GROUP SUNSPOT NUMBERS: A NEW SOLAR ACTIVITY RECONSTRUCTION*

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Abstract. In this paper, we construct a time series known as the Group Sunspot Number. The Group Sunspot Number is designed to be more internally self-consistent (i.e., less dependent upon seeing the tiniest spots) and less noisy than the Wolf Sunspot Number. It uses the number of sunspot groups observed, rather than groups and individual sunspots. Daily, monthly, and yearly means are derived from 1610 to the present. The Group Sunspot Numbers use 65 941 observations from 117 observers active before 1874 that were not used by Wolf in constructing his time series. Hence, we have calculated daily values of solar activity on 111 358 days for 1610–1995, compared to 66 168 days for the Wolf Sunspot Numbers. The Group Sunspot Numbers also have estimates of their random and systematic errors tabulated. The generation and preliminary analysis of the Group Sunspot Numbers allow us to make several conclusions: (1) Solar activity before 1882 is lower than generally assumed and consequently solar activity in the last few decades is higher than it has been for several centuries. (2) There was a solar activity peak in 1801 and not 1805 so there is no long anomalous cycle of 17 years as reported in the Wolf Sunspot Numbers. The longest cycle now lasts no more than 15 years. (3) The Wolf Sunspot Numbers have many inhomogeneities in them arising from observer noise and this noise affects the daily, monthly, and yearly means. The Group Sunspot Numbers also have observer noise, but it is considerably less than the noise in the Wolf Sunspot Numbers. The Group Sunspot Number is designed to be similar to the Wolf Sunspot Number, but, even if both indices had perfect inputs, some differences are expected, primarily in the daily values.

1. Introduction

For more than 100 years the Wolf or Zürich Sunspot Numbers have served as the primary time series to define solar activity since 1700. This time series was derived by Rudolf Wolf who worked on the problem from 1848 to 1893 and devoted more than 3000 pages to describing his data and techniques. His time series was maintained by his successors at Zürich.

The Wolf Sunspot Numbers before 1893 (henceforth R_Z) have remained unchanged since their original publication (Wolf, 1873; Waldmeier, 1947; McKinnon, 1986). These numbers were derived by hand using a single primary observer whose missing days were filled by secondary observers. The time series has no error bars associated with it. Finally, a considerable portion of the older observations were not located by Wolf in his research. The purpose of this paper then is fourfold:

* This paper has already been published once, in *Solar Physics* **179**, 189 but, due to a misunderstanding, no figures were included in the published version. To rectify this omission, the paper is reprinted here, including all the eight missing figures, but excluding the Appendices, which can be found on pages 206–219 in *Solar Physics* **179**.

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(1) identify observations not included in the R_Z study, (2) digitize them so they are available to all, (3) derive a new and more homogeneous time series, and (4) provide random and systematic error estimates.

The paper will first describe the collection and digitization of the data. Then we will describe Wolf's method of reconstructing solar activity followed by a description of our approach. This is followed by an error analysis of our time series, called the Group Sunspot Numbers (R_G). The Wolf Sunspot Numbers are then compared to the R_G numbers on the daily, monthly, yearly, and secular time scales. These comparisons will illustrate the differences between R_G and R_Z and show why R_G tracks solar behavior more uniformly on the long-term than do the R_Z's. Finally we will summarize our results and offer some suggestions on how our results might be improved.

Our major conclusion is that solar activity for 1700 to 1882 is lower than that given by Wolf by 25 to 50%. Activity is poorly determined before 1653, accurately found for 1654 to 1727, is uncertain by up to 15 to 20% or is unknown for many years from 1728 to 1800, is determined to about a 5% accuracy for 1800 to 1850, and is known to a 1 to 2% accuracy for 1851 to the present.

2. The Collection and Tabulation of the Observations

The first step in reconstructing solar activity is the collection and digitization of raw solar observations. An original impetus to this study arose when it was noticed that sunspot observations existed on days when there was no R_Z. This suggested that Wolf may have missed some observations in his 45 years of collecting them.

In our approach we only digitized the number of sunspot groups, for reasons to be explained shortly. The first step was digitizing the observations published by Wolf and his successors in the Zürich journal first called 'Mitteilungen über der Sonnenflecken' and later called 'Astronomische Mitteilungen'. This journal was published from 1858 to 1947. Because some observations are embedded in the text, the journal was repeatedly scanned to get all the observations. This journal supplied 224 503 observations from 306 observers. Later we received a copy of a tabulation of Wolf's observations from the Zürich Observatory called 'Sonnenflecken-Statistik 1610–1900'. This manuscript confirmed that we had not overlooked any observations.

The next step was locating modern observations after 1947 and searching journals and unpublished archives. Wolf documented the journals he examined so we concentrated upon journals he missed such as 'Raccato di Opusculi Scientifici a Filogiri', where Musano's observations for 1739–1742 reside. More than 20 serials were examined concentrating on Italian, Dutch, and English journals that Wolf neglected.

Other major sources of material were unpublished observations. These were located by using modern bibliographies listing library holdings and by an occasional journal reference to a manuscript. We obtained microfilm or xerox copies of manuscripts when possible, but also visited the libraries at the University of Aarhus, the Royal Astronomical Society, the Royal Society, Cambridge University, Hamilton College, and the St. Petersburg State Library in Russia. Rare books were examined primarily at the Naval Observatory Library and the Library of Congress. Several correspondents also sent us early data from manuscript or journal sources.

All this searching, which took more than three years, proved very fruitful. If, for example, we consider only those observers active before 1874 when the Royal Greenwich Observatory started observing, we have 330 observers with 147 462 observations (see Appendix 1 for a complete listing of observers; Appendix 1 is published in *Solar Physics*, Volume 179, pp. 206–214). In contrast, Wolf had 213 observers with 81 521 observations. Thus, our searching yielded 117 new observers with 65 941 observations or about an 80% increase in observations over what Wolf located. Because early observations are often scarce, most of our effort went into searching for early observers. Modern observations were not neglected though and here we tried to get as many as ten observers per year, a goal which was mostly achieved.

The final database we collected has 455 242 observations from 463 observers. From 1610 to 1995 there are 140 986 days, so we have on average about three observations per day. Unfortunately, the observations are not evenly spaced in time, but we do get an estimate of solar activity on 111 358 days, or 79% of the days, using this database. In comparison the R_Z's have 66 138 daily values with earliest daily values being in 1818.

It is worth spending a few words describing the different types of observers. These can be placed in several different categories described below:

(1) *Zürich-recorded observers.* These observations are tabulated in the 'Astronomische Mitteilungen' as mentioned above. They cover the period from 1610 to 1947 and consist of 306 observers with 224 503 observations. There are occasional typographical errors, which, when obvious, were corrected. These observations plus the unpublished observations for 1948 to the present form the raw database for the Wolf or Zürich Sunspot Number time series.

(2) *'New non-Zürich' observers.* These are the observations we collected from journals and unpublished archives as described above. There are 163 new observers with 230 739 observations. Appendix 1 lists all the observers, with their beginning and ending years of activity and the number of days they observed.

