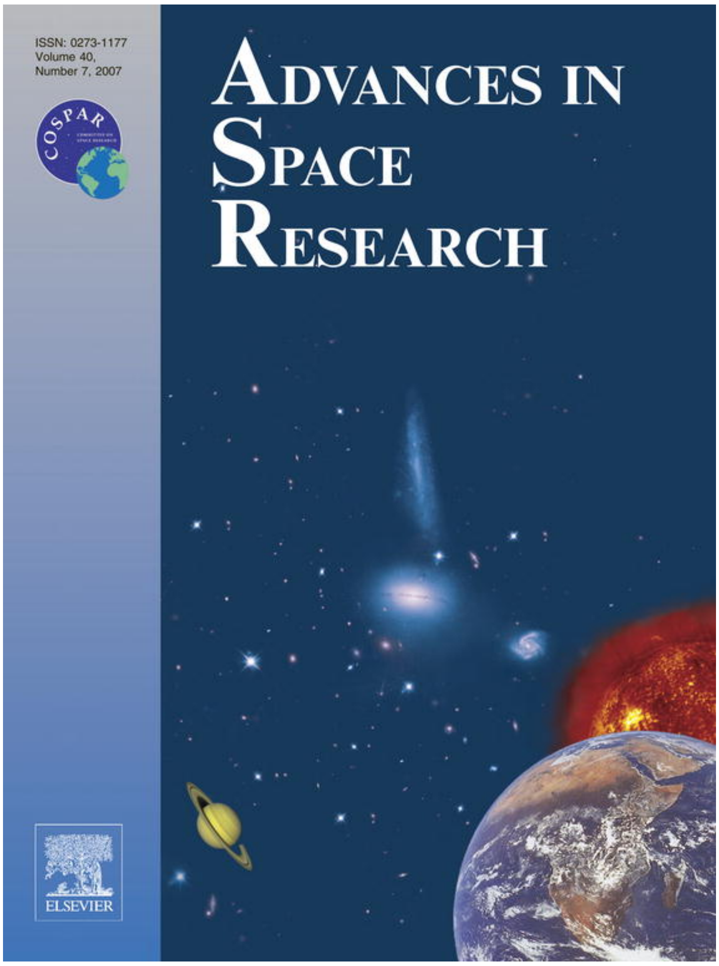
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From the Wolf number to the International Sunspot Index: 25 years of SIDC

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Abstract

By encompassing four centuries of solar evolution, the sunspot number provides the longest available record of solar activity. Nowadays, it is widely used as the main reference solar index on which hundreds of published studies are based, in various fields of science. In this review, we will retrace the history of this crucial solar index, from its roots at the Zürich Observatory up to the current multiple indices established and distributed by the Solar Influences Data Analysis Center (SIDC), World Data Center for the International Sunspot Index, which was founded in 1981, exactly 25 years ago. We describe the principles now in use for the statistical processing of input data coming from the worldwide observing network (~80 stations). Among the various SIDC data products and innovations, we highlight some recent ones, including the daily Estimated International Sunspot Number. Taking a wider perspective, we show how the sunspot index stands the test of time versus more recent quantitative indices, but we also consider the prospects and possible options for a future transition from the visual sunspot index heritage towards an equivalent global activity index. Based on past historical flaws, we conclude on the key requirements involved in the maintenance of any robust long-term solar activity index.

Keywords: Solar activity; Sunspots; Activity indices; Photosphere; Observing techniques

1. Introduction

Among all solar activity indices, the sunspot number (SN) provides the longest instrumental quantitative record of solar activity, spanning now four centuries, i.e. 35 solar cycles. Nowadays, it is still the most frequently used reference in long-term studies. Between 2000 and 2006, 440 publications listed by the Abstract Distribution System (ADS) referred to the "sunspot number".

The SN indeed has multiple applications in a wide range of science disciplines. In solar physics, it is used in solar cycle predictions, for constraining dynamo models and in reconstructions of solar irradiance. In the field of Sun–Earth relations and space climate, it provides a base index of the solar forcing on the Earth climate and of secular evolutions of the radiative, corpuscular and magnetic flux interacting with the Earth atmosphere and magnetosphere (Fröhlich and Lean, 2004; Hathaway and Wilson, 2004; Solanki et al., 2005; Wang et al., 2005). It also provides the calibration of long-term proxies that extend further back in time, like the cosmogenic isotope abundances or long-term geomagnetic indices (Lockwood, 2003; Solanki et al., 2004; Usoskin and Kovaltsov, 2004; Wang, 2004). Finally, it is now increasingly used for the operational mitigation of the impacts of solar activity on human activities at monthly to decadal timescales (space climate). This includes long-distance telecommunications, navigation systems, ground-based infrastructure (power grid, pipelines), space hardware (failure rates, atmospheric drag) and manned space mission planning (cumulative radiation exposure).

In this review, we will first describe the current methods and products of the SIDC. Then, in a temporal perspective,

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we will consider the meaning of the visual SN and the characteristics of the entire SN time series. A comparison with other more recent indices will allows us to identify the specific strengths of the SN as well as the requirements and options for a possible future quantitative photospheric index.

