INTER-CYCLE VARIATIONS OF SOLAR IRRADIANCE: SUNSPOT AREAS AS A POINTER

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(Received 4 September 1996; accepted 24 December 1996)

Abstract. Most of the present models and reconstructions of solar irradiance use the concept of Photometric Sunspot Index (PSI) to account for the influence of sunspots on solar brightness. Since PSI is based on measured sunspot areas a firm database of such areas is essential. We show, however, that a significant disagreement exists between the data provided by the Royal Greenwich Observatory (from 1874 to 1976) and newer measurements provided by the observatories of Rome, Yunnan, Catania, and the US Air Force. The overlap of the time intervals over which sunspot areas were measured at Greenwich and Rome allows us to quantify the difference between the Greenwich and other data sets. We find that the various data sets differ, at least in a statistical sense, mainly by a correction factor of between 1.15 and 1.25.

The revised time series of sunspot areas correlates well with the Zürich sunspot relative numbers over the last 120 years, with the relationship between sunspot areas and sunspot numbers changing only slightly from one cycle to the next. In particular, no indication exists for any extraordinary magnetic behavior of the Sun during the last 2 decades, as might falsely be concluded if the various sunspot area data sets are uncritically combined. There are, however, some indications that cycles 15 and 16 deviate from the rest. We expect that our results should have a significant influence on the reconstruction of the historical solar irradiance.

1. Introduction

Direct measurements of solar irradiance started in 1978, when the Earth Radiation Budget (ERB) experiment on the NIMBUS-7 satellite began operating. A number of experiments have followed and together they have provided a continuous record of the solar irradiance over the past 18 years. This time-span, however, is too short to establish a possible relationship between solar irradiance variations and the terrestrial climate. The reconstruction of solar irradiance for as long a period of time as possible is therefore of great importance. Reconstructions of irradiance at earlier times are based on indicators of magnetic activity with databases covering a sufficiently long time (e.g., Foukal and Lean, 1986, 1988, 1990; Lean and Foukal, 1988).

Magnetic indicators play a fundamental role because intrinsic variations of the solar brightness on a time scale of days to decades are, according to our current understanding, caused by changes in the magnetic field at the solar surface (Foukal, 1981; Woodard and Hudson, 1983; Chapman, 1987; Willson and Hudson, 1991; Fröhlich, 1992; see, however, Kuhn and Libbrecht, 1991, for a deviating point of view). One of the fundamental indicators used is the total projected area of all sunspots visible on the solar hemisphere, daily values of which have been recorded since 1874. Sunspot areas, together with sunspot numbers, therefore

Solar Physics **173:** 427–439, 1997.

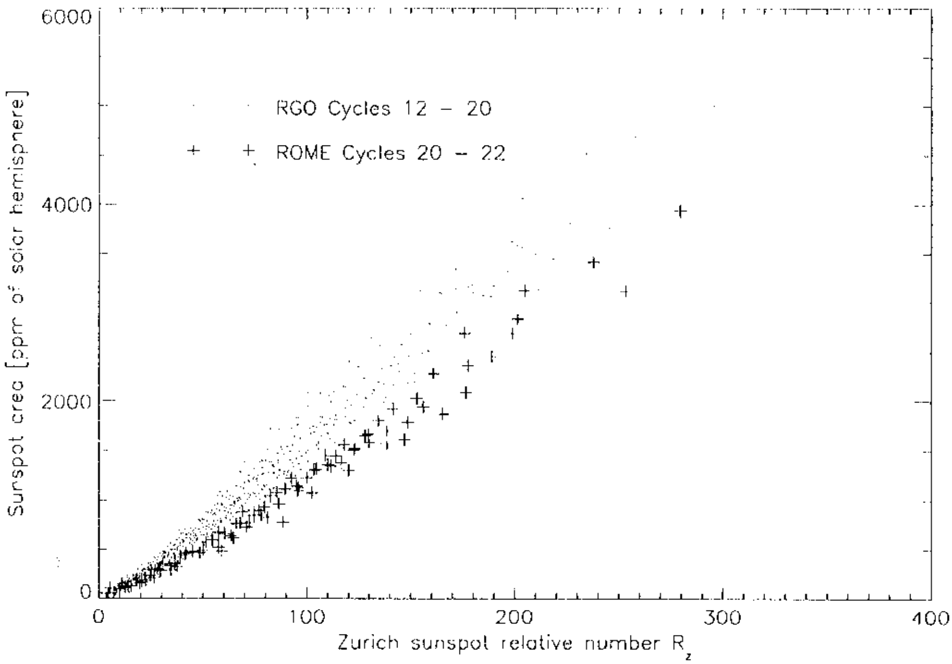

Figure 1. Sunspot area $\langle A_s \rangle$ versus sunspot number $\langle R_z \rangle$ for measurements published by the Royal Greenwich Observatory (dots) and the Observatory of Rome (plusses). Each symbol represents an average over bins of 50 points. The data from Rome lie significantly below the ones obtained by Greenwich Observatory. The intrinsic scatter of each data set, largely caused by inter-cycle variations, is too low to account for the observed disagreement.

provide the most complete database of solar activity over the last 120 years. A complete, reliable, and accurate time series of measured sunspot areas is essential for reconstructions of solar irradiance using current models.

