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On Sunspot Modulated Temporal Modes of Variability

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ABSTRACT

It has recently been reported (Baker, 2024) that the average number of visible dark patches on the Sun's surface in August 2024 was higher than any other month since September 2001, a full 23-year period. The final count was more than twice as high as experts from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) in Boulder Colorado initially predicted it would be. There was an average of 215.5 daily sunspots on the Sun's surface during August. The number of black spots peppering the Sun's surface in August was the highest for almost 23 years, new data from the NOAA SWPC showed. The latest SWPC sunspot count was more than twice as high as their initial forecasts predicted and is taken as a clear sign that the Sun's explosive peak, or solar maximum, is likely well underway, and will be far more active than scientists initially thought. Sunspots are regions of the Sun's surface where surges of electromagnetic radiation break through the star's magnetic field, creating relatively cool patches that appear black to us thanks to an optical illusion. Along with the size and frequency of solar flares and coronal mass ejections, sunspot numbers indicate the progress of the Sun's roughly 11-year solar cycle. During the Sun's least active phase, or solar minimum, there are very few or occasionally no sunspots. For example, in late 2019, shortly before the start of the current solar cycle (Solar Cycle 25), there were 40 consecutive days with no visible sunspots. But as the sun's magnetic field gets entangled with itself and weakens, sunspot numbers quickly climb before peaking during solar maximum. During this active phase, the Sun's magnetic field eventually snaps and completely flips, which triggers a falling-off period of solar activity and a decrease in sunspots until the whole solar cycle is generally believed to restart. The last time the monthly sunspot number was this high was September 2001, during the solar maximum of Solar Cycle 23, when the average was 238.2. The number of sunspots peaked on August 8 2024, when up to 337 sunspots were observed on the Sun, which is the highest total in a 24-hour period since March 2001. These numbers indicate what some scientists have already suspected, that we have entered solar maximum. However, we can't be certain of this until long after sunspot numbers begin to drop again. In this study we harvest sunspot data from 24 prior solar cycles and employ a Hilbert-Huang Transform (Huang et al., 1999; Huang & Wu, 2007) to reveal sunspot activity consisting of internal modes of variability in excess of solely an 11-year cycle. We show that there are a suite of well-defined modes of sunspot variability, from multiple months, to multiple years to multiple decades, and centuries, which likely have important implications and consequences for conventional Earth atmospheric and oceanic weather, and also for the electromagnetic field of the Planet.

Key Words: Sunspots, Cycles, Variability, Trend

INTRODUCTION

The August 2024 sunspot activity, as reported by the NOAA SWPC, is the highest since September 2001. When the current solar cycle began in 2020, a panel of SWPC scientists predicted that Solar Cycle 25 (starting with Solar Cycle 1 ~ 1760 AD would be relatively weak compared with historic cycles, much like Solar Cycle 24, which peaked around 2014 and was the weakest maximum for around 90 years. For example, the average sunspot number predicted for August 2024 was 107.8, which is less than half the actual number that has just been released. The SWPC forecast also suggested that the solar maximum would probably not arrive until 2025. However, from early on in the current cycle, the sunspot numbers have not matched the initial forecasts. The numbers began to climb in early 2022, reaching an eight-year high by the end of the year. By June 2023, the average number surpassed any of the months from Solar Cycle 24 and has increased ever since. As a result, in October 2023, the SWPC released a "revised prediction" for Solar Cycle 25, which forecast that solar maximum would likely arrive by mid-2024 and be more active than expected.

