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The one hundredth year of Rudolf Wolf's death: Do we have the correct reconstruction of solar activity?

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Abstract. In the one hundred years since Wolf died, little effort has gone into research to see if improved reconstructions of sunspot numbers can be made. We have gathered more than 349,000 observations of daily sunspot group counts from more than 350 observers active from 1610 to 1993. Based upon group counts alone, it is possible to make an objective and homogeneous reconstruction of sunspot numbers. From our study, it appears that the Sun has steadily increased in activity since 1700 with the exception of a brief decrease in the Dalton Minimum (1795-1823). The significant results here are the greater depth of the Dalton Minimum, the generally lower activity throughout the 1700's, and the gradual rise in activity from the Maunder Minimum to the present day. This solar activity reconstruction is quite similar to those Wolf published before 1868 rather than the revised Wolf reconstructions after 1873 which used geomagnetic fluctuations.

Introduction

The eleven-year or Schwabe cycle in solar activity was discovered by Heinrich Schwabe in 1843, based upon 17 years of observations. In the early 1850's Rudolf Wolf of Bern and later Zurich, Switzerland began a search of historic sunspot observations. Over the next 40 years, Wolf gathered thousands of observations from hundreds of observers and derived a record of sunspot number from the 1600's onwards. His index is known as the Wolf Sunspot Number. It is defined as ten times the number of sunspot groups plus the number of individual sunspots, all multiplied by a correction factor (k) for each observer. The Wolf Sunspot Number is considered to be reliable from 1848 to the present, good from 1818 to 1847, questionable for 1749-1817, and poor for the earlier years. These subjective judgments do not give us a numerical measure of how confident we can be in Wolf's reconstruction of sunspot numbers. Some measure of the random and systematic errors in his reconstructions are needed.

Wolf died on December 6, 1893. Since that time, little effort has been devoted to re-checking Wolf's sunspot number reconstruction. These reconstructions are very important for studies of solar variability related to climate change. Did he get a reliable answer? In this note, we will address this question, give a new reconstruction of sunspot numbers for 1610 to the present, and outline our plans for future work on this problem.

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Data Collection

Wolf reconstructed solar activity using both the number of sunspot groups and the number of individual sunspots. We have shown previously (Hoyt and Schatten, 1992a) that more than 90% of the variability is attributable to changes in the number of sunspot groups. There is no significant secular trend between the Wolf Sunspot Numbers and the number of sunspot groups measured by the Royal Greenwich Observatory from 1874 to 1976. This earlier study indicated that the ratio of the number of individual spots to groups is nearly a constant. Schaefer (1993), using theoretical arguments, shows that the Wolf Sunspot Number may be set equal to a constant times the number of sunspot groups. Therefore, both statistically and theoretically, one can argue that an index based solely upon the number of sunspot groups can simulate the Wolf Sunspot Number. This index will be called the Group Sunspot Number and will be discussed further below.

Based upon these considerations we started digitizing as many raw telescopic observations of daily counts of sunspot groups as we could find. Our objective is to relate all the observers to one standard observer so that all the sunspot group observations are self-consistent. Many of the observations are tabulated by Wolf and his successors in Astronomische Mittheilungen (1852-1946). Other observations are scattered throughout the literature, such as the observations by Kunitomo in 1835-1836, which were tabulated and published by Yamamoto in 1935 in the Kyoto Bulletin. In all, our database contains 349,405 observations from more than 350 observers, many of which were unavailable to Wolf. Although we continue to gather data, we now have a sufficient number of observations to make a significant reappraisal of sunspot numbers for 1610-1993.