The sunspot area enters into the irradiance reconstructions through the Photometric Sunspot Index (PSI), which describes dimming produced by the passage of sunspots across the solar disk (Foukal, 1981; Hudson, Silva, and Woodard, 1982). While reconstructing the solar irradiance over the past century using sunspot areas to derive the PSI, Foukal and Lean (1990) noticed that during cycles 21 and the beginning of cycle 22 the sunspot areas are unusually small relative to the sunspot number. In their model, based on the sunspot numbers, this effect produced a strong increase in solar irradiance over the last two cycles. Since the relationship between sunspot areas and sunspot numbers changed very little over the previous 10 cycles (as we show in Section 3), their interpretation would imply a fundamental change in the part of the solar activity related to sunspots between cycles 20 and 21. Consequently, the average size of sunspots or the average number of sunspots per group (or active region) would have been different in cycles 21 and 22 than in previous cycles. The average sunspot size and the number of sunspots in a group

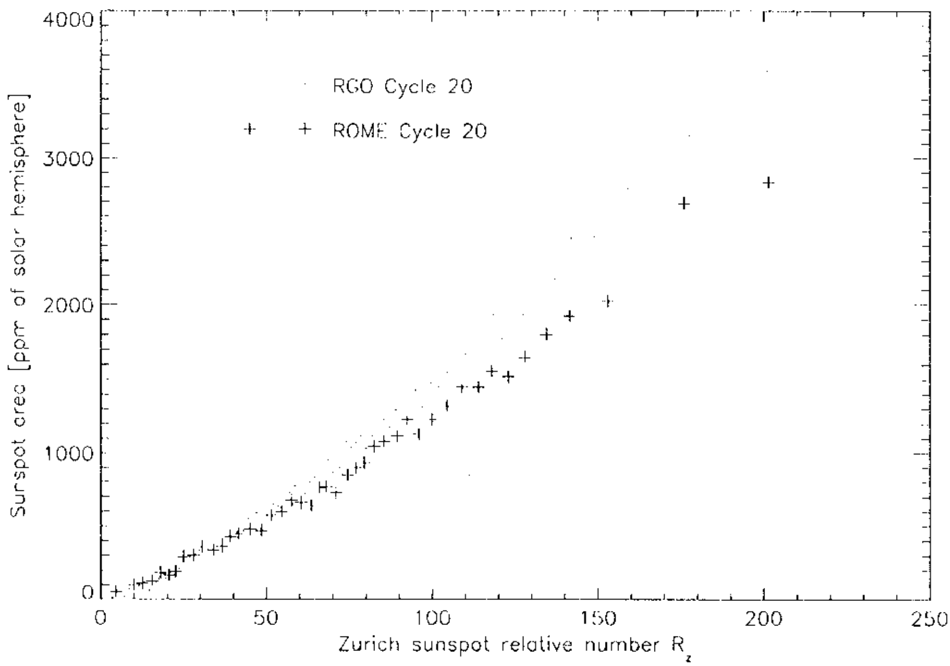

Figure 2. Sunspot area $\langle A_s \rangle$ versus sunspot numbers $\langle R_z \rangle$ for cycle 20 as measured by Rome (pluses) and Royal Greenwich Observatory (dots). The $\langle A_s \rangle$-values are again averaged over subsequent bins of 50 points each in order to stress their general trend. The difference between the two sets of data is particularly pronounced for $R_z \gtrsim 60$.

changes the ratio of sunspot relative number to sunspot area. In the present paper we consider an alternative and much more prosaic explanation.

In Section 2 we present evidence for an error in the inter-calibration of the different sunspot area databases and propose a consistent data set that covers the period 1874–1992. In Section 3 we investigate the inter-cycle variations of sunspot areas over the same period. We discuss the possibility of using Greenwich facular areas to reconstruct past solar irradiance changes in Section 4, and summarize our results in Section 5.

