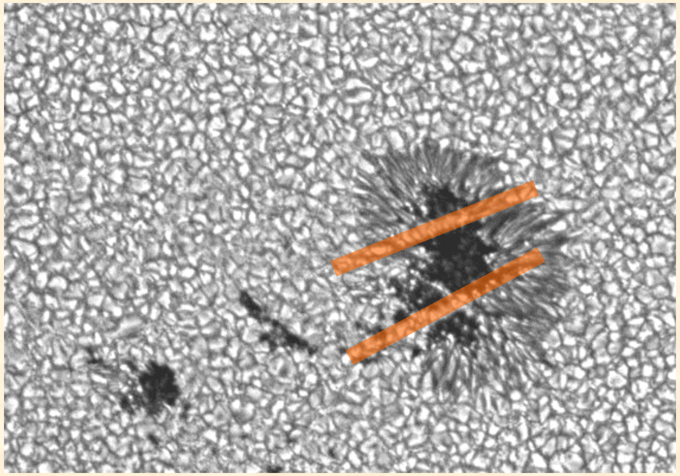
➡ **Small-aperture bias only expected for early historical observations before the 19th century (D << 70mm)**

Main biases: Group and umbral splitting

- **Group splitting:**
  - Topological criteria without external information (magnetograms)
  - No general scientific rule
  - Impact on W number limited:
    - Involves only a minority of groups
    - Can raise or lower W
- **Umbral splitting**:
  - Each umbra in common penumbra is counted as a separate spot (Wolfer rule)
  - Two umbrae considered as split only if separated by a complete light bridge
  - Prone to interpretation
  - Can lead to a net bias

Various group splitting rules *(Kunzel 1976)*:

- Non-bipolar groups: all spots within 5°x5° (60,000 x 60,000 km)
- Bipolar groups: up to 20° extension
- Rules for marginal cases:
  - Two spots up to 15° apart form a single group if they are the remainder of a large extended group
  - A bipolar collection of spots forms one group if Lat(West) ≤ Lat(East)
  - Typical tilt angles: 1-2° at 10° latitude, 4° at 30° latitude



An essential step: processing method

- **Change in the data processing method**
  = primary cause of possible biases

➡ **Problem common to all indices**

- **Zürich-Locarno Sunspot Index**:
  - Choice to drop smallest spots (Wolf)
  - Magnetic needle corrections (Wolf)
  - Weighting of sunspot counts (Wolfer – Waldmeier ?)
  - Change of primary station (Zürich – Locarno)
  - Change in the composition of network (observer mix, geographical distribution): e.g. Zürich-SIDC transition
    - Smaller impact for large networks (SIDC strategy)
  - Manual method: sparsely documented (occasional indications scattered over many different issues of the Mitteilungen)

