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On the Relation Between Sunspot Area and Sunspot Number

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February 2006

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LIST OF ACRONYMS

NOAA	National Oceanic and Atmospheric Administration
RGO	Royal Greenwich Observatory
SD	standard deviation
SIDC	Solar Influences Data analysis Center
SOON	Solar Optical Observing Network
USAF	United States Air Force

NOMENCLATURE

A	total corrected area in millionths of solar hemisphere
A_R	Rome Observatory for 1958–1998
A_X	RGO timeframe for 1958–1976 and USAF/NOAA SOON timeframe for 1977–1998
f	number of individual spots
g	number of sunspot groups
k	correction factor
n	number of Rome Observatory observing days
n_a	number of yearly values above the median
n_b	number of yearly values below the median
n_r	number of runs in the sample
R	relative spot number
r	Pearson linear correlation coefficient
r^2	coefficient of determination
s_R	sunspot number for Rome Observatory
s_{yx}	standard error of estimate
s_X	Swiss Federal Observatory (Zurich)
t	time
x	independent variable
y	dependent variable
z	statistic for determining randomness

TECHNICAL PUBLICATION

ON THE RELATION BETWEEN SUNSPOT AREA AND SUNSPOT NUMBER

1. INTRODUCTION

Prior to 1874, the primary measure of solar activity was sunspot number,[1–4] in particular, Wolf's relative sunspot number R, given as $R = k\,(10g + f)$, where g is the number of sunspot groups, f is the number of individual spots, and k is a correction factor, which Wolf originally assigned the value of 1. In 1882, Wolf's successors at the Swiss Federal Observatory in Zurich changed somewhat the counting method for R and assigned a new value of 0.60 for k, which reduced the new observations to the old scale. The Swiss Federal Observatory continued to provide Wolf or Zurich sunspot numbers through 1980. (Beginning in 1981 and continuing through the present, the international sunspot number is provided by the Royal Observatory of Belgium.)

Because the definition of R is rather arbitrary, dependent upon accurate measurements of g and f, which can vary considerably even with identical instruments and seeing conditions, a more objective measure of solar activity was desired—sunspot area. Beginning in May 1874, the Royal Greenwich Observatory (RGO) began cataloging daily sunspot positions and areas, based on systematic observations at Greenwich, England; Cape Town, South Africa; and Kodaikanal, India.[5] The data were obtained directly from photographs by means of reticules divided into small squares and measured relative to Sun center. Typically, the position of each sunspot was determined to 0.1 degrees (latitude and central meridian distance), and the area of each spot was determined to 0.1 millionth of the visible solar hemisphere. The RGO dataset ended in 1976.

To continue the sunspot positional/area record beyond 1976, United States Air Force/National Oceanic and Atmospheric Administration (USAF/NOAA) Solar Optical Observing Network (SOON) observations were employed.[6] Unlike the RGO photographic observations, the USAF/NOAA SOON observations are visually determined. A worldwide network of solar observatories (including Boulder, Holloman, Learmonth, Palehua, Ramey, San Vito, and occasionally, Culgoora—located so that 24-hr synoptic coverage can be achieved) comprises the SOON system. At each observatory, daily sunspot drawings on an 18-cm diameter image of the Sun are routinely made, with the scaling of positions and areas of sunspots being performed by hand using Stonyhurst disc overlays for positions and circle/ellipse overlays for sunspot area starting in 1981—grids were used to estimate sunspot area prior to 1981. Typically, positions are determined to 1-degree accuracy and areas are determined by rounding to the nearest 10 millionths of the visible solar hemisphere. The complete set of observations from May 1874 through the present, both RGO and SOON, is available online at http://science.nasa.gov/ssl/PAD/SOLAR/greenwch.htm.

The relation between total corrected sunspot area A (in millionths of the visible solar hemisphere) and sunspot number R is not particularly good for daily values, although it has often been stated that the relationship becomes better when using monthly or yearly averages. In fact, the claim[5, 7–11] has been made that for monthly or yearly averages the average relation between A and R is simply described as $A = 16.7\ R$.

In this study, yearly averages of A, R, and A/R for 1875–2004 are examined to determine the validity of the oft-quoted relationship between sunspot area and sunspot number. Also, because of the changes that have occurred in the solar activity record, the interval of 1958–1998 is examined in greater detail by comparing RGO and SOON sunspot areas against Rome Observatory sunspot areas and comparing Swiss Federal Observatory and Royal Observatory of Belgium sunspot number values against Rome Observatory determinations of sunspot number. Previously, it has been shown that both sunspot area and sunspot number, as determined today, appear slightly different (underestimated and overestimated, respectively) from earlier years when sunspot areas were determined by the RGO and sunspot numbers were determined by the Swiss Federal Observatory.[12]