2. Combining Sunspot Area Databases

The Royal Greenwich Observatory (RGO) has compiled the longest and most complete record of sunspot areas. Their database is almost free of gaps and covers the period 1874–1976, i.e., it ends at the minimum between cycles 20 and 21. We argue in the following that there is a systematic difference between the RGO sunspot areas and those from other observatories covering the crucial period after 1976, which includes the interval for which direct irradiance measurements are available. We first illustrate this difference on the basis of the two longest data sets of sunspot areas, namely those of RGO and the Rome Astronomical Observatory.

In Figure 1 we plot sunspot area, A_s, from both observatories versus Zürich sunspot relative number, R_z. All observations of completely covered cycles from each observatory are represented in this plot (i.e., cycles 12−20 for RGO and cycles 20−22 for Rome) but in order to exhibit the trends better we have binned the data of each cycle from each observatory separately according to R_z, with 50 points per bin. The data obtained at Rome lie significantly below the ones published by the RGO. The intrinsic scatter of each cycle, as well as the cycle-to-cycle variations are too small to account for the observed disagreement. In the following, symbols within angled brackets $\langle \ldots \rangle$ represents binned values. Based on RGO data the slope of $\langle A_s \rangle$ versus $\langle R_z \rangle$ averaged over cycles 12−20 is 18.1 $\pm$ 1.5. The slope for cycles 20−22 based on the data from Rome is 14.1 $\pm$ 0.33, which lies clearly outside the range of the RGO data.

In order to demonstrate that the difference between the two data sets is related to the measurements or reduction, rather than to any intrinsic change of the Sun with time we consider more closely cycle 20, which was completely covered by both observatories. In Figure 2 we have plotted $\langle A_s \rangle$ obtained from both data sets versus $\langle R_z \rangle$ for cycle 20 alone. The data show the typical, nearly linear relationship between $\langle A_s \rangle$ and $\langle R_z \rangle$. The slope of the curve representing the measurements of Rome is clearly smaller than the one based on RGO data. The difference is particularly pronounced for $\langle R_z \rangle \gtrsim 60$. The data from Rome have to be multiplied by a correction factor of 1.15−1.25 in order to match the data from RGO.

There are several other observatories that have regularly measured sunspot areas during the past few years or decades. Most of them, however, started their recordings after 1976. As far as we know only the Rome Astronomical Observatory, at which measurements began in 1958, has at least one activity cycle in common with RGO (actually one and a half cycles). Therefore, the database of Rome can be used to forge a link between the older database of RGO and the more recent measurements of observatories in Yunnan and Catania, as well as the compilation by the US Air Force. Plots similar to Figures 1 and 2, but including data from the other observatories, suggest that the data from all these sources agree much better with those from the Rome Observatory than with the RGO values.

In order to check whether the above results is not just an artifact of our binning procedure we have also plotted 12-month running means of all sunspot area records as a second diagnostic. The averaging is now over time and not over sunspot number. As can be seen from Figure 3 the measurements from Rome and Yunnan agree rather well with each other (to generally within 150 ppm) except possibly for the first year of measurements at Yunnan. The agreement between Rome and Catania as well as between Rome and the US Air Force record is of a similar quality (both are not plotted). In contrast, there is a significant difference between the sunspot areas published by RGO and the ones reported by Rome (up to 500 ppm). Again,

