SOLAR CYCLE MODULATION OF TOTAL IRRADIANCE: AN EMPIRICAL MODEL FROM 1874 TO 1988

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ABSTRACT

Evidence acquired during the past decade indicates that over time scales of the solar cycle, enhanced emission from bright solar faculae cause significant variations in the sun's total irradiance even though, on shorter time scales, the most pronounced variations are those resulting from the passage of dark sunspots across the solar disc. An empirical model which accounts for the competing effects of dark sunspots and bright faculae has been developed from the available radiometry in cycle 21, and extended back to the beginning of solar cycle 12. According to this model, the largest 11-year modulation of total irradiance during the C20th occurred in the most recent cycle 21.

OBSERVED VARIATIONS IN SOLAR TOTAL IRRADIANCE

Measurements of the sun's total irradiance have been made by two independent radiometers during solar cycle 21 and the ascending phase of cycle 22. These data are illustrated in Figure 1. Data obtained by the Active Cavity Radiometer (ACRIM)[1] on the Solar Maximum Mission satellite and by the Earth Radiation Budget (ERB)[2] experiment on the Nimbus 7 satellite were obtained from NASA's Climate Data System (NCDS) on 16 June 1989 and 21 Feb 1990, respectively. Both data sets in Figure 1 exhibit a solar cycle variation in which maximum irradiance coincides with maximum solar activity. Except for 1980, the ACRIM and ERB data are in general agreement during solar cycle 21, over both short and long time scales.[3] However, important differences between the long term trends are evident in the two measurements from 1987 to 1988, the ascending phase of the new solar cycle 22. These differences are currently being investigated.

A variety of previous studies have identified sites of enhanced magnetic activity on the solar disc as the primary origin of the sun's total irradiance variations,[3,4,5,6,7] over time scales of both solar rotation[6] and the solar cycle.[3,7] Dark sunspots, regions on the solar disc where magnetic flux is strongly concentrated, dominate the short term irradiance variations. Bright faculae, of greater spatial extent than sunspots, but of less concentrated magnetic flux, dominate variations over the 3 to 6 month time scales of active region evolution. Enhanced emission from scattered faculae outside of those active region boundaries identified by CaII K plage has been suggested as the source of additional brightness variations in the total irradiance over the solar cycle.[3,7] Global pulsations[1] and photospheric temperature changes[8] have also been suggested as alternative causes of the solar cycle modulation of total irradiance.

CALCULATING THE EFFECTS OF SUNSPOTS

Extant observations of the areas, locations and contrast of sunspots on the solar disc enable an independent estimate of the contribution of these active region features to changes in the total irradiance. This quantity, the sunspot blocking function, P_s, is calculated from Foukal[9] as

$$P_s = (C_s-1)\Sigma A_i\mu_i(3\mu_i+2)/2 \quad .....(1)$$

where A_i and μ_i are the area (in units of the solar hemisphere) and heliocentric location of the ith sunspot. $(C_s-1)=0.33$ is a measure of the average bolometric emission deficit in sunspots, relative to the background photosphere and $(3\mu+2)/5$ is the bolometric center-to-limb variation.

Other calculations of the sunspot blocking function, also called the photometric sunspot index, PSI, differ from that given in Equation 1. For example, Hoyt and Eddy[10] include separately the blocking by sunspot umbra and penumbra. Willson and Hudson[1] employ the same center-to-limb function as in Equation 1 but with $C_s-1=0.35$. Schatten et al.[5] have adopted a multi-parameter expression whose constants are derived by fitting the total irradiance observations. Shown in Figure 2 is a comparison of P_s determined from Equation 1 with the calculations of Hoyt and Eddy,[10] for data over three solar cycles. An approximately systematic difference of ~20%, thought to be associated with a different center-to-limb function in the Hoyt and Eddy calculations, is evident.