(3) *'Effectively new' observers.* Wolf relied upon correspondents to examine manuscripts for him and to send their interpretation of the results to him. In 1893, just before he died, he was sent tabulations of the observations by Thaddeus Derfflinger for 1802 to 1824 and Schwarzenbrunner for 1825 to 1830. These obser-

vations were never incorporated in the R_Z's and so may be labeled as effectively new.

(4) *'Enhanced' observers.* In some cases Wolf did not acquire all the observations from a particular observer. We suspect our database will prove eventually to have the same deficiency. Observers where we obtained more observations than Wolf did include Riccioli, Hevelius, Picard, La Hire, Stancarius, Flamsteed, E. Manfredi, Rost, Alischer (called Alishez by Wolf), Horrebow, William Herschel, Julius Schmidt, and Gustav Spoerer.

(5) *'Partially recorded' observers.* For some observers, not all their observations were published, such as Wolf, for whom our database is still missing observations in the 1850s. Other observers, such as the San Miguel Observatory in Argentina, are not complete because we could not locate a complete run of the serials. In both these cases and similar cases, these omissions do not substantially affect the final solar activity reconstruction since there are many other observations that can be used. However, improvements in our database can still be made.

(6) *'Corrected' observers.* In a couple of cases the tabulations sent to Wolf appear to have been erroneous. The observations by Pastorff from 1819 to 1833 are a prime example. These observations, as tabulated by Wolf, have very high numbers of groups because A. C. Ranyard who made the tabulation confused sunspot groups and individual sunspots. We re-examined the original drawings and made a new interpretation of the observations as discussed by Hoyt and Schatten (1995). In Appendix 1, Ranyard's and hence Wolf's interpretation is listed as 'Pastorff/Wolf'. Another corrected observer is Horrebow. 'Horrebow/Wolf' is Wolf's interpretation courtesy of Prof. D'Arrest, 'Horrebow' is our interpretation, and 'Horrebow – Version 2' is Horrebow's own interpretation of his observations made for just a few years.

(7) *'Vague' observers.* Some observers are 'vague' in one way or another so their observations could not be used. These observers generally comment on whether spots are present or not, but do not estimate the number of groups. They are commented upon in our bibliography, but are not listed in Appendix 1. Vague observers include Schroter, Hahn, Sturmer, and many others.

(8) *'Summary' observers.* Some observers do not supply details of their daily observations. This is particularly true among modern observers who publish only monthly means. These observers are mentioned in our bibliography as a reminder that their daily observations may yet be found. Another type of summary observer are those who comment that they have seen no sunspots from one date to another, despite actively observing the Sun. These days are filled in as days with no sunspots, but if another observer reports a sunspot in these intervals, his observations take

precedent over the summary observer. There are about 20 of these observers, mostly before 1700.

(9) *'Misplaced' observers.* Another type of observer are those whose observations we know exist, but repeated efforts to locate the observations failed to locate them. Prominent observers in this category include J. G. Fink (active 1788–1816), Soemmering (active 1826–1829), and Chevallier (active 1847–1849). Locating these observations could improve our solar activity reconstruction.

(10) *'Lost' observers.* Some observers we know were active and their observations were either definitely lost such as those of Horrox (active 1638) whose manuscripts were burned. For some observers, such as Scheiner, who observed sunspots on a nearly daily basis from 1611 to 1633, only a small portion of his observations survive in *Ursa Rosina* and his other publications. Another observer in this category is Alischer who kept a sunspot diary called 'Diaria macularum solarium' that may have observations from 1727 to 1746 when hardly any observations were made. Lost manuscripts also include observations by Picard (before 1665), Fogel (1662–1670) Weigel (1662–1664), Weickmann (1666–1667), and Siverus (1675–1690).

(11) *'Unknown' observers.* Despite considerable searching, there undoubtedly remain observers completely unknown to us. There could be manuscripts or journal articles that we have failed to identify.

(12) *'Poor' observers.* As many observations were collected as possible before the analysis began. Some observers, as will be seen later, may be classified as poor and are dropped entirely from the analysis. Most of these observers miss too many sunspot groups. One observation series, 'Mt. Wilson, Center of Disk,' by design misses sunspot groups near the limb, but these observations are omitted from any solar activity reconstruction. It is included in the database for completeness for possible use in other studies.

To summarize we have found many observations, but the search has not been as exhaustive as we would like. Appendix 1 summarizes the observers and observations we have found. A bibliography with comments that is part of our database identifies many of the problems discussed above. In Figure 1, we show the number of days each year that we have derived an estimate of solar activity from 1610 to 1995. We have complete or nearly complete coverage from about 1800 to 1995 and from 1645 to 1727. From 1610 to 1644 and from 1728 to 1799 observations become sparse in many years and there are six years (1636, 1637, 1641, 1744, 1745, and 1747) for which no reports of sunspot observations exist.

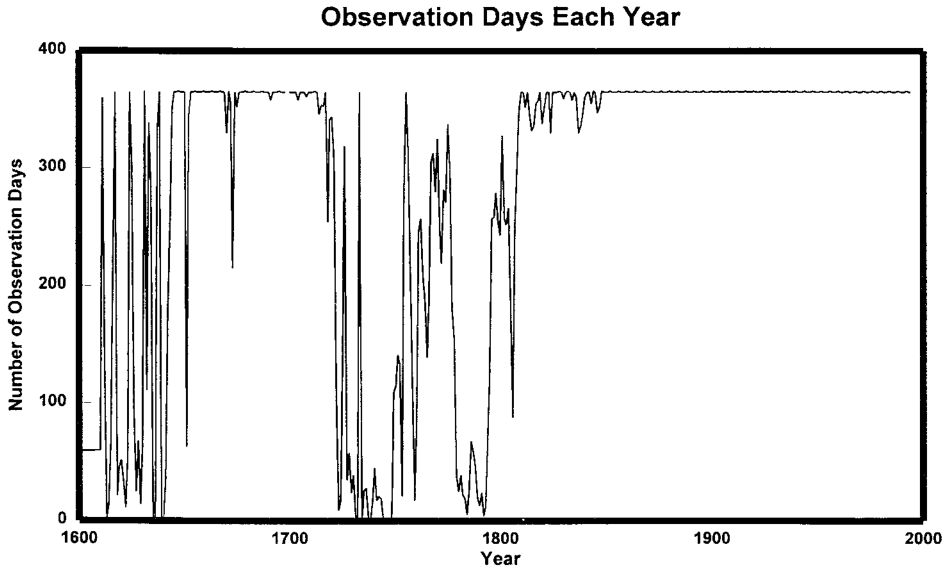

Figure 1. The number of days each year for which it is possible to derive a value of the Group Sunspot Number. From 1797 to the present there is good coverage, as there is from 1645 to 1730. Between 1730 and 1797 there are many years with few observations, making it difficult to reconstruct solar activity.

3. Rudolf Wolf's Techniques for Reconstructing Solar Activity

The Wolf Sunspot Number was originally developed by Rudolf Wolf of Zürich in the 1850s. It has been called the Wolf Sunspot Number, Zürich Sunspot Number, or International Sunspot Number at various times. Here we will refer to it as the Wolf Sunspot Number (R_Z). Wolf defined the sunspot number, R_Z, as

$$R_Z = k(10g + n) \, , \tag{1}$$

where g is the number of sunspot groups, n is the number of individual sunspots, and k is a correction factor for each observer. The R_Z for each day is calculated by using only the input from one observer. If the primary observer could not make an observation, then secondary, tertiary, etc., observers were used until as many days as possible were filled.

