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On the Variation of the Nimbus-7 Total Solar Irradiance

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ON THE VARIATION OF THE NIMBUS-7 TOTAL SOLAR IRRADIANCE

I. INTRODUCTION

Large-scale variations of the "solar constant" can have a major impact on the climate of the Earth.[1-8] One instrument designed to monitor such changes is the cavity pyrheliometer of the Earth Radiation Budget Experiment (called the ERB channel 10C) on the polar orbiting, Sun-synchronous Nimbus-7 satellite. The ERB experiment is located on the leading surface of Nimbus 7 and views the Sun for about 3 min each orbit as the satellite traverses the southern terminator.[9-11] The basic sensor of the radiometer is a toroidal-plated thermopile with an affixed-cavity receiver, composed of an inverted cone within a cylinder and having an interior that is coated with a specularly reflecting black paint.[9,12]

In this report, the daily Nimbus-7 ERB channel 10C observations that were just recently published (in "Solar Geophysical Data," vol. 564, part II, pp. 98–111, August 1991), spanning the interval November 16, 1978, through April 30, 1991, and including two solar maxima and the solar minimum between them, are averaged together to yield monthly means, and the monthly means are "smoothed" using the 12-month moving average (in the same sense as "smoothed" sunspot number[13]). The monthly means and smoothed monthly means are then compared to corresponding values of sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area in order to assess the degree of solar cycle dependency that may be inherent in the total solar irradiance measurements.

II. RESULTS

Figure 1 displays the monthly means of total solar irradiance based on the Nimbus-7 ERB channel 10C observations. The displayed data span from December 1978 through April 1991. The November 1978 mean is not used since the month of November was only partially observed (from the 16th through the 30th). Also shown in figure 1 are the composite mean (heavy line) and median (light line) values equal, respectively, to 1,372.02 and 1,371.86 (units are Wm^{-2}), the standard deviation ($sd = 0.65$), and the results of a runs test. From figure 1, one sees that during the 149-month period ending April 1991 the Nimbus-7 monthly mean solar irradiance (denoted s) was higher than average from December 1978 through 1980, below average during the interval 1981 to 1988, and again higher than average during 1989 through April 1991 (the end of the present data set). The coefficient of variation (= sd/mean) equals 0.047 percent, and s is inferred to vary nonrandomly at >99.9 percent level of confidence ($z = -8.019$; Lapin,[14] pp. 625–627).

In order to reduce the effect of random movements on time series data, one usually incorporates a "moving average" to describe the data set, which for monthly mean values is the "12-month moving average" (Longley-Cook,[15] pp. 175–177). Such smoothing, in fact, is often employed to illustrate the long-term behavior of a parameter (e.g., sunspot number and "smoothed" sunspot number) and, in particular, to illustrate the "solar cycle." In figure 2, the variation of s and s_o (i.e., the 12-month moving average) is shown in comparison with corresponding values of sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area for the interval November 1978 to September 1991. One sees that,

in the conventional sense, sunspot maximum for cycle 21 occurred in December 1979, with minimum for cycle 22 in September 1986 and maximum for cycle 22 in July 1989 (and a secondary maximum in early/mid-1991). On the other hand, the 10.7-cm solar radio flux and total corrected sunspot area had delayed maxima for cycle 21, occurring, respectively, in May 1981 and October 1981, the same cycle 22 minimum occurrence date (September 1986), and a similar cycle 22 maximum occurrence date (June 1989). The differing behavior of sunspot number and 10.7-cm solar radio flux in the vicinity of solar maximum has been traced to the variation of the magnetic complexity of active regions during the maximum phase of the solar cycle.[16] In contrast, the solar irradiance appears to have peaked prior to solar maximum for cycle 21 (on or before mid-1979), had a slightly delayed minimum occurrence date (January 1987), and has not yet peaked for cycle 22 (values are continuing to rise through the end of the data set, inferring that the solar irradiance maximum associated with cycle 22 has not yet occurred).