2. The SIDC now: current sunspot data products

The IAU World Data Center (WDC) for the SN was transferred from the Zürich Observatory to Brussels in June 1980, following the decision of the new Director of the ETH (Federal Institute of Technology), Dr. O. Stenflo, to terminate the 130-year-long Zürich sunspot number program initiated by R. Wolf. This decision was taken in a context of international controversies about the usefulness and reliability of the SN time series. However, thanks to the strong support of URSI and COSPAR, the new WDC, renamed as "Sunspot Index Data Center", was created at the Royal Observatory of Belgium with Dr. A. Koeckelenbergh as first Director. Since then, the SIDC has been producing the International Relative Sunspot Number, R_i continuously over the last 25 years (more details can be found in Vanlommel et al., 2004 and Berghmans et al., 2006).

2.1. Achievements of the last 25 years

The first action of the SIDC was to computerize the processing of the observations, formerly done manually. A major change was also introduced in the processing method: instead of using a single primary station, the new index is computed by a statistics over all available observations. In order to improve the statistical stability of the index, a large number of new observers were recruited, which led to a doubling of the contributing stations. The second SIDC Director, P. Cugnon (1994–2002) introduced the hemispheric SN (starting in 1992). For quality control, he also checked that no significant drift of R_i had occurred relative to the Zürich SN at the time of the 1980 transition, using parallel indices (10.7 cm radioflux, $F_{10.7}$) and also a subset of "high quality" stations, for the 20-year period straddling the Zürich-SIDC succession.

Another major evolution took place in January 2000, when the SIDC took over the Regional Warning Center for Western Europe, formerly hosted at the Paris–Meudon Observatory, as part of the international ISES network (International Space Environment Center). Since then, the SIDC, under its new denomination of "Solar Influences Data analysis Center", also provides extensive near real-time space weather services and alerts (Berghmans et al., 2005). The SIDC currently serves a community of 2000 subscribers (more than 500 for sunspot products), including individuals (wide public, radio amateurs, space scientists, meteorologists, paleo-climatologists) and institutions (public organizations, like IAU, ISES, UNESCO, private companies, aviation, civilian and military).

2.2. The index generation method

2.2.1. Observing network

Currently, the SIDC observing network includes 86 stations located in 29 different countries. As shown in Fig. 1, the network is still heavily concentrated in Western and Eastern Europe. This is partly due to the heritage of the past Zürich era and to the lack of contributing observers in Northern America, where the sunspots reports are traditionally sent to the AAVSO to produce the American SN R_A, which has unfortunately suffered from past unrecoverable processing errors (Coffey et al., 1999; Hossfield, 2002). Thirty-four percent of our stations are professional observatories, often using several observers, while 66% are dedicated individual amateur astronomers. The observers must satisfy several criteria to be included in the SIDC network: dedication (more than 10 observations per month), regularity (no missing months) and consistency. The latter is quantified through the k personal reduction coefficient, which is the scaling factor between the raw SN of an individual station and the global network average.

2.2.2. Data import

The main workload for the SIDC team resides in the initial filtering and corrections of imported reports. As shown in Fig. 2, successive consistency tests are applied to the format (e.g. wrong date, swapped columns, duplicate reports), to the total counts (e.g. confusion between zero count and "no observation"), to the hemispheric counts (e.g. confused with or exceeding the total count) and to the central zone counts, which include only sunspot groups located less than half the disk radius (i.e. less than 30°) from disk center. Finally, a test processing is executed with all the data. Any anomaly leads either to a correction after checking directly with the observer or to the rejection of a daily value or of the entire monthly report.

So far, this essential quality check was applied in a semi-automated way, as most reports were received by e-mail, and also partly by paper mail or telefax. Since January 2005, a new Web-based data import form was introduced and is now used by a large fraction of our observers. Programmed in PHP, this electronic form contains already a

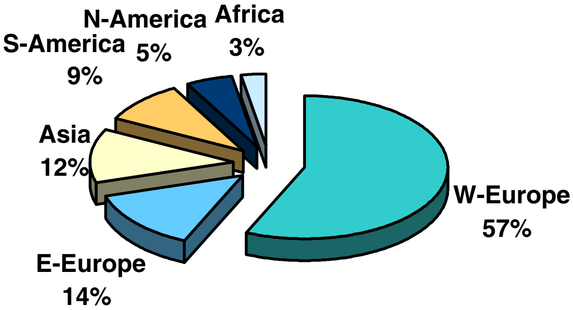

Fig. 1. Geographical distribution of the SIDC observing stations, showing clearly that Europe has still a dominant contribution relative to the other continents.

