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Long-term behavior of emission from solar faculae: steps towards a robust index

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Abstract. Facular emission is one of the major contributors to long-term solar irradiance variations. Reconstructions of past facular variations, however, are strongly hampered by the lack of reliable proxies, particularly on time-scales longer than a solar cycle. We consider the five potential facular proxies with records covering more than 40 years. By suitably weighting and combining them we create a new proxy. In comparison with sunspot relative number the combined proxy exhibits enhanced values during solar cycles 16 and 17. This suggests that the Sun may have been brighter during those cycles than earlier models, which used sunspot numbers as the facular proxy, indicate.

Key words: Sun: activity – Sun: faculae, plages – solar-terrestrial relations – sunspots

1. Introduction

Space-borne experiments reveal that solar brightness varies due to the evolution of the Sun's magnetic field (Willson et al. 1981; Eddy et al. 1982; Hudson et al. 1982; Willson & Hudson 1991; Lean 1997; Fröhlich et al. 1997). The variations result from the competing influence of dark and bright magnetic features, i.e. sunspots and faculae, respectively (e.g. Solanki & Unruh 1997).

Current reconstructions of the contributions of solar active phenomena to solar irradiance variations separately model sunspot dimming and facular brightening. Time-series of sunspot area measurements allow for a relatively accurate reconstruction of sunspot darkening on both, long (inter-cycle) and short (inner-cycle) time-scales by means of the photometric sunspot index (PSI; Foukal 1981; Hudson et al. 1982, Fröhlich et al. 1994).

Faculae cannot be dealt with in the same manner. On short time-scales, i.e. shorter than the solar cycle, global indices like 10.7cm radio flux or Lyα flux measurements correlate well with irradiance residuals corrected for sunspot dimming and provide a reliable measure of solar brightening due to faculae and enhanced network. However, long-term (inter-cycle) variations of solar brightening are much harder to track due to the absence of a reliable proxy available over a sufficiently long time span (Schatten et al. 1985; Pap et al. 1994).

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Zürich relative sunspot number, $R_{\rm Z}$, is often used to track facular brightening on time-scales of decades to centuries (Foukal & Lean 1990; Lean et al. 1995), whereby the relation between facular emission and sunspot number is assumed to remain the same from one cycle to the next. It has been shown, however, that on a time-scale of decades the relation between two other possible proxies of facular emission, namely sunspot areas and 10.7cm flux, and sunspot number is not constant (Fligge & Solanki 1997; henceforth referred to as Paper I). The quantitative relationship between $R_{\rm Z}$ and other possible indices, such as Ca K plage areas, or the white light facular area measurements of the Royal Greenwich Observatory, has so far not been investigated. In the present paper we compare such relationships and attempt to construct a better long-term proxy of facular emission than each individual proxy by combining them in a suitable manner. The time appears ripe for such an analysis because digitized Ca plage areas obtained from Mt. Wilson plates have only recently become available (Foukal 1996). We stress that in this paper we are only interested in variations from one cycle to the next.

2. Proxies of facular emission

We only consider indicators of solar activity that have been monitored for at least 40 years. These are: 1. the Zürich relative sunspot number ($R_{\rm Z}$); 2. sunspot areas (A_s); 3. 10.7cm radio flux measurements ($A_{10.7}$); 4. Ca II plage areas (A_p) and 5. white light facular areas (A_f). The various indices are available for the following periods: Daily values of $R_{\rm Z}$ from 1818 to the present[1], A_s from 1874 to the present, $A_{10.7}$ from 1947 to the present, A_p from 1915 to 1984 and A_f from 1906 to 1976. We take the A_s values from the Greenwich observatory record prior to 1976 and from other observatories since then (we use the combined and calibrated data set described in Paper I). The facular measurements obtained prior to 1906 are incomplete and of lower quality and hence have not been used.