While s and s_o share a common "down-flat-up" general signature with sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area, a casual look at figure 2 clearly suggests that the correlation between solar irradiance and the aforementioned solar cycle related parameters may not be particularly strong. Indeed, linear regression analysis, comparing s and s_o against corresponding values of sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area, confirms this suspicion. For example, the strongest correlation using monthly mean values is the one between s and sunspot number (often denoted R), having a coefficient of correlation $r = 0.64$, a coefficient of determination $r^2 = 0.41$ (implying that 41 percent of the variation in s may be "explained" by the variation in R), and a standard error $se = 0.50$. Likewise, the strongest correlation using smoothed values is the one between s_o and smoothed sunspot number, having $r = 0.83$, $r^2 = 0.70$, and $se = 0.28$. The linear regressions for these two cases are, respectively, $\hat{y} = 1,371.3276 + 0.0071x$ and $\hat{y} = 1,371.2178 + 0.0076x$.

Figure 3 plots the residuals (observed value minus predicted value from the regression) for the s versus R fit, where the jagged line represents the actual residuals and the smoothed line is a 12-month moving average of the residuals (equivalent to the residual of s_o versus R_o, with subtle differences being attributed to round-off effects). Quite noticeable in figure 3 is the striking nonrandom variation of the residuals, suggesting a major "excess" in 1979 to 1980, a fairly large "deficit" in 1981 (and smaller deficits in 1983 to 1984 and 1988 to 1989), and the possibility of another "excess" in 1990, with perhaps a 2- to 3-year quasi-periodic variation imbedded in the residuals. A runs test of the residuals supports this view, with the indication being that the residuals vary nonrandomly at a >99.8-percent level of confidence.

Closer inspection of figure 2 reveals that, while a crude direct correlation may exist between s (and s_o) and the selected solar cycle parameters, in addition, there appears to be an inverse correlation involving their deviations, as well, where the deviation of a parameter is the difference between its monthly unsmoothed and smoothed values. Hence, when sunspot number, 10.7-cm solar radio flux, or total corrected sunspot area is higher than its moving average, one finds that the solar irradiance usually is below its moving average, and vice versa.[17-31]

III. DISCUSSION AND CONCLUSIONS

From the previous section, it is obvious that the total solar irradiance as measured by the Nimbus-7 ERB channel 10C experiment has undergone considerable variation over the period of observation, having monthly means that ranged from 1,370.85 (January 1984) to 1,374.28 (March 1979) and smoothed monthly means that ranged from 1,371.34 (January 1987) to 1,373.35 (July 1979).

Such peak-to-peak ranges suggest a variation about the mean of 0.25 and 0.15 percent, respectively. Additionally, while the long-term variation of s crudely resembles the long-term variation of R, significant differences in "timing" are apparent. Namely, peak s_o occurred on or before July 1979, minimum in January 1987, and maximum for cycle 22 on or after October 1990, the end of the presently available record; this is to be compared to maximum R_o having occurred in December 1979, minimum in September 1986, and maximum for cycle 22 in July 1989. Accepting the inferred correlation between s (s_o) and R (R_o) to be real, one finds evidence for large systematic excursions (excesses and deficits) occurring about every 2 to 3 years in the solar irradiance, perhaps, implying that some unknown effect must be imbedded within it. Such relative variations have also been reported by Willson and Hudson[28,29] on the basis of the Active Cavity Radiometer Irradiance Monitor Experiment aboard the now defunct Solar Maximum Mission satellite (1980 to 1989).

Table 1 summarizes important aspects of the total solar irradiance during the interval of December 1978 to April 1991 as measured by the Nimbus-7 ERB channel 10C experiment. Presuming the mean value of s to be absolutely determined (not really true, since Hickey et al.[9] have noted that the absolute calibration of the Nimbus-7 ERB channel 10C is uncertain to about ±0.5 percent, although its sensitivity and long-range stability is much better than this, as evinced from the coefficient of variation; for comparison, Mecherikunnel et al.[10] have noted that the Nimbus-7 ERB data are about 0.4-percent higher, on average, than that determined using the SMM ACRIM I data (see also Hoyt et al.[32])), and, representative of the Sun, one easily calculates the luminosity of the Sun to be $L = 3.86\times10^{33}$ erg s^{-1} which, when combined with the size of the Sun's radius ($R = 6.96\times10^{10}$ cm), allows one to compute the Sun's effective temperature ($T = 5{,}782.6$ K) and wavelength of maximum emission (from Wien's displacement law, 5,011.4 Å). Because of the observed variation in the solar irradiance, one infers that the Sun's luminosity, probably, is varying, as well (although it could be related to a redistribution of the outward flow of solar energy). Attributing the variation of L to be the result of "global" effects, one infers that either R and/or T must also have varied during the interval of observation. Based on the variation of s_o, having a peak-to-peak variation of 0.15 percent, one deduces that L had a peak-to-peak variation of 0.13 percent during the same interval. Also, based on the variation of s, having a peak-to-peak variation of 0.25 percent, one deduces that L had a peak-to-peak variation of 0.26 percent. Such values are not considered strong contributors to short-term climatic change on Earth, but perhaps could become important if the envelope of activity associated with the solar cycle should greatly increase (thereby, perhaps, contributing to global warming) or decrease (thereby, perhaps, contributing to global cooling). Based on the modern era of sunspot cycles, evidence exists supporting a long-term upward increase in solar activity;[33-35] thus, it may be that the mean total solar irradiance is increasing, as well (on decadal time scales), presuming, of course, a legitimate association between solar irradiance and the solar cycle.