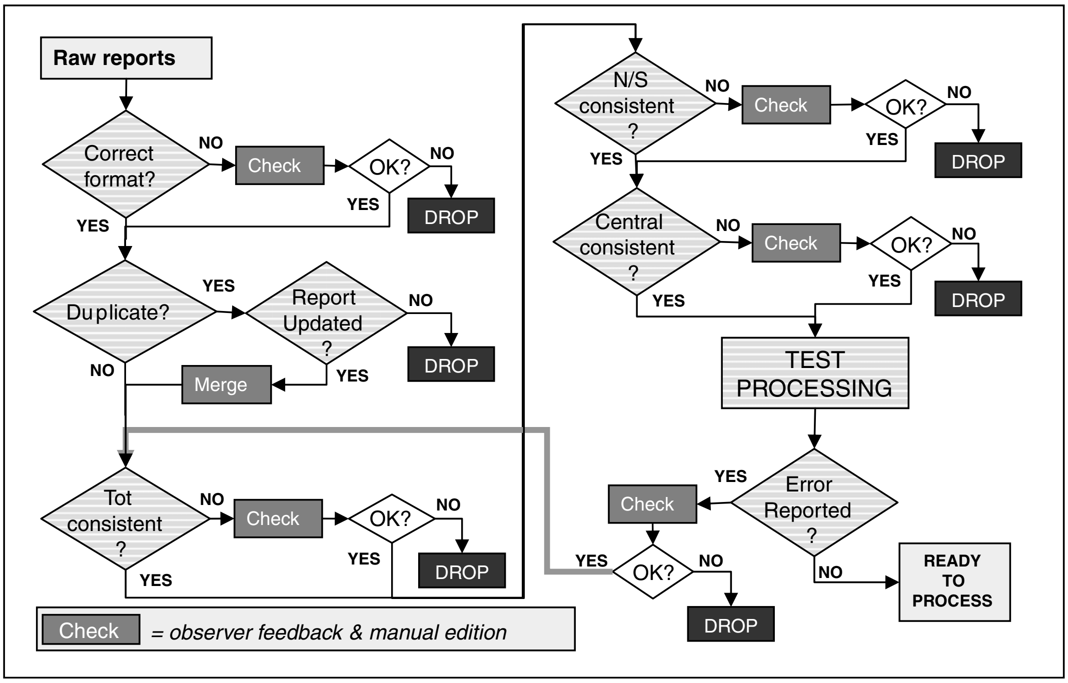

Fig. 2. Flowchart of the SIDC data import procedure, illustrating the succession of hierarchical tests applied to raw observing reports.

number of the above consistency checks and the imported data are stored in a global database, which leads already to a significant reduction in the error-checking workload.

2.2.3. Processing principles

The R_i processing consists in two main steps, as illustrated in Fig. 3. In a first step, the k personal reduction coefficients are computed relative to the Locarno pilot station that was formerly the main station of the Zürich Observatory, our long-term reference (see Section 3.2 below). For each station, daily values deviating by more than $2\sigma_K$ from the monthly station average are discarded. The monthly averages are recomputed iteratively until k values are consistent for all station. It is in this essential step that the current R_i index is tied to the Locarno reference, that covers both the Zürich period (23 years, 1957–1980) and the SIDC period (25 years). Note that no reliability weighting is applied “a priori” to individual

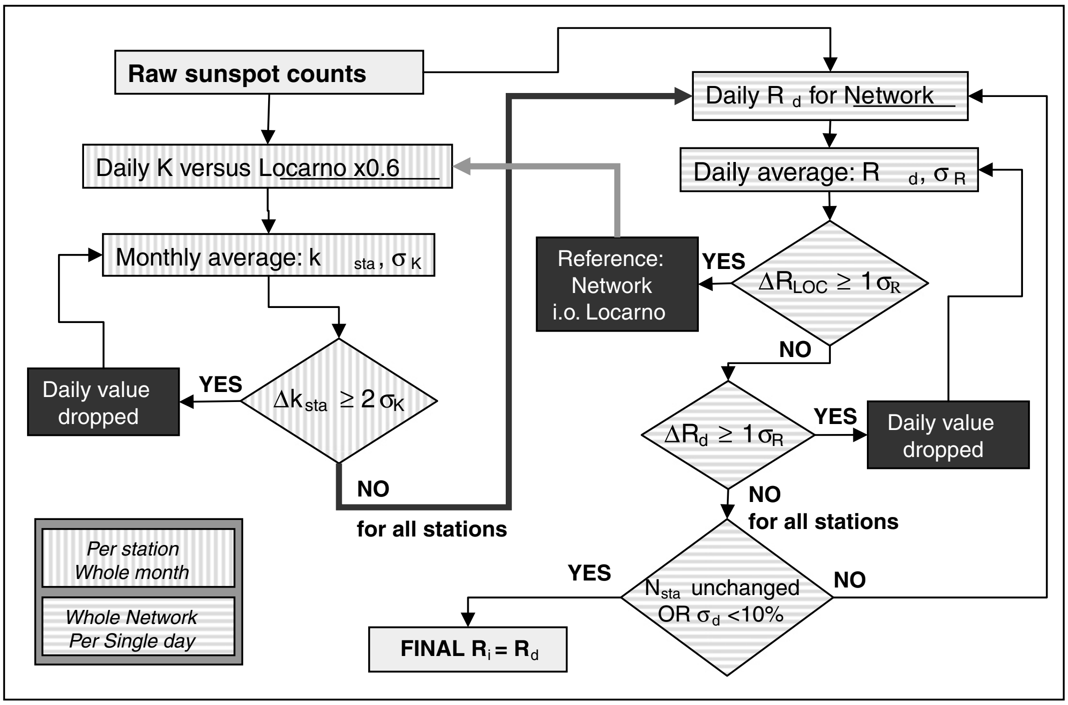

Fig. 3. Flowchart of the R_i determination procedure, illustrating the two-step principle that ties the whole network to the Locarno pilot station.

observers, as it would add unnecessary subjectivity. Single observations or all observations from one station are simply rejected when the daily deviation with the network or the monthly σ_K of the station exceeds the statistical confidence level.

