Simple Tools for Detecting & Predicting Anomalies in Terrestrial Environment caused by Sun

Rissnalin Syiemlieh and Eeshankur Saikia

Gauhati University, Applied Sciences, Assam, India

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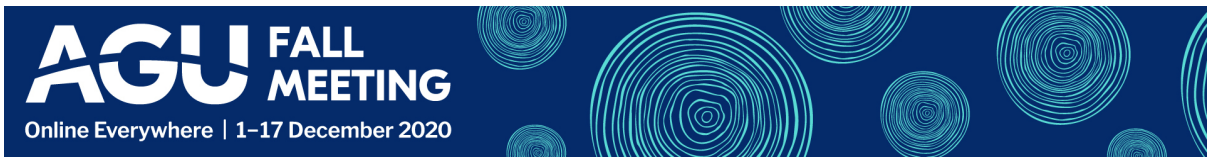

INTRODUCTION

The ascendancy of galactic and solar activity over Space and Terrestrial climate has been a matter of debate for a long time. Better insight and understanding of galactic and solar activity can contribute to the better prediction of space weather. One such recent event is the Solar Eclipse that occurred on 21st June 2020. Taking this in focus we used Wavelet Transformation and Multifactral analysis to study its effects on the Earth's atmosphere. This would enable us to learn more about the atmospheric response to solar flares and other space weather events [1,2,3,4].

Our analysis is focused to investigate and find the unique signature of Solar-Earth's interaction that arises due to such an event. Wavelet transformation yields localized time-frequency information without requiring that the time-series be stationary [5,7,8]. It estimates the spectral characteristics as a function of time [5] . Wavelet spectrum shows a distinct energy density parcel in time-frequency domain [10] . It also has the advantage of being able to divide the pure details in a signal. Smaller wavelets can be applied to dissociate the most elementary details in a signal, while very large wavelets can identify other details of the coarse analysis. Wavelet theory is competent to declare aspects of data that other signal analysis method misses [6]. The wavelet transformation can be univariate, also known as Continuous Wavelet Transformation (CWT), and bivariate, known as Cross Wavelet Transformation (XWT) [10].

The Multi Fractal Analysis (MFA) was first introduced for the study of turbulence which was later used by many mathematicians and physicists for their studies. The spectrum also is known as the multifractal spectrum or singularity spectrum gives either geometrical or probabilistic information of the distribution of points that have the same singularity[11,12].

DATA & METHOD

Data:

Data is acquired from SWPC Data Service available at https://www.swpc.noaa.gov/. In order to carry forward the analysis, Ap-index, which measures the general activity of terrestrial magnetic disturbances caused by external transient and Solar Wind (SW) plasma speed, bearing signatures of all Solar atmosphere activities including Coronal Mass Ejection at an interval of 3 hours, are considered. Lastly, the property of mean cloud height (top) images acquired from MODIS Data Service available at https://modis-images.gsfc.nasa.gov/.

Methodology:

As stated methods used are based on finding Wavelet Transformation [7,8,9] of the two-time series focusing on the Solar eclipse event on 21 st June 2020. Wavelet scalograms [10] of these parameters considered would convey their distinct periodic behaviors, possible modulations, and coherence of the interaction.

XWT is mathematically expressed as;

$$W_{\psi_1\psi_2}(s,\tau) =< \hat{\psi_1}(s,\tau)\hat{\psi_2}^{*}(s,\tau) >= |W_{\psi_1\psi_2}(s,\tau)|e^{i\phi_i(s)}$$

where $\psi_1(t)$ and $\psi_2(t)$ are the two time-series understudy simultaneously and (s, τ) is an integer.