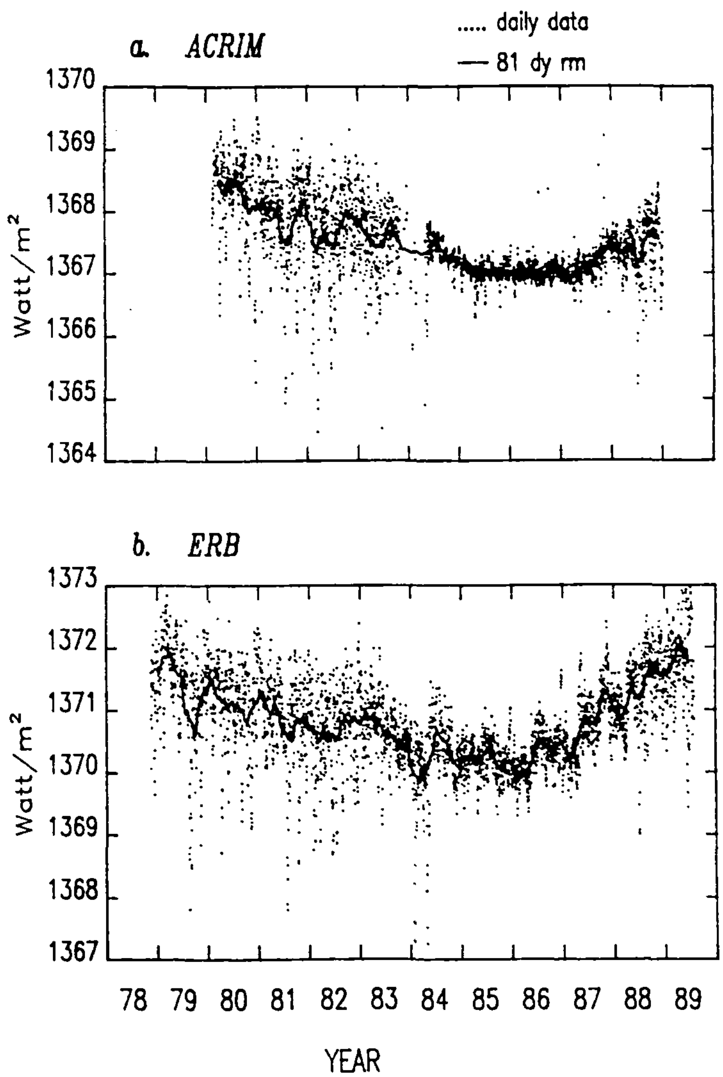

Fig. 1. Measurements of the sun's total irradiance during solar cycles 21 and 22, measured by the ACRIM and ERB experiments.

Standardizing the calculations of the blocking of the sun's total irradiance by sunspots is an important priority for future modelling efforts.

PARAMETERIZING THE FACULAR CONTRIBUTION

Faculae have been identified as playing a major role in the variations of the sun's total irradiance. However, a direct, independent estimate of their contribution to the irradiance variations is considerably less reliable than for the sunspot effect because faculae are more difficult to quantify. Their contrast at visible wavelengths is only a few percent, compared with ~33% for sunspots and, although their total disc area may be a factor of ten or more larger than that of sunspots, individual faculae, comprising polar faculae, ephemeral regions and network emission, are more dispersed across the solar disc, and less compact than sunspots.

In lieu of adequate observations of the disc coverage of faculae areas and of their contrast, an alternative approach to estimating their contribution to variations in the total irradiance is illustrated in Figures 3 and 4. Subtracting the calculated sunspot blocking function, P_s, and the quiet sun irradiance, S_o, from the measured irradiance, S, yields a residual time series, $S-P_s-S_o$. This residual time series represents the brightness source in the total