The primary observer for the R_Z's are Staudacher (1749–1787), Flaugergues (1788–1825), Schwabe (1826–1847), Wolf (1848–1893), Wolfer (1893–1928), Brunner (1929–1944), Waldmeier (1945–1980), and Koeckelenbergh at Brussels from 1980 to the present. The order of secondary and higher-order observations is not made explicit but can sometimes be deduced by careful analysis of the raw data and processed numbers.

The observing factors k were determined by ratioing the primary observers to Wolf and then by ratioing secondary and tertiary observers to the primary observers.

Values of k for any observer can vary with time to match the unvarying k's of the primary observers. No error bars for these values of k were calculated, so the R_Z's have no error bars associated with them.

After filling as many observing days as possible, Wolf still had gaps in his data. These gaps occur first in the interval 1818 to 1848, where nonetheless missing days are few enough to be manageable. For 1817 and earlier, the number of missing days were so great that Wolf only tabulated monthly means. For many months from 1749 to 1818 and for fewer months after 1818, there are no observations. Wolf filled these months by interpolation in some cases, such as February 1824. Some missing months were filled by using magnetic needle observations* and others by calculating the missing months by a linear regression technique. It is important to realize the R_Z's are a mixture of direct sunspot observations and calculated values.

Wolf also provides yearly values from 1700 onwards. He did not publish earlier yearly means because of a lack of data and his doubts that many years were entirely free of sunspots during the grand sunspot minimum now called the Maunder Minimum. Missing years such as 1744, 1745, and 1747 are fill values and are not based upon any sunspot observations.

Finally, in collecting data, Wolf did not travel to view the original observations, but rather relied upon correspondents to analyze and send the results to him. As shown in an earlier paper (Hoyt and Schatten, 1995), the quality of these interpretations was sometimes poor since the distinction between the definition of a group and individual spot was not always clear to his correspondents .

4. Technique for Deriving Group Sunspot Numbers

The technique used here has some parallels to Wolf's approach, but also has some significant differences. We define a sunspot index called the Group Sunspot Number (R_G) as follows:

$$R_G = \frac{12.08}{N} \sum k_i' G_i \; , \tag{2}$$

where G_i is the number of sunspot groups recorded by the ith observer, k_i' is the ith observer's correction factor, N is the number of observers used to form the daily value, and 12.08 is a normalization number chosen to make the mean R_G's identical with the mean R_Z's for 1874 to 1976 when the Royal Greenwich Observatory (RGO) actively made sunspot observations using Equation (2). The

* 'Magnetic needle observations' are measurements of 'geomagnetic activity' related to aurora, and hence CMEs, flares, solar activity, sunspots, etc. – the direction of a magnetic needle (on the Earth's surface) made during the course of a day. When the Sun is active the needle varies more than when the Sun is quiet due to solar-wind-carried magnetic fields, etc. These observations were made mostly between 1780 and 1860 in different European cities.

normalization number can be interpreted as saying the average sunspot group consists of about two spots (i.e., 2.08), but that is not the basis for chosing its value. This number will vary slightly depending on how many observations are used and so differs from our previously reported value of 11.93 (Hoyt and Schatten, 1994), because of the addition of more than 100 000 observations since that preliminary study. This technique for deriving sunspot number is used because 90% of the variance is caused by changes in the number of groups and many observers specify only the number of groups rather than both the number of groups and number of individual spots (see Schatten and Hoyt, 1994).

k', the observer's correction factor to place him on the same scale as RGO, is defined as 1.000 for our primary observer, RGO ($i = 332$ in Appendix 1). Observers who overlap the RGO can be directly compared to RGO. We form a ratio by dividing the total number of sunspot groups observed by the comparison observer and by RGO, limiting the ratio to those days when both observers saw one or more sunspots. This ratio is k'. The quality of the comparison is defined as equal to the number of intercomparison days divided by the quantity $(|1 - k')|$. Thus, a high-quality secondary observer is one who made many comparisons to the primary observer (RGO) and whose measurements are most similar to those by RGO.

These secondary observers allow us to compare observers further back in time to RGO. If the value of k' for a secondary or any higher order observer is less than 0.6 or greater than 1.4, that observer is not used for any intercomparisons. The value of k' for a tertiary observer is found by weighing their ratios to the secondary observers by the quality of the secondary observer. The process above is repeated for 4th, 5th, 6th, and 7th level observers. This technique maximizes the contribution of the best and most active observers and minimizes the number of intermediate observers between RGO and observer for whom k' is being calculated. It utilizes all the information we have rather than a selected subset. Finally, because multiple intercomparison paths are followed, both the mean k' and its standard deviation can be calculated. These values are tabulated in Appendix 1. Our method of deriving k' is basically identical to that used by Wolf in deriving his k values, although our weighting scheme is more complex. Although the daily sunspot groups follow a Poisson distribution, the daily ratios of one observer to another tend to follow a Gaussian distribution, allowing both Wolf and ourselves to use this method of determining k'.

This technique works well to about 1800 by covering most observers and gives some answers for observers in the 1700's such as Horrebow. However, because of the scarcity of observations from 1730 to 1800 (see Figure 1), comparisons during this period become difficult. Therefore, we established Horrebow as the primary observer for this period so we could calculate k' for more observers. For Horrebow, we successively tried values of k' of 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8 and calculated the k' values for all possible observers by the technique described above. These groups of k' values were then compared to the group of k' values

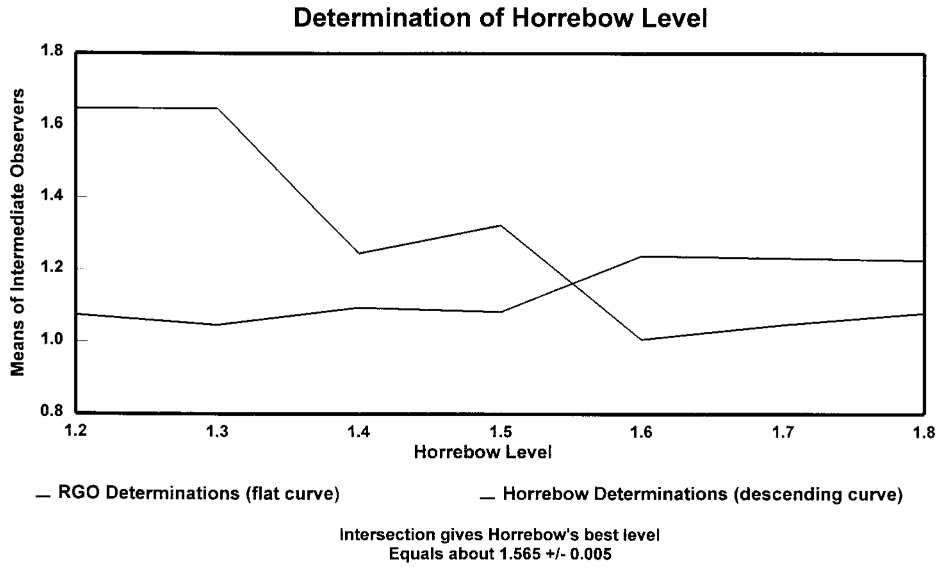

Figure 2. The intersection of these two curves defines the value of k' for Horrebow at 1.565. The value of k' for Horrebow was chosen to 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8 (x-axis). For each of these k' values, the values of k' for secondary, tertiary, etc., observervers was calculated. A similar process was done starting with RGO as the primary observer. The mean k' values starting with Horrebow and with RGO are then compared for the group of observers whose k' values can be derived by the two comparison routes. The comparison group has the same mean k' values when $k' = 1.565$ for Horrebow. On average about 121 observers are in the comparison group.