In the second step, using the updated monthly k coefficients, the R value is computed for each station, and network averages R_d and standard deviations σ_R are computed for each day. The daily Locarno SN is first checked relative to R_d. If the difference exceeds $1\sigma_R$, which happens only occasionally, the Locarno reference is replaced by the network average R_d, and the k coefficients are recomputed relative to the latter. Then, each station is checked versus the daily average R_d. If it deviates by more than $1\sigma_R$, the value is dropped and the daily average recomputed. This consistency check is repeated iteratively until no more value is dropped or the overall daily $\sigma_R < 10\%$. R_d is then taken as the final daily R_i value.

On the first day of each month, a provisional R_i value (PISN) is calculated by the above technique for the month just elapsed, using reports from about 45 "fast" stations. On a quarterly basis, with a 3-month delay, a definitive R_i value (DISN) is computed exactly in the same way but with the entire network of more than 80 stations. If the DISN differs by less than 5% from the PISN, the provisional value is left unchanged (DISN = PISN). Otherwise, it is replaced by the DISN, after inspection of the distribution of values, when the latter is complex. The DISN is final and is appended to the master SN time series in the SIDC archive.

2.3. *Array of data products*

2.3.1. *Primary sunspot indices*

The SIDC issues a wide range of indices next to the primary total R_i series:

- Daily total SN: R_i (Provisional + definitive, from 1818)
- Daily hemispheric SN: R_N, R_S (Provisional + definitive, from 1992)
- Monthly mean total SN (Provisional + definitive, from 1749)
- Monthly mean hemispheric SN (Provisional + definitive, from 1992)
- 13-month smoothed monthly SN (Definitive, from 1755)
- Yearly mean SN (Definitive, from 1700)

All these indices have been produced consistently with the processing method described above since 1981. All index values preceding 1981 were inherited without modification from the Zürich time series, R_z, and present time-varying characteristics as explained below in Section 3.2. In addition, the SIDC provides 12-month ahead predictions of the smoothed monthly sunspot number (18 month ahead of the last definitive smoothed value), based both on the Standard Curve method (Waldmeier, 1968b) and its extension, the Combined method (Denkmayr and Cugnon, 1997; Hanslmeier et al., 1999), which performs better during the transition between two cycles.

2.3.2. *EISN: a new daily index*

Since January 2005, a new "quick" sunspot index was introduced in response to increasing demands for a daily-updated index adapted to the predictive modelling of the ionospheric radio propagation. The Estimated International Sunspot Number (EISN) is now calculated daily for the current day and the day before and appears in the daily URSIGRAM of the RWC. It is calculated by a simple arithmetic mean using a subset of about 15 real-time stations. It benefits from the k reduction coefficients derived from the full processing of the network. Consistency checks with the PISN indicate a good agreement within about 5 units r.m.s. (Fig. 4). The EISN is an ephemeral index addressing only space weather needs, as it is automatically replaced by the PISN at the end of each month.

2.3.3. *Data distribution*

On a monthly basis, the SIDC issues two prompt electronic reports (Monthly R_i Report and Monthly

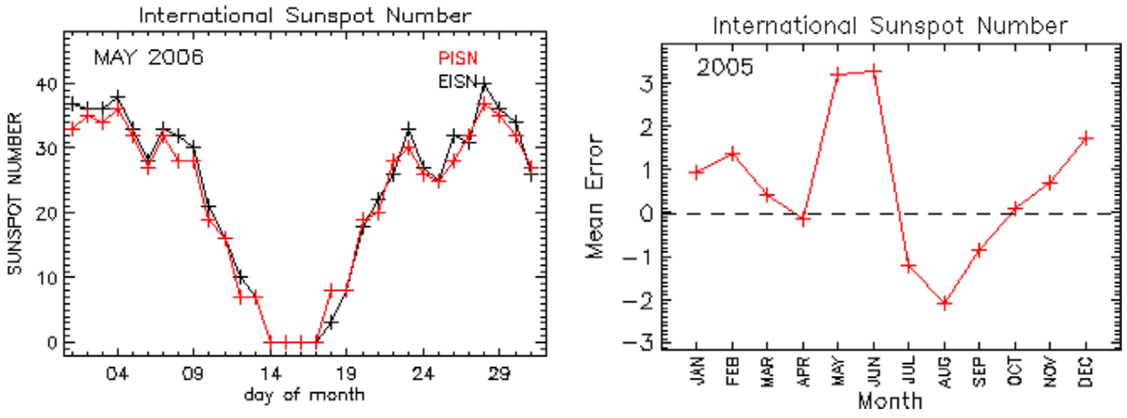

Fig. 4. Sample plot showing a comparison of the daily EISN with the PISN for May 2006, as an example (left). On the right, a plot of the monthly averages of daily differences EISN-PISN for the 12 months of 2005 gives a measure of the possible systematic biases in the EISN. The rms daily difference between the EISN and the PISN was 5% during the year 2005, which gives a measure of the precision of the estimated index.