2. RESULTS AND DISCUSSION

2.1 Sunspot Areas, Sunspot Numbers, and Their Ratios (1875–2004)

Figure 1 displays yearly plots of R, A, and A/R for the interval 1875–2004. The numbers at the bottom (12, 13, etc.) refer to specific sunspot cycles. The thick and thin vertical lines refer, respectively, to the occurrences of sunspot number maximums and minimums. The numbered triangles across the top (1, 2, and 3) refer to times when changes occurred in the solar activity record, where No. 1 refers to the change in the method for counting sunspot number (using $k=0.60$) that occurred in 1882, No. 2 refers to the end of the RGO record and the beginning of the SOON record in 1976/1977, and No. 3 refers to the end of sunspot number determination at the Swiss Federal Observatory and the start of sunspot number determination at the Royal Observatory in Belgium, specifically, the Solar Influences Data analysis Center (SIDC) in 1980/1981. The horizontal lines are the medians for each parameter. Also shown is the mean, standard deviation, and the results of a runs test for each parameter, where n_a refers to the number of yearly values above the median, n_b refers to the number of yearly values below the median, n_r refers to the number of runs in the sample, and z is the statistic for determining randomness (where $z \geq 1.96$ indicates that the fluctuations are nonrandom in nature, in this case, being due to the systematic variation of the solar cycle).[13]

As can be seen, based on the yearly averages, A and R peak together for all cycles, except cycles 20, 21, and 23, when A peaked 2 yr after R. For A/R, it was at minimum value at sunspot number minimum for cycles 13, 15, 16, 19, 20, and 22. It occurred 2 yr before sunspot number minimum for cycle 17; 1 yr before sunspot number minimum for cycles 14 and 23; and 1 yr after sunspot number minimum for cycles 12, 18, and 21. A/R was at maximum value 2 yr before sunspot number maximum for cycle 16; 1 yr before sunspot number maximum for cycles 18 and 20; at sunspot number maximum for cycles 12 and 14; 1 yr after sunspot number maximum for cycle 17; 2 yr after sunspot number maximum for cycles 19, 22, and 23; 3 yr after sunspot number maximum for cycle 21; 4 yr after sunspot number maximum for cycle 13; and 5 yr after sunspot number maximum for cycle 15.

For the entire interval, 1875–2004, A/R has a median value of 13.6 and a mean value of 13.1, with a standard deviation of 3.5. During the RGO timeframe (1875–1976) A/R averages 14.1, with a standard deviation of 3.2; and during the SOON timeframe (1977–2004) A/R averages 9.8, with a standard deviation of 2.1). Presuming that A/R is normally distributed during each of the subtimeframes, one finds that the t statistic for independent samples[14] is statistically meaningful, meaning that A/R is definitely lower during the latter timeframe than the former timeframe.

Figure 2 depicts scatterplots of yearly values of A versus R for the two separate timeframes, 1875–1976 (bottom) and 1977–2004 (top). Clearly, during each timeframe A is strongly correlated against R, although the slopes and y-intercepts are different. As an example, given a value of 100 for R, during the former timeframe it would suggest a value of A of $\approx$1,538 ± 174 (1-σ accuracy), but only a value of A of $\approx$1,076 ± 123 during the latter timeframe. This suggests that yearly area averages are $\approx$30 percent smaller during the present timeframe than during the RGO timeframe.

