Temporal Dependence in GOES X-ray Flux: Autocorrelation & Long-Range Memory

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Introduction

This study investigates the temporal correlation structure of X-ray flux levels captured by the Geostationary Operational Environmental Satellites (GOES), which monitor solar activity affecting Earth's magnetosphere. The GOES satellites record high-frequency flux data approximately every two seconds, offering a detailed view into solar emissions that influence space weather. These emissions are driven by phenomena such as the solar cycle, sunspots, and coronal mass ejections. This can disrupt critical infrastructure, including power grids and satellite communications. The dataset analyzed contains over 14.5 million observations recorded throughout 2017, providing a rich time series for studying statistical dependence over time. By examining patterns of persistence and dependence in the flux data, this analysis aims to characterize both short- and long-term temporal dynamics of solar radiation, contributing to a better understanding of space weather behavior.

Methods

To assess short-term temporal dependence in the GOES X-ray flux data, we computed Kendall's tau autocorrelation across non-overlapping blocks of 8,000 observations, each representing approximately 4.4 hours of data. This block-wise approach allows us to account for potential non-stationarity in the year-long time series, enabling local estimates of dependence without assuming global stationarity. Within each block, autocorrelation was estimated over a sequence of time lags ranging up to six minutes. We visualized the resulting curves using a subset of blocks to capture block-level variability and summarized the overall structure using quantiles at each lag. To explore how short-lag dependence evolved throughout the year, we focused on a fixed lag of one minute and tracked the corresponding autocorrelation values across all blocks. A LOWESS smoother was then applied to these values to reveal broader temporal trends in short-term persistence.

To assess the presence of long-range dependence in the GOES X-ray flux data, we estimated the Hurst parameter H using two complementary techniques: the variance scaling method and the triangle total areas method. The variance scaling method partitions the time series into blocks of increasing size and computes the variance of the sample mean within each block. The rate at which this variance grows with block size is used to estimate H. The triangle total areas method instead evaluates the cumulative structure of the time series using a non-parametric rescaling of median-centered values. This provides a robust alternative that does not rely on variance. Both methods were first validated on simulated white noise and short-range dependent data, where the theoretical Hurst value is 0.5. We then applied these estimators to the GOES data by dividing the year-long time series into 20 non-overlapping chunks and computing H separately for each segment.

Results

Figure 1 displays Kendall tau autocorrelation curves for a random subset of blocks, illustrating the typical pattern of autocorrelation decay over time. Most blocks exhibit strong initial correlation that decreases rapidly within the first few minutes, though the rate and extent of decay vary considerably, reflecting heterogeneity in local temporal dependence. To summarize this variability, Figure 2 presents the 25th, 50th (median), and 75th percentiles of the autocorrelation values across all blocks. The median curve shows a sharp decline within the first two minutes, then stabilizing at lower levels thereafter. While the interquartile range highlights substantial variation in dependence strength across the dataset. To quantify how short-term dependence varies over the year, we examined Kendall's tau autocorrelation at a fixed lag of approximately one minute across all blocks. The autocorrelation values ranged from 0.045 to 0.994, with a mean of 0.460 and a standard deviation of 0.278, indicating substantial variability in local persistence. A smoothed trend using LOWESS revealed a modest overall decline of 0.066 in autocorrelation from January to November 2017, suggesting a slight weakening of short-term temporal dependence over the course of the year.

Using both the variance scaling and triangle total areas methods for estimating the Hurst exponent, we consistently obtained Hurst values above 0.5 across the majority of time blocks, indicating persistent long-range dependence in the X-ray flux data. The variance scaling method yielded Hurst values ranging from approximately 0.52 to 0.98, while the triangle total areas method produced estimates as high as 1.24 in certain segments. These elevated H values suggest that the autocorrelation structure of the flux levels decays slowly, with distant observations remaining positively correlated over time — suggesting long-memory behavior.

Figure 3 presents the log-log plot of the variance of block means against block sizes, following the variance scaling method for Hurst estimation. The linear relationship observed in the log-log space is indicative of long-range dependence, as expected under power-law scaling behavior. The slope of the fitted line corresponds to an estimated Hurst exponent greater than 0.5, suggesting persistent temporal correlation in the X-ray flux series. Finally, Figure 4 summarizes the distribution of Hurst exponent estimates across non-overlapping time blocks using the variance scaling method. The boxplot shows that most Hurst values lie above 0.9, with a median near 0.97, reinforcing the presence of strong long-memory behavior. The narrow interquartile range and relatively few low outliers indicate that this persistence is consistent across the year-long dataset.

Interpretation

The results from the short-term autocorrelation analysis reveal that solar X-ray flux exhibits strong but highly variable short-lag dependence throughout the year. The steep initial drop in Kendall tau values suggests that most of the temporal structure in the flux series dissipates within a few minutes. However, the wide range of observed autocorrelation levels—both within individual time blocks and across the year—indicates that solar emissions fluctuate between periods of strong local persistence and more erratic, weakly correlated behavior. This variability may reflect intermittent solar events such as flares or coronal mass ejections, which cause bursts of sustained activity interspersed with quieter intervals. The modest downward trend in fixed-lag autocorrelation over time also raises the possibility of broader seasonal or cycle related shifts in solar dynamics over the course of the year.

In contrast, the long-range dependence analysis points to a more persistent memory structure embedded within the overall time series. The consistently high Hurst estimates suggest that despite local fluctuations, the flux levels retain a durable and long-term correlation structure. This is consistent with known solar processes that operate across multiple timescales—from daily rotation to multi-year solar cycles. The fact that both estimation techniques (variance scaling and triangle areas) independently support the presence of long memory strengthens the conclusion that GOES X-ray flux dynamics are not purely short-lived or noise-driven. All in all, the short and long range analyses emphasize the complex temporal patterns of solar radiation, likely shaped by transient disruptions and persistent underlying trends.