It is difficult to decide which of these proxies to choose as a unique representative of facular brightness since each of them

[1] For periods before 1874, i.e. before the interval covered by this paper, the group sunspot number of Hoyt et al. (1994) is probably the more reliable quantity and should be used. After 1874 the two data sets are almost indistinguishable.

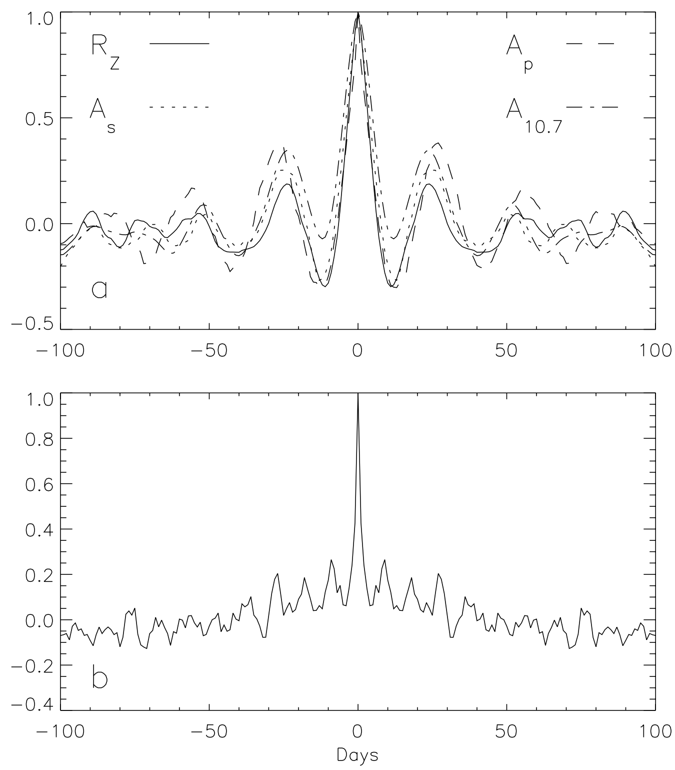

Fig. 1. Autocorrelation functions of the five investigated proxies for the year 1968 during the maximum of solar cycle 20. The shapes of the autocorrelation functions of $R_{\rm Z}$, A_s, A_p and $A_{10.7}$ (a) look very similar and are dominated by the 27 day rotation of the Sun. The autocorrelation function of A_f (b) shows a completely different behavior, mainly because the visibility of white light faculae is restricted to locations near the solar limb.

suffers from its own particular shortcoming. In the past $R_{\rm Z}$ has often been considered to be better than, say, A_s because the latter did not correlate so well with a well-established facular proxy, such as $A_{10.7}$. In Paper I we showed that this was mainly due to a flawed A_s data set. The corrected A_s time series correlates almost as well with $A_{10.7}$ as $R_{\rm Z}$.

To better compare the time-series of A_f to the other four proxies we plot their auto-correlation functions in Fig. 1 for the year 1968 during the maximum of solar cycle 20. The shapes of the auto-correlation functions of $R_{\rm Z}$, A_s, A_p and $A_{10.7}$ (upper panel) look very similar and are dominated by the solar rotation period around 27 days. The peaks have about equal widths in all four proxies, suggesting that they are tracking features of similar life-time. Note the anti-correlation present at a lag of around 12–14 days, which suggests an absence of active longitudes separated by 180° during the analyzed period.

In contrast, the auto-correlation function of A_f behaves rather differently (lower panel; see Brown & Evans 1980 and Foukal 1993 for more on A_f). Firstly, the central peak of the A_f autocorrelation is much narrower than of the other proxies (half width of 0.9 days versus 3–5 days), indicating that most faculae are detected only for a short time (1–2 days) near the limb (although the most prominent may well be followed over significant fractions of the disc). This is due to the limited visibility of white light faculae at the center of the solar disc and the influence of foreshortening near the limb. Secondly, the secondary maxima exhibited by the autocorrelation of A_f are lower than of the other proxies except $R_{\rm Z}$. Both the above facts, together with the expectation that faculae live just as long as, e.g., Ca plages, indicate that many faculae went undetected during at least one of their limb passages in the Greenwich record. This is easily possible due to their low contrast and fragmented morphology. The sum of the above features makes us give the Greenwich facular areas the lowest weight among the five considered proxies. We stress, however, that our conclusions are not affected by this choice.