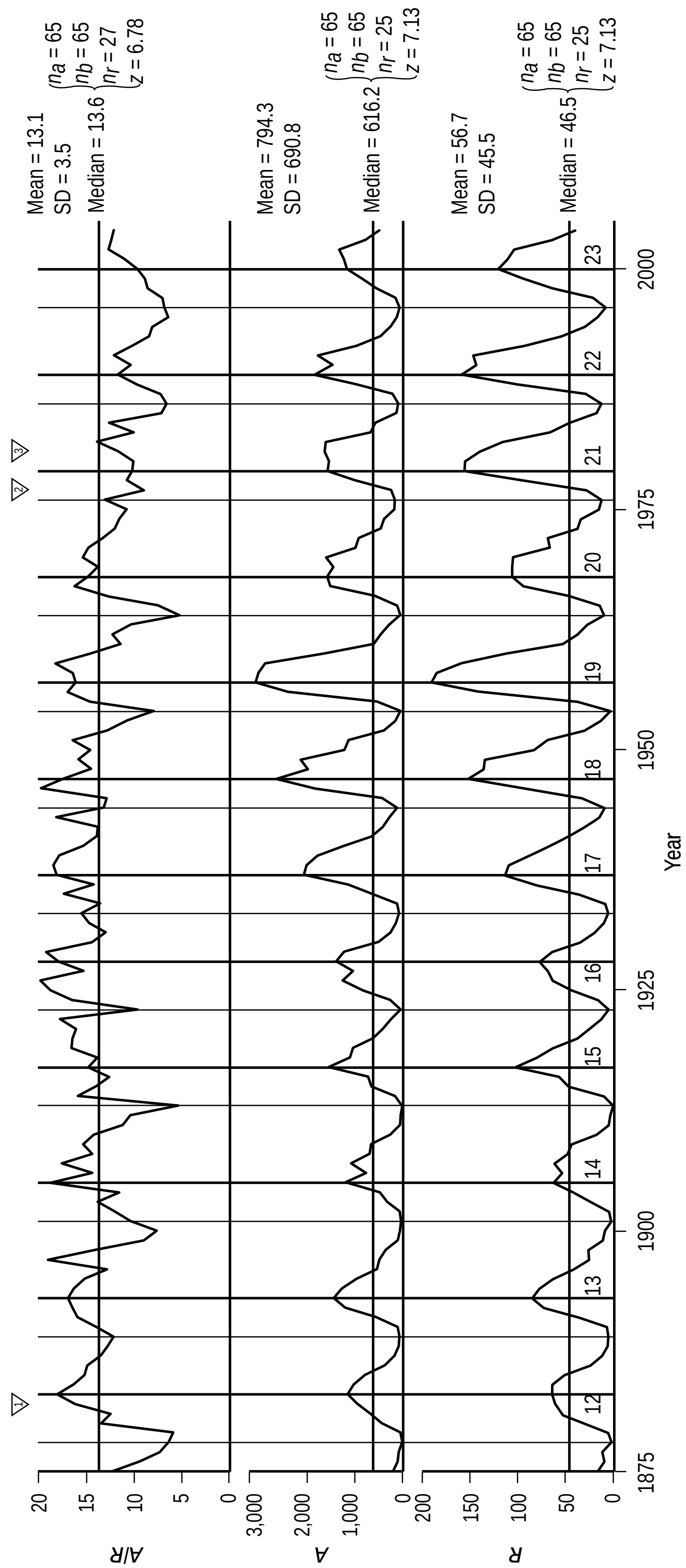

Figure 1. Variation of yearly averages of sunspot number *R* (lower panel), sunspot area *A* (middle panel), and ratio *A*/*R* (upper panel) for 1875–2004.