If the change in luminosity is due entirely to a change in the solar radius, then one infers that during the interval of observation R had a peak-to-peak variation of about 0.07 percent (smoothed values) which is equivalent to a change of about 0.7 arc s, or about 0.13 percent (monthly mean values) which is equivalent to about 1.25 arc s. On the other hand, if the change in luminosity is due entirely to a change in the Sun's effective temperature, then one infers that during the interval of observation T had a peak-to-peak variation of about 0.04 percent (smoothed values) or about 0.06 percent (monthly mean values). It is not yet clear as to which mechanism, if either (i.e., a change in R and/or T), may be responsible for the inferred variation in L.[36,37]

The above comments presume, of course, that the variation in the Nimbus-7 ERB channel 10C total solar irradiance measurements are directly attributable to a variation in the Sun's luminosity and, further, that the inferred change in the Sun's luminosity is due to "global" effects, in particular, to

changes in either the Sun's radius or its effective temperature. The first presumption (that the variation in s implies a real variation in L) seems to be acceptable in that the same relative variations are found in both the Nimbus-7 ERB results and the SMM ACRIM I results,[28,29] that the two data sets appear to be closely correlated,[9] and that sensor drift/degradation is not believed to be a major contributor to the reported variations.[9,32] On the other hand, the second presumption (that the variation in L is due to "global" effects, in particular, to a real change in R) is controversial. The inferred change in the Sun's radius (about 0.1 arc s per year between 1979 and 1987), although small, is inconsistent with recent findings as reported by Wittman, Alge, and Bianda,[38] who conclude that there is no conclusive evidence for a genuine solar variation in the Sun's radius in excess of ±0.3 arc s, based on a study between July 7 and October 11, 1990 (values actually ranged from 959.703 to 961.505 arc s during the interval; however, the differences were attributed to "seeing" conditions; see also Ribes et al.[39] and Maier, Twigg, and Sofia[40]). As an alternative to a "global" effects explanation for the variation in irradiance, it should be noted that Pap[24] has reported a strong inverse correlation between dips in the solar irradiance records of SMM ACRIM I and the projected sunspot areas (i.e., the "uncorrected" sunspot area, as compared to the total "corrected" sunspot area used in this study) in quickly developing sunspot groups, and that an increase in irradiance above that blocked by newly forming groups seems more appropriate for older features, suggesting that a physical process may be taking place in deeper regions of the Sun through the interaction of magnetic fields with the convection (Hathaway and Wilson[41] and Arendt[42]). The influence of faculae has also been strongly touted as a possible explanation for irradiance variations (e.g., Foukal and Lean[25-27] and Foukal, Harvey, and Hill[43]). However, while rotational and evolutionary changes of sunspots and faculae are, indeed, consistent with gross features of the variability in solar irradiance (especially the short-term fluctuations during the relatively unchanging interval near solar minimum: 1982 to 1988), they appear incapable of fully accounting for the significant long-term fluctuation found in the data or, in particular, for the inferred "excesses" that were seen in 1979 to 1980 and 1990 to 1991 (Willson and Hudson[29]).