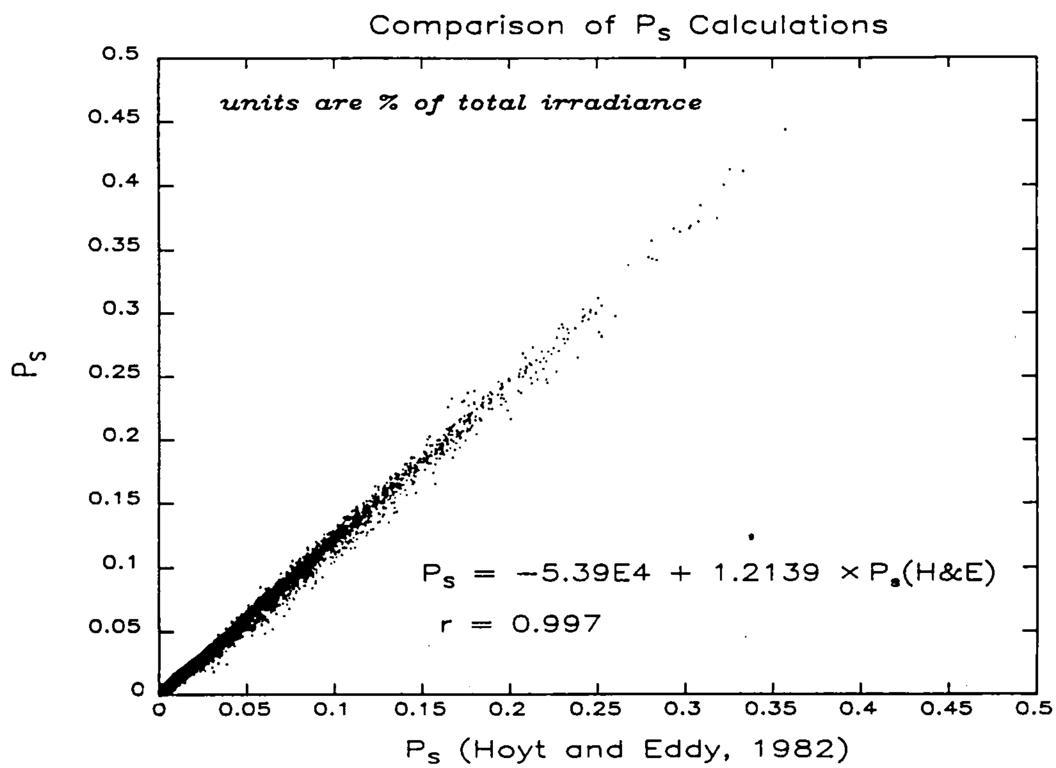

Fig. 2. Scatter plot of the sunspot blocking function, P_s, calculated by using Equation 1, with that calculated by Hoyt and Eddy,[10] from 1954 to 1984. The P_s calculated from Equation 1 are systematically higher, by about ~20%, than the calculations by Hoyt and Eddy.[10]

irradiance. Its temporal variations have been shown to track closely the changes in a variety of other emissions from the full solar disc, such as CaII K[12], the equivalent width (EW) of the Helium 1083 nm line[3,12] and HI Lyman α[13,14], whose variations are known to be dominated by changes in enhanced emission from CaII K plage, the chromospheric extensions of photospheric faculae. As illustrated in Figures 3 and 4, the correspondence between $S-P_S-S_O$ and $L\alpha$ is equally good during the ~27-day time scale of solar rotation, and over longer, solar cycle time scales. Fitting the $S-P_S-S_O$ residuals to a suitable facular proxy (such as the $L\alpha$ data) during the time interval of the S measurements allows the brightness variations in total irradiance to be calculated from that proxy time series during times when S was not measured.[14]