An essential step: processing method

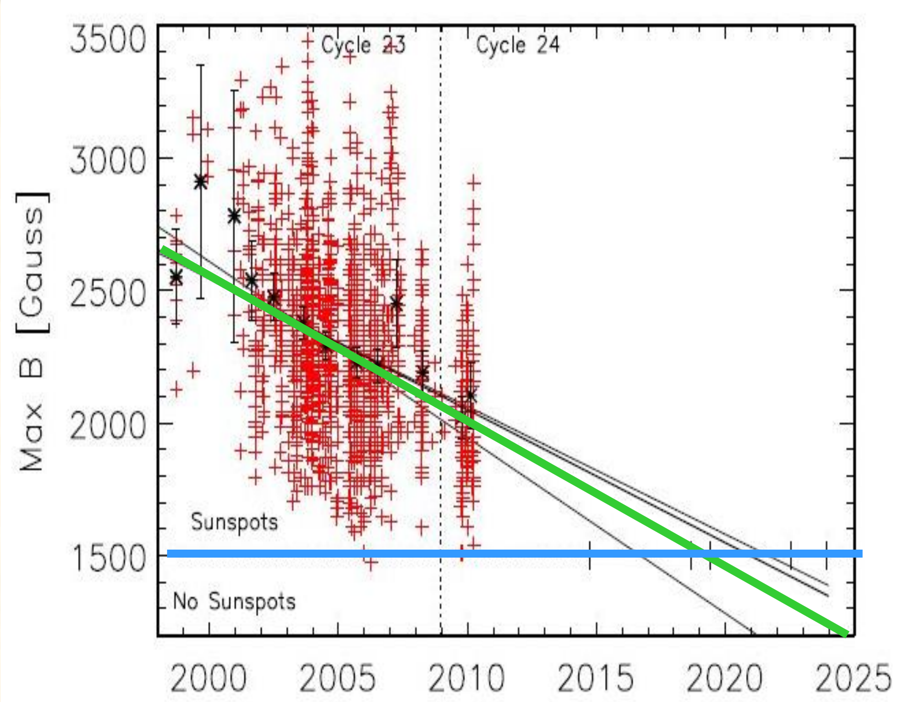
- **The case of the American number R_A (AAVSO):**
  - Lack of reference station
  - Manual processing
  - Additional observer rating factor
  - Flaws in the processing method: found after 50 years
  - Original data lost before 1992 → No correction possible

<u>The Golden rules</u>

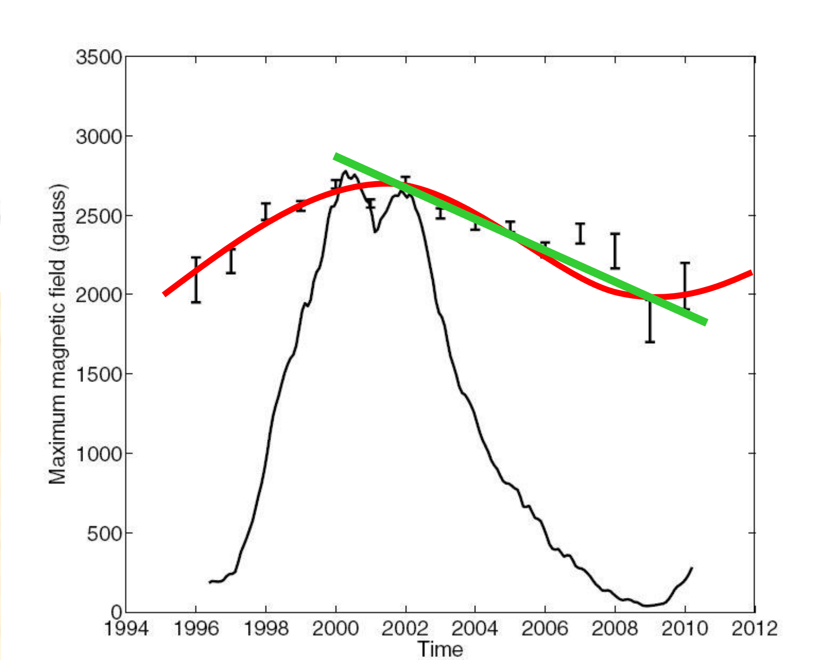
1. **Archival of all raw input data**
2. **Detailed documentation of the processing method and definitions and of the observing technique**
3. **Tracking of processing changes**
4. **Change only when it is essential (e.g. discovery of a flaw)**
5. **Long overlap periods:**
   old and new indices computed in parallel (min. one solar cycle)

Cycle 23-24

Fading sunspots ?