derived starting from RGO. The best mean value for k' for Horrebow was found to be 1.565 defined by the intersection of the two curves in Figure 2. At this intersection the mean k' derived starting from RGO and from Horrebow are the same. This intersection is interpreted as giving the best fit value for k' for Horrebow. Other interpolation schemes, whether linear or nonlinear, would give a value of k' for Horrebow between 1.5 and 1.6. Several different interpolations were tried by varying the allowable range of intermediate k' values that could be used (plots not shown). The number of observers for which k' could be derived starting at RGO and at Horrebow averaged to 121 observers for these different interpolations. The mean value of k' for Horrebow equaled 1.565 to within 1% and was virtually independent of the choice of allowable k' values for intermediate observers. The same technique was followed for the observations before 1730 where Plantade was chosen as the primary observer with a calculated k' of 1.107.

A number of observers, particularly in the early years, are isolated from all other observers. Most often they contribute a single observation day when no other observers were active. In these cases, we assigned them a k' value of 1.255 ± 0.112 based on the mean of group of modern observers (see Schatten and Hoyt, 1994). Sometimes there are clusters of observers isolated from all other observers. For example, the earliest observers in the 1600s are isolated. Here we treated *Galileo* as the primary observer and assigned him a k' value of 1.25 so as to make this cluster more internally self-consistent. 3.5% of all the observations are isolated. Since 1700, 1.2% of the observations are isolated. Of this 1.2%, 0.5% are isolated because they were made on days with no sunspots. Most of the isolated observers before 1700 are isolated because they were made on zero sunspot days. Thus, the solar activity reconstruction is insensitive to the value of k' for isolated observers.

Once the k' values for all observers are calculated, the solar activity reconstruction can begin by calculating the daily means using all available observers for that day. Before doing so, poor observers are excluded with $k' < 0.6$ and $k' > 1.4$. This criterion was applied only after 1848 when observations are plentiful and we can afford to discard observers. About 40 observers are discarded in all. Before 1848 Pastorff's observations as tabulated by Wolf are discarded along with one observation by F. G. W. Struve. Next, the daily means and standard deviations are the calculated. If a value used to calculate the mean is more than two standard deviations away from the mean, that value is discarded, and a new mean and standard deviation for that day are calculated. Gaps of up to 4 days for an active Sun and 6 days for a quiet Sun are filled by linear interpolation. These interpolations will give correct answers to within 1 group 95% of the time.

In Figure 3, we show a plot of the yearly mean R_G's and R_Z's. These numbers along with estimates of their sytematic errors and the Wolf Sunspot Numbers are tabulated in Appendix 2 which is published in *Solar Physics*, Volume 179, pp.215–219. The systematic errors in the Group Sunspot Numbers consist of four components: (1) errors arising from missing observations, (2) errors arising from uncertainties in the values of k', (3) errors arising from random errors in the daily values, and (4) errors arising from drifts in the k' values.

Errors arising from missing observations are easy to compute and are the dominant error term. For each year with less than 365 (366 in leap years) days of observations, we took the same subset of observed days and calculated the yearly means for the 146 years where complete coverage of the year is available (i.e., 1850 to 1995) and compared the subset mean to the completely sampled mean. The absolute mean percentage difference gives an estimate of the systematic error arising from missing observations. This systematic error is plotted as function of the number observed days in Figure 4. For 20 or more days of observations (D), the error E follows a linear relationship:

$$E = 0.217 - 0.00059D\ .$$

As D approaches 365 or 366, this systematic error approaches zero. For D less than 20, erratic results are found, so we conclude no reliable yearly mean can be found in such circumstances. Twenty-five out 386 years thus can not have their yearly means accurately found, even though individual days and months in those years may have reliable values.

Errors arising from uncertainties in k' were evaluated by deriving the mean uncertainties for five selected eras: (1) 1610–1653, (2) 1653–1730, (3) 1731–