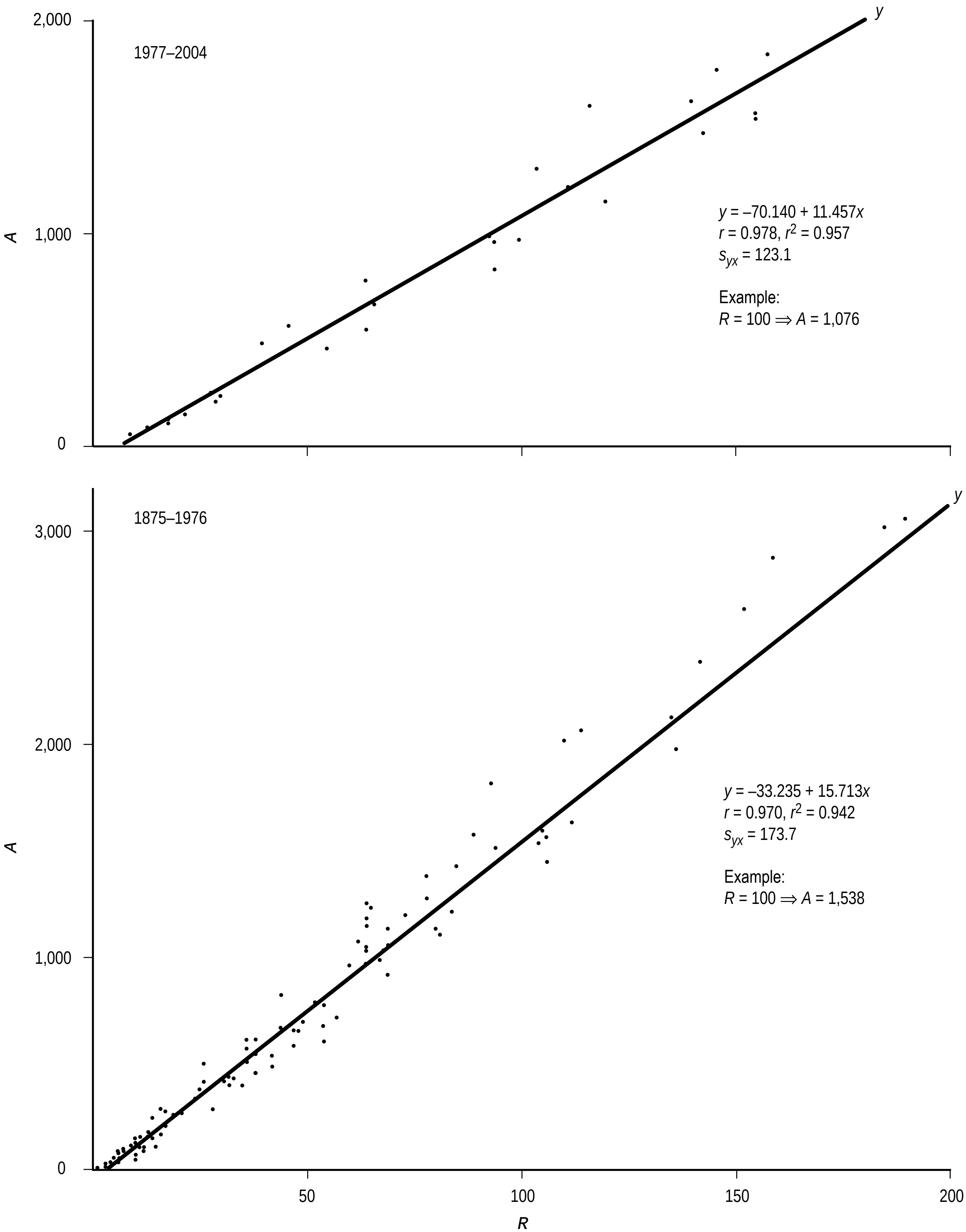

Figure 2. Scatterplots of *A* versus *R* for 1875–1976 (lower panel) and 1977–2004 (upper panel). See Nomenclature list for details.

Figure 3 compares cycle 23 yearly values of R (bottom), A (middle), and A/R (top) against the mean parametric values of cycles 12-22 relative to the epoch of sunspot minimum year. Values of R for cycle 23 lie above the mean for all years, except yr 3, with peak value occurring in yr 4, as found for the mean of cycles 12–22. In terms of maximum amplitude, cycle 23 ranks fifth below cycles 19, 22, 21, and 18, and above cycles 12–17 and 20. The behavior of cycle 23's R is such that minimum for cycle 24 is anticipated for year 10, that is, 2006.

Concerning cycle 23's values of A, they lie below the mean of cycles 12–22 for all years, except the last three, when they are essentially the same as the mean of cycles 12–22, having a maximum yearly area that peaked in yr 6 that is only slightly larger than values for cycles 12 and 14. Concerning the ratio A/R, cycle 23's ratio has always fallen below the mean of cycles 12–22, and, interestingly, its maximum ratio value is similar to what was seen for cycles 21 and 22, suggesting that something clearly is amiss with sunspot areas measured today as compared to years prior to 1977.

2.2 Comparisons Against Rome Observatory Measures (1958–1998)

Figure 4 (top panel) shows the number of days during each year for 1958–1998 that the Rome Observatory reported measurements of sunspot area, number of sunspot groups and number of individual spots, and the latter two parameters allowing for the computation of sunspot number as determined by the Rome Observatory. The bottom panel of figure 4 compares sunspot number s_X and s_R, where s_X refers to the Swiss Federal Observatory (Zurich) timeframe for 1958–1980 and to the Royal Observatory of Belgium (SIDC) timeframe for 1981–1998 and s_R refers to the Rome Observatory for the years 1958–1998, all values computed using the same days. The bottom-middle panel of figure 4 compares sunspot area A_X and A_R, where A_X refers to the RGO timeframe for 1958–1976 and to the USAF/NOAA SOON timeframe for 1977–1998 and A_R refers to the Rome Observatory for 1958–1998, again all values computed using the same days. The top-middle panel of figure 4 compares the ratios A_X/s_X and A_R/s_R for 1958–1998.

Notice that s_X and s_R are virtually identical for 1958–1980, but differ markedly during the latter interval (1981–1998). For 1958–1980, the average deviation between Zurich sunspot number and Rome Observatory sunspot number measured only 3.7 units of sunspot number, with a standard deviation of 3 units of sunspot number. For 1981–1998, the average deviation between SIDC sunspot number and Rome Observatory sunspot number measured 10.9 units of sunspot number, with a standard deviation of 12.5 units of sunspot number. In particular, SIDC sunspot number for maximum amplitude for cycle 22 (in 1989) measured 160.2, some 34.6 units higher than measured by the Rome Observatory sunspot number.

Concerning sunspot areas: whereas Rome Observatory areas tended to be slightly below areas measured by the RGO (average deviation equal to 111.1 millionths of the visible solar hemisphere, with a standard deviation of 127.7 millionths of the visible solar hemisphere), for the USAF/NOAA SOON interval (1977–1998), Rome sunspot areas tended to be somewhat larger than areas measured by SOON (average deviation equal to 112.2 millionths of the visible solar hemisphere, with a standard deviation of 94.2 millionths of the visible solar hemisphere).