Figures

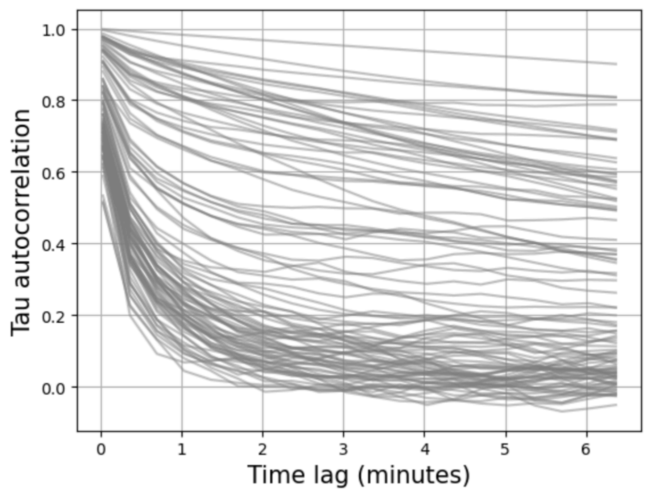

Figure 1: Block-wise Kendall Tau Autocorrelation Curves

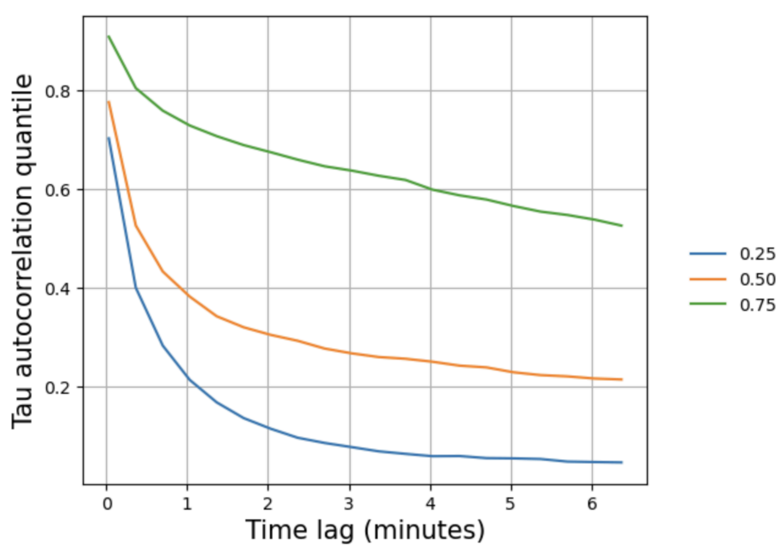

Figure 2: Quantiles of Autocorrelation Across Time Blocks

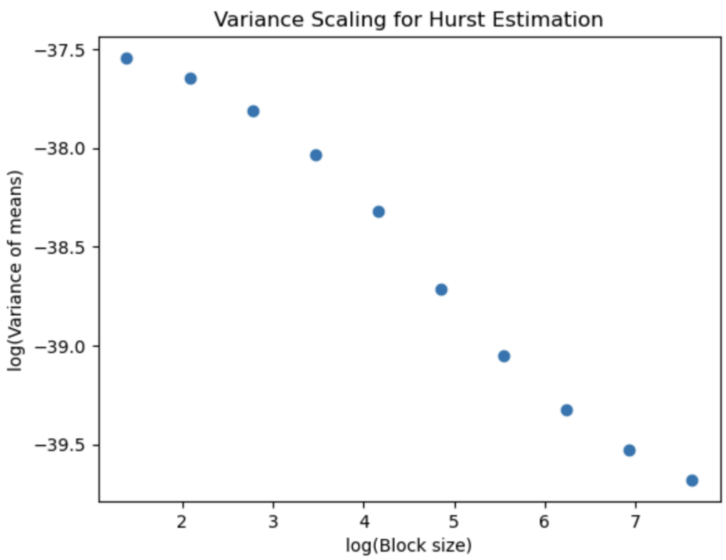

Figure 3: Log–Log Relationship Between Block Size and Variance of Means

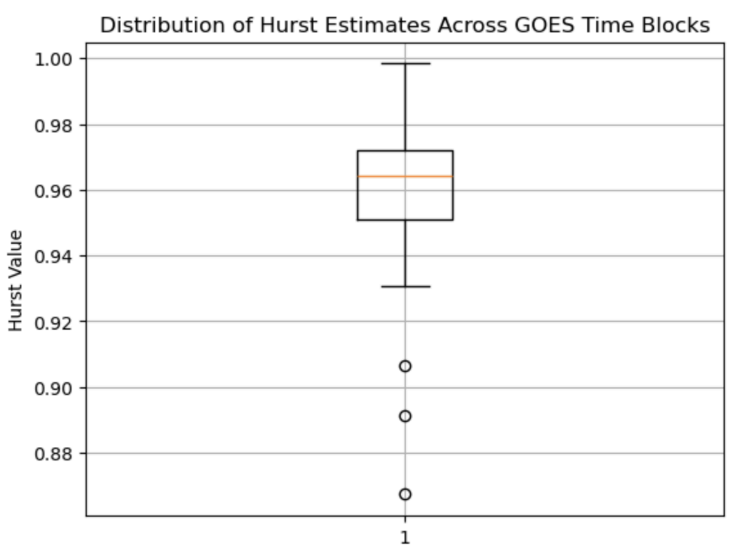

Figure 4: Distribution of Hurst Exponent Estimates Across Time Blocks