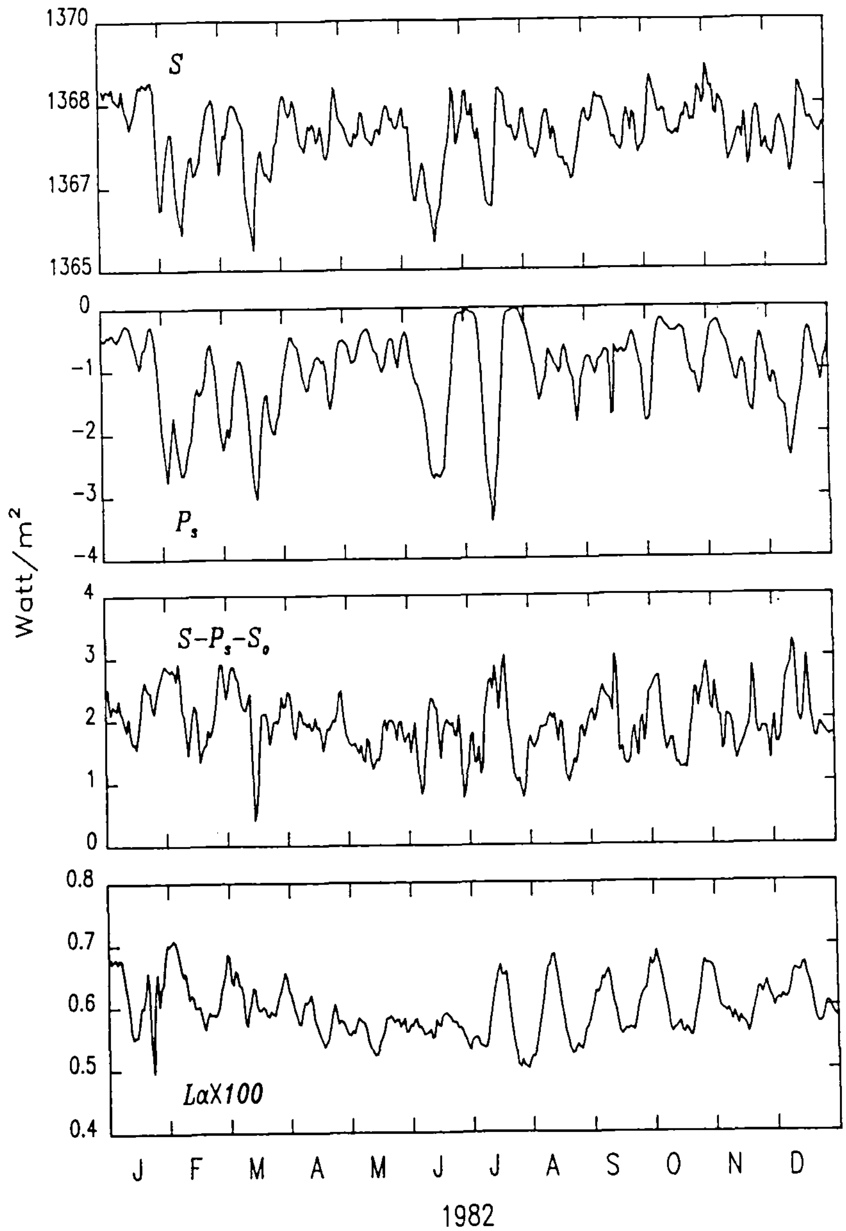

Fig. 3. Variations in 1982 associated with solar rotation in S, the total irradiance measured by ACRIM (top panel), P_S, the calculated sunspot blocking function (second panel), $S-P_S-S_O$ (third panel) and HI $L\alpha$, the Lyman α irradiance at 121.6 nm, measured by the solar spectrometer on the Solar Mesosphere Explorer (SME) satellite[11] (bottom panel).

EMPIRICAL MODEL OF TOTAL IRRADIANCE VARIATIONS

An empirical model of solar total irradiance variations is constructed by using P_S from Equation 1 to represent the sunspot blocking, together with a facular proxy transformed to an equivalent facular enhancement via its correlation with the $S-P_S-S_O$ residuals. Such models of the sun's total irradiance variation have been developed by using both the Helium 1083 nm EW and the Lyman α irradiance as proxies for the facular emissions during solar cycle 21,[3,14] and by using the 10.7 cm radio flux as a facular proxy during solar cycles 19, 20 and 21.[15]

ESTIMATED LONG TERM TOTAL IRRADIANCE VARIATIONS

To calculate historical solar total irradiance variations requires information about both the sunspot blocking and the facular brightening during each solar activity cycle. Observations of sunspot areas and locations made by the Greenwhich observatory allow P_S to be calculated from 1874, onwards. Obtaining an appropriate proxy for the facular variations prior to solar cycle 19 is more difficult. Foukal and Lean[14] have demonstrated that during solar cycles 19, 20 and 21, long term variations in the 10.7 cm full disk radio emission are highly correlated with long term variations in the sunspot number, R_Z.