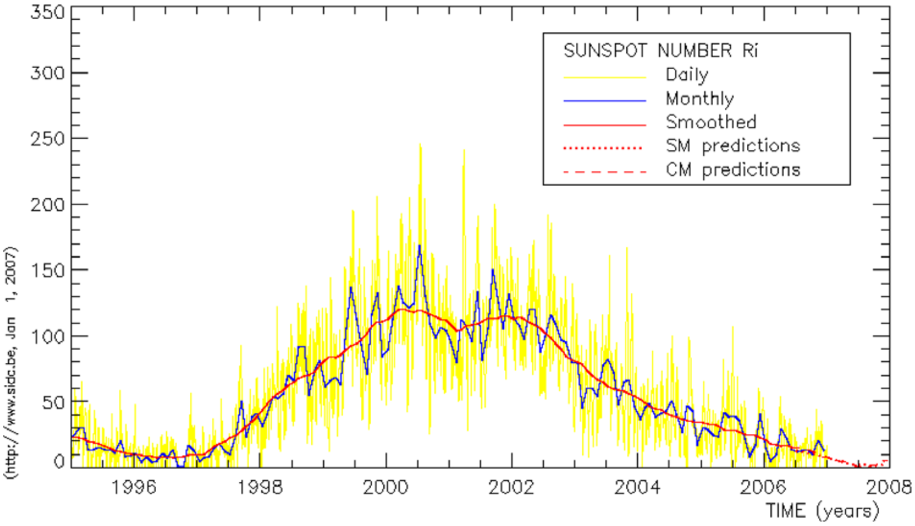

Fig. 5. One of the graphical products distributed on the SIDC web site is this 13-year plot of the daily, monthly and smoothed monthly sunspot number, including the 12-month-ahead prediction (red dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

R_i_Hemispheric Report) for more than 300 subscribers and also the "Sunspot Bulletin", which is the main SIDC publication. The Sunspot Bulletin contains all SIDC products in tabular and graphical form, with now in addition, a monthly summary of solar and geomagnetic activity from the RWC section. Next to the primary sunspot products, the SIDC also relays the values of several solar and geomagnetic indices received with the URSIGRAM messages (PPSI photometric sunspot index, 600 MHz and 2.8 GHz radio fluxes, A_k geomagnetic index, etc.), as well as more detailed data from the Uccle station, including a list of major individual sunspot groups and their possible return dates. The Sunspot Bulletin is distributed to about 450 subscribers, now mostly in electronic form (PDF document). The definitive values are added on a quarterly basis in an "SIDC News" issue. Externally, the SIDC sunspot indices are provided to the Quarterly Bulletin of Solar Activity and are mirrored in the NGDC archive (National Geophysical Data Center, NOAA, USA).

However, the primary access point is the SIDC web site (http://www.sidc.be) that was fully renewed in 2006, with a dedicated section for the R_i sunspot index as well as a subscription page to the various electronic, fax or paper bulletins issued by the SIDC (free of charge except for the paper versions). The different data sets are public and freely downloadable in ASCII table form or in graphical form (e.g. Fig. 5).

3. R_i index: its meaning and properties

3.1. R_i definition and uncertainties

Given its enduring and almost traditional role in solar physics, it is legitimate to wonder about the exact meaning and significance of the SN as defined by R. Wolf. The Wolf number $N_W = 10N_G + N_S$ consists of a weighted mean of the group count N_G and spot count N_S. Originally, this choice has been primarily dictated by the need to assemble Wolf's own observations with the earlier observations obtained with simple and smaller telescopes of lower quality. As the main uncertainty resides in the smallest sunspots near the limit of telescope resolving power, a larger weight was given to N_G to reduce the scatter and possible biases. However, our present understanding of the origin and magnetic nature of sunspots can shed a new light on this simple expression.

In the weighted mean, the N_G term accounts for the clustering of individual sunspots actually belonging to a single emerging magnetic flux rope. However, by itself, it cannot reproduce the wide range of sizes and morphological classes that each group can take. On the other hand, N_S takes into account all sunspots, but they are counted equally although they can have different significances:

- Multiple spots inside a big group are just sub-elements of the same magnetic structure
- Single isolated sunspots are single markers of a whole magnetic concentration

Therefore, the Wolf formula manages, in a basic but efficient way, to reflect the underlying magnetic flux strength and spatial density. This is further confirmed by the high degree of linear correlation of R_i with other indices, as described hereafter. Although there is no precise explanation for the choice of 10 as the weighting factor, more recent sunspot group statistics with modern instruments (e.g. Waldmeier, 1968a) indicate that on average $N_S = 10N_G$. Therefore, on average, Wolf's definition gives an equal role to N_G and N_S, close to an exact balance.

As a quantitative measure, the precision of R_i is limited primarily by the following subjective criteria, which translate as random inconsistencies among observers:

- The division of multiple umbrae inside a common penumbra
- The splitting of neighbouring sunspot groups (largest impact at high solar activity)
- The distinction between the smallest spots and pores (largest impact at low solar activity)

3.2. The R_i time series: four main eras

Although it is archived as a single time series, the sunspot number is actually formed by an historical succession of sunspot indices of different intrinsic nature and accuracy. We can distinguish four main eras in the SN series, as described in Table 1.

The historical era is entirely based on reconstruction from sparse data and is still a topic of research (e.g. Letfus, 2000; Usoskin et al., 2003; Vaquero, 2007). Both the historical and the Wolf era suffer from a lack of clear rules defining the sunspot count, from the relatively small number of available observers and from a non-systematic or indirect determination of the k personal reduction coefficients. In recent years, the most significant progress in the reconstruction of the early sunspot index was achieved by Hoyt et al. (1994) and Hoyt and Schatten (1998) who managed to recover many overlooked sunspot observations, more than doubling the number of past observations compared to R. Wolf. Given the random quality of early observations, they compiled the observations in terms of the group sunspot number R_G first studied by Waldmeier (1968a).