Present rising sunspot numbers are not the only indication that in the fall of 2024, the Earth experienced a solar maximum. In early May 2024, the Earth was bombarded with a powerful magnetic storm, which painted an abnormally large portion of the planet's skies with auroras. And just a few days later, our Sun spat out an X8.7 magnitude solar flare, the most powerful solar explosion since 2017. Solar maximums can last for one to two years or more, meaning there is still a decent chance that activity will continue to ramp up over the next 12 months or so. During Solar Cycle 23, sunspot numbers peaked at a maximum monthly value of 244.3 in July 2000. And in Solar Cycle 22, the monthly record was 284.5 during June 1989. If solar activity continues to increase and the Earth is bombarded with more powerful solar storms, like the 1859 Carrington Event, it could impact ground-based infrastructure, trigger widespread auroras at lower latitudes and could cause satellites to tumble back to Earth. The geomagnetic storm of 1859, was the largest geomagnetic storm ever recorded. The storm, which occurred on September 2 1859, produced intense aurora displays as far south as the tropics. It also caused wildfires as the enhanced electric current flowing through telegraph wires ignited recording tapes at multiple telegraph stations. On the previous day, British astronomer Richard Carrington of the Royal Greenwich Observatory had made the first observations of a white-light solar flare, a bright spot suddenly appearing on the Sun. Carrington noted the coincidence (but did not claim a direct connection) between the geomagnetic storm and the solar flare, thus prefiguring the discipline of space weather research.

Sunspots have been counted every day since 1610, and the observations are kept at the Royal Observatory of Belgium's World Data Center for the Sunspot Index and Long-term Solar Observations. This catalog of sunspots provides visual evidence for the solar cycle, a roughly 11-year period during which the number of sunspots goes from low to high and then back down to low. Tracking sunspots is one way to track solar activity, but as cited in Baker (2024) “it’s really the level of radiant energy the sun puts out across the wavelength spectrum that causes changes,” to Earth’s weather. For instance, shorter wavelengths of light produce more energy, so emitting longer wavelength light and less short wavelength light could, for instance, reduce the energy released by the sun. The present Solar Cycle 25, which began in 2020, looks like it will be stronger than predicted. When there are a great number of sunspots, there is a very slight increase in the energy output from the sun, according to the NOAA National Weather Service (NWS). According to Baker (2024), “Years having higher numbers of sunspots generally correspond with warmer times on the Earth, not cooler times. It’s about 1.5 degrees Celsius (2.7 degrees Fahrenheit) warmer on average when it’s most active. That does have an effect both globally and regionally on Earth’s temperatures, winds, fires and weather patterns.”

It has been found by Hathaway (2015) that there are significant variations in solar activity on time scales shorter than the sunspot cycle. This is evident when the sunspot number record is filtered to remove both solar rotation effects (periods of about 27-days and less) and solar cycle effects. This signal is shown in Figure 1 for the years 1850 to 2013. In this figure the daily sunspot numbers are filtered with a tapered Gaussian-shaped filter of 54 days (Bendat & Piersol, 2015). This reduces all signals with periods shorter than 54-days to less than 2% of their original amplitude. The resulting signal is sampled at 27-day intervals and then filtered again with a similar Gaussian of 24 rotations. The lower panel of Figure 1 shows this final signal for the time period, while the upper panel shows the residual obtained when this smoothed sunspot number signal is subtracted from 54-day filtered data. This residual signal is quite chaotic but shows some interesting behavior and quasi-periodicities.