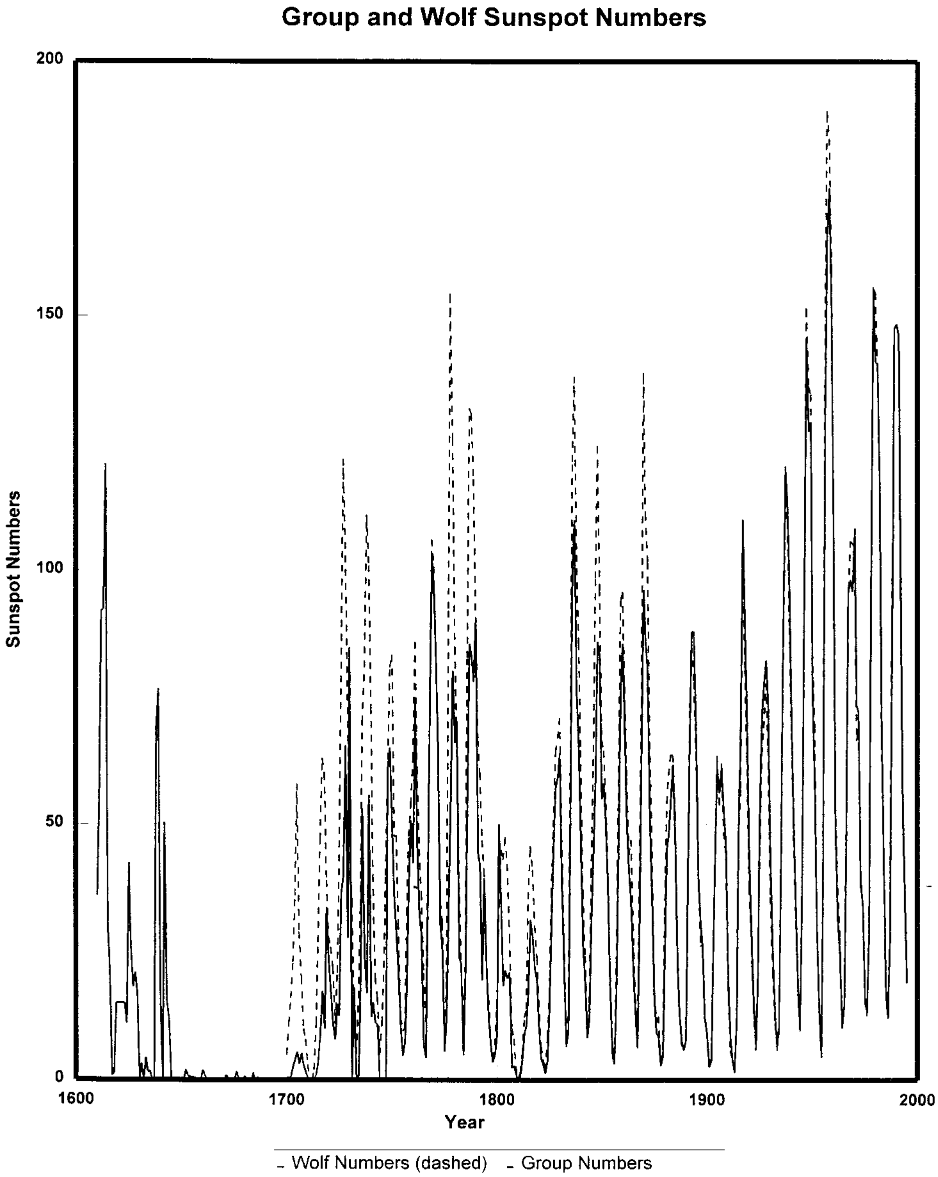

Figure 3. The yearly mean Group Sunspot Numbers and Wolf Sunspot Numbers are plotted. Systematic errors in the Group Sunspot Numbers are small after 1800 and before 1730 and are listed in Appendix 2.

1797, (4) 1798–1850, and (5) 1851–1995. These eras have the common property that they can be classified as poorly observed, partly observed, or fully observed. Observers in these eras tend to form large nearly isolated clusters of observers in all but the case of 1798 to 1850. This era is broken out separately since most of its

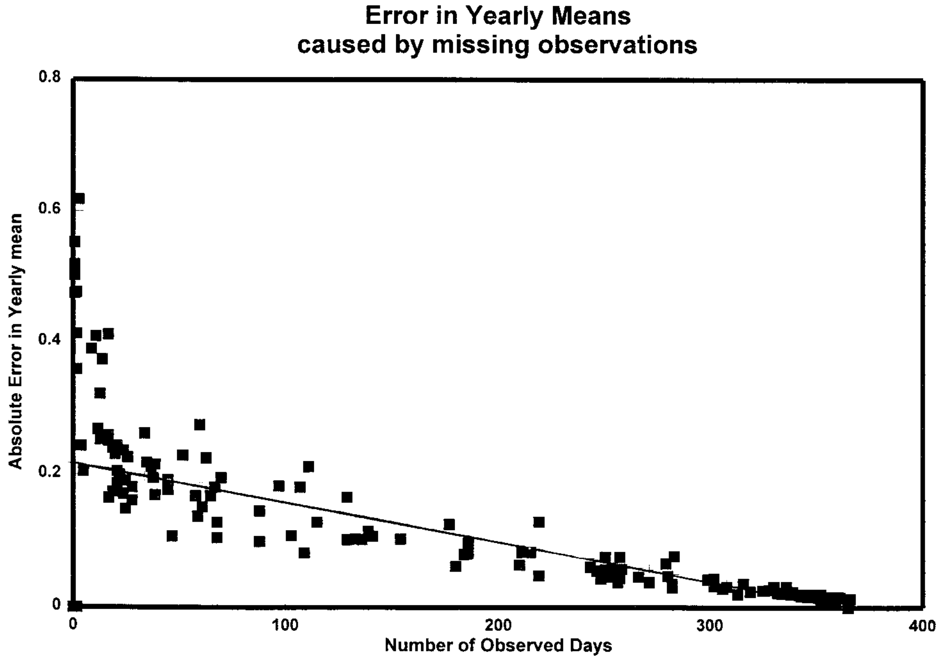

Figure 4. The systematic error in yearly means attributable to missing observations. Each point represents a year which only has partial observations ranging from 1 to 364 days (x-axis). The errors were calculated by using 146 years when complete observations exist when the mean with all information is known. The partial year means for these 146 fully sampled were then calculated using the same calendar days of observations in the partially sampled year. The mean difference between the 146 partially sampled and fully sampled years is a point on the plot. For more than 20 observation days, the points track the regression line shown. For less than 20 observations, no reliable yearly mean can be found.

years are not fully observed. Errors for these eras were found to be equal to 5%, 7%, 24%, 7%, and 2%, respectively.

Each daily mean has an uncertainty associated with it of about 12%. This uncertainty is nearly constant time, rising to about 14% circa 1880 when the meaning of a group was not the same for all observers. The systematic error arising from these daily random errors was calculated as 0.12 divided by the square root of the number of observing days. For a completely sampled year, this error is 0.63%.

The final source of systematic error is possible secular changes in k' for the observers. k' has one value for observer which applies to all his observations. Errors arising from changes in k' cannot be calculated in any way known to us, but are probably small since drifts by one observer will tend to be canceled out by opposite drifts from other observers. Thus, this error is taken as zero in our error analysis.

The final systematic error is the root-mean-sum of the errors above. The errors are plotted in Figure 5. These errors are less than 10% everywhere except for 1728

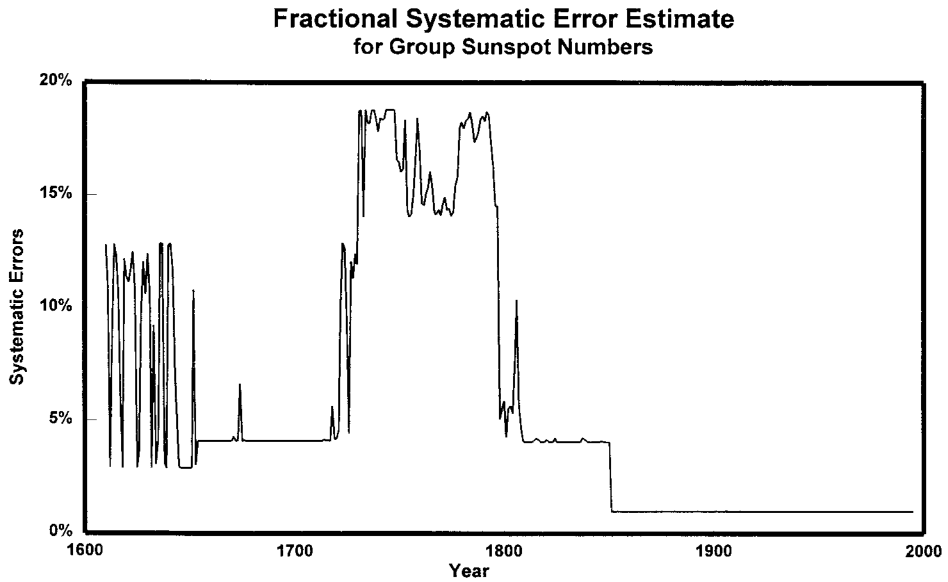

Figure 5. The systematic errors in the Group Sunspot Numbers as a function of time. Systematic errors arise from partial sampling, uncertainties in k', and random errors as explained in the text. The dominant cause of errors is missing observations between 1730 and 1800.

to 1799. Observations are scarce then so poor sampling and near isolation of the observations both combine to drive the error up to values of the order of 15–20%.

5. Some Comparisons of the Wolf and Group Sunspot Numbers

Numerous comparisons between the Group Sunspot Numbers and Wolf Sunspot Numbers can be made. In the last third of the paper, we present sample comparisons between R_G and R_Z based upon four time scales: daily, monthly, and yearly values, and secular trends. These comparisons are made to help elucidate some of the reasons the two time series differ.