Related to the above issue is the apparent nonrandom variation of the residuals found for irradiance based on a presumed correlation between irradiance and the solar cycle (sunspot number). Recall that figure 3 shows this variation and suggests that there have been both large positive (excess) and negative (deficit) excursions during the interval of observation, displaying an apparent 2- to 3-year quasi-periodicity. Such a periodicity, if real, is strikingly similar to the 2- to 3-year periodicity reported by investigators performing studies on neutrino fluctuations, who argue for a pulsating character of the nuclear energy generation inside the core of the Sun (e.g., Raychauduri[44-46]), and to possible long-period oscillations of the solar diameter (e.g., Delache, Laclare, and Sadsaoud[47] and Ribes et al.[39]). On the other hand, perhaps, the inferred 2- to 3-year quasi-periodicity found in the residuals is somehow merely an artifact of the analysis, although this seems unlikely because of the now two apparent "excesses" (1979 to 1980, also noted by SMM ACRIM I, and suggested for 1990 to 1991), as well as the apparent phase change in irradiance relative to solar maximum (irradiance maximum occurred before sunspot maximum in cycle 21, while it occurred after sunspot maximum in cycle 22).

In conclusion, the Nimbus-7 ERB channel 10C total solar irradiance has been shown to vary nonrandomly during the interval December 1978 to April 1991, about a mean of 1,372.02 Wm^{-2} ($sd = 0.65$ Wm^{-2}). Smoothing the monthly means by means of a 12-month moving average (in the same sense as sunspot number) generates a curve ($se = 0.24$ Wm^{-2}) that is, at first glance, strikingly similar to that of the sunspot number, although careful inspection suggests differences. For example, the timing of irradiance maxima (relative to sunspot maxima for cycles 21 and 22) and minimum (relative to sunspot minimum for cycle 22) do not exactly match. Solar irradiance maximum for cycle 21 appears to have occurred several months or more prior to sunspot maximum, and solar irradiance minimum for cycle 22 appears to have occurred several months after sunspot minimum. Also, while sunspot maximum for

cycle 22 is observed to have occurred in July 1989, solar irradiance maximum appears to have not yet occurred. Additionally, while both cycles 21 and 22 appear to have been of comparable size (sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area), the maximum observed smoothed value of solar irradiance for cycle 22 is 0.74 units smaller than was observed for cycle 21. Because solar irradiance has a more sinusoidal appearance than sunspot number, it may be that the occurrences of irradiance maximum and minimum values will always be imprecise.

Linear regression analysis, comparing solar irradiance against sunspot number (or 10.7-cm solar radio flux or total corrected sunspot area), suggests only the possibility of a weak correlation. Presuming the correlation to be genuine, however, one finds that the residuals (observed solar irradiance values minus predicted values) vary nonrandomly, with a major "excess" having occurred in 1979 to 1980, a major "deficit" in 1981, and, perhaps, another major "excess" in 1990 to 1991, with a quasi-periodic 2- to 3-year variation possibly having occurred throughout the interval of observation.

Finally, the observed variation in solar irradiance implies that the Sun's luminosity varies with time. The inferred 0.1-percent variation in luminosity can be easily accounted for by a real change in the Sun's radius (0.07 percent or about an arc s) and/or by a real change in the Sun's effective temperature (0.04 percent or about a few degrees) during the interval of observation. Such an explanation, however, remains highly controversial, but may be required if one is to fully explain the long-term behavior of solar irradiance variation, especially in the vicinities of solar maxima (i.e., intervals of "excess" solar irradiance). Continued monitoring of the solar irradiance is mandatory to determine if the observed variations are truly attributable to the solar cycle and to determine the ramifications of a long-term upward trend in sunspot number values.

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Table 1. Solar irradiance, luminosity, radius, temperature, and wavelength of maximum emission.

Date	Comment	Value	L	R	T	Wavelength
January 1984	Lowest Obs. s	1,370.85	3.855	6.957	5,781.4	5,012.4
January 1987	Lowest Obs. s_o	1,371.34	3.857	6.958	5,781.9	5,012.0
—	Mean s	1,372.02	3.859	6.960	5,782.6	5,011.4
July 1979	Highest Obs. s_o	1,373.35	3.862	6.963	5,784.0	5,010.2
March 1979	Highest Obs. s	1,374.28	3.865	6.966	5,785.0	5,009.3