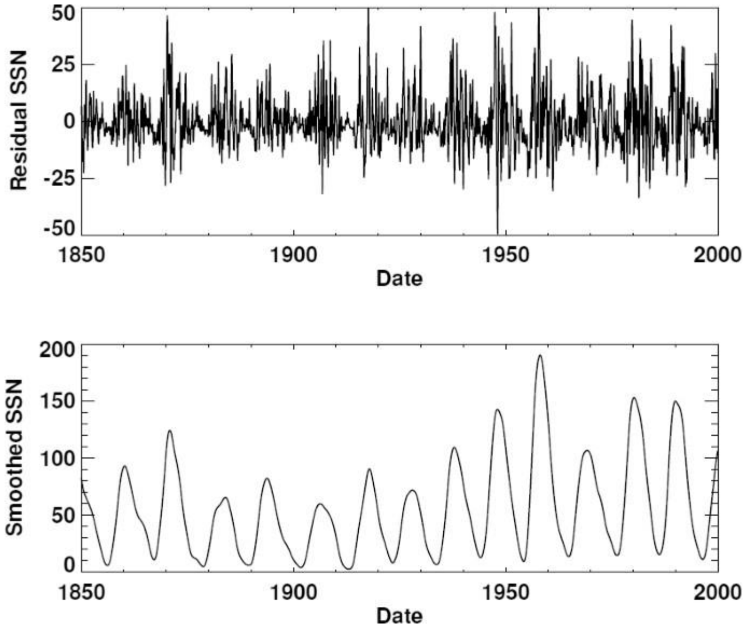

Figure 1. Short-term variations of Sunspot activity

Note: The lower panel shows the daily International Sunspot Number (SSN) smoothed with a 24-rotation Gaussian filter. The upper panel shows the residual SSN signal smoothed with a 54-day Gaussian and sampled at 27-day intervals.

Scientists have long studied how the sun affects the global surface temperature on Earth. The output of light energy from the sun as experienced on Earth's upper atmosphere is called total solar irradiance (TSI). TSI falls if there is a sustained drop in solar activity, which reduces the energy that hits Earth. However, TSI varies at most by 0.15% across the solar cycle, meaning its impact is dwarfed by human-caused climate change and other effects. For example, a National Aeronautics and Space Administration (NASA) study found just 0.1 °C of warming resulted from an increase in solar radiance in recent solar cycles, which was dwarfed by the impact of other natural phenomena such as the warming caused by volcanoes and the El Niño Southern Oscillation climate cycle in the Pacific Ocean. Herein, we address the sunspot time series and evaluate its internal modes of variability. We address the question: Is the 11-year solar cycle all there is?

DATA AND METHODS

Arguably, the Sun and its solar activity constitute the “big dog”, controlling the habitability and climate of the Earth. The Sunspot Number is a crucial tool in the study of climate change. In fact, the Solar Sunspot time series is the longest continuous time series of any natural phenomena. However, there have been issues related to Sunspot records over the long period of human observations employing a sequence of varying tools. We now address those given the collective record of Sunspot activity, a significant human undertaking.

The Maunder Minimum, 1645 to 1715, when sunspots were reportedly scarce and winters were documented in the historic record to have been harsh, and thus suggested a link between solar activity and climate change. From 1715 to the present, some 307 years, there is general consensus that solar activity has been trending upwards, reaching a relative peak in the late 20th

Century, called the Modern Grand Maximum. This trend has led some scientists to conclude that the Sun has played a significant role in modern climate change; some even speculating that the Sun is responsible for climate warming. This hypothesis has been disproved by Pietrafesa et al. (2019). The Wolf Sunspot Time Series is the oldest time series in solar terrestrial physics still in use today, having remained untouched for over 160 years. Established by Rudolf Wolf in 1856, the method is based on both the number of groups of sunspots and the total number of spots within all the groups. In 1994, the question began to arise as to whether the WSN was the correct method of constructing a historical sunspot record. The limitations of early telescopes meant that it was easy for smaller spots to be missed. With this in mind, a new index was established in 1998: the Group Sunspot Number (GSN), which is easier to measure and goes all the way back to the measurements done by Galileo. This index was based solely on the number of sunspot groups. Establishing this system performed a valuable service by finding and digitizing many sunspot observations not known or used by Wolf and his successors, effectively doubling the amount of data available before Wolf's tabulations. Unfortunately, the two series disagreed substantially prior to 1885, and the GSN has not been maintained since the 1998 publication of the series. The GSN also revealed a pattern of continually rising solar activity, beginning in the 18th century and culminating in a Modern Grand Maximum in the latter part of the 20th century, which Wolf's method does not suggest.