MFA uses the Holder spectrum formalism which in turn depends on Holder regularity(α). The parameter mainly depends on the statistical approaches or theories for a given set of functions. The strength of the singularities of μ is measured by exponent α(x) called Hölder exponent which distinguishes the multifractals. K_α which describes the points of equal strength lying on interwoven fractal sets;

$$K_\alpha = |x|\epsilon\mathbb{R}^d : \alpha(x) = \lim_{B\to\,(x)} \frac{\log\mu(B)}{\log|B|}$$

where, B is a ball containing x with its diameter |B| tending to zero.

Hausdorff dimension measures the size of the fractal sets K_α to identify the geometry of the singular distribution μ as[13,14],

$$f_H(\alpha) = dim(K_\alpha)$$

Cross-Wavelet Power Spectrum

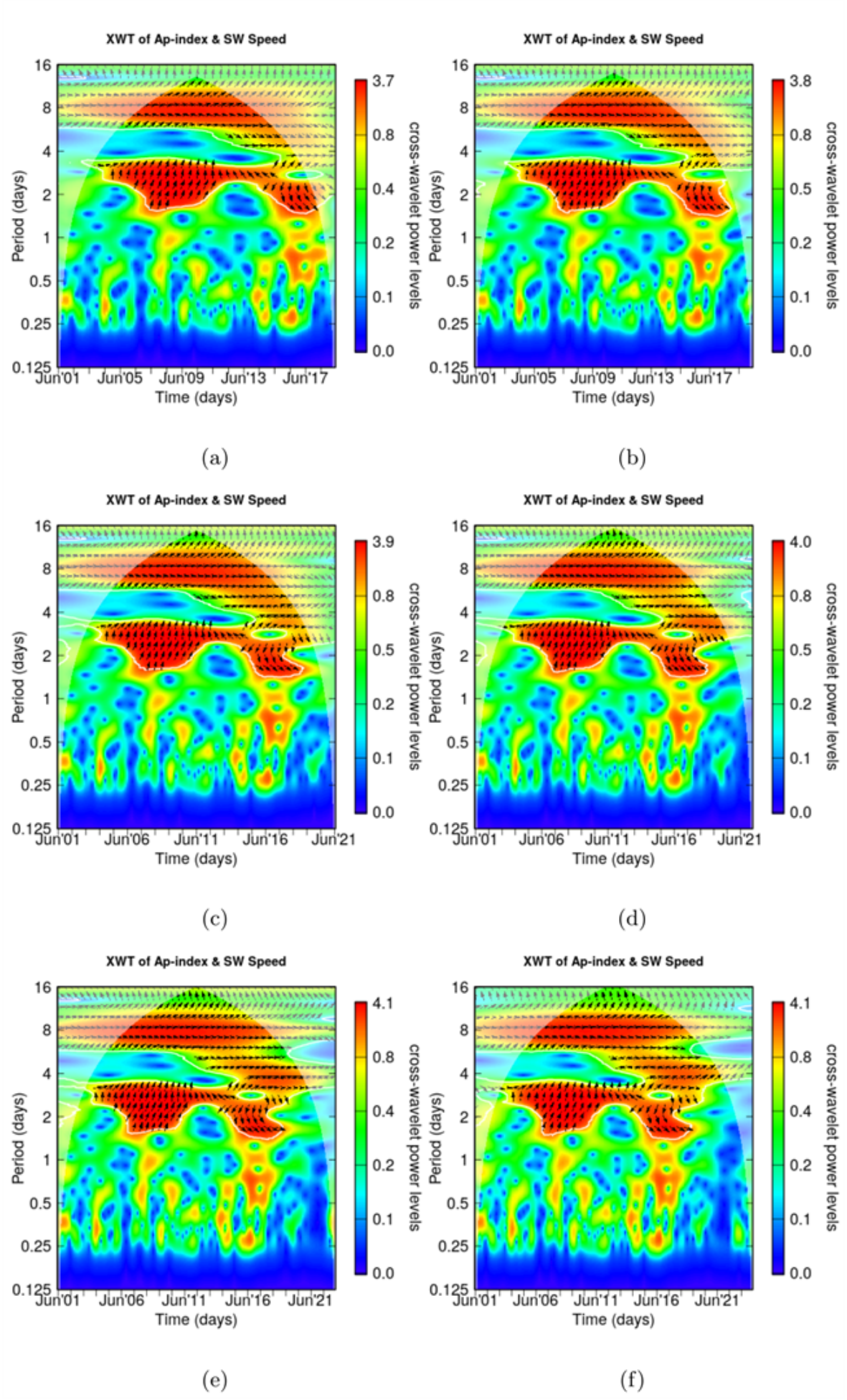

Figure-1: Plot describes XWT of Ap-index Vs SW plasma speed (a)1st to 18th June; (b) 1st to 19th June; (c) 1st to 20th June; (d) 1st to 21st June; (e) 1st to 22nd June and (f) 1st to 23rd June 2020 (Note: 21st June is the Solar eclipse event).