NOTE: Solar irradiance is in units of Wm^{-2}, luminosity (L) in units of 10^{33} erg s^{-1}, the radius (R) in units of 10^{10} cm and based on a constant effective temperature (= 5,782.6 K), effective temperature (T) in units of degrees Kelvin and based on a constant solar radius (= 6.96×10^{10} cm), and wavelength of maximum emission in units of Angstroms (10^{-8} cm).
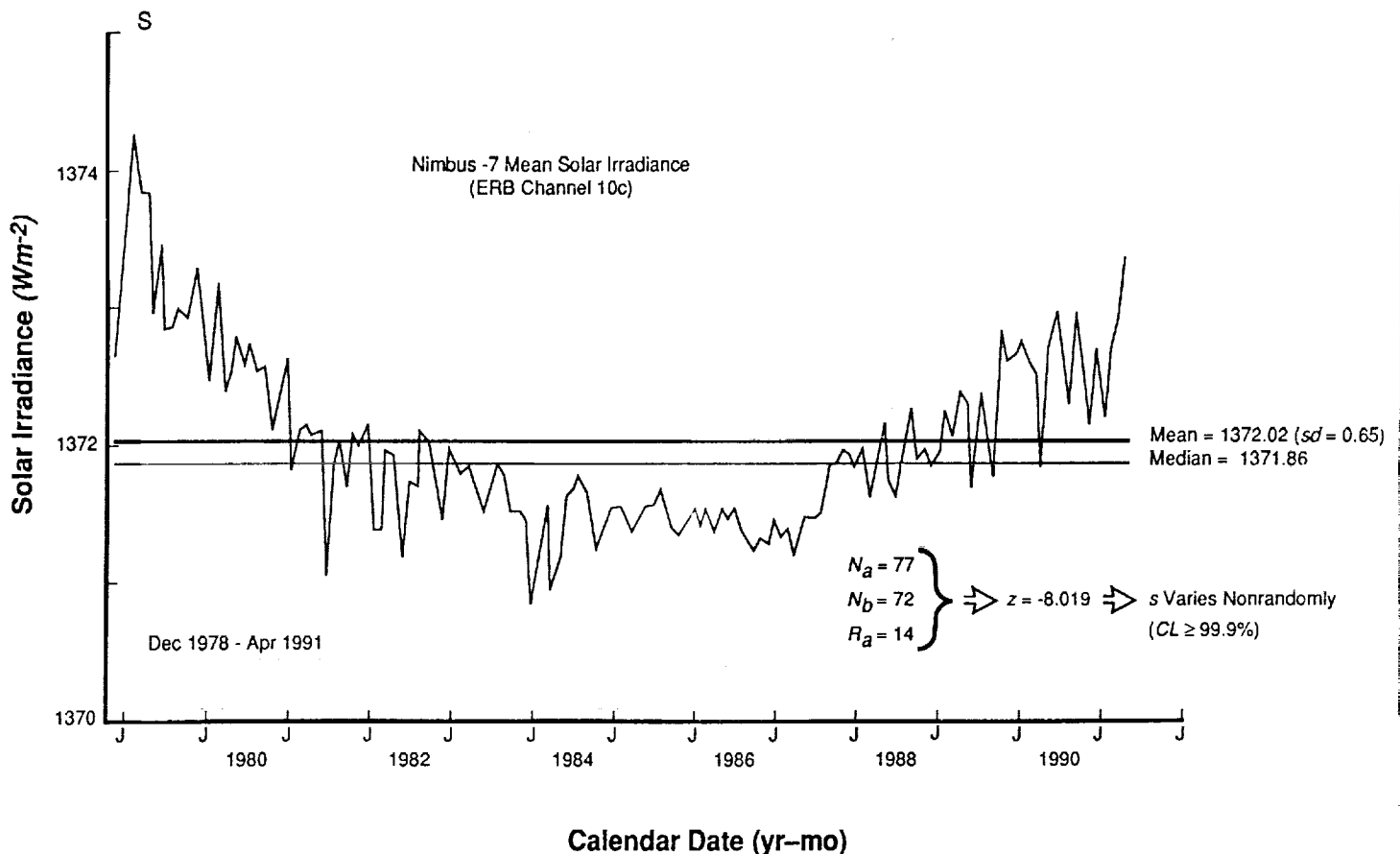