Another comparison between the proxies is shown in Fig. 2, which shows a scatter-plot for cycle 18 of each of the other four facular proxies versus $R_{\rm Z}$. The proxies A_p and A_f depend non-linearly on $R_{\rm Z}$, while A_s and $A_{10.7}$ are linearly related. The quadratic terms of the fits through the A_p vs. $R_{\rm Z}$ and A_f vs. $R_{\rm Z}$ plots are significant at the 14σ level. Interestingly, total (i.e. disc integrated) Ca K core brightness varies linearly with $R_{\rm Z}$. Taken together with the non-linear relationship seen in Fig. 2a this means that the relationship between Ca K full disk brightness and A_p is non-linear, with larger areas of plage having a greater brightness density.

We know little about the cycle-to-cycle variation of this non-linear relationship between A_p and Ca K brightness. Furthermore, the A_p record ends at an unfortunate time, with less than half a cycle's overlap with direct irradiance measurements. Finally, the Ca plage areas partly suffer from poor calibration, since many of the older photographic plates are uncalibrated although this may be largely countered by the relatively high contrast of Ca plage areas. These factors somewhat reduce the reliability or usefulness of A_p, although we believe not to the level of A_f. Another point seen in Fig. 2 is that the scatter exhibited by A_f relative to $R_{\rm Z}$ (or to the other proxies for that matter) is larger than of the other proxies. This also supports the low weight we have given A_f.

The sunspot areas are well measured, but, again, the relationship between total facular brightness and spot area may itself show a cycle-to-cycle dependence. Also, on short scales A_s reproduces irradiance residuals less well than $R_{\rm Z}$.

10.7cm flux is probably the best facular proxy of those considered, being free of subjectivity in the measurements and obtaining a large contribution from plages and the network (Tapping 1987), although sunspots also contribute significantly (Tapping & Harvey 1994). In addition, models that reconstruct solar irradiance using 10.7cm flux reproduce the observations made with the ACRIM instrument (Willson & Hudson, 1991) better than models using $R_{\rm Z}$ or A_s as facular proxies (as mentioned above, A_p is not available for a sufficient length of time to test it against ACRIM as stringently). 10.7cm flux is only available for a relatively short period of time, however, which is not long enough to be of interest for climate studies. We therefore need to combine all the proxies to obtain a more reliable long-term record.