Data Analysis

The observations by the Royal Greenwich Observatory (RGO), 1874-1976, are among the most reliable sunspot observations made. Our approach is to use RGO data as the "standard observer" and normalize earlier observers so that counts of sunspot groups would equal those of RGO. To do this, we sum up all observations made by the RGO, and separately by the other observer, on days when both made measurements. The ratio of the number of RGO groups to the number of groups by the other observers then gives a correction factor (f) by which this observer's group counts must be multiplied to place them on the same scale as the RGO data. For example, Schmidt of Athens obtained 3392 days of measurements in common with the RGO from 1874 to 1883. Schmidt observed 6221 groups and RGO observed 7017 groups. The correction for Schmidt therefore is 1.127. Schmidt also observed in the 1840's along with Schwabe who observed from 1826 to 1867. Schmidt and Schwabe had 1837 common observation days and observed 6260 and 6080 groups respectively. Because Schwabe ceased observing after 1867, it is not possible to directly compare his observations to RGO, but by taking the ratio Schwabe to Schmidt and the ratio Schmidt to RGO, one can find the ratio Schwabe to RGO. Other intermediate observers, such as Weber of Peckeloh and Wolf of Bern and Zurich, can be used to find the ratio of Schwabe to RGO. Our analysis indicates that Schwabe's sunspot group numbers need to be multiplied by 1.285 to equal those of RGO.

By using one or more intermediate observers, nearly all the observers from 1749 to the present can be put on the RGO scale. Our approach is to use the minimum number of intermediate observers, but to use the maximum number of available paths of comparison. For example, for Christian Horrebow for whom we have daily observations for 1767 to 1776, we find a correction factor of 1.17 using four intermediate observers in each of 12 different paths or ratio determinations. Our analysis indicates that the monthly mean group number tabulation of Horrebow's sunspot groups by Thiele (1859) is less correct than the daily observations used by Wolf. Some isolated observers exist and the observers prior to 1749 are isolated from the modern day observers. The average modern observer, who depends upon visual observations, needs to have his sunspot group counts multiplied by 1.255 to bring them in agreement with the RGO photographic counts. Other careful modern observers using photographic plates, such as those at Mt. Wilson or at the Debrecen Heliophysical Observatory, have ratios to the RGO data between 0.966 and 1.049. For the isolated observers, whose observations do not occur on the same days as any other observer, we use a correction factor of 1.255. This correction factor adjusts for missing sunspot groups which are small, near the solar limb, or considered not remarkable enough to comment on. Finally, it is important in these analyses to use primary sources or reliable secondary sources.

Given that all the observers are normalized to the RGO scale of observations, how do we convert them to Group Sunspot Numbers? For the period 1874 to 1991, we normalized the Group Sunspot Numbers by requiring that their average equal the average of the Wolf Sunspot Numbers for this period. This requires that the number of sunspot groups be multiplied by 11.93. Therefore, the definition of the Group Sunspot Number, R_g, is:

$$R_g = 11.93 G_{RGO}$$

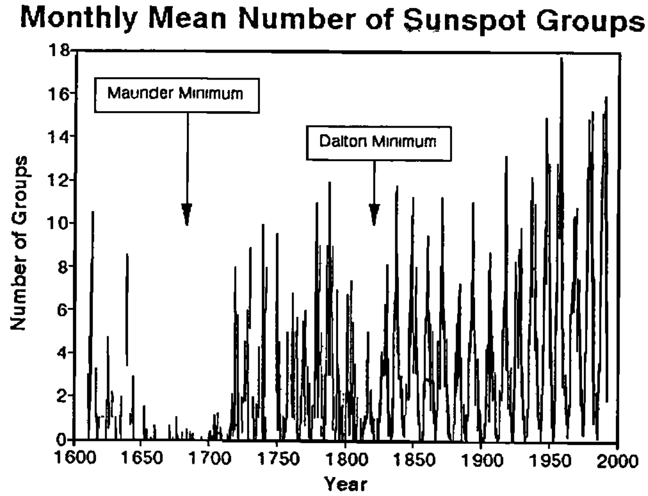

Figure 1. The reconstruction of solar activity from 1610 to 1993 using only the counts of sunspot groups. More than 349,000 observations were used to reconstruct sunspot group numbers.

where G_{RGO} is the number of sunspot groups which would be counted if RGO were observing.