Figure 1. Monthly mean solar irradiance as measured by the Nimbus-7 ERB experiment (channel 10C) for the interval December 1978 to April 1991. Also displayed are the overall mean, standard deviation, and median values and the results of a runs test which suggests a nonrandom variation in s during the period of observation.
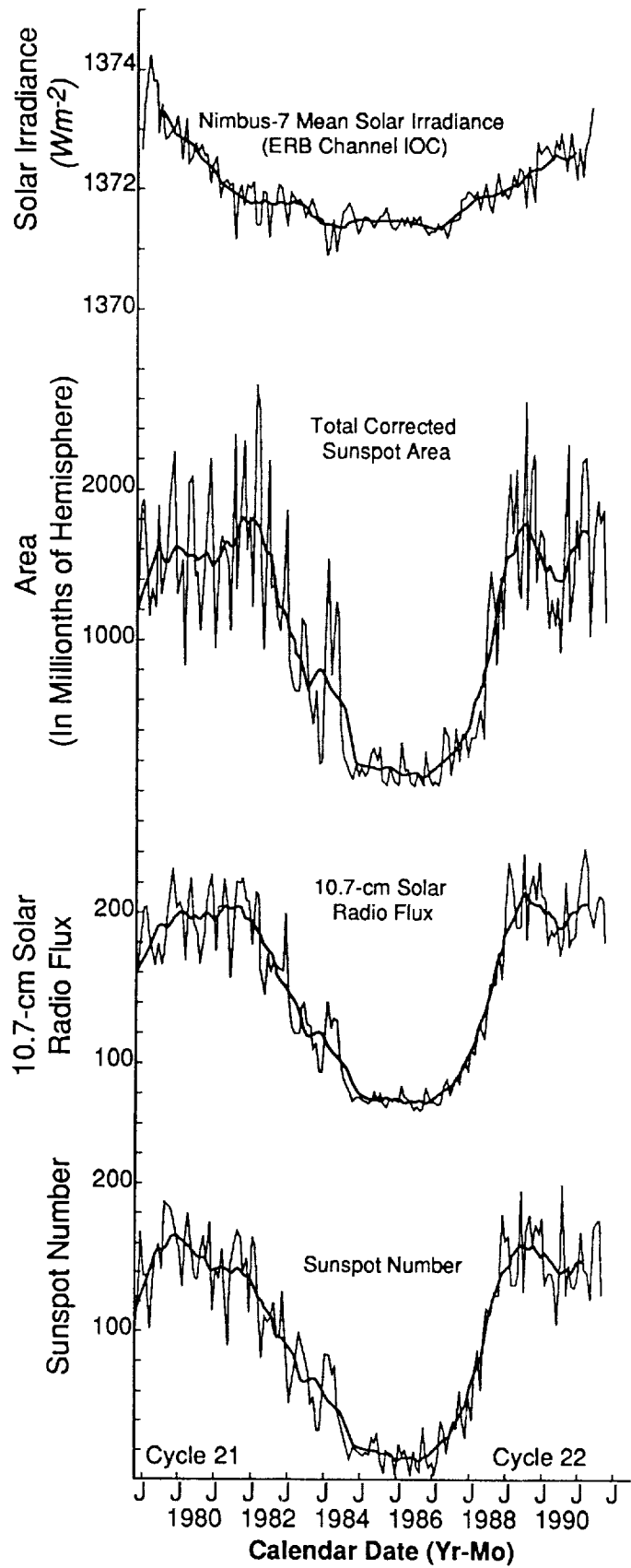