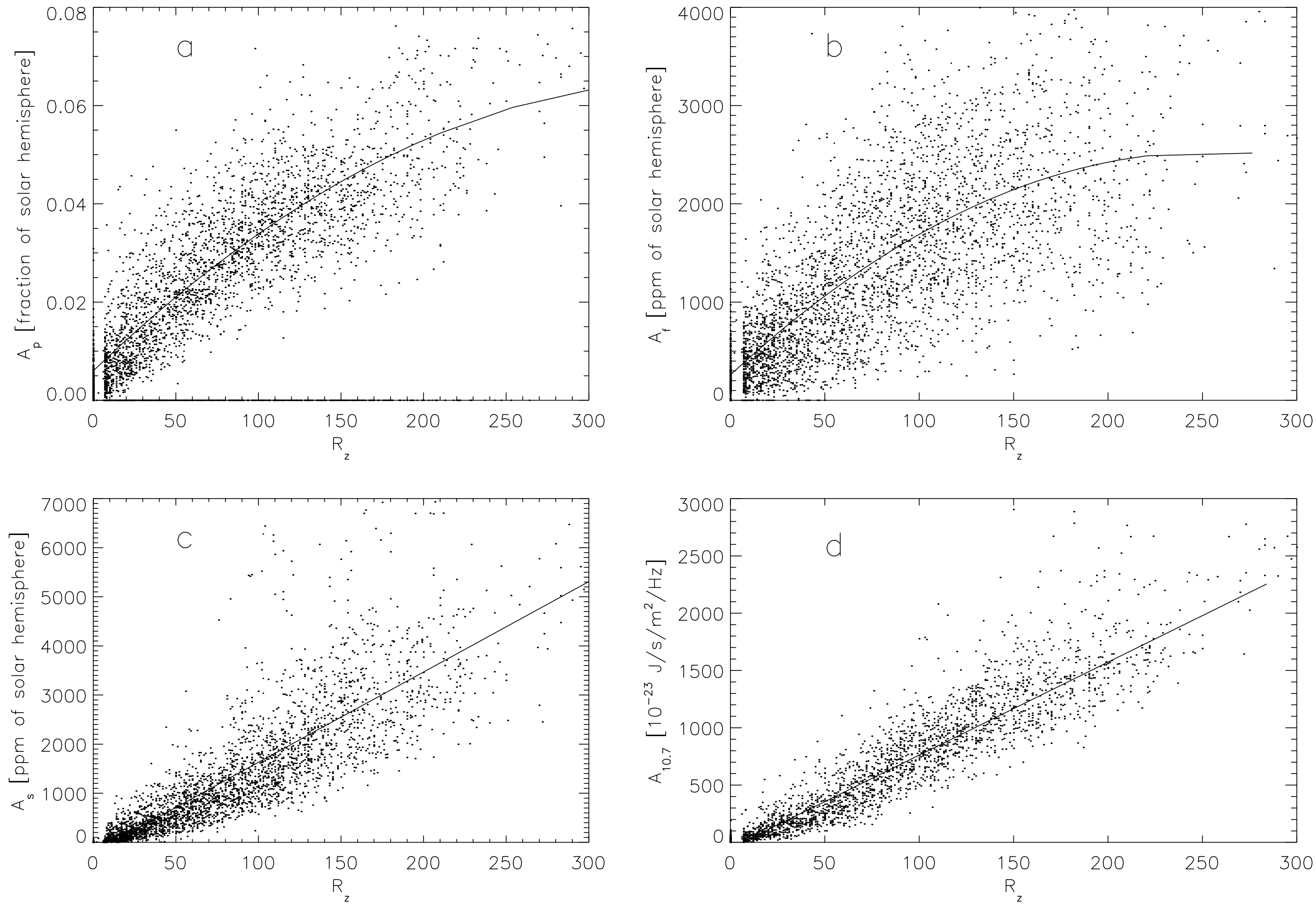

Fig. 2a–d Scatter-plots for cycle 18 of daily values of four potential facular proxies versus R_Z. **a** Plage areas measured in the Ca II K-line. **b** Areas of white-light limb faculae. **c** Sunspot areas. **d** Full disk measurements of 10.7cm radio flux. The solid curves are quadratic (upper frames) and linear (lower frame) regressions.

3. Inter-cycle variations of facular emission

Following Foukal & Lean (1990) we assume that the shorter-term variations of facular brightness (i.e. variations on time scales of days to years) are well described by R_Z. This is a reasonable choice for irradiance reconstructions aiming to cover long periods, since only $A_{10.7}$ of the other proxies is known to reproduce direct irradiance observations better, but possesses too short a record.

We search here for possible departures from the sunspot number record on time scales longer than a solar cycle by looking for common features in the other four proxies. This may help us to construct a more robust proxy from their combination. Hence we need to consider only the ratio of the cycle-averaged value of one of the other four proxies (let us generically call it A_x) to the cycle-averaged value of R_Z:

$$\tilde{C}_x(n) = \frac{\sum_i A_x(i,n)}{\sum_i R_Z(i,n)}. \quad (1)$$

The sum over i runs over all (or alternatively a part of) the points in a cycle, and n is the number of the cycle (n lies between 12 and 22).