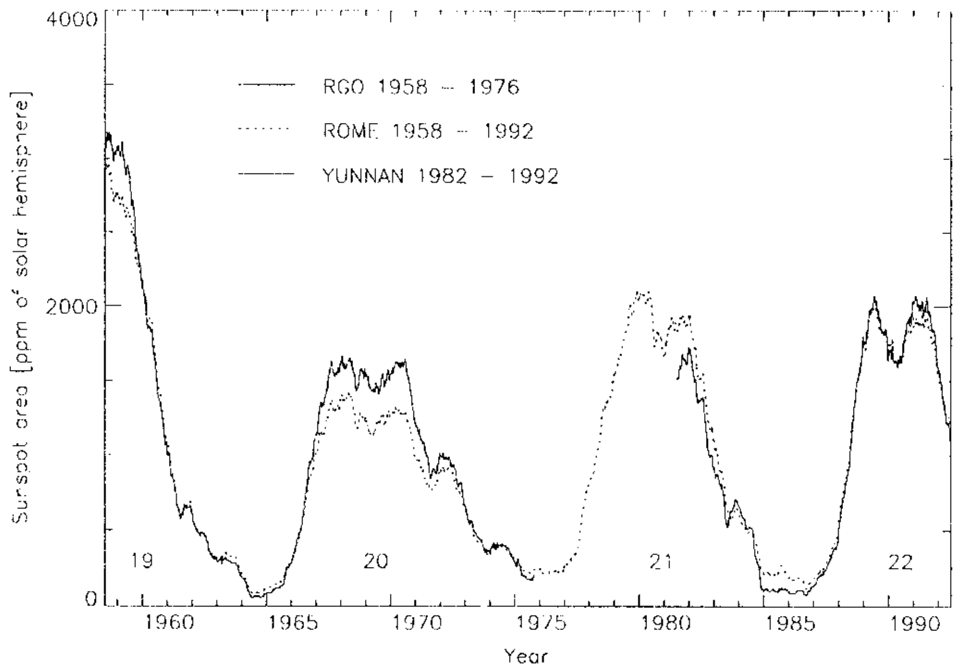

Figure 3. Comparison of different sunspot area measurements over the interval 1958 to 1992. The values of Rome, represented by a dotted line, can be used to forge a link between measurements of Royal Greenwich Observatory (RGO) (solid line form 1958–1976) and newer measurements of other observatories, e.g., Yunnan (solid line for 1982–1992). A 365-day running mean has been performed on all time series.

the difference is particularly pronounced around the maximum of cycles 19 and 20, in agreement with the results obtained from Figure 2.

The data from RGO differ by 15–25% from the Rome data averaged over the interval in which the two time series overlap. This correction factor is based on both cycles (19 and 20) and agrees with that derived from the direct comparison of $\langle A_s \rangle$ versus $\langle R_z \rangle$ for cycle 20. The uncertainty in this factor results mainly from differences between the shapes of the two curves (they differ significantly only for $\langle R_z \rangle \gtrsim 60$), from cycle-to-cycle variations (cycles 19 and 20 give different factors), and from differences between the Rome and other data sets for cycles 21 and 22.

Of course we cannot decide whether the RGO data have to be divided by the correction factor or the data from the other stations have to be multiplied by it. The sunspot area recorded at a given station depends on different things. Besides the personal bias of each observer, which according to Waldmeier (1978) can easily account for systematic differences of up to 15%, there are other effects due to different observing techniques or conditions which can significantly change the measured sunspot areas. For example, the result depends on the size of the smallest dark features counted as sunspots and on the way the location of the boundary of a sunspot is estimated (or defined).

The first effect can easily become significant, for, as Bogdan *et al.* (1988) showed, the smallest sunspots are by far the most common. We find from the size distribution they derived that if the lower limit in diameter of the smallest dark feature counted as a sunspot is increased from $1''$ to , e.g., $2.5''$ this would already explain the observed difference of about 20% in total sunspot area. Limited seeing produced by the Earth's atmosphere smears sunspot images and reduces contrast. It can cause the contrast of small sunspots and pores to become so small that they become effectively invisible. The fraction of the area of larger spots with a contrast above some threshold can also be decreased by seeing. If the estimate of the sunspot diameter differ by 10% between RGO and other stations, this would also explain the entire difference between the two. Hence, a difference in seeing between the South African station of RGO (which accounts for almost half of the data published by RGO) and the other observatories could conceivably account for the difference in A_s.

Any error or uncertainty in A_s affects the PSI, which in turn enters into and influences the reconstruction of solar irradiance (e.g., Fröhlich, Pap, and Hudson, 1994). Other factors entering into the PSI are the dependence of contrast on sunspot size (Steinegger *et al.*, 1990; Chapman, Cookson, and Dobias, 1994) and on solar cycle phase (Albregtsen and Maltby, 1978). These dependences are generally not taken into account when calculating the PSI. Fortunately, the reconstruction technique of Foukal and Lean (1986, 1988, 1990) to a large extent compensates for imperfections in PSI, as long as these are systematically the same over the whole time interval. They subtract the PSI from the total measured irradiance. The residuals are considered to be the facular contribution. These residuals are used to calibrate whichever proxy for facular brightness is used, e.g., 10.7 cm solar radio flux, Ca K plage index, He I 10830 Å index or sunspot relative number. If the PSI is increased by a constant factor over the whole time series (e.g., because of an error in A_s) then the residual or facular contribution is also increased, thus compensating largely for any error in A_s. Note, however, that the absolute value of the luminosity variations is affected by a PSI increase.

We have calculated that a change in A_s vs R_z taking place *in the course of the time series* has a significantly larger influence on the reconstructed irradiance curve than a systematic error affecting the whole time series equally. Therefore, as long as we are interested mainly in the shape of the irradiance variation curve as a function of time, and not in its exact amplitude, it is relatively unimportant whether the RGO data are scaled down or the other data are scaled up. In essence, for many purposes it is more important for the time series of A_s to be internally consistent, rather than correct in an absolute sense. This is fortunate since the latter appears currently difficult to achieve.