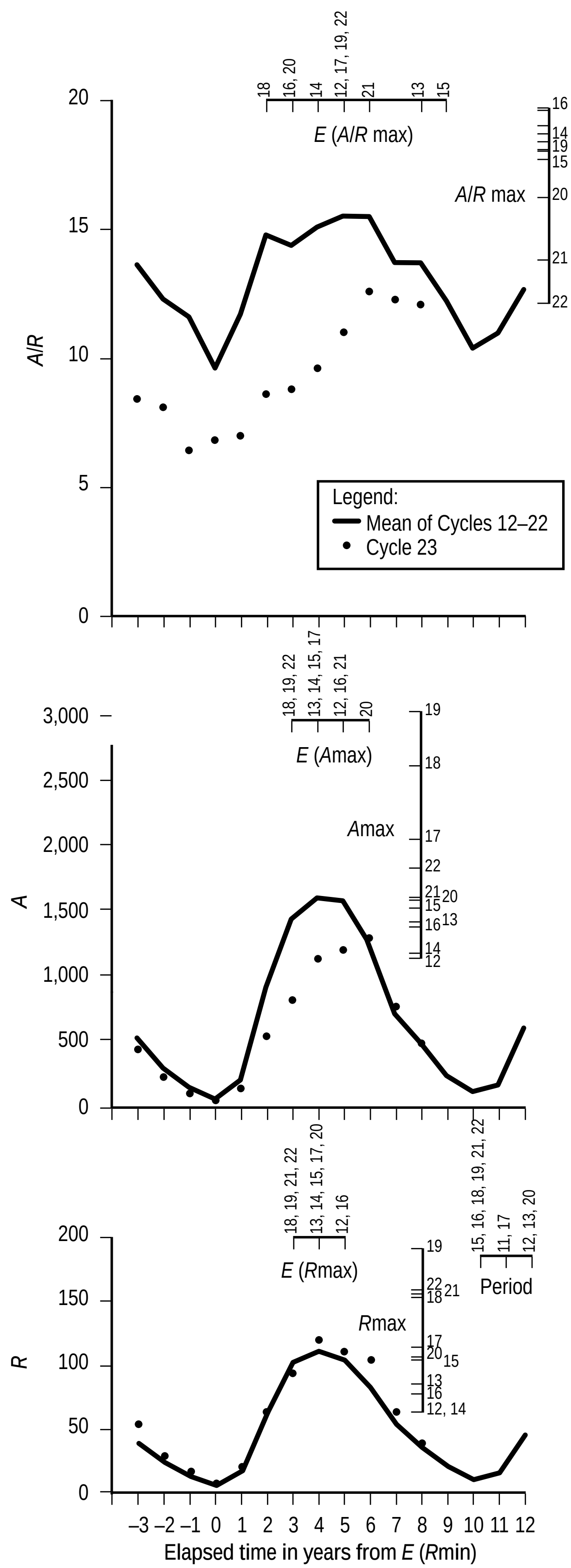

Figure 3. Comparison of cycle 23 against mean of cycles 12–22 for *R* (lower panel), *A* (middle panel), and *A*/*R* (upper panel).