Results

Figure 1 shows the monthly mean Group Sunspot Numbers. For the present day period there is good overall agreement with the Wolf Sunspot Numbers as might be expected, although since about 1920 the Wolf Sunspot Numbers have risen faster than the Group Sunspot Numbers. Figure 2 shows this more clearly with plots of the Group

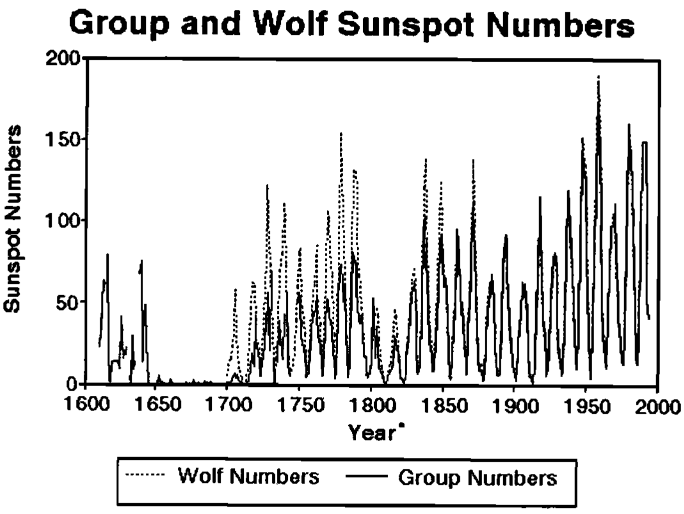

Figure 2. The reconstruction as given by Wolf and the Zurich Observatory and that reconstructed here using sunspot groups only. In general, the Group Sunspot Numbers are lower than the Wolf Sunspot Numbers prior to 1848, more consistent with Wolf's reconstructions prior to 1868. Some of the annual mean Group Sunspot Numbers between 1728 and 1795 must still be considered preliminary, because of the lack of observations for many of these years. Note the gradual rise in activity from 1700 to the present.

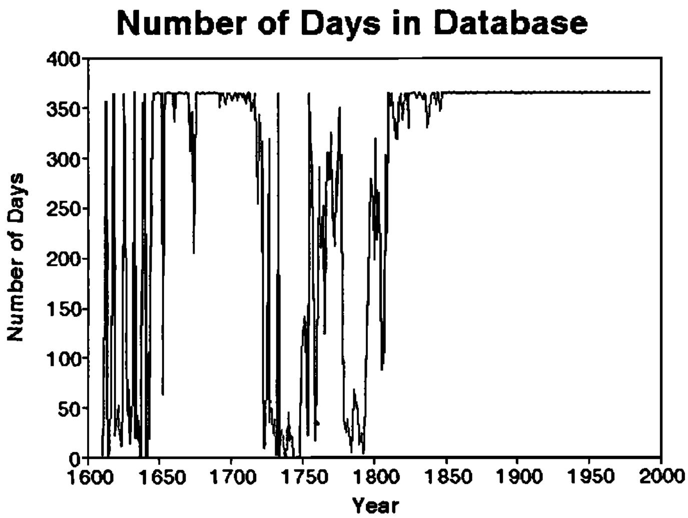

Figure 3. The number of days each year for we which have observations or interpolated values. If more than 5% of the days are observed in a year, a good yearly mean can usually be found. Most years meet this criteria. Note that the Sun was well observed during the Maunder Minimum.

Sunspot Numbers and the Wolf Sunspot Numbers. Cycle number 11 peaking in 1870 is weaker in our reconstruction than in Wolf's reconstruction. But the major differences occur for the years prior to 1848. Here the Wolf Sunspot Numbers are systematically higher than the Group Sunspot Numbers. Curiously, our Group Sunspot Numbers are similar to the Wolf Sunspot Numbers published by Wolf prior to 1868. In 1874, Wolf revised his original sunspot numbers by multiplying them by a factor of 1.25 for 1826 to 1848 and by about 1.2 to 1.5 for the earlier years. Wolf's correction was apparently determined using variations of the magnetic needle at Milan. Based upon our analysis, this correction is erroneous.