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Figure 2. A comparison of monthly means and smoothed monthly means of solar irradiance, sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area.
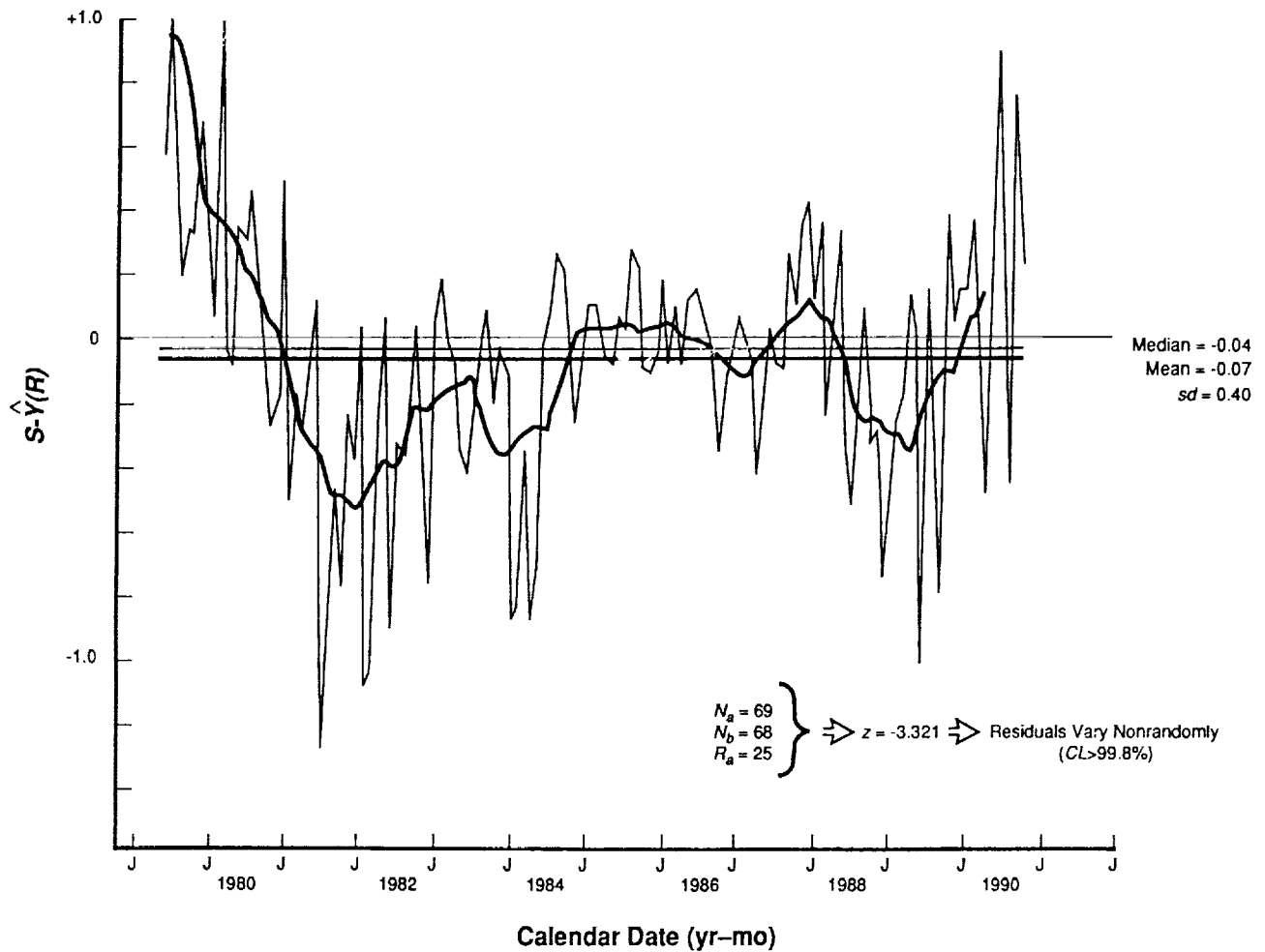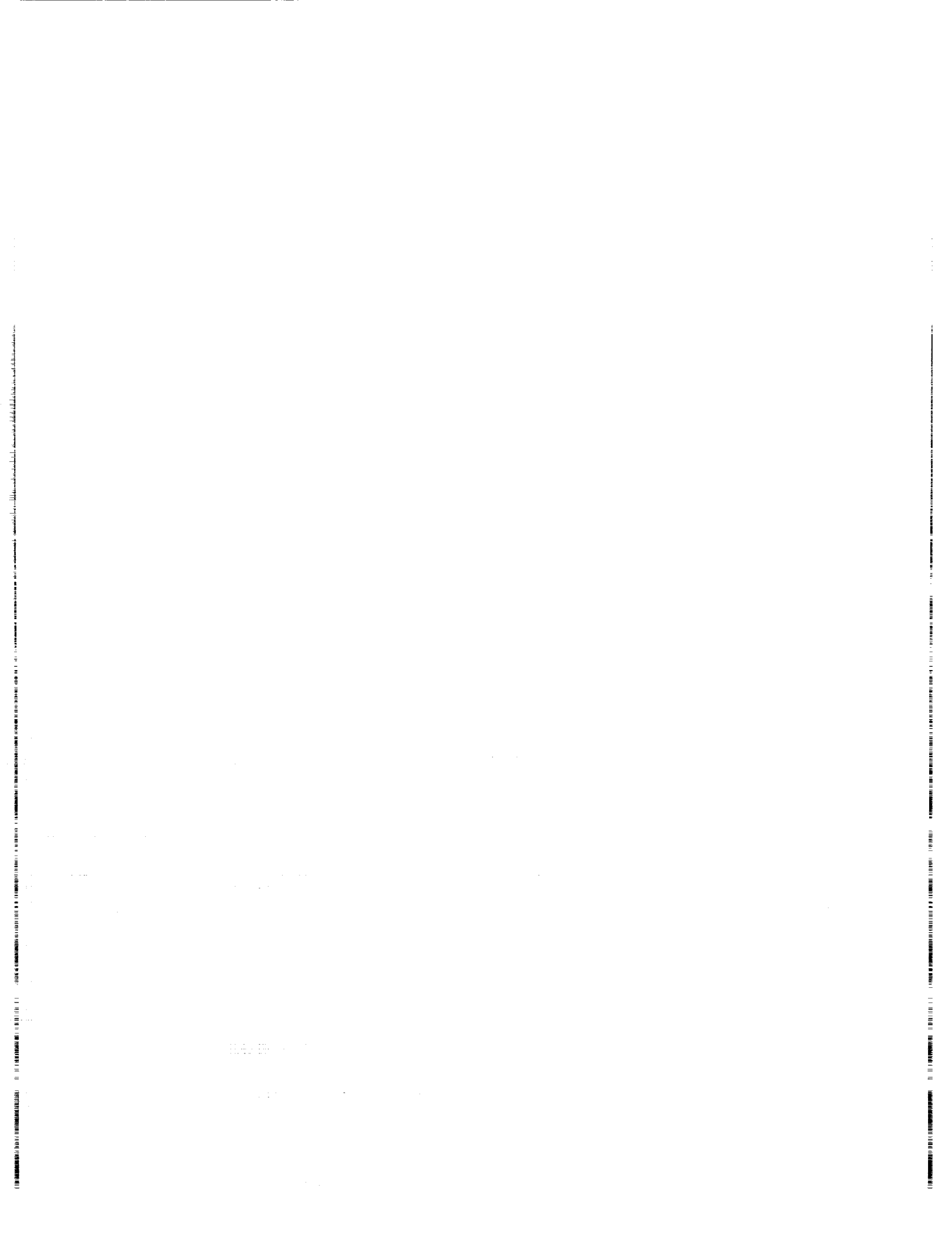
Figure 3. The residuals of $s-\hat{y}(R)$. Also displayed are the mean, standard deviation, and median values of the residuals and the results of a runs test which suggests that the residuals vary nonrandomly.