Average Cross-Wavelet Power Spectrum

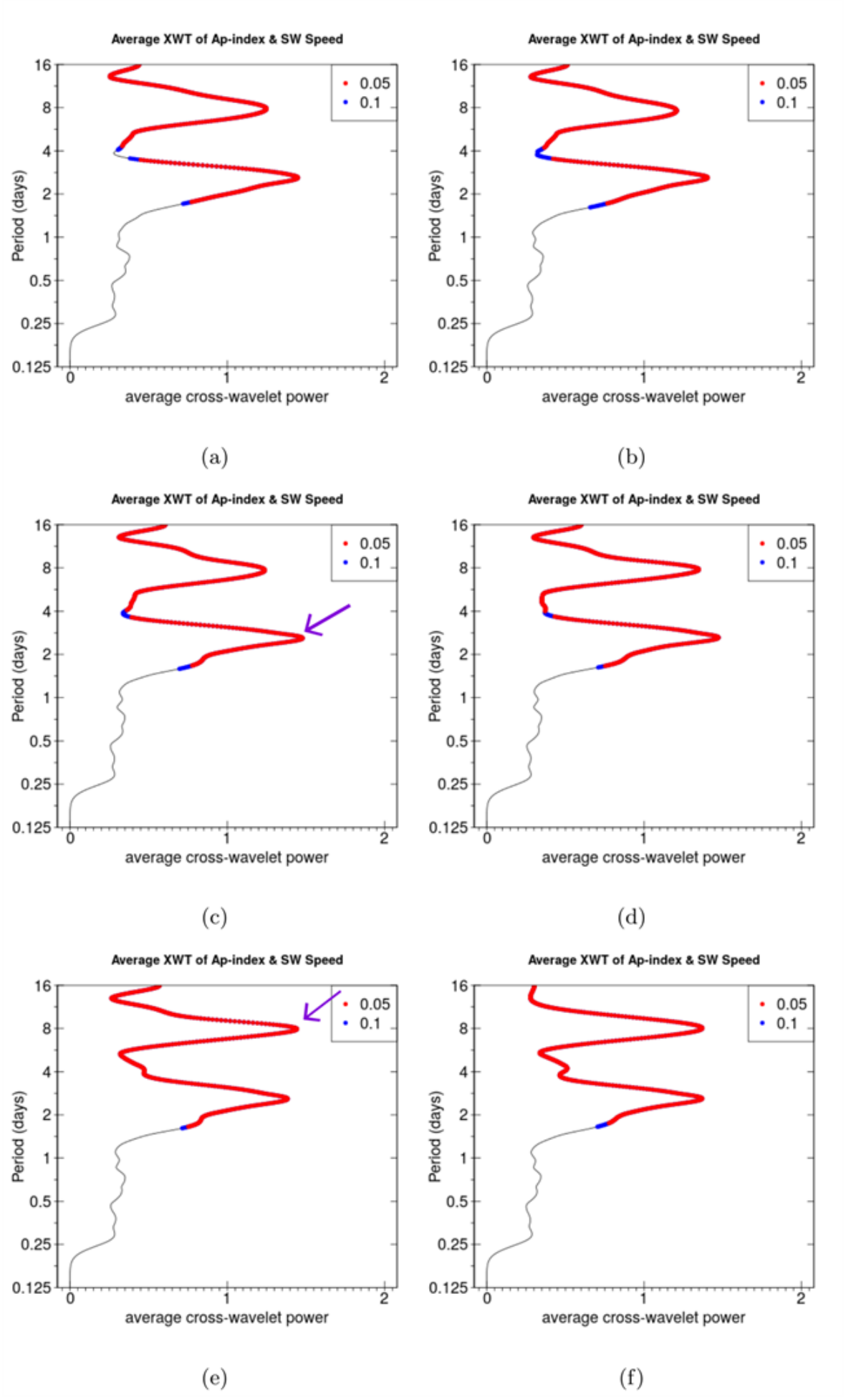

Figure-2: Plot describes Average XWT of Ap-index Vs SW plasma speed (a) 1st to 18th June; (b) 1st to 19th June; (c) 1st to 20th June; (d) 1st to 21st June; (e) 1st to 22nd June and (f) 1st to 23rd June 2020.