For better comparison all values are normalized to the mean of the cycles that are common to all five proxies, namely 18–20, i.e. we introduce the normalized values C_x:

$$C_x(n) = \frac{3\tilde{C}_x(n)}{\tilde{C}_x(18) + \tilde{C}_x(19) + \tilde{C}_x(20)}. \quad (2)$$

We have found that the results depend only insignificantly on the details of the normalization.

By changing the summation boundaries in Eq. (1), we are able to estimate the contribution from different parts of a cycle. Hence, we restrict the summation boundaries in Eq. (1) to values of R_Z lying between two fixed boundaries, e.g. between 0–200, 0–400, 50–400 and 100–400 (cf. Paper I) and calculate an average over the four values for each cycle. The resulting ratios $\langle C_x \rangle$ are presented in Fig. 3, where $x = s, f, p$ or 10.7. Note that the summation index i is ordered according to increasing R_Z, so that changing the summation boundaries is equivalent to summing over different horizontal intervals in Fig. 2. The results depend on the summation interval most strongly for A_p and A_f, due to their non-linear dependence on R_Z. This is reflected in the larger error bars for $\langle C_p \rangle$ and $\langle C_f \rangle$ in Fig. 3 which mark the standard deviations of $\langle C_x \rangle$ obtained by varying the

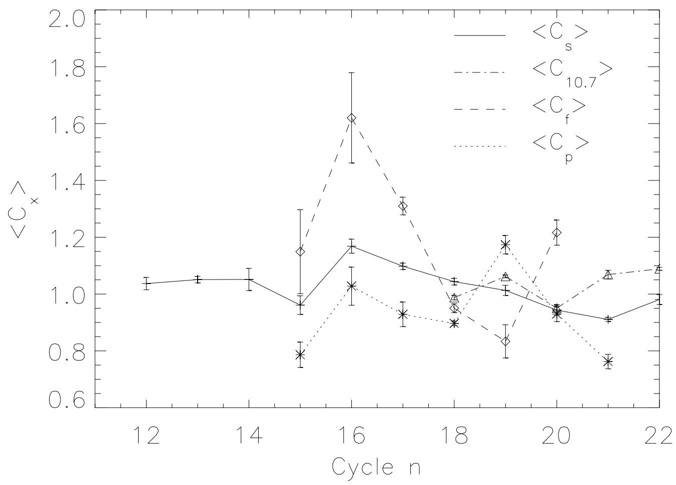

Fig. 3. Inter-cycle variations of ratios of sunspot areas ($\langle C_s \rangle$, solid line), 10.7cm radio flux measurements ($\langle C_{10.7} \rangle$, dash dotted), white light facular areas ($\langle C_f \rangle$, dashed) and Ca II K-line plage areas ($\langle C_p \rangle$, dotted) to sunspot number. The ratios are normalized and averaged as described in the text.

Table 1. Weights used to combine the four facular proxies. a_f, a_s, a_p and $a_{10.7}$ are the weights for, respectively, white light faculae, sunspot areas, Ca K plage areas and 10.7cm radio flux. $Q(16)$ and $Q(19)$ indicate the strength (relative to the mean of cycles 18, 19 and 20) of cycle 16 and 19, respectively.

$a_f : a_s : a_p : a_{10.7}$	Q(16)	Q(19)
1 : 1 : 1 : 1	1.27	1.02
1 : 2 : 2 : 4	1.20	1.05
1 : 3 : 3 : 9	1.17	1.06
1 : 4 : 4 : 16	1.16	1.06
1 : 8 : 8 : 16	1.13	1.07
1 : 8 : 8 : 64	1.13	1.07
1 : 8 : 4 : 16	1.17	1.06
1 : 4 : 8 : 16	1.12	1.08

summation boundaries. The inter-cycle variations of $\langle C_s \rangle$ and $\langle C_{10.7} \rangle$ are identical to those already seen in Paper I. The influence of restricting the summation over $R_{\rm Z}$ can also be judged from Fig. 5 of that paper.