RGO and Yunnan observatory provide the most complete databases of sunspot areas during the periods over which they have carried out measurements. Based on this we propose the following combination of databases to obtain a consistent A_s time series:

1874–1976	Royal Greenwich Observatory,
1977–1980	Rome (multiplied by 1.2 ± 0.05),
1981–1992	Yunnan (multiplied by 1.2 ± 0.05).

As new data become available (e.g., from the Debrecen Heliophysical Observatory in Hungary) they may replace one or more of the above data sets after suitable calibration.

3. Inter-Cycle Variations of Sunspot Area Relative to Sunspot Number

In this section we consider changes in the sunspot area relative to sunspot number from one cycle to the next. Note that the ratio of A_s to R_z is (mainly) a measure of the concentration of sunspots into groups and the average size of sunspots. The A_s/R_z ratio is important since R_z has been used as a proxy of facular emission since 1874 by Foukal and Lean (1990). Accordingly, A_s/R_z is also a measure of the contribution to solar irradiance variations of sunspots relative to faculae. For the longer term evolution of solar irradiance it is therefore important to follow this ratio on a solar cycle time scale. We use the A_s record constructed in Section 2 for all further investigations.

Solar cycles 21 and 22 have sometimes been considered exceptional compared to previous cycles because the sunspot dimming function, PSI, during these two cycles is small compared to the expectations based on R_z and the relationship between R_z and A_s over the previous 9 cycles. Over these 9 cycles a reasonably good correlation between the two quantities is present, compare cycles 12–20 in Figures 4(a) and 4(b) (the PSI was calculated following Foukal, 1981). The A_s of cycles 21 and 22 become consistent with those of previous cycles, however, as soon as the various data sets of sunspot areas are combined in the manner described in Section 2. Compare Figure 4(a) with the solid curve in Figure 4(b). Hence, there is no indication to a large change in the ratio of sunspot area to sunspot number during the last two decades or over the last 11 cycles for that matter. Consequently, as far as the concentration of magnetic field into sunspots and sunspot groups is concerned the Sun remained surprisingly stable over the last 11 activity cycles.

Although the A_s/R_z ratio now varies less from cycle-to-cycle than before our relative calibration, it is nevertheless interesting to identify such variations.

One of the diagnostics we used in Section 2 (plots of $\langle A_s \rangle$ vs $\langle R_z \rangle$, such as Figures 1 and Figure 2) enables a closer look at inter-cycle variations of the solar activity pattern. The almost line ar relation between $\langle A_s \rangle$ and $\langle R_z \rangle$ and the small scatter of the binned data points within a given activity cycle make it possible to distinguish between the slopes of the different cycles. The value of this slope for

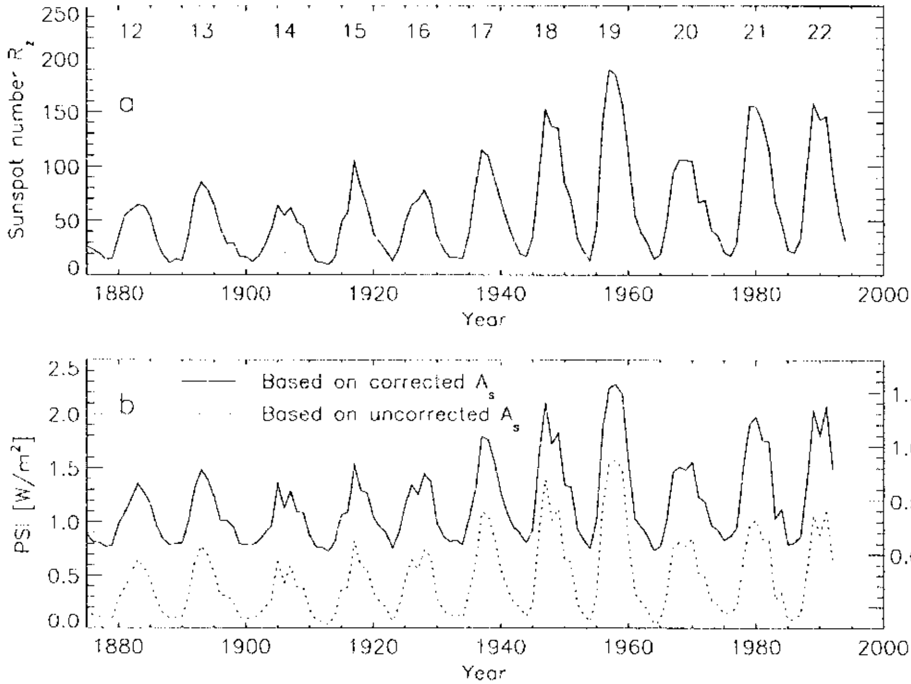

Figure 4. Evolution of Zürich relative sunspot number R_z (upper frame) and PSI (lower frame) over the last 120 years. The strong correlation between R_z and PSI based on the uncalibrated A_s values ends after cycle 20, when a strong increase in sunspot numbers is not accompanied by an appropriate increase in PSI (dotted line in the lower frame, which refers to the left-hand scale). The PSI based on the revised time series (solid line and right-hand scale in the lower frame), however, exhibits a good correlation with R_z for all cycles.