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13. ABSTRACT (Maximum 200 words)

For the interval December 1978 to April 1991, the value of the mean total solar irradiance, as measured by the Nimbus-7 Earth Radiation Budget Experiment channel 10C, was 1,372.02 Wm^{-2}, having a standard deviation of 0.65 Wm^{-2}, a coefficient of variation (mean divided by the standard deviation) of 0.047 percent, and a normal deviate z (a measure of the randomness of the data) of -8.019 (inferring a highly significant non-random variation in the solar irradiance measurements, presumably related to the action of the solar cycle). Comparison of the 12-month moving average (also called the 13-month running mean) of solar irradiance to those of the usual descriptors of the solar cycle (i.e., sunspot number, 10.7-cm solar radio flux, and total corrected sunspot area) suggests possibly significant temporal differences. For example, solar irradiance is found to have been greatest on or before mid 1979 (leading solar maximum for cycle 21), lowest in early 1987 (lagging solar minimum for cycle 22), and was rising again through late 1990 (thus, lagging solar maximum for cycle 22), having last reported values below those that were seen in 1979 (even though cycles 21 and 22 were of comparable strength). Presuming a genuine correlation between solar irradiance and the solar cycle (in particular, sunspot number) one infers that the correlation is weak (having a coefficient of correlation $r < 0.84$) and that major excursions (both as "excesses" and "deficits") have occurred (about every 2 to 3 years, perhaps suggesting a pulsating Sun).

14. SUBJECT TERMS

Sun, Solar Irradiance, Solar Cycle, Numbus-7, Solar Gradient, Solar Variation, Solar Luminosity

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