The discrepancy between the above discussed two parallel series of sunspot number counts has been a contentious issue among solar scientists. The two methods of counting the sunspot number, the Wolf Sunspot Number and the Group Sunspot Number 2, indicated significantly different levels of solar activity before about 1885 and also around 1945. With these discrepancies now eliminated, there is no longer any substantial difference between the two historical records. The new correction of the sunspot number, called the Sunspot Number Version 2.0, led by Frédéric Clette (Director of the World Data Centre [WDC]–SILSO), Ed Cliver (National Solar Observatory) and Leif Svalgaard (Stanford University, California, U.S.), nullifies the claim that there has been a Modern Grand Maximum. It has now been recalibrated and shows a consistent history of solar activity over the past few centuries. The new record has no significant long-term upward trend in solar activity since 1700, as was previously indicated. This suggests that rising global Earth temperatures since the industrial revolution cannot be attributed to increased solar activity. The new results make it difficult to explain the observed changes in the climate that started in the 18th Century and extended through the industrial revolution to the 20th Century as being significantly influenced by natural solar trends.

The Sunspot Number is the only direct record of the evolution of the solar cycle over multiple centuries and is the longest scientific experiment still ongoing. The apparent upward trend of solar activity between the 18th Century and the late 20th Century has now been identified as a major calibration error in the Group Sunspot Number. Now that this error has been corrected, solar activity appears to have remained relatively stable since the 1700's. The newly corrected sunspot numbers now provide a homogenous record of solar activity dating back some 400 years. Figures 2 a, b present the Sunspot time series. Relative peaks in the time series occurred in June 1778 and in March 1858 when 309 and 285, respectively, were recorded. All of this said, the general consensus is that the Sun's sunspot cycle is nominally locked into an 11-year period with only amplitude modulations (Baker, 2024). Clearly the sunspot time series shown in Figure 2 suggests that there may be significant modulated periods, i.e. modulated frequencies of occurrence, in addition to modulated amplitudes in the time series as well. However, they appear visually to be both non-stationary and non-linear. We will investigate this time series employing a mathematical methodology that can handle both non-stationary and non-linear time series. We will discuss that methodology next.

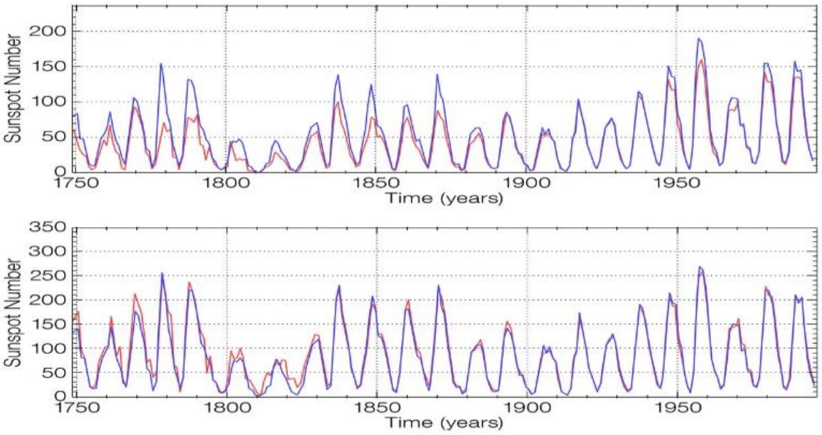

Figure 2. a) The Wolf Sunspot Number versus the Group Sunspot Number (Red Line), which has been adjusted in (b), showing the agreement between the two time series

The Hilbert Transform (Gabor, 1946) has been applied to calculate the accompanying imaginary part of a continuous time series. It was employed by Huang et al. (1999) and Huang and Wu (2008) to obtain the complex expression of the instantaneous amplitude and frequency in any continuous time series. Herein the Hilbert Transform was extended and became the Hilbert-Huang Transform (the HHT); explained in the latter two publications. Due to the HHT being a global domain integral, the instantaneous amplitude and instantaneous frequency obtained using the HHT is not “temporally local” or instantaneous, and the direct quadrature algorithm is implemented to obtain the instantaneous amplitude and instantaneous frequency (Huang et al., 2009). Employing the HHT, a data time series, *x(t)*, is subsequently decomposed in terms of “intrinsic mode functions” (IMFs), c_j, i.e.,