The Maunder Minimum clearly shows up in our reconstruction. It appears that the Sun steadily increased in activity from 1700 to 1750 and then leveled off for 50 years before entering the Dalton Minimum (1795-1823). The significant result here is that there is a steady increase in activity following the Maunder Minimum, rather than a step-like increase to near modern values.

In Figure 3, we show the fraction of the time for which we have observations of the Sun. There is a paucity of observations in the 1740's and the 1780's, so the level of solar activity during these periods remains uncertain. This lack of observations can be attributed primarily to the prevailing attitude among leading scientists of these times that sunspots were not a subject worthy of study.

The Sun was well observed during both the Maunder and Dalton Minima. Some of these earlier years show 100% of observations based upon comments by some observers that no sunspots were observed during entire years. In fact, these years were observed on more than 50% of the days (Ribes et al., 1988) and future work will give us a better measure of the fraction of time that the Sun was observed.

If more than 5% of the days in any one year are randomly observed throughout the year, a reasonable value for the yearly mean can be found. Most years meet this requirement. In 1877, Wolf reported he averaged 90 observation days/year for 1749-1783, 70 days/year for 1784-1818, and 260 days/year for 1819-1848. Our database has 139, 161, and 345 days/year respectively for these three groups of years. For cycle five, we find a peak in 1801 versus Wolf's conclusion of a peak in 1805. For the years 1800 to 1810, we average about 192 days/year whereas Wolf reported that he had less than 10 days/year for many of these years. Thus, we are confident that for solar cycle five, we have a better reconstruction of the solar behavior.

Conclusions

The Group Sunspot Numbers here are preliminary and will improve as we acquire more data. Already, though, we have seen that our understanding of long-term secular variations in sunspot numbers may require some revisions. The correct reconstruction of sunspot numbers could eventually lead to a better understanding of the Sun and its influence upon climatic change.

Our work on reconstructing sunspot numbers is an ongoing endeavor. More than 350 observers and 349,000 observations have been entered into computer readable files. Nonetheless we have identified more than 50 observers for which further research is required, involving location of their data or entering of their data into our database. To date, we have managed to acquire about 85% of the data that we eventually expect to get. Some observers already included in the present database, such as Thomas Hussey from 1826 to 1837, were never available to Wolf. This study includes 30 observers missed wholly or in part by Wolf such as William and John Herschel, Shea, Greisbach, Lawson, Sharp, Picard, La Hire, Hevelius, Wasse, Scheuchzer, Graham, Carbone, Willoughby, and Remoquietanus. Identified observers for which we plan further research are: 1) In the 1600's: Jungius, Mogling, Schaller, Hessen, Weigel, Arnold, Ihle, Blancanus, Chiaramonti, Cysat, Rheita, Fridanus, Grienberger, Guldin, Zucchius, Hortensius, Antoninus, Cornaeus, Mair (Marius), Ehinger, Rosius, Fogel (Vogelius), Weickmann, and Rentchius. 2) In the 1700's: Manfredi, Blanchini, Hoffmann, Hertel, Sturm, Schutz, Alischer, Becker, Adelburner, Beyer, Boscovich, Bose, Frobes, Schubert, Horrebow, Muller, Dunn, Schulen, Wilson, Hornsby, Hahn. 3) In the 1800's: Maur, Ruprecht, Soemmering, Henry, Kriel, Main, Chevallier, Borck, Schott, Schwabe, Wolf, Bernaerts, Jahn, Lichtenberger, Steinmann, Parpart, von Heneke, Schurig, Charnoc, Carl, and Bogulawski. Many of these scientists made infrequent observations of the Sun so their future inclusion are expected to change only the details of our activity reconstruction.

If readers know of sunspot observations by these observers or others, particularly for 1848 and earlier years, we would be interested in adding them to our database. Once the database is complete, we plan to give it to the National Geophysical Data Center in Boulder, Colorado so it will be available to all researchers.

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