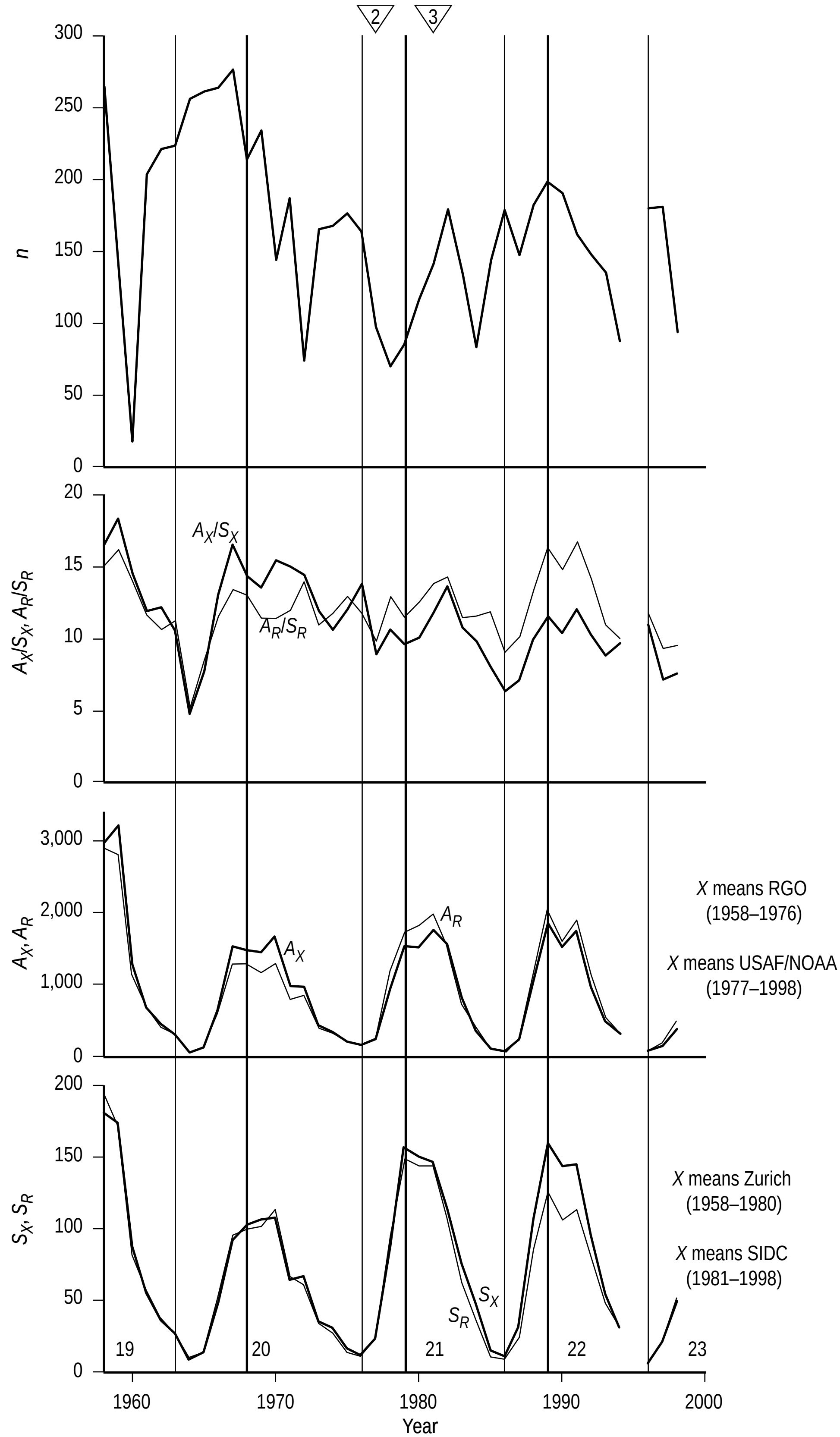

Figure 4. Comparison of s_X and s_R (lower panel) A_X and A_R (lower-middle panel), A_X/s_X and A_R/s_R (upper-middle panel), and n (upper panel) for 1958–1998.

Concerning the ratios, ratios for Rome Observatory tended to be below those using RGO areas and Zurich sunspot numbers, but above those using SOON areas and SIDC sunspot numbers. For 1958–1976, the ratios based on RGO and Zurich data, on average, are ≈1.5 units higher than the ratio based on Rome Observatory data. For 1981–1998, the ratios based on SOON and SIDC data, on average, are ≈2.6 units lower than the ratio based on Rome Observatory data. (For the brief interval of 1977–1980, when the transitions occurred, the ratio based on Rome Observatory data, on average, was ≈1.9 units higher.)

Figure 5 displays scatterplots of area versus sunspot number, where the two plots on the left refer to Rome Observatory data for 1958–1976 (bottom-left panel) and 1977–1998 (top-left panel) and the two plots on the right refer to RGO and Zurich data (bottom-right panel) and SOON, Zurich and SIDC data (top-right panel). All scatterplots have linear correlation coefficients $r > 0.97$ and are statistically significant. The importance of these plots is that the Rome Observatory data remain consistent for 1958-1976 and 1977–1998, while a sharp change occurs in the relation after the end of the RGO record. For example, given a sunspot number of 100 implies a sunspot area of 1,388.8 ± 134.4 or 1,363.8 ± 156.6 millionths of the visible solar hemisphere for 1958–1976 and 1977–1998, respectively, using Rome Observatory, and a sunspot area of 1,578.3 ± 120.8 or 1,081.0 ± 117.7 millionths of the visible solar hemisphere for 1958–1976 and 1977–1998, respectively, using the RGO, Zurich, and SIDC data.