In 1882, A. Wolfer, who later succeeded to Wolf as Director of the Zürich Observatory in 1894, introduced an important change in the counting method (Hossfield, 2002). While Wolf had decided not to count the smallest sunspots visible only in good conditions and also not to take into account multiple umbrae in complex extended penumbrae, in order to better match his counts with the earlier observations, the new index included all small sunspots and multiple umbrae. By removing factors of personal subjectivity, this led to a much more robust definition of the SN that formed the baseline for all published counts after 1882. To complete this transition, A.Wolfer determined the scaling ratio between the new count and the Wolf SN series over the 16-year Wolf–Wolfer overlap period (1877–1892). This led to the constant Zürich reduction coefficient ($K_Z = 0.6$) still used today to scale the modern SN to the pre-1882 Wolf sunspot counts. Based on the group sunspot number R_G, Hoyt and Schatten (1998) conclude that the Wolf SN seems to overestimate the true SN by about 25% before this 1882 transition. The overestimate might be due to improper corrections introduced by Wolf, based on magnetic needle readings, erroneously increasing the original raw values. Therefore, the use of R_G instead of R_Z is recommended especially before 1850 to avoid this possible early bias (Letfus, 2000; Hathaway et al., 2002; Usoskin et al., 2003).

With the Zürich era, the SN enters its modern period, becoming more reliable and accurate, thanks to clearer counting rules, the progressive inclusion of additional stations, and the systematic updating of k coefficients (yearly). The Zürich sunspot observing program was continued by the successive Directors: A. Wolfer (1894–1926), W. Brunner (1927–1944) and M. Waldmeier (1945–1980). However, all the processing was done manually and was kept simple by using only one primary station (Zürich) and using external observations only for filling the unavoidable gaps in the Zürich observations and, as a safeguard, for verifying possible inconsistencies of the Zürich primary station. Some improvement came also with the use of additional data from the Arosa station (founded in1939) and the Locarno station (founded in1957), next to the Zürich Observatory.

In the last era, the SIDC introduces a global multi-station treatment by a computerized statistical processing. The k coefficients are updated on a monthly basis, thus tracking seasonal biases. The geographical coverage is also expanded to achieve a 100% time sampling, thus improving the statistics of small short-lived sunspot groups. Those various progresses translate both into a steady reduction of the uncertainties (precision) and a decrease of possible biases (accuracy), as shown by the estimated values of

Table 1
Main characteristics of the sunspot number in the course of the four main eras that can be distinguished in its production

Epoch	Historical (1610–1848)	Wolf (1848–1882)	Zürich (1882–1980)	SIDC (1981–now)
Observations	Sparse	Systematic	Systematic	Systematic
Obs. technique	Variable	Eyepiece	Drawing (proj.)	Drawing (proj.)
Stations (daily)	Base: 1	Base: 1 Aux: a few	Base: 1 (triple) Aux: ~30	20–50 (all)
Geog. distrib.	W-Europe	W-Europe	Europe + Asia	Worldwide
Processing	Manual	Manual	Manual	Computer
Reference	Wolf (Zürich) $k_W = 1$	Wolf (Zürich) $k_W = 1$	Zürich + Locarno $k_Z = 0.6$	Locarno $k_Z = 0.6$
Small spots	No	No	Yes	Yes
k coefficients	Estimates	Regular	Systematic (yearly)	Systematic (monthly)
Est. yearly error	10– 45%	10%	<5%	<1%
Est. accuracy	20–50%	20%	5–10%	~5%
Drift control	Loose, indirect	Loose, indirect	Direct (RGO, $F_{10.7}$)	Direct (many)

Table 1, based on various published studies and direct comparisons with parallel solar activity indices.

4. R_i: improvements and extensions

Further improvements to the R_i production can be considered. Some of them are internal and their implementation is already in progress at the SIDC, like the generalization of internet data exchange (data import, web distribution), the systematic storage of all raw observation in digital form (database), the modernization of the processing software (old FORTRAN77 code). The new tools open the possibility of a future extension of the observing network.

We have also identified several worthwhile efforts involving a connection with external resources, like the implementation of a more systematic cross-analysis with other solar indices (primarily, sunspot areas A_S and $F_{10.7}$) to obtain a continuous monitoring of possible slow drifts. Such drifts may be caused by subtle slow changes in the pilot station (e.g. long-term trends in the average seeing) or to the evolving composition of the observing network over decades. It seems also important to improve the link between R_i and the group SN, R_G. Indeed, as the R_G scaling is referred to the RGO SN (Royal Greenwich Observatory) between 1874 and 1976, we thus need a better knowledge of the relation R_i versus the RGO SN. Moreover, the R_G definition consists in a simple fixed linear relation to scale R_G relative to the SN (Hoyt and Schatten, 1998):

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

where k_i and g_i are the personal reduction coefficient and the raw group count from individual station i.

However, given the different occurrence rates of the different group types in different phases of the solar cycle (low, high, ascending and declining), the relation between group counts and sunspot counts is probably more complex and time dependent. This could lead to long-term changes in the relative scaling of R_G versus R_i and other indices. The validity and accuracy of the R_G definition thus deserves further investigation.

Recent analyses of solar activity tracers and dynamo models (e.g. Swinson et al., 1986; Antonucci et al., 1990; Ossendrijver, 2003; Charbonneau, 2005a, 2007) have shown the importance of treating separately the North and South hemispheres of the Sun. Therefore, a significant effort has been undertaken by the Kanzelhöhe Observatory (Temmer et al., 2006) to reconstruct the hemispheric sunspot numbers, but currently the reconstruction spans only 6 cycles, back to 1940 and with a 80% partial coverage using two stations (Kanzelhöhe and Skalnaté Pleso). This endeavour can and should be expanded, by adding existing sunspot data from other stations and possibly back to the late 19th century.