$$x(t)=\sum_{j=1}^{n} c_j(t)+r_n(t), \tag{1a}$$

where

$$c_j(t)=a_j(t)\cos\left\lfloor \int \omega_j(t)dt \right\rfloor, \tag{1b}$$

and r_n is the residual of the data *x(t)*, after *n* intrinsic mode functions (IMFs) are extracted from the instantaneous frequency, omega from high frequency to low frequency intrinsic modes from j=1 to the finite number “j = n”, determined via the “sifting” process and which constitute the limits of the integral (i.e. 1 to finite number “j”=n). Here “instantaneous frequency” is defined in context, and the integral can be considered as the local mean for IMF c_n. Clearly, The IMFs expressed in Equation (1b) are simple oscillatory functions with relatively slowly varying and non-negative amplitude and relatively fast changing and non-negative frequency at any temporal point.

In practice, the HHT is implemented through a sifting process that uses only local extrema. From any data set, $x(t)= r_{j-1}$, say, the procedure is as follows: 1) identify all the local extrema (the combination of both maxima and minima) and connect all these local maxima (minima) with a cubic spline as the upper (lower) envelope; 2) obtain the first component *h* by taking the difference between the data and the local mean of the two envelopes; and 3) treat *h* as the data and repeat steps 1 and 2 as many times as is required until the envelopes are symmetric about zero within a certain tolerance. The final *h* is designated as c_j. A complete sifting process stops when the residue, r_n, becomes a monotonic function or a function only containing one internal extremum from which no more IMFs can be extracted. In EEMD, multiple noise realizations, are added to one time series of observations to mimic an ensemble average approach for corresponding IMFs can be used to extract scale-consistent signals. The major steps of the HHT method are: 1) add a white noise time series to the targeted data; 2) decompose the data with added white noise into IMFs; 3) repeat step 1 and step 2 again and again, but with different white noise series each time; and 4) obtain the (ensemble) means of corresponding IMFs of the decompositions as the final result. After a time series is decomposed into IMFs, natural amplitude-frequency modulated oscillatory functions, various methods can be applied to obtain instantaneous frequencies for each IMF that lead to time-frequency-amplitude representation of the data.

In Figure 3, we present the HHT decomposition of the corrected Solar Sunspot time series. Ten internal IMF modes of variability, including the first half of a long cycle (IMF 10), are displayed. The IMF modes and the average amplitude of events per period are: (1) 2-4 months and up to 50 events; (2) 5-7 months and up to 50 events; (3) 11-13 months and up to 40 events; (4) 2-4 years and up to 40 events; (5) 10-12 years and up to 120 events; (6) 20-22 years and up to 40 events; (7) 40-44 years and up to 40 events; (8) ~ 110 years and up to 20 events; (9) ~ 150 years and nominally 15 events; and (10) the first half of a likely ~ 540-year cycle, and only increasing by 4 events, rising nominally from 84 to 88 events per year over the 273-year length of the record, and dropping in Solar Cycle 24. We note that IMF 5, the 10–12-year cycle, which embraces the well-known “11-year cycle” has the largest amplitude being 2 to 3 times greater than those of all other IMF modes. However, all of the IMF modes are significant in amplitude relative to each other. IMF modes 1, 2, 3, 4 are all enhanced during high activity years of Mode 5, the nominal mode of reverse polarity of the Sun’s magnetic field which occurs over a period centered about 22 years. Because nearly all manifestations are insensitive to polarity, the 11-year solar cycle remains the focus of Solar research; however, the two halves of the 20–22-year cycle are typically not identical, such that the 11-year cycles usually alternate between higher and lower sums of Wolf's sunspot numbers, referred to as the “Gnevyshev-Ohl Rule”. The ~ 40–44-year cycle may be a lower harmonic of the 11-year magnetic field reversal and the 22-year full reversal period.

Table 1 depicts the 10 HHT internal modes of variability.