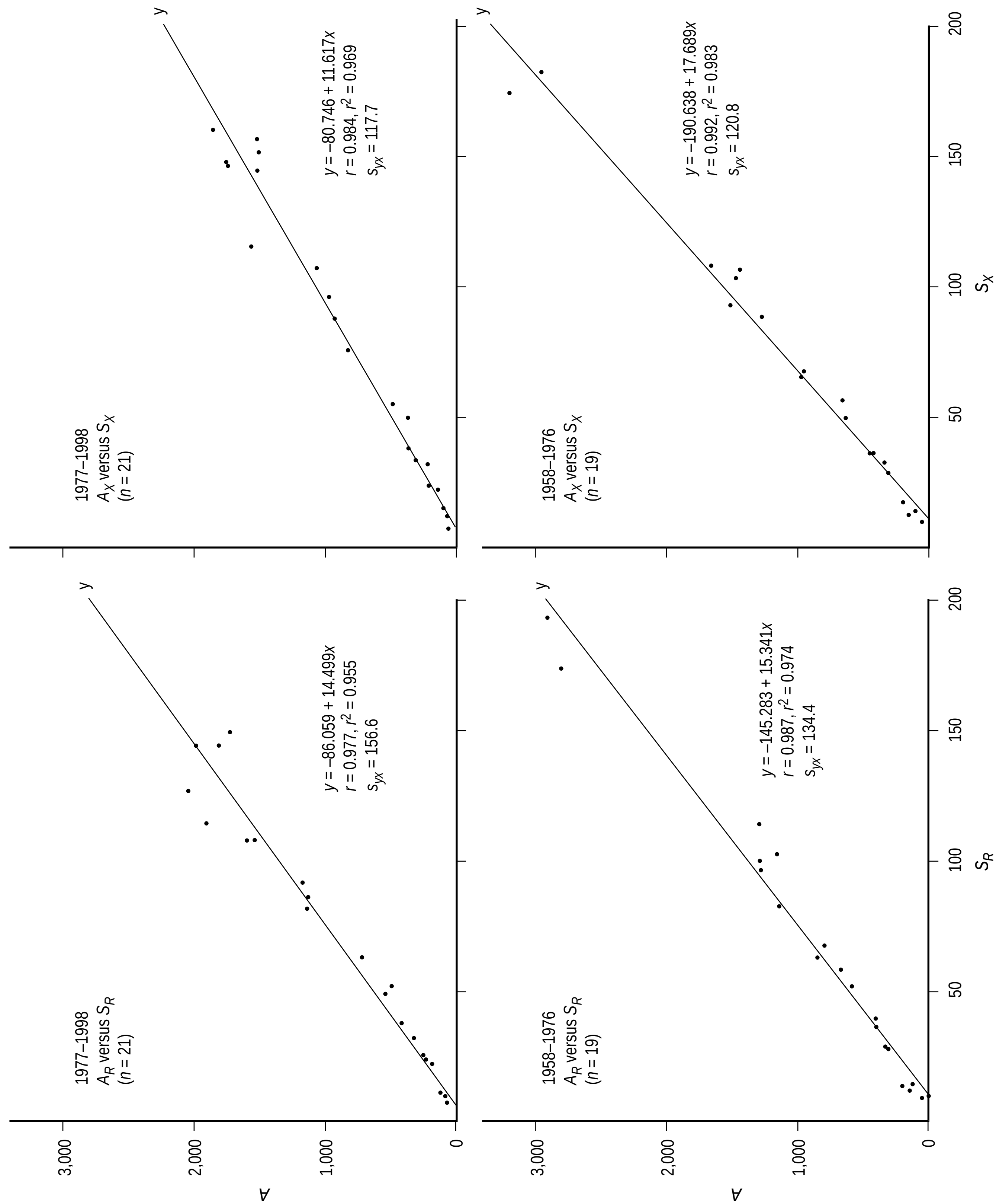

Figure 5. Scatterplots of A_R versus s_R (lower-left panel) and A_X versus s_X (lower-right panel) for 1958–1976. Scatterplots of A_R versus s_R (upper-left panel), and A_X versus s_X (upper-right panel) for 1977–1998.

3. CONCLUSION

The preceding shows clearly that the relation between yearly averages of sunspot area A and sunspot number R is not simply related, as has often been stated, as $A = 16.7R$. For the entire interval of 1875-2004, a better description is $A = (13.1 \pm 3.5)\ R$, where 13.1 is the mean value of the ratio A/R and 3.5 is the standard deviation of the ratio. During the RGO timeframe (1875–1976), the relation is better expressed as $A = (14.1 \pm 3.2)\ R$, while during the most recent USAF/NOAA SOON timeframe (1977–2004), the relation is better expressed as $A = (9.8 \pm 2.1)\ R$. Certainly, A versus R is highly linearly correlated ($r > 0.97$) for both timeframes, although it appears very likely that A as measured today is underestimated, and R may be slightly overestimated.

Figure 6 displays the variation of the minimum and maximum values of the A/R ratio for cycles 12–23. Minimum A/R averages $\approx 8.5 \pm 2.9$ for cycles 12–23, 8.9 ± 3.2 for cycles 12–20 (the RGO/Zurich timeframe) and only 7.3 ± 1.4 for cycles 21–23 (the SOON/Zurich/SIDC timeframe), where the first number in each interval is the mean value and the second number is the standard deviation. Maximum A/R averages, respectively, $\approx 17.0 \pm 2.7$, 18.4 ± 1.1 and only 12.8 ± 0.9 for the same timeframes. Thus, it is anticipated that cycle 24 will have a minimum A/R of $\approx 7.3 \pm 1.4$ that will occur probably in 2006 (half of cycles 12–23 had minimum A/R in the year of sunspot minimum and all but cycle 17 had minimum A/R within 1 yr either side of sunspot minimum). For the year 2004, A/R averaged 12.1 and for the yr 2005 (through November), it has averaged 13.3 ± 4.3—inferring that minimum A/R likely will occur in 2006 or 2007 and will have a value lower than 12.1.