Multifractal Spectrum

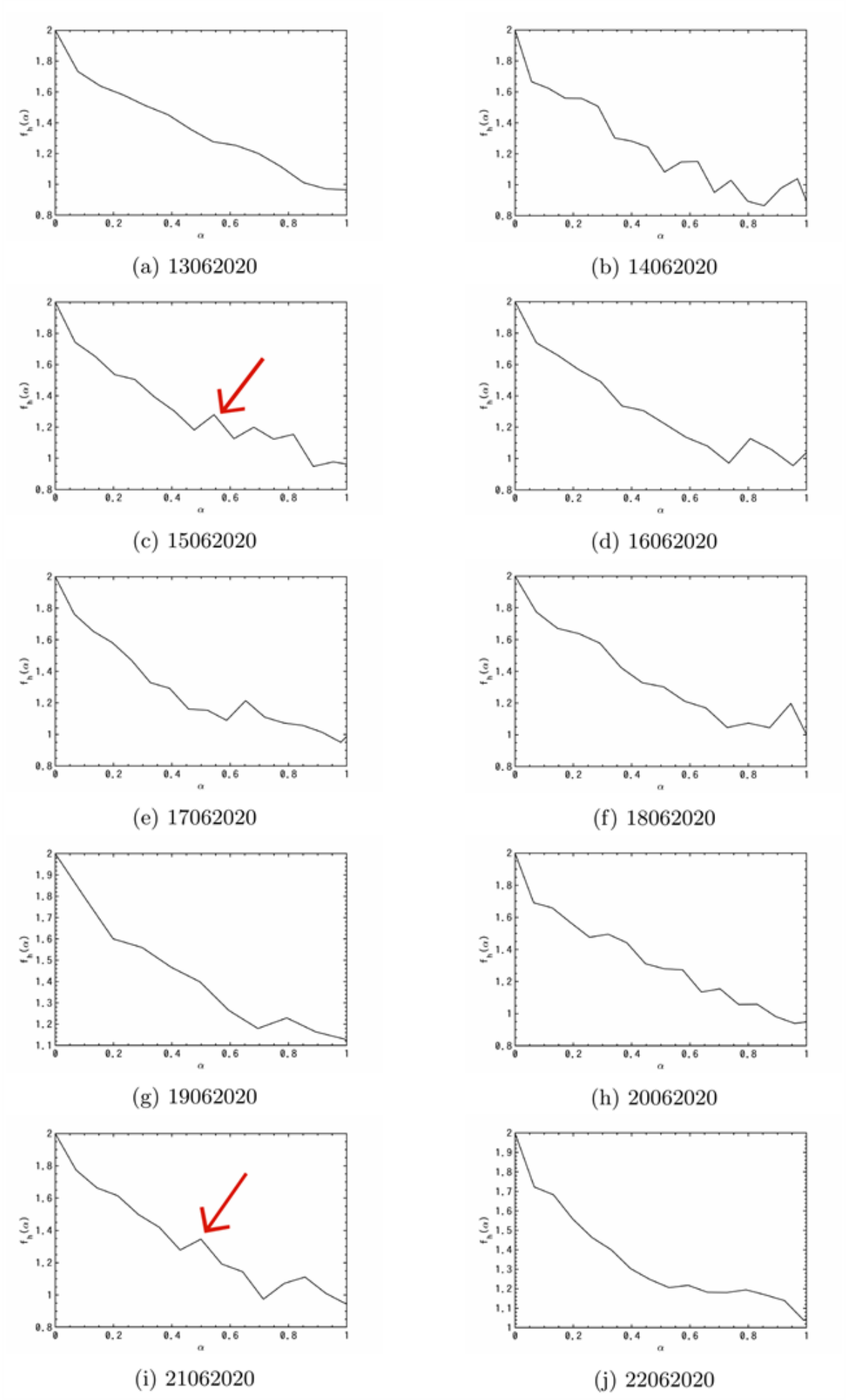

Figure-3: These plots describe the Multifractal or Hausdorff spectrum of the mean Cloud height (top) from 13th to 22nd June 2020.

DISCUSSION

1. Figure-1 describes the Cross Wavelet Transformation (XWT) power spectrum, which measures the strength & periodicity of the interaction between the Earth's magnetic field and Solar activity.
    - The periodic signature in the wavelet scalogram is of 95% significance inside the cone of confidence, whereas it is of 99% significance inside the contour region.
    - XWT power is seen to increase from 1st to 22nd June and is sustained.
2. Figure-2 compares the Average XWT power from 18th to 22nd June.
    - We observe, there is **swapping of the peak between the ~9 day and ~3 day periods (denoted by purple arrow).**
    - This change in the overall distribution of the average power value can be attributed to the event occurring on June 21st.
3. Figure-3 shows the Singularity Spectrum obtained from Multi Fractal Analysis (MFA) using the data from 13th to 22nd June 2020
    - A **sharp peak (shown by a red arrow) is observed at α=~0.5 in subfigure 3(c) (15th June) and 3(i) (21st June)**.
4. MFA spectrum has shown that this **anomalous behavior could have been predicted by 16th June 2020 (using data up to June 15th), which is 5 days ahead in time.**

CONCLUSION

