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 to 23): 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.
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)

• 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

Fröhlich & Lean 2004
The $R_z-R_i$ history in 4 chapters

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

**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)

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$R_z - R_i$: the whole series

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

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

- 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)

![Map of the SIDC worldwide network showing station distribution by continent and participation type.](image-url)
**Raw Wolf numbers**

Daily K versus *Locarno x0.6*

Monthly average: $K_{sta}$, $\sigma_{sta}$

Daily K dropped

$\Delta K_{sta} \geq 1 \sigma_{sta}$

**Reduced Wolf numbers for Network**

Daily average: $R_d$, $\sigma_d$

All K for date dropped

$R_{LOC} - R_d < 1 \sigma_d$

**ITERATE**

Daily average: $R_d$, $\sigma_d$

**Per station**

Whole month

Whole Network

Per Single day

YES

NO for all stations

$\Delta R_d < 1 \sigma_d$

$N_{sta}$ unchanged

OR $\sigma_d < 10\%$

YES

NO for all stations

**R_d = FINAL R_i**
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

- Only group counts
- Assumption: on average, always the same average number of spots per group
- Reference: RGO photographic catalog (1874-1976)
- After ~1880: R_i and R_G agree within ~5% rms

\[
R_G = \frac{1}{N} \sum_{i=1}^{N} k_i 12.08 g_i
\]

(Hoyt & Schatten, 1998)
$R_G$: 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 \((\text{Wang,Y-M. et al. 2005})\)

- Accuracy issues:
  - Disagreements between different radiometers: 0.6% (instrument models)
  - \(4 \times\) the solar cycle amplitude (0.15%)!

- Non-linear relation for \(R_i > 150\) 
  \((\text{Solanki & Fligge 1999})\)

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 \( R_i \)

Discrepancies do not mean disagreements and flaws!

*Index differences = solar information*
A recent $R_i - F_{10.7}$ disagreement

  \[R_i = 1.14 F_{10.7} - 73.21\]
  (Lin. Corr.=0.98)

- Since 2000: $R_i \sim 15\%$ 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)

- 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 small 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

Since 2010, return to pre-2000 values
Cycle 24: what the SSN tells us ...

[Graph showing smoothed monthly sunspot index over time relative to Ri = 57.0 (years)]
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

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

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

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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 direct proxies by multiple sunspot parameter combinations

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
The $R_i$ pilot station: Specola Solare in Locarno

- “Specola Solare Ticinese” station at Locarno Monti (Altitude: 370 m)
- Instrument: **Zeiss coudé refractor**: $D=15\text{cm}$, $F=2.25\text{m}$
- Main observer: **Sergio Cortesi** since 1955 ... still observing!

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The key role of the Locarno station

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

<table>
<thead>
<tr>
<th>Dispersion %</th>
<th>Daily</th>
<th>Monthly</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>2.93</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>P-P</td>
<td>8.7</td>
<td>4.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

$R_i$ and $W_{Locarno}$ are almost equivalent
Internal Locarno diagnostics

- $R_i = \text{absolute index (cf. TSI)}$

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

Well! By now, you should know that guy...

Sergio Cortesi
Specola
Main Observer

Marco Cagnotti
Specola
Director

Michele Bianda
IRSOL
Director

André Koeckelenbergh
SIDC - ROB
Founder and Director
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: $\theta = \frac{138}{D(mm)}$
    - Dawes criterion: $\theta = \frac{116}{D(mm)}$
  - **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

- 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)

<table>
<thead>
<tr>
<th>Source</th>
<th>Spot diameter</th>
<th>Spot lifetime</th>
<th>Pore diameter</th>
<th>Pore lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bray &amp; Laughhead 1964</td>
<td>With penumbra</td>
<td></td>
<td>Without penumbra</td>
<td></td>
</tr>
<tr>
<td>Waldmeier (Husar 1967)</td>
<td>&gt;3” (2000km)</td>
<td>&gt; 30 min</td>
<td>&lt; 3”</td>
<td>&lt; 30min</td>
</tr>
<tr>
<td></td>
<td>= 1 granule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bruzec &amp; Durrant 1977</td>
<td>&gt;10” (6000km)</td>
<td>&gt; 1 day</td>
<td>&lt; 5”</td>
<td>&lt; 1 day</td>
</tr>
<tr>
<td>McIntosh 1981</td>
<td>&gt; 4” (2500km)</td>
<td></td>
<td></td>
<td>&lt; 4”</td>
</tr>
<tr>
<td></td>
<td>= 1 granule</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sunspots and “pores”
What is the smallest possible sunspot?

- Best “observational” definition:

<table>
<thead>
<tr>
<th>Granulation (pore)</th>
<th>Sunspot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Lifetime</td>
</tr>
<tr>
<td>&lt; 3”</td>
<td>&lt; 30 min</td>
</tr>
<tr>
<td>&lt; 2500km</td>
<td>&gt; 30 min</td>
</tr>
</tbody>
</table>

- 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° x 5° (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

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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

The Golden rules

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?

- Aaa

Penn & Livingston 2010

Watson et al. 2011
Locarno versus F10.7cm
Locarno versus NOAA-Boulder SSN
Locarno versus ISOON SSN
Locarno versus $R_A$ SSN (AAVSO)
Locarno versus Kanzelhöhe

![Graph showing comparison between Locarno and WKZ]

- Mean of Sunspot Numbers (6 months)
- Ratio Lo/WKZ
- Years: 1990 to 2010
Other solar indices
### Main activity indices

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