cycles 12–22 is plotted in Figure 5 (solid line; all values are normalized to the slope of cycle 18). In the following we test whether the fluctuations exhibited by this quantity are significant

The accuracy of the slope is limited by the deviation of $\langle A_s \rangle$ vs $\langle R_z \rangle$ from a straight line, especially at low $\langle R_z \rangle$. Consequently, we also calculated the ratio $\sum A_s / \sum R_z$, where the sums run over all the data points in each cycle. In addition, by restricting the sums to data from days on which R_z lies within a given range we are able to estimate the contribution from different parts of a cycle and also judge the sensitivity of the result to the summation boundaries.

These results are also shown in Figure 5. All values are normalized to cycle 18. The various curves may differ in detail, but all possess the same salient features. In general, the relationship between A_s and R_z changes only slightly from one cycle to the next (i.e., by less than 10%). There was, however, a significant increase in the $\sum A_s$ to $\sum R_z$ ratio as well as in the slope of $\langle A_s \rangle$ vs $\langle R_z \rangle$ from cycle 15 to cycle 16 (by about 25–30%).

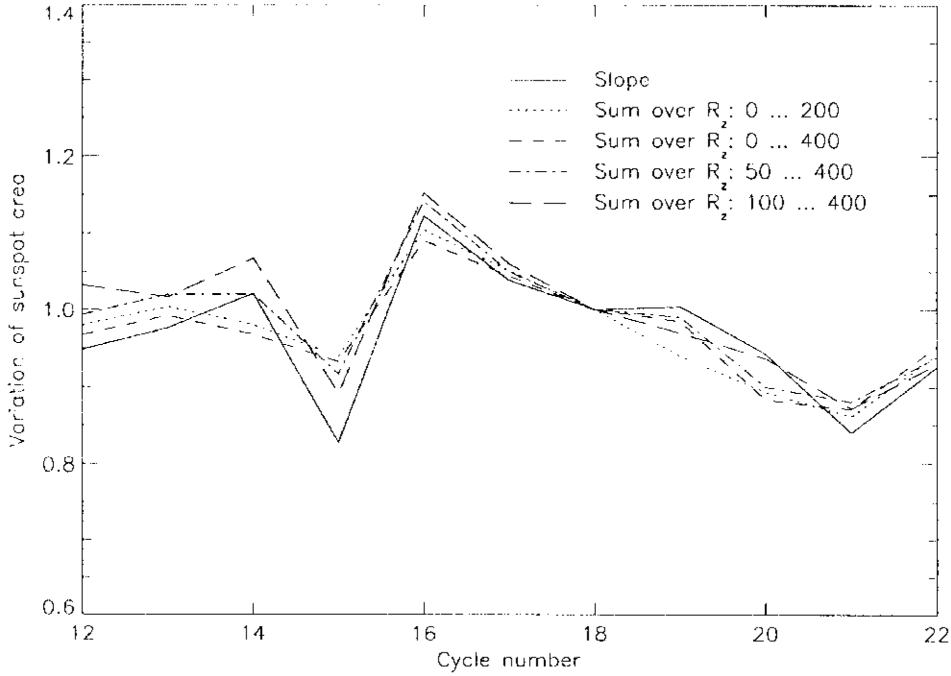

Figure 5. Cycle-to-cycle variation of corrected sunspot areas $\langle A_s \rangle$ vs $\langle R_z \rangle$. The variation is strongest between cycles 15 and 16. The solid line represents a comparison of the 10 cycles based on the slope of a linear regression (see text for details). The dotted, dashed, dot-dashed, and long dashed curves represents the summed averages over the following R_z ranges: 0–200, 0–400, 50–400, and 100–400, respectively (see again text for details). All values are normalized to those of cycle 18.