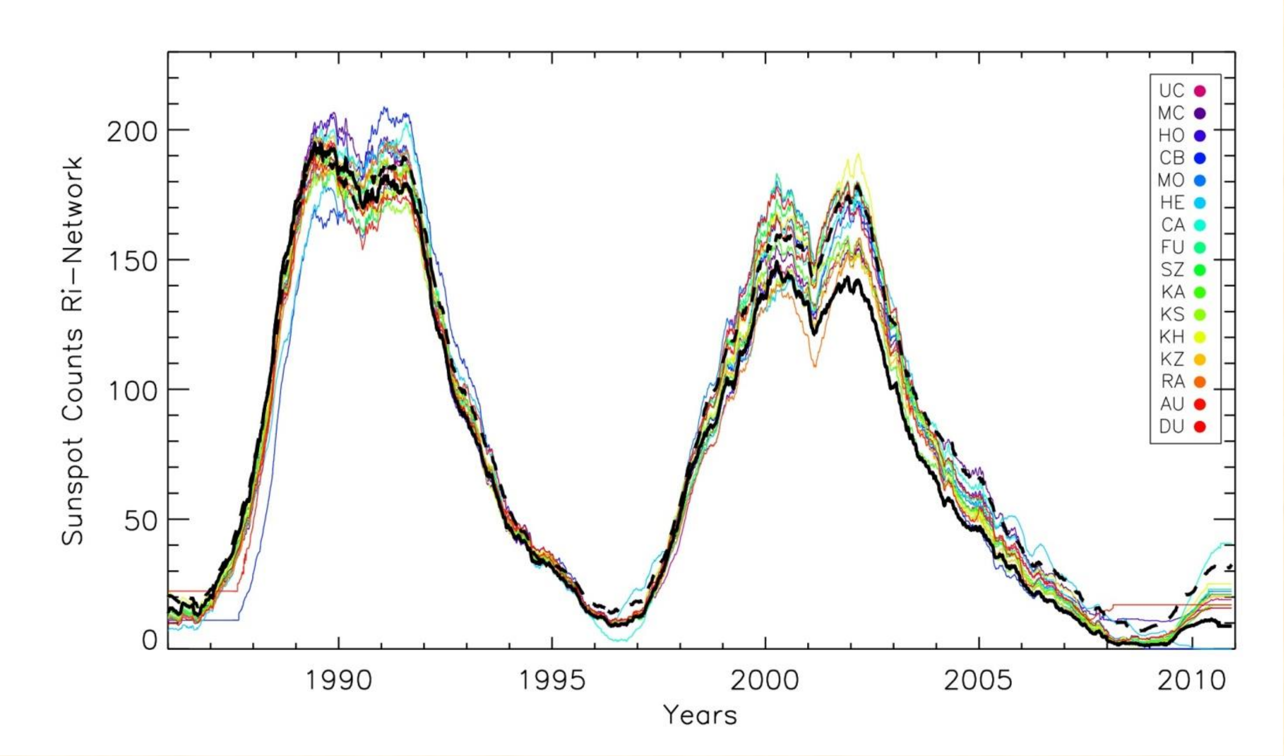


Penn & Livingston 2010



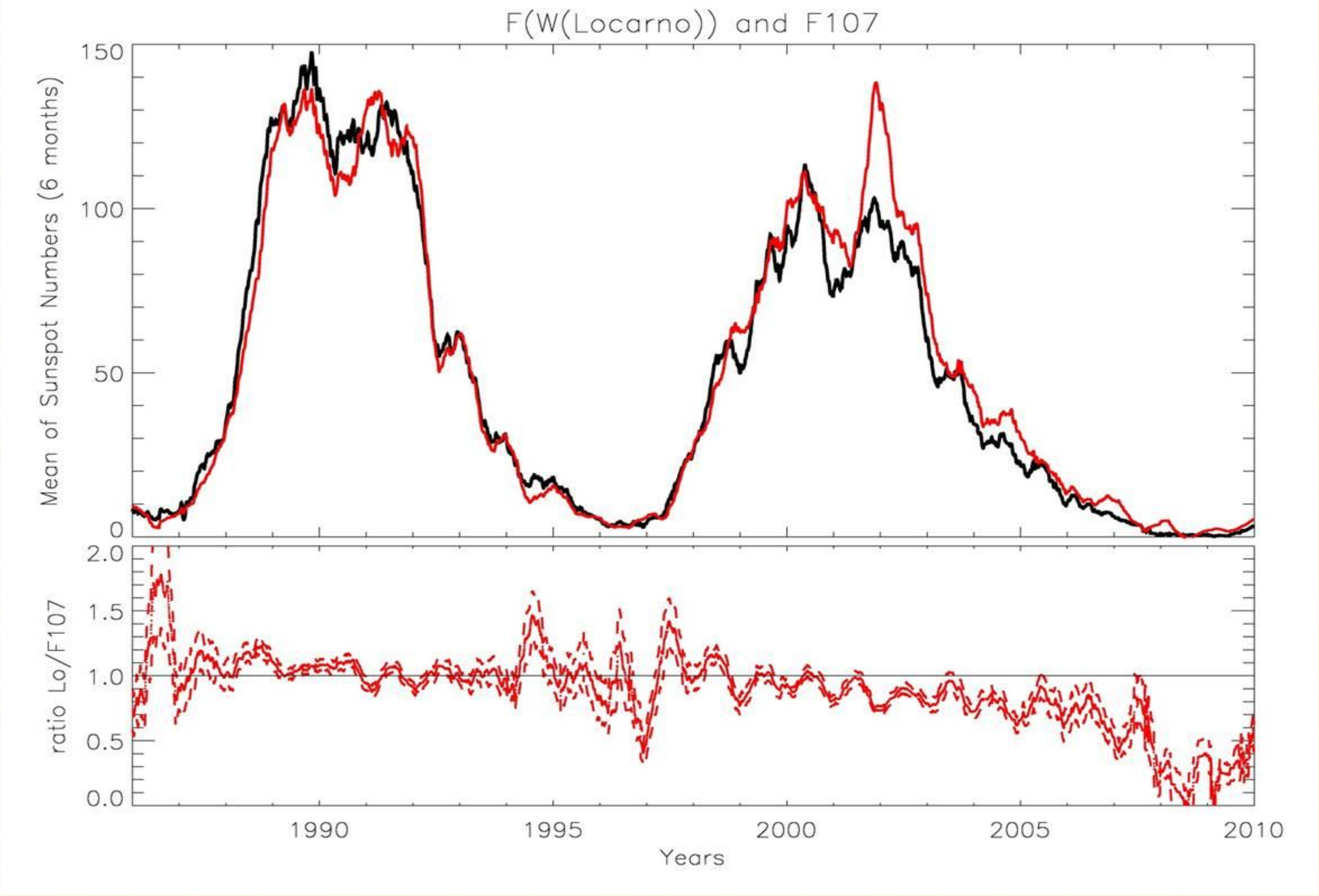