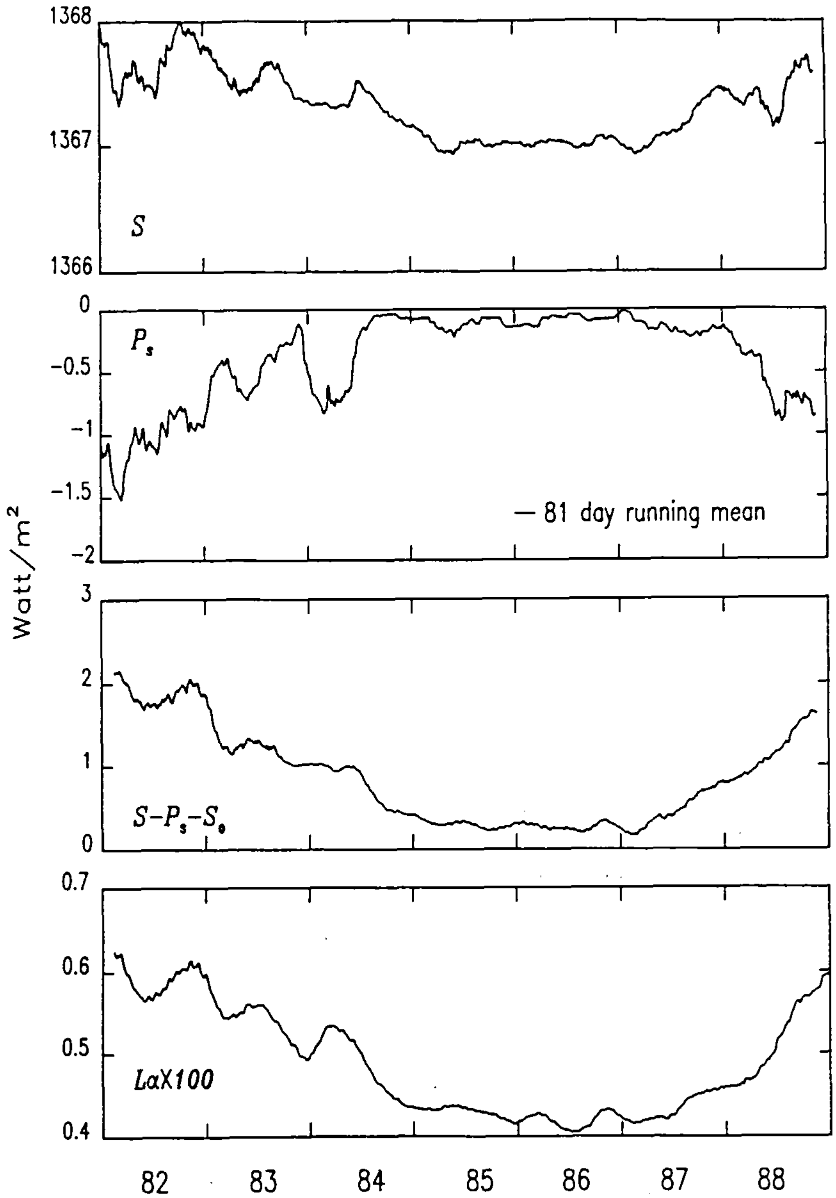

Fig. 4. Variations during solar cycle 21 and the ascending phase of solar cycle 22 in 81-day running means of S, the total irradiance measured by ACRIM (top panel), P_S, the calculated sunspot blocking function (second panel), $S-P_S-S_O$ (third panel) and HI Lα, the Lyman alpha irradiance at 121.6 nm, measured by the solar spectrometer on the SME satellite (bottom panel).

This correlation presumably reflects the weighting of R_z by the number of sunspot groups (rather than by individual sunspot numbers), indicative of the occurrence on the solar disk of large scale, complexes of magnetic activity which are sites of enhanced facular emission. Since R_z is available since 1874, the use of R_z as a facular proxy allows estimates of S variations from solar cycle 12 to the present.

Shown in Figure 5 are scatter plots of monthly mean values of the irradiance residuals $S-P_s-S_o$ with monthly mean R_z, during the interval 1980 to 1988. Figure 6 compares the measured irradiance residuals with reconstructions using the monthly mean R_z, converted to irradiance units via the linear regression coefficients determined from the scatter plots in Figure 5. By combining the facular variations estimated in this way from R_z, with the sunspot blocking calculated by using Equation 1, variations in the total irradiance can be estimated from 1874, onwards. Shown in Figure 7 are the monthly mean values of S, as calculated by an empirical model developed from both the ACRIM and ERB irradiance residuals. Note that there are slight differences between the S variations in Figure 7 derived from ACRIM radiometry and the S data in Foukal and Lean.[14] This is because, although the S data published in Foukal and Lean were labelled as being derived from ACRIM radiometry, they were actually derived from ERB radiometry, but using an earlier version of the ERB data than are used here to generate the variations shown in Figure 7.