Cycles 21 and 22 are still relatively low even after the corrections described in Section 2. It must, however, be kept in mind that both cycles are subject to considerably larger errors due to the change of the underlying databases, the imperfections of our corrections and the incompleteness of the newer measurements. Based on this argument it appears more likely that the Sun has undergone a change in its magnetic activity pattern during cycles 15 and 16 than in more recent times. The cycle-to-cycle variations of A_s relative to R_z may be caused either by measurement errors (these would have to be observer-specific systematic errors since each point plotted in Figure 5 is an average of up to 4000 data points*), or may be of solar origin and thus could affect solar irradiance. Note that solar irradiance reconstructions making use of PSI automatically take such fluctuations into account.

* Note in particular that we found no change in observing staff at RGO between cycles 15 and 16, so that this explanation of the difference in the relation between A_s and R_z appears unlikely.

4. Greenwich Facular Areas: a Reliable Proxy?

Solar irradiance changes are thought to be the net result of the interplay of dark and bright photospheric features that evolve and move across the solar disc. In Sections 2 and 3 we have critically considered and re-calibrated data of one major proxy for the darkening due to sunspots. In this section we briefly consider proxies for facular brightening.

Unfortunately, no ideal proxy of solar brightening due to faculae is available, at least not on a longer time scale. The only source of information on facular emission for an equally long time period as A_s are white-light facular areas measured on a daily basis by RGO. These data do, however, suffer from many disadvantages. For one, they are extremely noisy, so that, unlike the A_s, they cannot be used on a day-by-day basis. Secondly, the record of white-light facular areas ends in 1976 just before satellite observations of the Sun started and to our knowledge no such facular area measurements have been performed since. Since only limb faculae are detected only a small fraction of all faculae on the solar disk at a given time are recorded. This underrepresentation is possibly even more severe due to the low intrinsic contrast of faculae, implying that smaller or weaker faculae may often have been missed, so that the results are probably strongly biased towards large, bright faculae. In addition, we find that the Greenwich facular areas change very strongly from one cycle to the next, much more strongly than the more reliably measured sunspot areas. We estimate that the cycle-to-cycle variation exhibited by Greenwich facular areas is a factor of 3–4 larger than the variations shown by A_s and, as we show later in this section, by 10.7 cm flux.

For the last few solar cycles facular brightness proxies such as Ca II K index (Foukal and Lean, 1988), Ca II K plage index (Foukal and Lean, 1988), He I 10830 Å equivalent width (Foukal and Lean, 1988; Brandt, Stix, and Weinhardt, 1994), Mg II h and k core-to-wing ratio (Pap *et al.*, 1994) or 10.7 cm radio flux (Brandt, Stix, and Weinhardt, 1994; Fröhlich, 1994) have been used with some success to reproduce solar irradiance measurements although some of these proxies are also affected by sunspots. These proxies can also be used to test whether the Greenwich facular areas can be used, at least after heavy averaging, to provide some information on the long-term evolution of solar facular brightness.

We have chosen daily solar radio flux measurements at 10.7 cm reported by telescopes near Ottawa (1947–1991) and Penticton (after 1991). They provide a long-term record of solar radio flux which covers more than 5 activity cycles. The main source of the 10.7 cm radio flux are faculae and the enhanced network, although there are also contributions from the undisturbed solar surface and sunspots (Tapping, 1987). The main disadvantage is that the 10.7 cm flux arises in the solar upper atmosphere, i.e., under rather different conditions than the photosphere and low chromosphere where the largest fraction of the total irradiance change occurs.