Watson et al. 2011

- Aaa

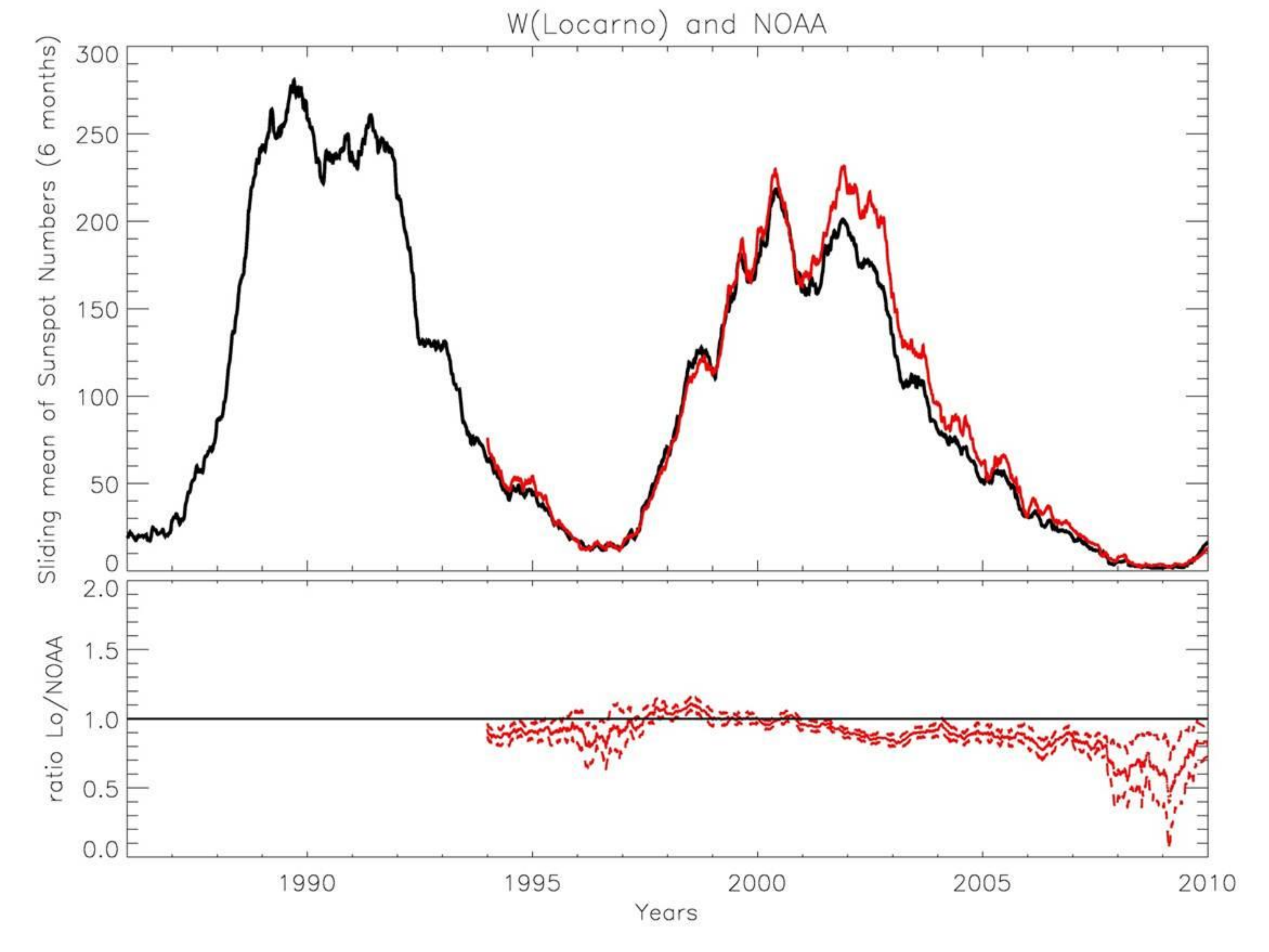


Sunspot Counts Ri−Network
200
150
100
50
0
1990
1995
2000
2005
2010
Years
UC
MC
HO
CB
MO
HE
CA
FU
SZ
KA
KS
KH
KZ
RA
AU
DU