Figure 7 illustrates that, according to this empirical model, there has been an overall increase of ~ 0.1% in the sun's total irradiance throughout the C20th, with the largest variation occurring in solar cycle 21. When the variations in Figure 7 are used as input for simple climate models, the corresponding change in global temperature is of the order of 0.02^o, or 6.7% of the 0.3^o temperature increase that has been detected since 1850.[14]

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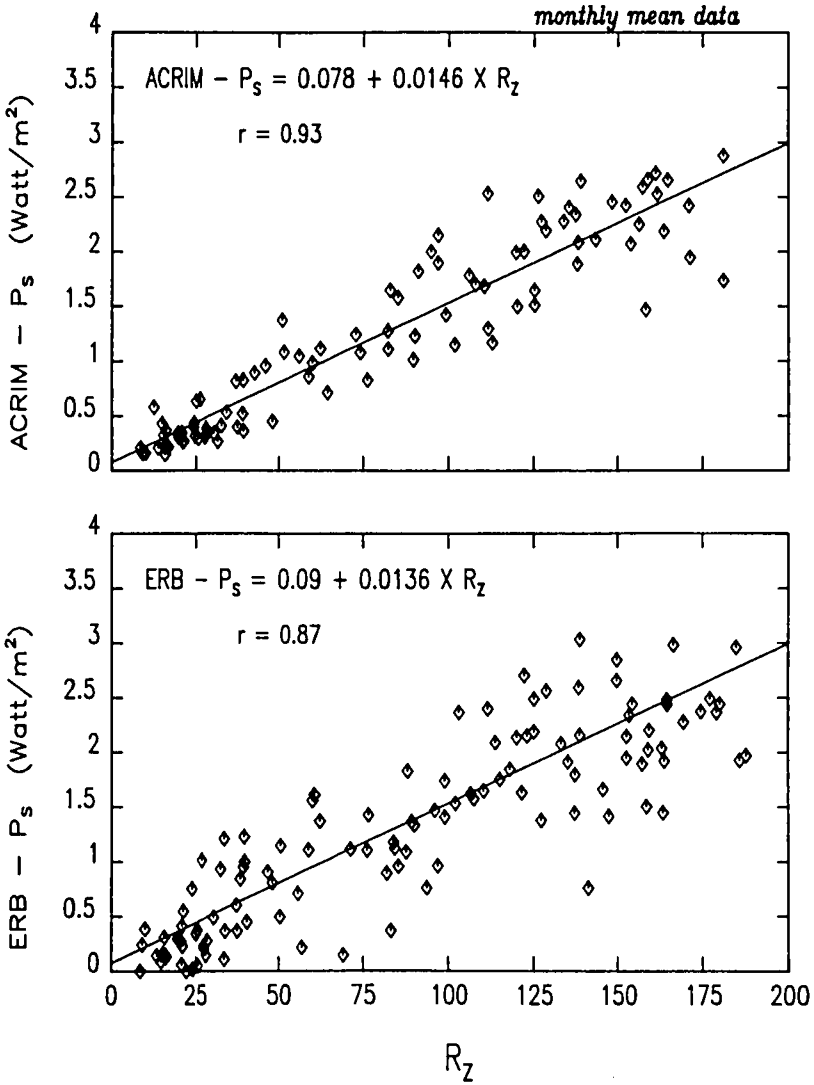

Fig. 5. Scatter plot of monthly mean values of R_Z with $S-P_S-S_O$, the residuals obtained by subtracting the sunspot blocking function from the total irradiance variations measured by ACRIM (upper panel) and ERB (lower panel).