On the whole, the ratios are constant to within 20%, except for $\langle C_f \rangle$. Whereas $\langle C_s \rangle$, $\langle C_p \rangle$ and $\langle C_{10.7} \rangle$ in Fig. 3 exhibit approximately the same level of variation, the $\langle C_f \rangle$ show a factor of four larger fluctuations. Another striking feature is that all three proxies extending sufficiently far back, i.e. sunspot, facular and plage areas, show a prominent increase relative to $R_{\rm Z}$ for cycle 16. The Ca II plage areas show an even stronger peak at cycle 19 which, however, is absent in the other proxies, as has already been pointed out by Foukal (1996). The peak of $\langle C_x \rangle$ at cycle 16 is the only feature that is common to all data sets.

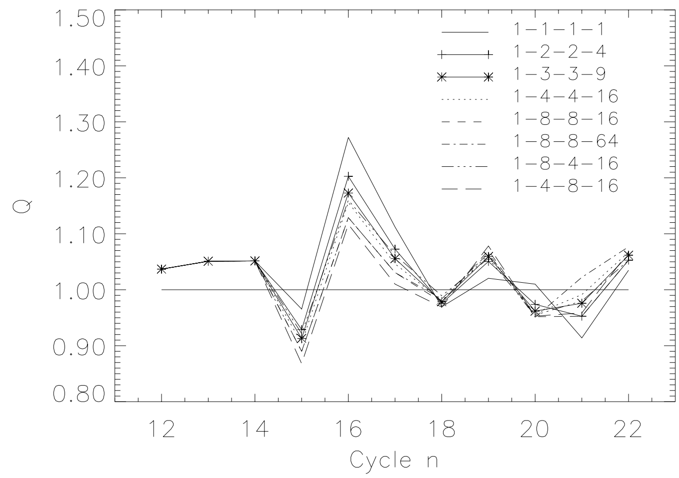

Fig. 4. Inter-cycle variations of the ratio, Q, of the combined proxy relative to $R_{\rm Z}$. The various curves correspond to the weights given in Table 1.

4. A combined proxy

In an attempt to obtain a more reliable and robust proxy of the long-term behavior of facular emission over the last 11 activity cycles we combine together the ratios of all four proxies to $R_{\rm Z}$. Their different estimated reliabilities are taken into account by weighting the $\langle C_x \rangle$ curves accordingly. Hence the $\langle C_x \rangle$ curves are combined by calculating

$$Q(n) = \frac{\sum_x a_x \cdot \langle C_x(n) \rangle}{\sum_x a_x}, \qquad x = f, s, p, 10.7, \tag{3}$$

where the weight a_x is set to zero if A_x and therefore $\langle C_x \rangle$ is not available for cycle number n.

The main problem with this approach is that assigning a weight to each proxy is relatively subjective. We have therefore tested how strongly Q depends on the choice of weights, subject to the following general restrictions. The time-series of white-light faculae is considered to be the least reliable and is consequently given the smallest weight: we always set $a_f = 1$. Full-disk measurements of $10.7cm$ radio flux, on the other hand, are given the largest weight ($a_{10.7}$). Weights to sunspot and plage area measurements are placed between these two extremes.

The tested weights, together with the resulting strengths of cycles 16 and 19 relative to the mean of cycles 18, 19 and 20 ($Q(16)$ and $Q(19)$, respectively), are listed in Table 1. The corresponding $Q(n)$ curves are plotted in Fig. 4.

The general shape of the Q curve is relatively insensitive to the exact choice of weights (at least within the above general restrictions on the relative weights). In particular, the dominance of cycle 16 is seen for all sets of weights we have tested. In view of the merits and demerits of the various data sets we have chosen $a_f : a_s : a_p : a_{10.7} = 1 : 3 : 3 : 9$ for our final proxy. This choice results in a Q curve that lies well inside the extremes we have found. The long-term variation of this proxy relative to $R_{\rm Z}$ is plotted in Fig. 5. The error bars take into account uncertainties introduced by changing the boundary conditions in Eq. (1) and the uncertainty in the weights a_x.