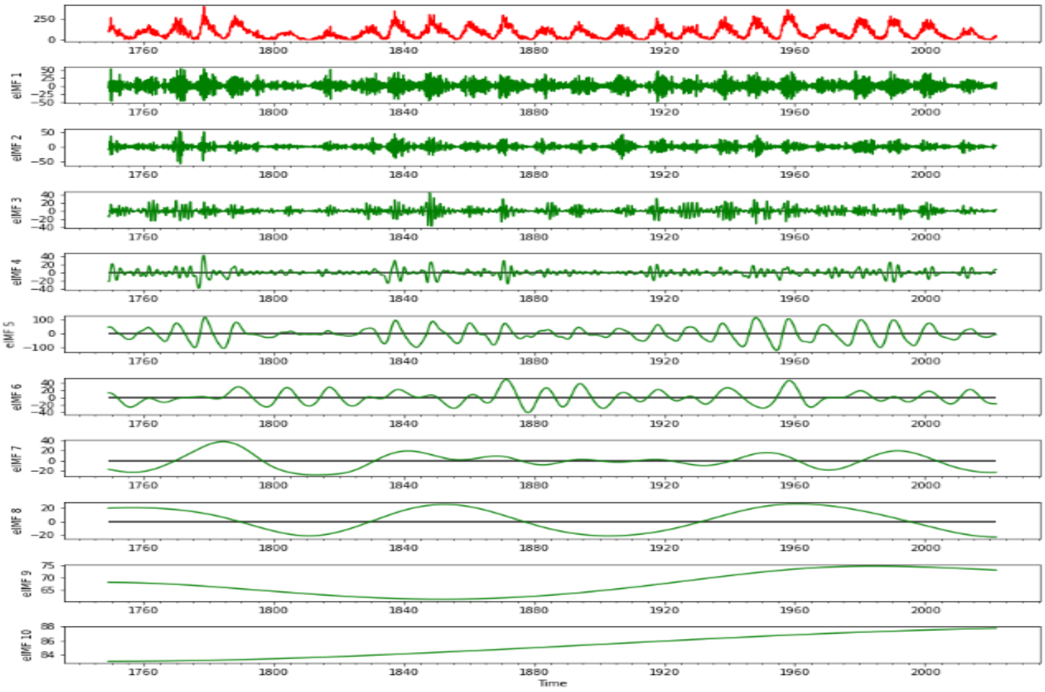

Figure 3. The HHT Decomposition of the Solar Sunspot Monthly time series presented in the Top Panel (the Red time series)

Note: There are eleven internal or IMF modes of variability, including the overall Trend.

Table 1. The HHT decomposition of the 273 Year record of Solar Sunspot Activity and Internal Modes of Variability (mnth = months, yrs = years)

	IMF's Length of Series	2-4 mnth	5-7 mnth ---	11-13 mnth	2-4 yrs	10-12 yrs	20-22 yrs	40-44 yrs	110 yrs	150 yrs	540 yrs
Solar Sunspot	273 years and 5-408 events	50	50	40	40	120	40	40	20	15	4

DISCUSSION AND CONCLUSIONS

In a comprehensive study, Hathaway (2015) reported that understanding the Solar Sunspot Cycle remains one of the most compelling and oldest challenges in solar physics. In this study, we harvested sunspot data going back 273 years, encompassing 24 solar cycles, as defined by the NOAA SWPC. We then employed a Hilbert-Huang Transform (Huang et al., 1999; Huang & Wu, 2007) to reveal 10 periods of internal variability in sunspot activity, 8 of which are in addition to the well-known 11-year cycle. The gravest mode, or IMF 10, may be an overall trend or just half of a 540-year cycle. We show that there are multiple modes of sunspot variability, from multiple months centered about 3, 6 and 12 months, to multiple years centered about 3, 11, 22, 44, 110 and 150 years and a slightly upward trend of 4 spots/year at 273 years. All of these variations in sunspot activity likely have important implications and consequences for Earth weather, both the electromagnetic field of the Planet, and the more conventional atmospheric and oceanic weather and climate fields.

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