Evidence of 6 000-Year Periodicity in Reconstructed Sunspot Numbers

M.A. Xapsos · E.A. Burke

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Abstract Reconstructed sunspot data are available that extend solar activity back to 11 360 years before the present. We have examined these data using Hurst analysis, a moving average filter, and Fourier analysis. All of the procedures indicate the presence of a long term (≈6000 year) cycle not previously reported. A number of shorter cycles formerly identified in the literature by using Fourier analysis, Bayes methods, and maximum entropy methods were also detected in the reconstructed sunspot data.

Keywords Solar activity, periodic · Hurst analysis · Smoothing filter · Fourier analysis

1. Introduction

Solanki et al. (2004) reported reconstructed sunspot numbers extending back in time almost 11 400 years. The reconstruction was based upon $^{14}$C in tree rings and $^{10}$Be in ice cores. Past studies have shown that long-term records of many natural phenomena exhibit persistent behavior. These include floods, rainfall, temperatures, and sunspot numbers (SSN). A classic example is the Nile River, where prolonged periods of dryness were followed by periods of floods. A method of analyzing this behavior, now known as rescaled range analysis (commonly referred to as $R/S$ analysis), was developed by the hydrologist Hurst (1951) and Hurst, Black, and Simaika (1965). An important element in this analysis involves calculating the cumulative deviation from the average of a stochastic quantity (in the present case SSN) over the time period of interest. Persistence is characterized by a parameter now commonly referred to as the $H$ coefficient. Coefficients with a value significantly greater than 0.5 are taken to indicate correlated or persistent behavior.

In a paper by Ruzmaikin, Feynman, and Robinson (1994), $R/S$ analysis was applied to $^{14}$C data extending over a period of 3 000 years and the authors derived an $H$ coefficient of
Figure 1 Reconstructed sunspot record from Solanki et al. (2004). Also shown are results for a moving average filter applied to the data as described in a later section. The time period covers 11,360 years with observations in 10-year increments.

0.84. In this paper the Hurst method has been applied to the 11,360 years of data reported by Solanki et al. (2004). The value of $H$ derived from this longer series is 0.81, which is quite close to the 0.84 value reported by Ruzmaikin, Feynman, and Robinson (1994) given the differences in the data sets. However, the focus in this paper is not the Hurst coefficient but what appears to be evidence of a long cycle with a period of about 6,000 years uncovered during the course of $R/S$ analysis.

2. Hurst Analysis

In the following description the notation of Beran (1998) is used. For a period of $T$ years beginning at time $t$ the cumulative measure of SSN activity is defined as

$$Y_{t+T} = \sum_{i=t}^{t+T} X_i.$$  \hspace{1cm} (1)

In this application the $X_i$ are taken as the 10-year averaged SSN in the Solanki data set (Solanki et al., 2004). $Y_{t+T}$ is the sum of the 1,136 SSN that span a period of $T = 11,360$ years. The cumulative deviation is then

$$\Delta Y_{t+T} = \sum_{i=t}^{t+T} (X_i - \bar{Y}_{t+T}),$$  \hspace{1cm} (2)

where $\bar{Y}_{t+T}$ is the average of the stochastic quantity $X_i$. The cumulative deviation represents the difference between the cumulative measure of SSN at a given time and a cumulative calculation based on the average over the total time period of interest.

Hurst analysis provides a method for determining whether or not a stochastic series exhibits long-range correlation. The series of $N$ observations are divided into segments of