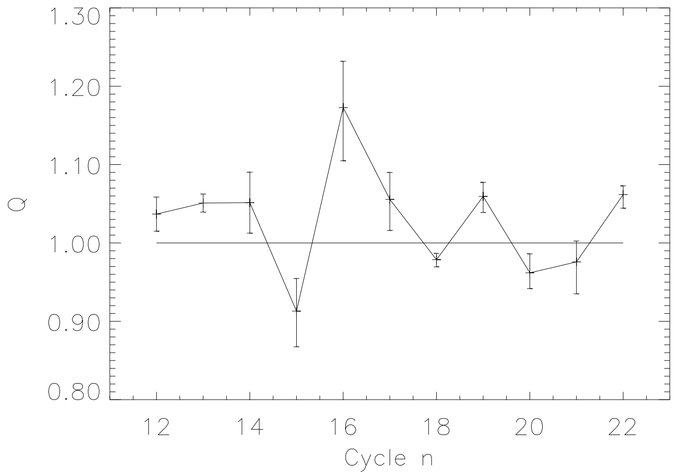

Fig. 5. Ratio, Q, of the final combined proxy of long-term facular emission to R_{Z} over the last 11 activity cycles. The presented curve results from a combination of all four proxies using the weights $a_f : a_s : a_p : a_{10.7} = 1 : 3 : 3 : 9$. It shows a prominent increase of facular emission relative to that by R_{Z} during cycle 16.

5. Summary and conclusions

Solar irradiance variations are thought to affect the Earth's climate system, although it is still controversial to what extent (Eddy 1977; Kelly & Wigley 1992). Current models of past solar irradiance on time-scales longer than the solar cycle generally use R_{Z} as a proxy of facular emission (Foukal & Lean 1990, Zhang et al. 1994, Lean et al. 1995). Our analysis, however, indicates that R_{Z} may not be the most appropriate parameter to track facular variations on time scales longer than the solar cycle. Other possible proxies of facular brightening show significant inter-cycle variations relative to R_{Z}. In particular, they all exhibit a prominent increase of facular emission during cycle 16 and to a lesser extent cycle 17. Consequently, the above models tend to underestimate the contribution of facular emission to total irradiance during the 1920s and 1930s.

This may have important consequences, since on time-scales longer than months, facular emission is the major contributor to irradiance variations over a solar cycle (Fröhlich & Pap 1989). In addition, it has been proposed that gradual brightness variations of the quiet Sun also follow a facular index (Zhang et al. 1994; Lean et al. 1995).

In this context it is interesting that R_{Z} lags the global land/sea surface temperature (as provided by the International Panel on Climate change IPCC), leading to a problem of causality between Earth's climate change and solar activity. Increased facular emission during cycle 16 (and 17) may conceivably contribute to resolving this dilemma. Detailed reconstructions of solar brightness over the past century, taking inter-cycle variations into account, are needed to answer this question in a satisfactory manner, however. This is because the contribution of active regions to total irradiance variations is dictated by a delicate balance between the darkening caused by sunspots and the brightening due to faculae. Any change in this balance can cause disproportionately large changes in irradiance. Reconstructions of solar irradiance variations taking our composite facular index into account are beyond the scope of this paper and are presented by Solanki & Fligge (1998).

Finally, we wish to point out that since all the proxies considered here only or mainly provide information on active regions, our final facular proxy is not a priori a *direct* indicator of the long-term behavior of the network or possible brightenings caused by intra-network magnetic fields. This proxy is also not sensitive to changes in the brightness of the quiet Sun due to, e.g., variations in convective properties. There is indirect evidence, however, that a facular proxy such as ours may track such quiet-Sun contributions to long-term irradiance variations (Zhang et al. 1994; Lean et al. 1995; Baliunas & Soon 1995).

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