5.1. Daily Values

The daily R_G's have a mean value tabulated along with their standard deviation and number of observers used to form the mean. The R_Z's have a daily value derived from one observer with no error estimate. The R_Z's have daily values starting in 1818, but complete daily coverage does not start until 1849. The R_G's have daily values whenever possible. There is nearly complete daily coverage from 1645 to 1727 and from 1847 to the present. There is substantial daily coverage from 1797 to 1846. The coverage is illustrated in Figure 1.

The daily R_G's are more homogeneous than are the daily R_Z's. This can be illustrated by a couple of specific examples, such as the year 1829. In Figure 6, the

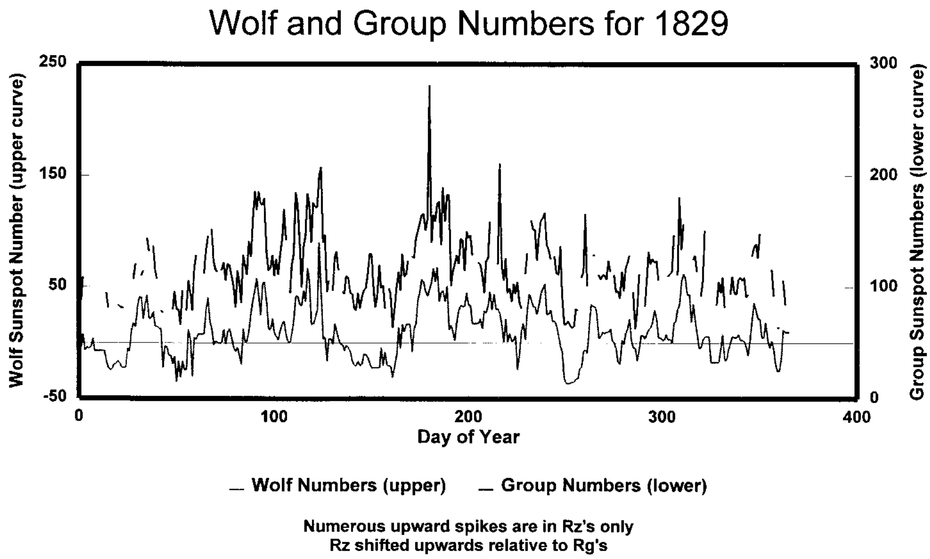

Figure 6. A comparison of the daily R_Z's and R_G's for 1829. The curves are offset so they can be more easily compared. Note the large number of upward spikes in the R_Z's (upper curve). These spikes are not solar behavior but are inhomogeneities in the R_Z's caused by incorrect merging of different observers.

R_G's and R_Z's for this year are plotted and in Figure 7 we show the differences between the two time series. The R_G's have complete coverage for this year using eight observers, two of whom Wolf did not have access to. The R_Z's have 291 days. There are a number of upward spikes in the R_Z's that are not present in the R_G's. For 1829 Wolf used Schwabe as his primary observer. One of his secondary observers was Pastorff. For each spike, Schwabe had no observation, but Pastorff did. These spikes are caused by Pastorff's observations which are not homogeneous with Schwabe's observations. In Figure 6, one can see that the day-to-day fluctuations in the R_Z's are greater than the R_G's everywhere.

The example in Figure 6 shows how improper merger of observers leads to unrealistic fluctuations in the R_Z's. Other fluctuations arise because observations were taken on hazy days so small sunspot groups are missed. This effect shows up as sudden one day drops in solar activity. Other effects must be going on as well as an examination of five days in February 1860 shows (Table I).

The day-to-day fluctuations of the R_Z's have a solar component and a component caused by the observers. The component caused by the observers can be called 'observer noise'. For R_Z, this observer noise is greater than the observer noise in the R_G's, particularly for the earlier years. Gradually, the derivation of the R_Z's improves and by the 1950s both the R_Z's and R_G's have the same levels of observer noise. It is our conclusion that the R_G's are more homogeneous on the time scale of days. However, we would like to add that R_Z and R_G are two distinct indices of solar behaviour so some differences will occur even if the measurements were

Table I

R_Z and R_G for 5 days in February 1860. The R_Z varies erratically up and down, but the R_G are more steady. The number of groups observed by eight observers during this interval are given. Wolf had access to all the observations except those by Howlett and Shea. The reason for the large value on 10 February is unclear as well as the reason for low value on 9 February. Many such unexplained non-solar variations appear in the R_Z's.

Date	R_Z	R_G	Schwabe	Schmidt	Wolf	Carrington	Coast survey	Weber	Howlett	Shea
8 Feb.	103	82	6						4	
9 Feb.	52	68	5	7		6	7	5	2	2
10 Feb	161	47	2	5			5	3		3
11 Feb	71	51			3			4		4
12 Feb	103	51	4			4		3		4

error free. The primary objective in deriving R_G was to obtain a self-consistent index of the long-term solar activity.

5.2. Monthly values

Monthly means can be formed when daily values are available. Generally three or four widely separate days within a month are adequate to form a monthly mean. Often though there are no observations at all. For the R_G's these missing months are filled with a value of -99. Monthly means are formed for all other cases and the number of days used to form these monthly means are given too, so we leave it to the user of the numbers to evaluate their usefulness.

From January 1749 to the present, there are 84 missing months in the R_G time series. In contrast the published R_Z's have complete monthly coverage for this interval. Wolf used two procedures to fill in missing values: (1) linear interpolation, and (2) using magnetic needle observations and linear regression model to fill in missing months. It is not always clear which procedure is being followed for each filled month.

We have chosen not to fill the monthly means. The R_G's are a pure time series in that are based solely upon telescopic observations of sunspot groups. The R_Z's are a mixed time series based upon telescopic observations and magnetic needle observations.

After 1800 the R_G's have no missing months, but the R_Z's have many interpolated months. For example, February 1824 is interpolated in the R_Z's to give a value of 10.8. For the R_G's, 29 days of observations are available, so its monthly mean can be calculated to be 0.5, which is substantially different from the interpolated value. The January to March 1824 interval is summarized in Table II.

Finally, the month-to-month differences for the R_G's are less than for the R_Z's, which is an indication of less observer noise in the R_G's.

Table II

The monthly mean R_Z's and R_G's for January to March 1824. This shows that monthly interpolations are not always reliable and that the R_G's have more data to form monthly means

Month	R_Z days	R_Z	R_G days	R_G
January	3	21.7	10	15.7
February	0	10.8	29	0.5
March	21	0.0	31	0.0

5.3. Yearly values

R_Z's have yearly values since 1700 or for 296 years. R_G's have yearly values from 1610 to 1995 or 386 years. Of these 386 years, six years had no observations and so do not have a yearly value. Another 20 years have 20 or fewer observations, so their yearly means are unreliable. An 'unreliable mean' is one whose uncertainty is greater than 25%. Years that have no value or an unreliable value are 1610, 1614, 1615, 1623, 1630, 1636, 1637, 1640, 1641, 1723, 1724, 1731, 1732. 1734. 1737, 1738, 1739, 1741, 1743, 1744, 1745, 1746, 1747, 1748, 1759, 1783, 1784, 1789, 1790, 1792, 1793, and 1794. In general then we would say solar activity is poorly known or unknown for 1610–1641, for 1731–1748, and for 1789–1794. For 1642 to 1730, for 1750 to 1788, and for 1795 to the present, the R_G's are well determined. We would recommend ignoring values before 1642 and using interpolated or modeled values for 1731 to 1748 and from 1789 to 1794. Values between 1642 and 1653 may also be suspect because although we have reports of low activity then, it is not certain yet that these reports are true.