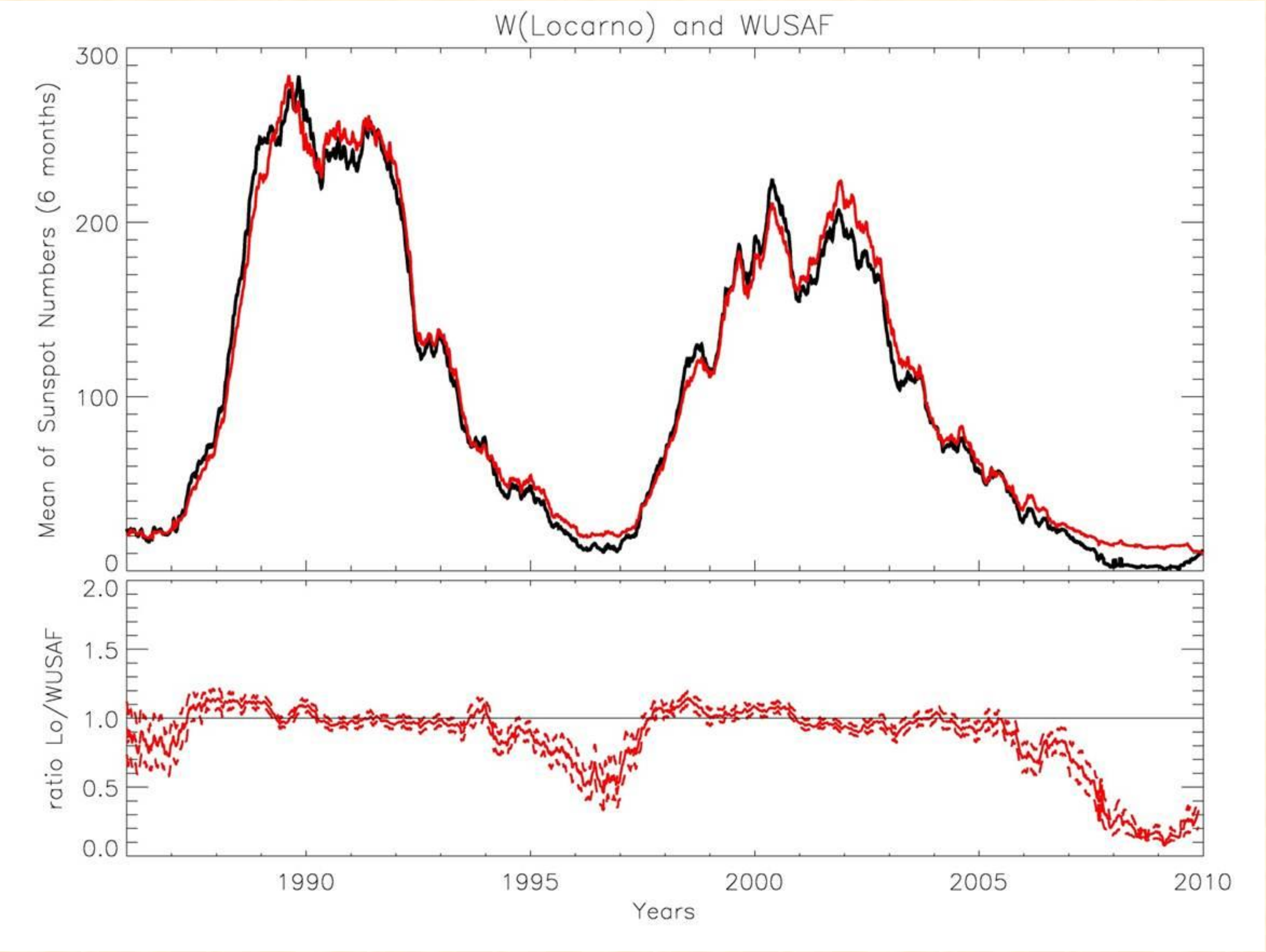
Locarno versus F10.7cm



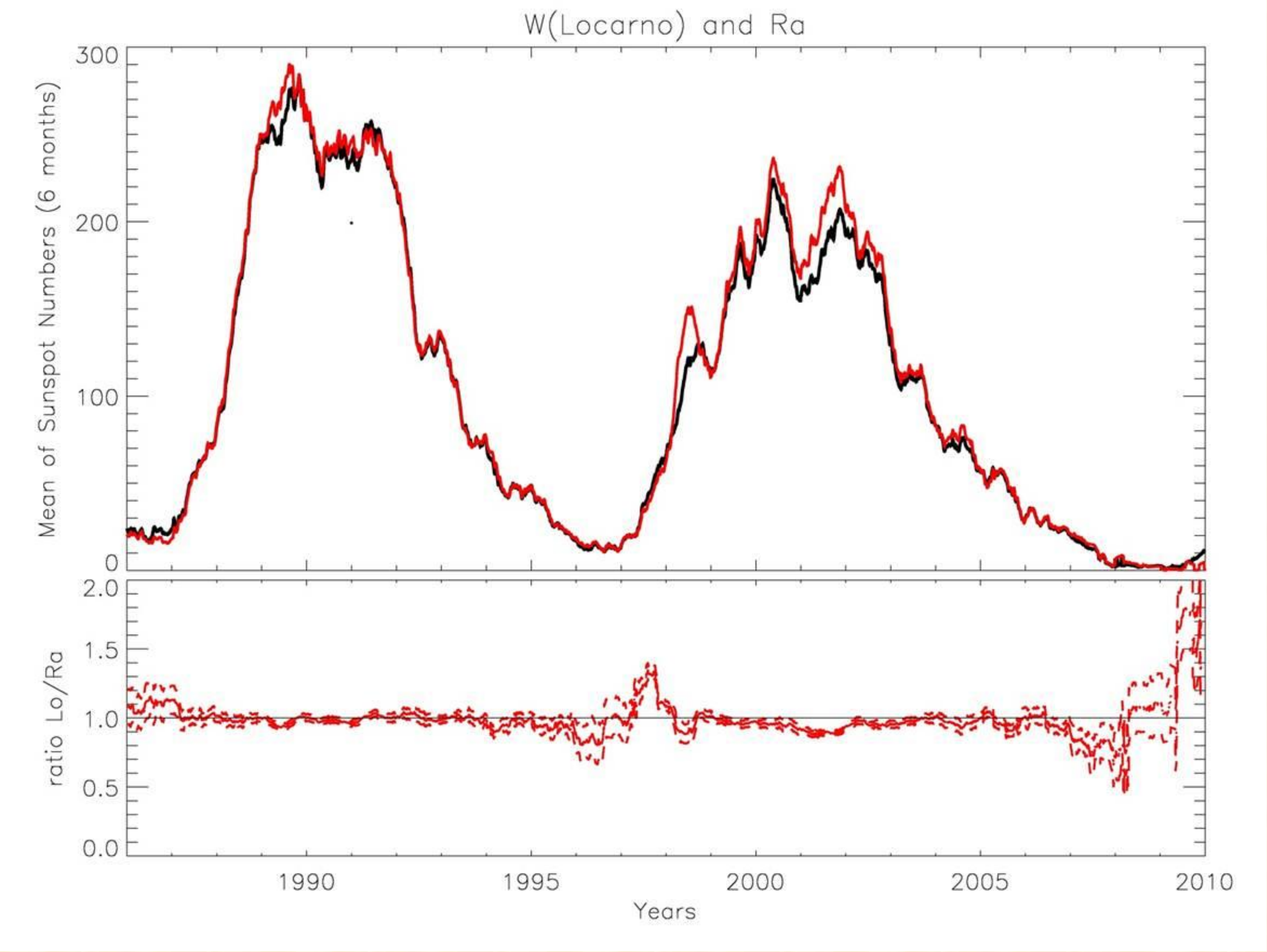
Locarno versus NOAA-Boulder SSN



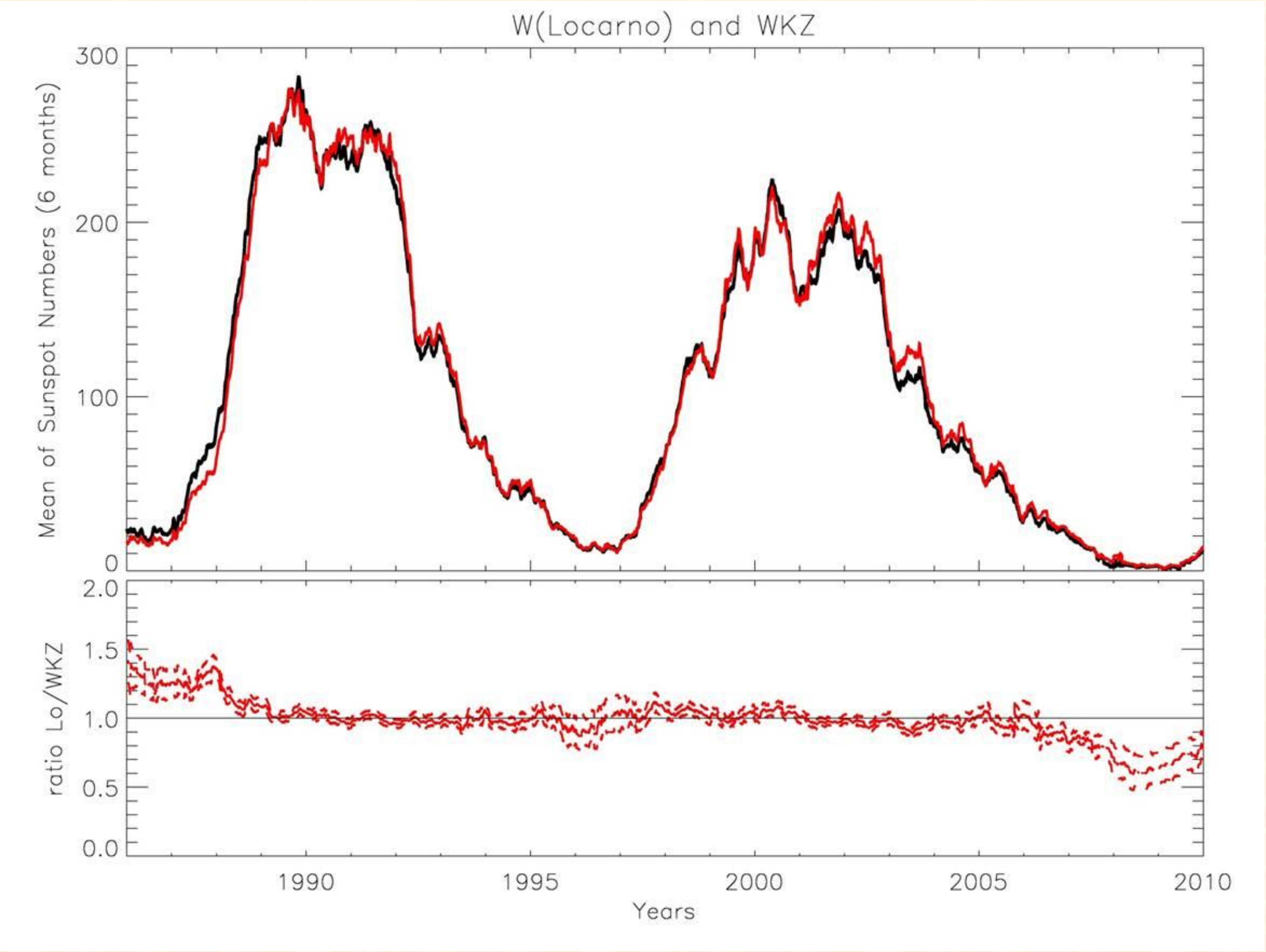
Locarno versus ISOON SSN



Locarno versus R_A SSN (AAVSO)



Locarno versus Kanzelhöhe



Other solar indices

Main activity indices

Index	Duration (cycles)	Since	Lin. Corr.	Linearity	Accuracy (%)	Issues
Sunspot area A	12	1874	0.97	Linear	10-20	▪Definition of boundaries ▪Ratio RGO/SOON*(USAF)*
CaII-K index	8	1915	?	Phase lag	No calib.	▪Several uncalibrated series ▪NB: since 1996: PSPT
Radio F10.7cm	6	1940	0.98	Linear (R_i>30)	3.5	▪Undersampling ▪Empirical filtering rules
TS Irradiance	2.5	1976	0.96	Non-linear (R_i>150)	0.1	▪Mixed contributions from spots and faculae
MgII, HeII index	2.5	1976	?	~linear	~1	▪Space-based: ▪Long-term continuity?
Total/polar magnetic flux	3	1970	>0.93	linear	?	▪Inaccurate near-limb measurements ▪0 Gauss level calibration