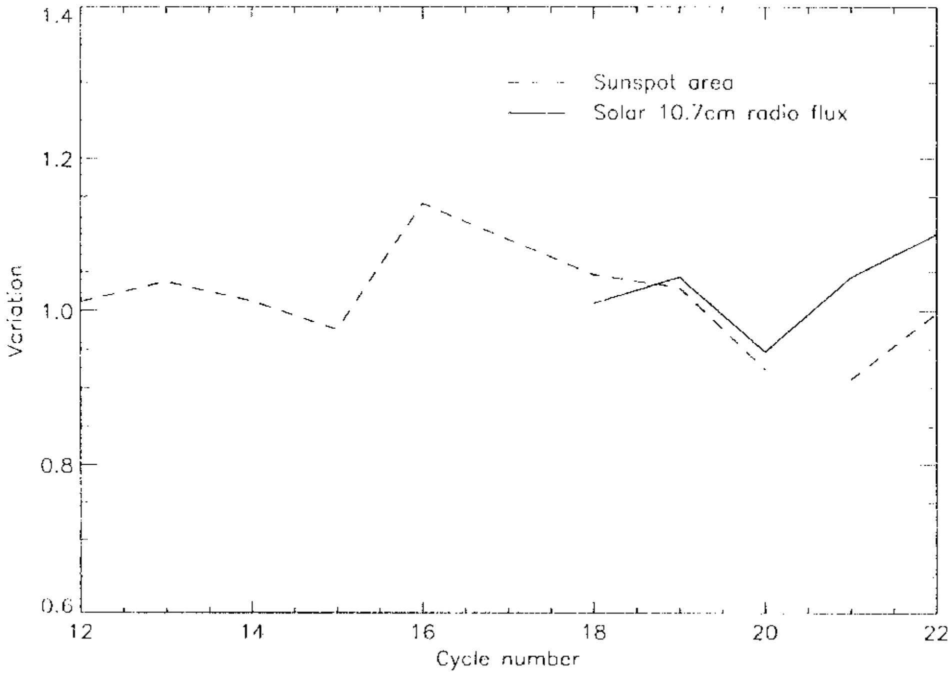

Figure 6. Comparison of Σ 10.7 cm / ΣR_z (solid) and $\langle A_s \rangle / \langle R_z \rangle$ (dashed) variations. The sums run over the whole range of R_z. The data are normalized to the mean value of cycles 18–20. While both curves agree well during cycles 18–20 there is a drop in the relation of A_s vs R_z relative to 10.7 cm vs R_z for cycles 21 and 22. The difference can probably be attributed to a larger uncertainty in A_s of the last two cycles relative to earlier cycles.

The 10.7 cm solar radio flux shows a good correlation with R_z (Covington, 1954, 1959, 1969; Foukal and Lean, 1990). However, there are small inter-cycle variations (see also Willson, Rabin, and Moore, 1987) which, again, can be studied by binning the 10.7 cm data according to R_z or calculating the ratio of Σ 10.7 cm / ΣR_z (in the manner described in Section 3 for A_s).

As expected, both averaging procedures lead to the same inter-cycle behaviour. The cycle-to-cycle variations of the Σ 10.7 cm / ΣR_z summed over the whole range of R_z are shown in Figure 6. They turn out to be approximately the same as the variations of $\Sigma A_s / \Sigma R_z$, which are also plotted in Figure 6. In fact the r.m.s. of the two curves in Figure 6 between cycles 18 and 22 is very similar. The inter-cycle variations of Σ 10.7 cm / ΣR_z are thus a factor 3–4 smaller than the inter-cycle variations exhibited by the RGO facular areas. This casts further doubt on the adequacy of RGO facular areas as a reliable facular brightness proxy. Both curves in Figure 6 are normalized to the mean of cycles 18–20. From this figure we see the limits of R_z as a proxy of facular brightness on a time scale of many solar cycles. Σ 10.7 cm / ΣR_z deviates significantly from a straight line.

There is good agreement between the inter-cycle variations of 10.7 cm flux relative to R_z and of A_s relative to R_z over cycles 18 to 20 which is no longer true for cycles 21 and 22. Considering, however, the uncertainty in A_s of cycles 21 and 22 relative to earlier cycles, it is not excluded that sunspot areas A_s and 10.7 cm radio flux correlate well on a cycle by cycle basis. In view of this it appears just as reasonable, at least on time scales longer than the solar cycle period, to use sunspot areas as proxies of facular brightness as it is to use sunspot number.

5. Summary and Conclusions

Sunspot areas are one of the basic parameters entering current models of long-term solar irradiance reconstructions. Here we have investigated the relationship between sunspot areas and Zürich sunspot relative numbers and find that this relationship has remained remarkably stable during the last 10 activity cycles. The change in this parameter apparent right after solar cycle 20 is attributed to a measurement uncertainty and disappears as soon as all data sets of sunspot areas are carefully inter-calibrated. In particular, we find that sunspot areas measured at RGO are systematically 15–25% larger than sunspot areas recorded at other observatories. The remaining inter-cycle variations of the relation between sunspot areas and sunspot numbers are strongest between cycle 15 and cycle 16.

Due to the lack of a long-term record of facular emission or an appropriate proxy similar to sunspot area, the inter-cycle variations of solar brightening due to faculae relative to R_z are usually neglected when reconstructing solar irradiance. The relation between 10.7 cm solar radio flux and R_z and between sunspot areas, A_s and R_z show some similarity on time scales longer than the solar cycle, and thus provides hints at similar inter-cycle variations of facular emission and sunspot blocking. Longer time series of facular proxies are necessary to put such a relationship on firmer ground.

Reconstructions of solar irradiance incorporating these results will be presented in a separate paper.

Acknowledgements

We are very grateful to Helen E. Coffey for the information she has provided on the NOAA/NGDC database concerning solar variability (from which all of the data used in this paper were taken). We are also thankful to Bernard Yallop for his helpful information on the sunspot program of the Royal Greenwich Observatory.

This work was supported by the Swiss Nationalfonds under NF grant No. 21–40428.94.

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