Solar and Stellar Magnetic Fields: Origins and Manifestations
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Statistical analysis of geomagnetic storms and their relation with the solar cycle

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Abstract. Geomagnetic storms can be modeled as stochastic processes with log-normal probability distribution function over their minimum $D_{\rm st}$ index value measured during the main phase of each event. Considering a time series of geomagnetic storm events between 1957 and 2019 we have analyzed the probability of occurrence of small, moderate, strong and extreme events. The data were separated according to solar cycle (SC) and solar cycle phases and fitted through maximum likelihood method in order to compare rates of occurrence of the last Solar Cycle (SC24) with previous ones. Our results show that for $D_{\rm st} < -100$ nT events in SC24 are similar to those in SC20, obtaining $\sim$42 vs 21 median rate storms per cycle with 95% confidence intervals using Bootstrap Method. As SC24 has been the least active solar cycle in over 200 years, we conclude that this method tends to overestimate geomagnetic storms occurrence rates even for small events.

Keywords. Space Weather, Geomagnetic Storms, Solar Cycle

1. Introduction

Geomagnetic storms are disturbances in the Earth's magnetic field caused by interactions with magnetized plasma ejected from the sun. These events transfer extreme amounts of energy to the magnetosphere that can result in a wide range of damages to satellites and communication systems (Wrenn *et al.* 2002), as well as pose a threat to human exploration at high altitudes, thus resulting in technological disruptions, economic losses and dangers to human life. For this reason, the study of geomagnetic storm occurrence and intensity over time as well as the relationship between geomagnetic storms rate occurrence for different solar cycles and their phases is fundamental to improve our forecasting models, and thus to prevent and reduce the risk associated with them.

Geomagnetic storms are traditionally classified according to the strength on their impact in the magnetospheric system, which is recorded from ground-base observations in a series of indices such as $D_{\rm st}$, SYM-H and Kp among others. In particular, the Disturbance Storm Index ($D_{\rm st}$) is an indicator of enhancement of the magnetospheric ring current near equator that results in an effective decrease of the Earth's magnetic field. Large drops are generally associated with storms produced by Coronal Mass Ejections (CME), although solar flares and high-speed streams associated with coronal holes can also produce similar magnetospheric effects. In general, geomagnetic disturbances in which the minimum $D_{\rm st} < 50$ nT are considered as geomagnetic storms. Moderate storms correspond to minimum $D_{\rm st} > -100$ nT, and strong storms are events with $D_{\rm st} > -200$ nT. (Gonzalez *et al.* 1994). Stronger storms are traditionally considered extreme events and tend to occur only sporadically, generally no more than a few times per solar cycle.

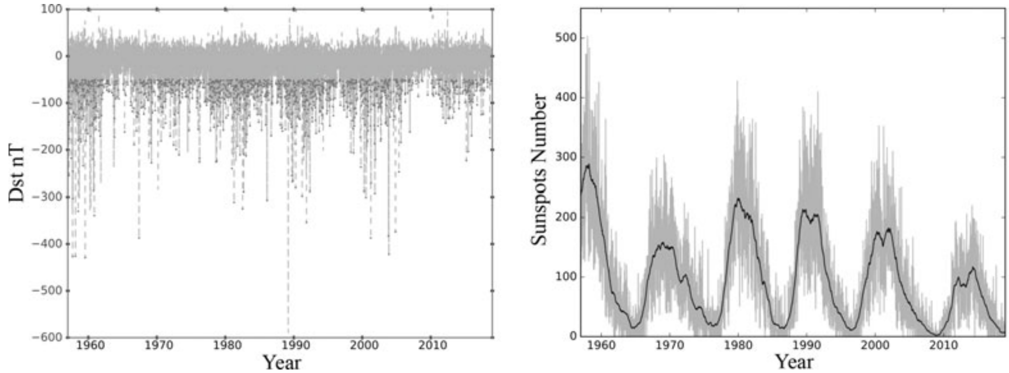

Figure 1. (left) 1367 storms found with $D_{\rm st} < -50$ nT between 1957–2019. (right) raw sunspots number count are shown in grey with black lines to indicate yearly moving average sunspot number.