Maximum A/R for cycle 24 should be $\approx 12.8 \pm 0.9$, with the peak value occurring anytime during the maximum phase of the cycle. Thus, if cycle 24 should turn out to be ≈ 140 in size,[15–17] one anticipates a maximum yearly average for sunspot area of $\approx 1{,}792 \pm 126$ millionths of the visible solar hemisphere, based on USAF/NOAA SOON observations.

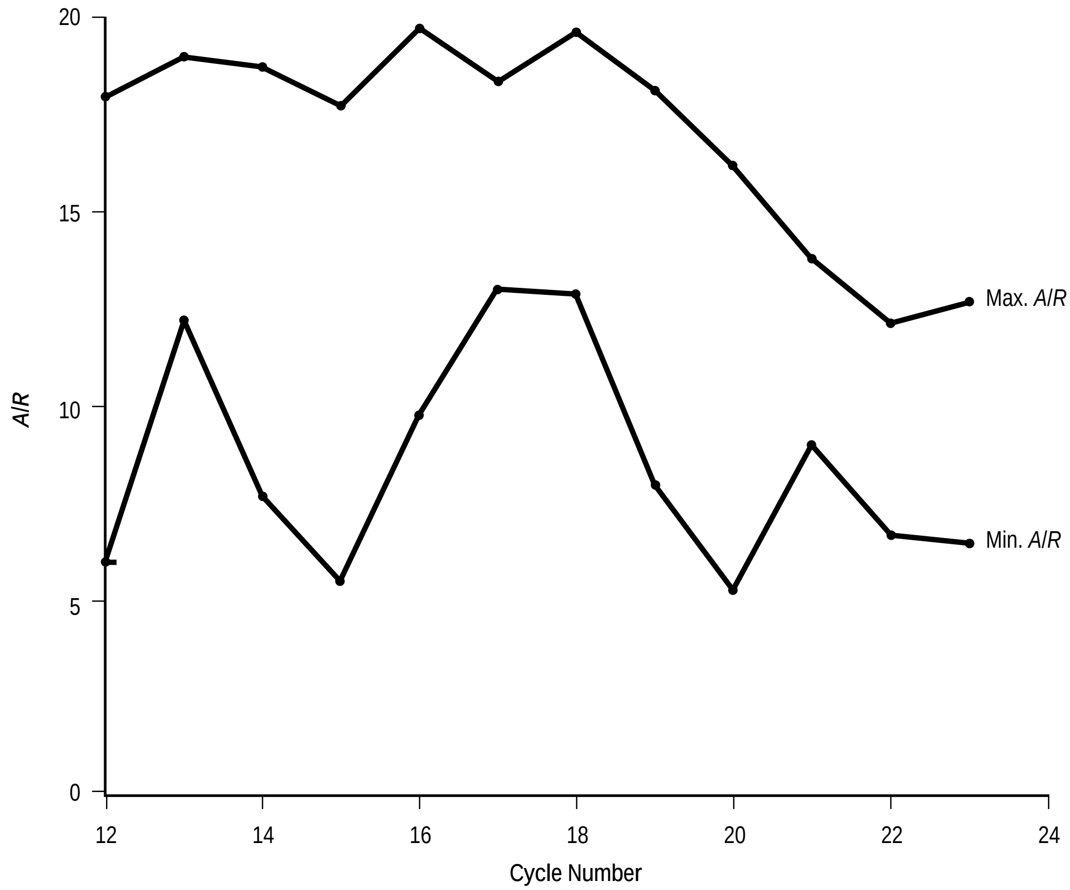

Figure 6. Variation of *A*/*R* minimum and maximum values for cycles 12–23.

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13. ABSTRACT *(Maximum 200 words)*

Often, the relation between monthly or yearly averages of total sunspot area, A, and sunspot number, R, has been described using the formula $A = 16.7\ R$. Such a simple relation, however, is erroneous. The yearly ratio of A/R has varied between 5.3 in 1964 to 19.7 in 1926, having a mean of 13.1 with a standard deviation of 3.5. For 1875–1976 (corresponding to the Royal Greenwich Observatory timeframe), the yearly ratio of A/R has a mean of 14.1 with a standard deviation of 3.2, and it is found to differ significantly from the mean for 1977–2004 (corresponding to the United States Air Force/National Oceanic and Atmospheric Administration Solar Optical Observing Network timeframe), which equals 9.8 with a standard deviation of 2.1. Scatterplots of yearly values of A versus R are highly correlated for both timeframes and they suggest that a value of $R = 100$ implies $A = 1{,}538 \pm 174$ during the first timeframe, but only $A = 1{,}076 \pm 123$ for the second timeframe. Comparison of the yearly ratios adjusted for same day coverage against yearly ratios using Rome Observatory measures for the interval 1958–1998 indicates that sunspot areas during the second timeframe are inherently too low.

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