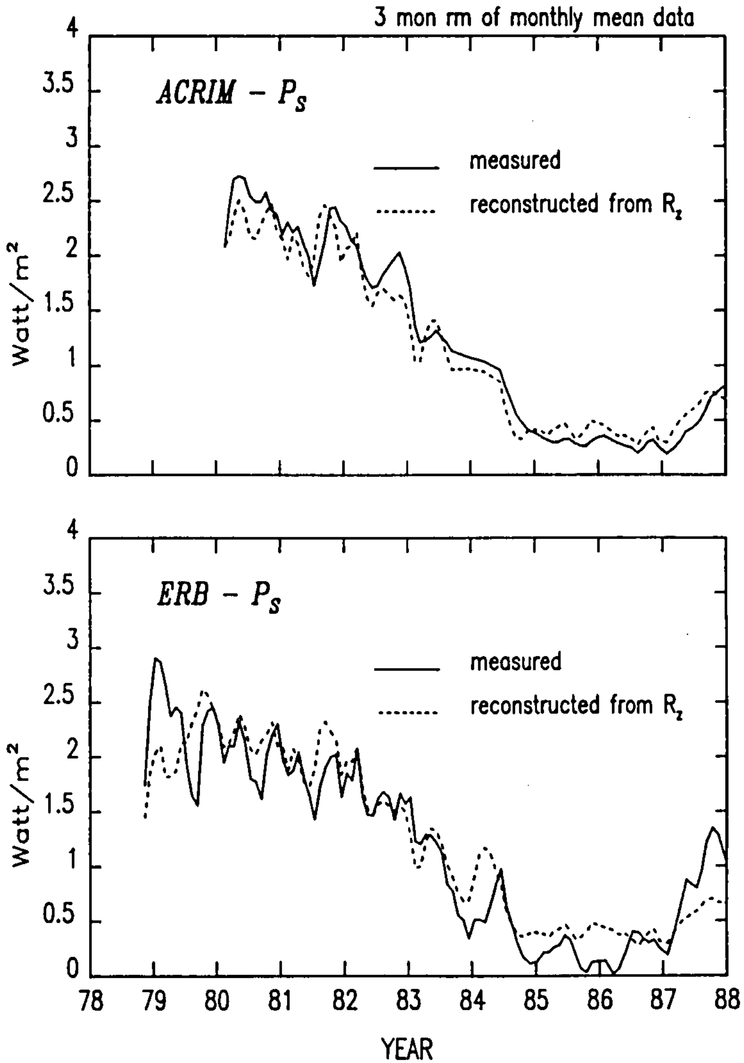

Fig. 6. Variations in 3-month running means of the monthly means of the irradiance residuals $S-P_S-S_O$ derived from ACRIM (upper panel) and ERB (lower panel), compared with the residuals calculated from monthly R_Z.

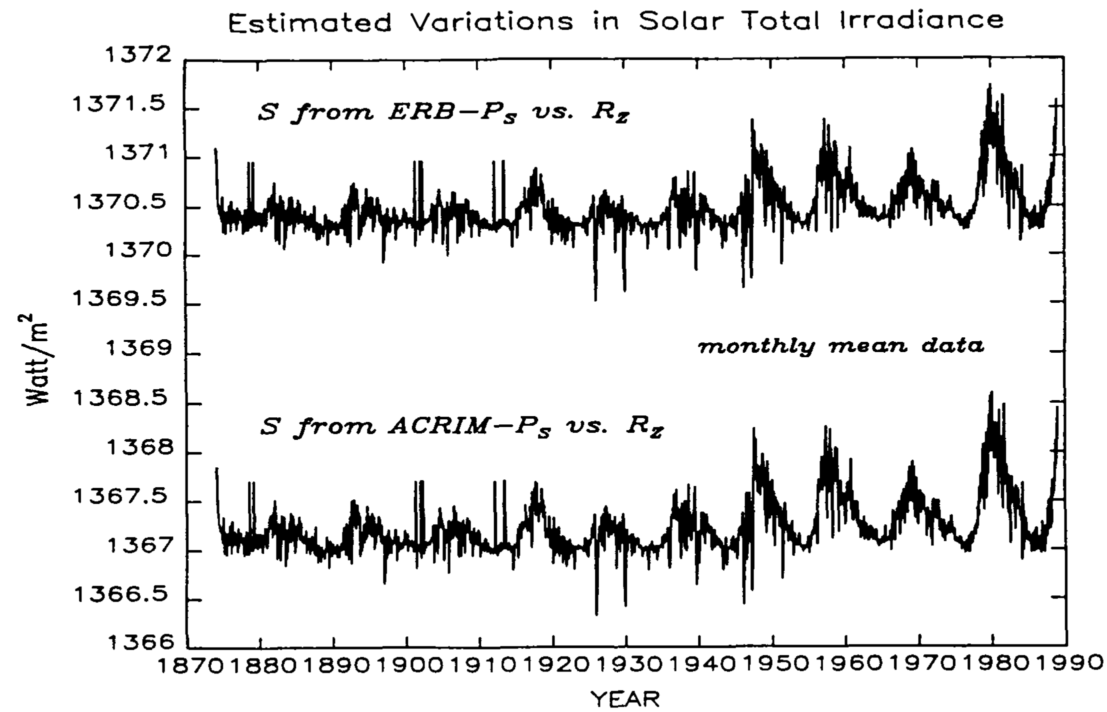

Fig. 7. Calculations of the variations in S during 1874 to 1985, estimated from both the ACRIM and ERB residuals.

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