In Appendix 2, we tabulate the yearly mean R_G's along with their one-standard-deviation uncertainty and number of days observed during the year. For comparison, the R_Z yearly means are listed too. Most of the differences in the two time series occur before 1882 when the sunspot counting technique of Wolf was altered according to Hossfield (1997), but some significant differences occur even for recent years. For example, for 1980 the R_G is 141.1 but the R_Z is 154.6 or 9.6% higher. The Ottawa Sunspot Number for 1980 is 142.3. For the adjacent years, 1979 and 1981, the R_Z and R_G agree to within 1%. Why then do they differ for 1980? There is no simple answer to this question. For nine of the twelve months, the R_Z's exceed the R_G's. For three of the months, the R_Z's exceed the R_G's by more than 10%: (1) February (+23%), (2) April (+43%), and November (+20%). Focussing on April, the R_Z daily values range from 95 to 252, while the R_G's range from 83 to 142. On 13 April, the R_Z peaks at 252, the R_G equals 128, the American Sunspot Number is 213, and the Ottawa sunspot number is 176.3. The number of recorded groups are 8 (SEL), 8 (Rome), 10 (Catania), 11 (Mt. Wilson), 7 (Taipei), 8 (NAO, Japan), and 9 (Koyama). Ignoring correction factors for the

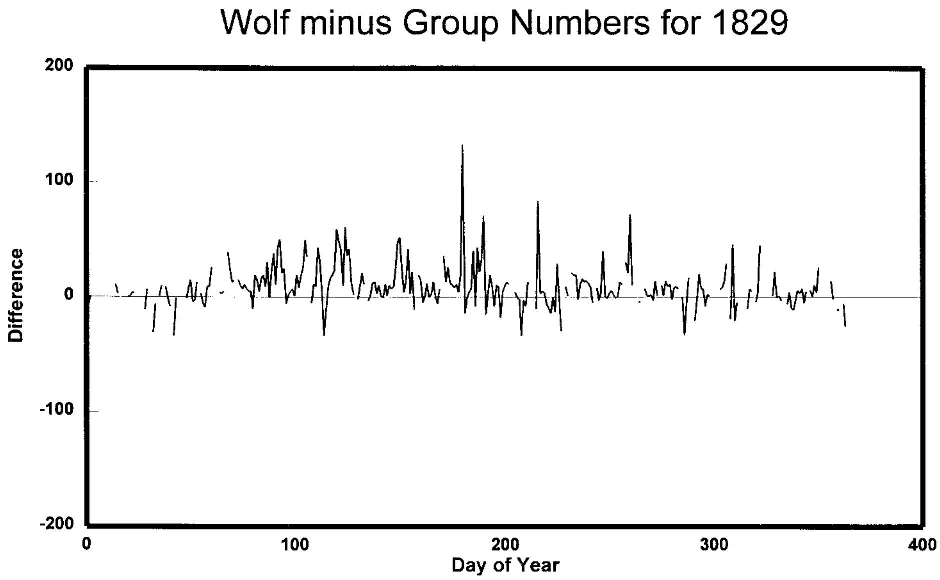

Figure 7. The difference between the R_Z's and R_G's for 1829. The upward spikes are again evident. These spikes raise the yearly mean R_Z for 1829 by about 5 units and have even larger effects on the monthly means.

observers, this corresponds to 8.7 groups. With correction factors used, we estimate 10.6 groups, meaning on average observers missed counting two, presumably small, groups. Yet the R_Z of 252 for this day implies about 20 groups should be present. One possibility is that the groups present on that day were extraordinarily complex having of the order of 15 individual spots per group. This explanation is not quite satisfactory since the discrepancies between the R_Z and R_G appear to occur erratically and not systematically, since other periods with high activity and presumably complex groups agree with each other. The raw numbers used to generate the R_Z's in these cases are not available in the published literature so the differences cannot be resolved. Again, we emphasize that R_G and R_Z are similar solar indices, so even in ideal circumstances their daily numbers will not agree.

Despite these differences, more than 90% of the years after 1900 have R_G's and R_Z's that agree to within 10 units. The disagreements may arise from some inhomogeneity in the R_Z's or the R_G's, or it may be expecting too much to have identical R_Z's and R_G's since the two indices are defined differently.

5.4. Secular Trends

A major impetus for deriving the Group Sunspot Numbers was to see if a homogeneous time series could be constructed. In particular, we sought to make the earlier observations consistent with the modern observations. In Section 4, we described our method of deriving these numbers and the errors associated with their deriv-

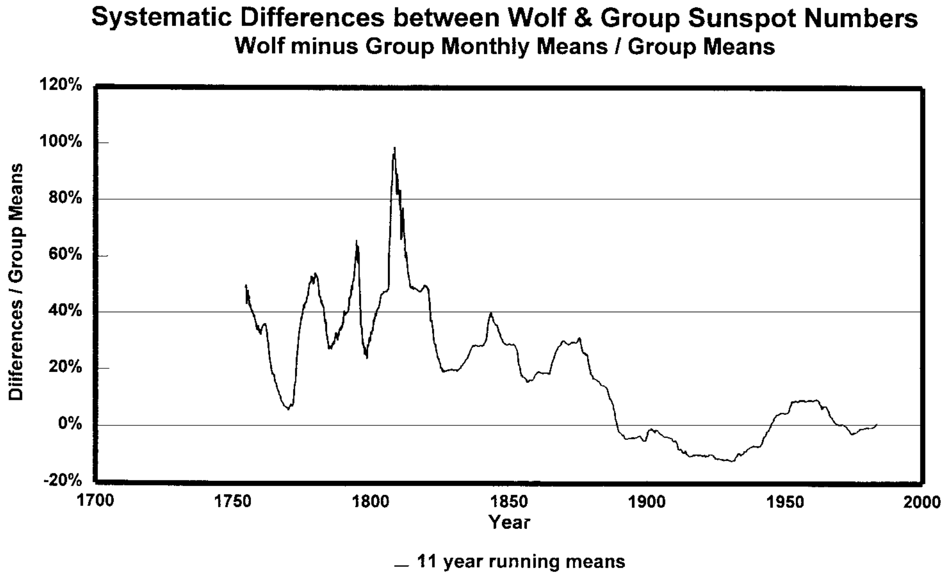

Figure 8. The systematic differences between the R_Z's and R_G's. The quantity $(R_Z - R_G)/R_G$ is plotted using monthly means. Higher values indicate the R_Z's are systematically higher than the R_G's. Before about 1882 these differences average between 20 and 30% much of the time. Even in this century the two time series are not completely self-consistent, fluctuating in a band of ±10% about their means.

ation. It appears that the observations from 1653 to 1730 and from 1797 to the present are internally self-consistent to within 5%. Derived values between 1731 and 1796 are probably only self-consistent with modern observations to about the 15 to 20% level. Without the discovery of more observations, it will be difficult to reduce these errors.