Due to the combination of spatial and temporal patterns in the solar cycle, there is an overlap of about two years between successive solar cycles in the R_i time series, around the time of the activity minimum (Wilson et al., 1996). There is thus confusion between the evolution of two cycles that coexist in different parts of the convective region (e.g. Yoshimura, 1978; Wilson et al., 1988; Charbonneau, 2005b), masking the actual start and end phases of each cycle. This motivates the introduction of a "cycle" SN, where the counts would distinguish sunspot groups belonging to each cycle. The splitting could be based on their latitude of emergence or on their magnetic polarity, if available.

In its low range ($R_i < 30$), the SN suffers from a quantification effect that is inherent to its mathematical definition and that stretches artificially the low range of SN values. This is reflected by a deviation from a linear relation with other solar indices ($F_{10.7}$, A_S) in this low range. A linearization procedure could be defined according to recent "flux" indices and be applied backward to the whole SN series to produce a parallel linearized index. Next to the standard R_i series, this auxiliary R_i-derived index could serve for instance as a more adapted proxy for irradiance reconstructions.

5. R_i and other long-term indices

Over the last decades, an increasing number of global solar activity indices have appeared. Relative to R_i, they can provide coherency tests (quality control), add complementary information extending the R_i index and potentially, form the base for a future long-term index succeeding to the sunspot visual record. We will briefly review the main indices currently available. Table 2 summarizes the characteristics of the 6 indices most commonly used as reference scales for the solar activity:

- Total sunspot area, As (Baranyi et al., 2001; Hathaway et al., 2002; Balmaceda et al., 2005)
- CaII-K index (Donnelly et al., 1994; Foukal, 1996, 1998)
- 10.7 cm radio flux, $F_{10.7}$ (Tapping and Charrois, 1994)
- Total solar irradiance (TSI, Willson and Mordvinov, 2003; Fröhlich and Lean, 2004)
- Space-based MgII core-to-wing ratio (Viereck and Puga, 1999; Snow et al., 2005) and HeII flux (Floyd et al., 2002)
- Total and dipolar magnetic flux (Benevolenskaya, 2004; Krivova and Solanki, 2004), e.g. SODA index (Schatten and Pesnell, 1993)

All the indices have a much shorter temporal extent than R_i, sometimes less than 3 cycles. Several indices are produced by a single station and instrument ($F_{10.7}$, MgII, HeII), preventing an independent control of calibration and biases. Moreover, such isolated instruments, on the ground or in space, cannot provide a guarantee of long-term continuity. Other indices rest on several stations but

Table 2
Main characteristics of the global long-term solar indices, now available next to R_i

Index	Duration (cycles)	Since	Lin. Corr.	Linearity	Accuracy (%)	Issues
Sunspot area A_S	12	1874	0.97	Linear	10–20	• Definition of boundaries • Ratio RGO/SOON *(USAF)*
CaII-K index	8	1915		Time lag	No calibration	• Several uncalibrated series • NB: since 1996: PSPT
Radio $F_{10.7\ \mathrm{cm}}$	6	1940	0.98	Linear	3.5	• Undersampling • Empirical filtering rules
Total Solar 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

Some limitations and problems are briefly listed in the last column. Accurate indices are only available for the last few solar cycles.

with discontinuous records collected over different time periods (A_S, CaII-K index, magnetic flux, total solar irradiance). As each series relies on different instruments, detectors, observing techniques and processing methods, it is highly difficult and subjective to piece the individual series together. This is affecting particularly the sunspot area, due to varying definitions of sunspot boundaries (Pettauer and Brandt, 1997; Baranyi et al., 2001), and the CaII-K plage index, due to a lack of proper calibration of early photographic plates (Foukal, 1998).

Finally, many of the indices are chromospheric ($F_{10.7}$, CaII, MgII, HeII) or contain a significant chromospheric component (TSI). They are thus linked to the emerging magnetic flux by different emission processes (Donnelly et al., 1983; Gilliland, 1986). In particular, the weak and open magnetic fields (plages, network) play a significant and sometimes even a dominant role compared to strong closed fields (sunspots). This translates into non-linear or even non-univocal relations with R_i (e.g. TSI, Fig. 1 in Solanki and Fligge, 1999). Note however that there is a very strong linear correlation (correlation coefficient > 0.9) between R_i and many of those "young" indices, though sometimes over a limited range of values ($F_{10.7}$, TSI). This close correlation is particularly true for $F_{10.7}$ and the purely photospheric indices (A_S, magnetic flux) and gives a confirmation of the validity of visual sunspot counts as a quantitative measure of solar activity (Hathaway et al., 2002; Kane, 2002). Consequently, when considering a possible successor to R_i, it appears essential to use a photospheric index mostly sensitive to freshly emerged dipolar magnetic flux.

6. Towards a new global photospheric index?

Given the scientific and technical progresses that have accumulated since the invention of the SN, it is legitimate to consider a future replacement of the visual counts by another technique. However, as R_i will remain our only direct link with the past solar activity, it is critical to build an index in full continuity with the visual R_i series, thanks to a thorough understanding of the conversion between the new and the existing historical record.