By taking the case study of the last Solar eclipse on June 21st, 2020, we have been able to detect the erratic behaviour in the terrestrial climate in response to the spurious geomagnetic field variations. This is due to the complex interplay of SW plasma and Geomagnetic field in the presence of lunar gravity, leading to terrestrial storms. We have used Wavelet Transformations of SW and Earth's magnetic field parameters to find the signature. Finally, our prediction of the event that occurred on June 21st, 5 days before its actual occurrence, confirms that the tools of MFA are used effectively.

ABSTRACT

Though spurious geomagnetic activity lead to terrestrial storms, which in turn impacts space weather as a result of interaction between Solar wind (SW) plasma carried by Solar wind moving towards Earth due to Coronal Mass Ejection (CME) and interplanetary magnetic field, the interplay linking the Solar plasma to the Earth's magnetic field is yet to be understood thoroughly, and hence modelling the space weather is still perceived as a challenge. To address this issue, we resort to geometrical analysis of the phenomena using state-of-the-art Multi Fractal Analysis (MFA) techniques as well as Wavelet Transforms of SW and Earth's magnetic field parameters during the period starting from few days before up to few days after the last Solar Eclipse on June 21, 2020, in order to predict abnormal behaviour in terrestrial environment, may or may not be leading to geomagnetic storms, well before the occurrence of the event.

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