The R_Z's are higher than the R_G's before 1882 at which time the method of constructing R_Z's was changed (Hossfield, 1997). In Figure 8, we summarize the differences between the R_Z's and R_G's by taking the ratio of the difference of the monthly means to the R_G's (i.e., $[R_Z - R_G]/R_G$) and smoothing them with an 11-year running mean. The largest difference occurs in 1808 when the R_Z's exceed the R_G's by 97%. For the interval 1803 to 1813 Wolf had very few observations. For 1803 he had five days and for 1804 he had four days. In Table III, we summarize the number of observations used as input for the R_Z's and R_G's for 1800 to 1813.

From the table it is evident we have more observations every year. More than 4000 observations are used to construct the R_G's while less than 1000 observations were available to Wolf. The paucity of observations caused Wolf to no longer give daily values before 1818. Because the R_G's are created from a larger input database, there is more opportunity to compare the observations to those made later. Thus, we are confident that the large differences between the R_Z's and R_G's shown in Figure 8 are caused by errors in the R_Z's. Furthermore, the R_Z's have

Table III
Number of days from all observers used by Wolf to construct the R_Z's from 1800 to 1813 compared to the number of observations available to derive the R_G's

Year	R_Z observations	R_G observations
1800	66	173
1801	38	235
1802	54	145
1803	5	150
1804	4	141
1805	75	100
1806	12	52
1807	31	266
1808	55	273
1809	41	305
1810	114	659
1811	67	820
1812	147	312
1813	174	462
Totals	883	4093

an activity peak in 1805 compared to an activity peak in 1801 for the R_G's. The supposed long cycle of 17 years from 1788 to 1805 should actually be a cycle that extends from 1788 to 1801, or 13 years. There is a chance that the previous peak was in 1790 and not 1788 (see Appendix 2 which is published in *Solar Physics*, Volume 179, pp. 215 – 219), but since 1790 was poorly observed, it cannot yet be definitively said this cycle lasted 11 years. There is another long cycle from 1801 to 1815 (14 years) which may be characteristic of the Sun when activity is low. The low activity cycles around 1800 are often called the Dalton Minimum.

Returning to Figure 8, we see that the R_Z's exceed the R_G's by about 30% for the interval 1750 to 1800. This difference exceeds by a factor of two our estimates of the systematic errors in the R_G's. The R_G's are similar to the numbers published by Wolf (1861) as shown in Table IV. In 1873 Wolf revised his numbers upwards using magnetic needle observations. The analysis in this paper supports his earlier derivation of solar activity instead of the later revisions which are now universally used. For the years 1749 to 1800 inclusive, the average R_G is 39.6, the 1861 R_Z average is 43.5, and the modern R_Z average is 53.7. The modern R_Z's exceed the 1861 R_Z's by 23%. This upward adjustment does not seem correct. Wolf's adjustment does produce the R_Z's such that the level of solar activity is roughly constant in each of the 50-year intervals from 1700 to the present and that may have been a motivation for his modification.

Table IV

A comparison of yearly mean sunspot numbers for solar maxima between 1749 and 1850. Shown are the Group Sunspot Numbers, the Wolf Sunspot Numbers as published in 1861, and the Wolf Sunspot Numbers as published today. Note that the 1861 R_Z's are close to the R_G's. Both of these determinations relied on telescopic observations whereas the modern R_Z's for this era are a mixture of telescopic observations and magnetic needle observations. The question mark after the number 70.0 for the peak in 1805 reflects Wolf's uncertainty in his assigned value.

Year of solar max.	R_G	R_Z in 1861	R_Z today
1749	65.0	68.2	80.9
		in 1750	
1761	74.0	75.0	85.9
1769	102.4	85.7	106.1
1779	80.2	99.2	154.4
		in 1778	
1790	90.5	92.8	132.0
		in 1787	in 1787
1801	49.9	70.0 (?)	47.5
		in 1805	in 1805
1816	31.3	45.5	45.8
1830	64.0	59.1	70.9
1837	109.9	111.0	138.3
1848	86.0	100.4	124.7

For the period 1700 to 1730, the R_Z's exceed the R_G's by a large percentage. We have thousands of observations for this period which Wolf did not have. Since no more than one group appeared on the solar disk before 1715, the cycle peaking in 1705 must be less than 10 and not the value of 58 reported by Wolf. The rise out of the Maunder Minimum took several cycles before it reached peaks comparable to more modern activity levels. The first cycle after the Maunder Minimum has a double peak in 1705 and 1707 as also reported by Baiada and Merighi (1982).

6. Conclusions

We have created a greatly improved record of solar activity via sunspot numbers that can be used by many disciplines (from solar physics to climatology). The objective of this study was the creation of self-consistent time series for solar activity with systematic and random errors estimated. This goal is met. The first step in the process was the collection of data. In this goal we succeeded in collecting many observations missed by Wolf and in improving the quality of the raw data for some observers. The number of observations available to construct the R_G's considerably exceeds the number used to construct the R_Z's.

By using multiple observers each day, the random errors in the daily means of the R_G's can be calculated. By using groups alone, versus groups and individual sunspots, it is possible to compare observers to one another and derive values for their observation constants, or k's, more easily. These k's were calculated by giving greater weights to the highest quality and most active observers and by minimizing the number of intermediate observers between the observer and the standard observer, RGO. Thus, the minimum path length, maximum number of minimum paths, and best comparisons are used to derive the k' values. This technique assures the maximum use of the data as opposed to selective and subjective approaches used by Wolf in deriving his observer constants. The technique allows us to place error bars on the k' values and we think gives us the best chance of producing a homogeneous time series.

The final data products consist of daily, monthly, and yearly means along with their one-standard-deviation uncertainties and the number of observations used to generate them. A supplemental bibliography with comments has also been generated so that the input data is traceable to the original sources, be they journals, books, or manuscripts. The raw data, the Group Sunspot Numbers, and supporting documentation are in 16 files at the National Geophysical Data Center in Boulder, Colorado. They may be accessed on the Worldwide Web at http://www.ngdc.noaa.gov/ or at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/GROUP_SUNSPOT_NUMBERS.

This generation and preliminary review of the Group Sunspot Numbers allow several conclusions to be made: (1) Solar activity before 1882 is lower than generally assumed and consequently solar activity in the last few decades is higher than it has been for several centuries. (2) There was a solar activity peak in 1801 and not 1805 so there is no long anomalous cycle of 17 years. The longest cycle observed now lasts no more than 15 years. (3) The R_Z's have many inhomogeneities in them arising from observer noise and this noise affects the daily, monthly, and yearly means. The Group Sunspot Numbers also have observer noise, but this is considerably less than the noise in the Wolf Sunspot Numbers.

There are no immediate plans to continuing working on the Group Sunspot Numbers or in keeping them current. If the observations by Chevallier, Soemmering (see Carrington, 1860), Fink (see Zinner, 1952), or other misplaced or missing observers become available, the database and processed results will be updated.

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