6.1. Key requirements

Past mistakes and shortcomings of historical solar indices allow us to establish the following stringent requirements for future long-term activity indices. First, the "structural" requirements are:

- Sufficient observing base, i.e. multiple permanent observatories
- Absence of data gaps: robust and reliable technique (no instrument downtime allowed), multi-station network spread in longitude, stable funding

The above two requirements strongly point in the direction of simple instruments and processing techniques. This allows easy and cheap replication of the instruments, low maintenance and limited qualification requirements for the observers (e.g. voluntary contributors).

In addition, any new index will have to fulfil the following "integrity" requirements:

- Long training period (multiple solar cycles): full understanding of cycle phase dependencies.
- Clear fixed procedures and definitions must be adopted (as important as the observing technique)
- All raw observations must be archived (preferably in digital form): recovery from overlooked errors and updates of the index series based on improved knowledge and definitions are then possible

6.2. A promising option: white-light CCD imaging

An obvious technique now available is the broadband CCD imaging of the photosphere, as large CCD detectors and cameras are becoming cheaper and widely available. The CCD detector offers a high-linearity and digital data,

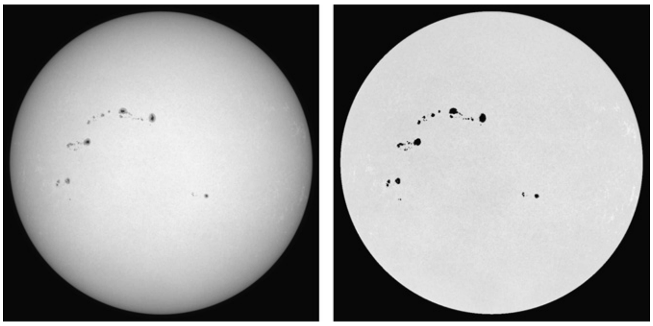

Fig. 6. Example of the application of image segmentation for the extraction of sunspots from a full-disk CCD image of the photosphere (From Zharkova et al., 2005).

allowing direct application of advanced image processing tools: real-time image selection, photometric and geometric corrections, limb darkening fit, feature extraction, image segmentation (Turmon et al., 2002; Zharkov et al., 2005; Zharkova et al., 2005) as illustrated in Fig. 6. In addition to straight sunspot counts, many other parameters can be extracted from such images (areas, contrast, position, proper motion, morphologies, etc.). Moreover, a quantitative measure of image quality can be derived from CCD images and thus a statistical relation can be established between image quality and the index value.

The central issue is then how to combine the spatially resolved image information into a single scalar value representing the overall solar activity. By just replicating the traditional sunspot count, we discard the information of the true spot size. On the other hand, a total sunspot area index will be affected by the problem of sunspot boundary definition and carries no information about spot clustering, just like the group SN R_G. Therefore, we might rather start from the original Wolf formula, which can be rewritten in the form:

$$R_W = \sum_g \left(10 + \sum_{f \in g} 1\right) \tag{2}$$

where the inner sum over index f refers to spots belonging to each separate group, and we could expand it by combining counts (sums) with variable weights, as follows:

$$R_C = \sum_g \left(W_g + \sum_{f \in g} S_A \cdot A_f\right) \tag{3}$$

where A_f is the true area of each spot, while the group-weight W_g could be defined according to the group morphology (group type) or evolutionary stage (emerging, stable, decaying). W_g and the scale factor S_A can be treated as free parameters and determined by the cross-analysis with the parallel R_i time series.

A major unknown that must also be determined to cross-calibrate such an index with R_i is the different impact of atmospheric seeing and contrast on visual and CCD observations. We can expect a non-linear relation leading to a seasonal dependency (1 year period) and a solar cycle dependency (variable ratio of small/big sunspots).

7. Conclusion

Over the last decades, the sunspot number has reached its maturity. We have shown here that it has developed and preserved several enduring assets, especially following the key transitions of 1882 and later of 1980. The simplicity and efficiency of ground-based sunspot instruments have provided long-lived uninterrupted observing sources, benefiting also from the natural ability of human vision to compensate the seeing effects. It relies over a stable observing principle and a wide observing base of many stations. All this leads to a robust index generation, where the subjectivity of individual observers is largely erased by the bulk number of independent observers.

Although several other parallel indices are now available, no immediate replacement of R_i by another long-term index is possible. Cross correlations with other individual or combined indices will be needed over multiple solar cycles to obtain a full understanding of seasonal, solar rotation or solar cycle effects.

Finally, we cannot finish without evoking the large educational and social impact of the SN. The meaning of the R_i index is easy to comprehend and provides a powerful communication tool between the public and the solar physics community, for all what touches the Sun and Sun–Earth relations. Moreover, anyone can take part directly and contribute to the sunspot record. Visual sunspot observing has thus also provided to many novice amateur astronomers the entry point to a vocation for professional astrophysics.

Data policy statement

All sunspot data produced by the SIDC are freely accessible in the framework of an *open source* data policy. However, we kindly request that any paper or electronic publication using or reproducing SIDC data includes explicit credit to the SIDC, or by preference, an entry in the reference list, as follows:

"SIDC team, *Monthly Report on the International Sunspot Number*, online catalogue: http://www.sidc.be/sunspot-data/, World Data Center for the Sunspot Index, Royal Observatory of Belgium, 'year(s)-of-data'."

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