The direct relation between solar activity and the solar cycle has been known for a long time (Allen 1944). The solar activity can be measured through sunspots numbers, and its periodic variation of ∼11 years is used to define the solar cycle. Sunspots are visual manifestations of the Suns magnetic activity and the presence of sunspots on the sun is related to CME (Hayakawa *et al.* 2018), CIR and sometimes flaring. Several studies have explored and quantified such relation between storms and sunspot number (see for example Riley & Love 2018). and have found that generally the number and magnitude of geomagnetic storms during a given solar cycle increase as the number of sunspots increases. To better understand the relationship between the occurrence of geomagnetic storms and the solar cycle, here we present a statistical study in which, treating storms as stochastic processes, we compare the occurrence rate of storms during the Solar Cycle 24 (SC24) with predictions based on previous solar cycles.

2. Data: geomagnetic storms and and solar indexes

Geomagnetic storms can be treated as a stochastic processes. Thus, the probability distribution function (PDF) of geomagnetic storms occurrence as a function of the $D_{\rm st}$ index can be fitted with a log-normal distribution. This is believed to be due to different processes (solar cycle dynamo action, the geo-effectiveness of the solar wind-magnetospheric coupling and the dynamic evolution of a geomagnetic storm) all acting together (Love *et al.* 2015). Namely;

$$F(x|\mu,\sigma^2) = \frac{1}{2}\mathrm{erfc}\left[\frac{\ln(\mathrm{x}) - \mu}{\sqrt{2\sigma^2}}\right] \tag{2.1}$$

gives us the occurrence probability F for an event with size exceeding $x = -D_{st}$. Here, μ and σ represent the average and standard deviation of the distribution respectively. By obtaining a good fit for the PDF it is possible to make predictions for the occurrence rate of storms and, more important, to evaluate the PDF and extrapolate the probability of occurrence for large and extreme events. To build the PDF we considered two indexes: $D_{\rm st}$ index to characterize storm strength, and sunspot activity index to separate the data on solar cycles (see right panel in Figure 1). $D_{\rm st}$ index data was obtained from the World Data Center for Geomagnetism of Kyoto's website from 1957 to 2019 at 1 hour time resolution. The dataset of sunspots number was obtained from World Data Center for the Production, Preservation and Dissemination of the International Sunspot Number (Silso's web).

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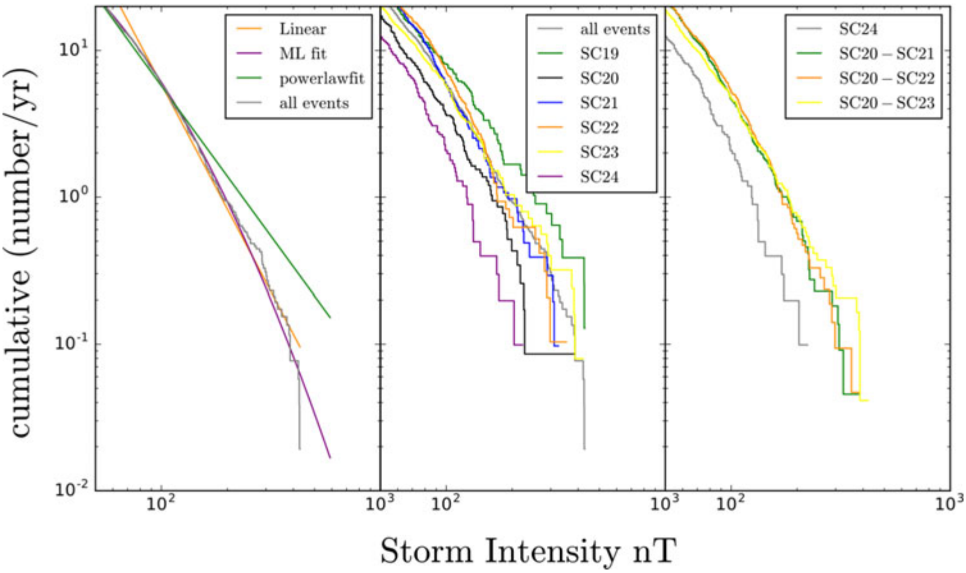

Figure 2. (left) Three different fits to exceedance cumulative of all events, Next figures shows data separated by (center) solar cycle and (right) a combination of them.

3. Methods and results

For the statistics we represent storms by their maximum intensity during main phase with $D_{\rm st} < -50\,{\rm nT}$ as shown in Figure 1 (left panel), where data was grouped by solar cycles from 20 to 23 or different combinations of them. Then, $-D_{\rm st}$ was fitted through Maximum Likelihood method, assuming that data corresponds to a log-normal function [Eq. (2.1)] to finally use a bootstrap method to estimate extrapolated storms median rate occurrence error with 95% confidence, in order to compare each fitted data to SC24 number of events.

Bootstrap method is a statistical technique which its main application is estimate the variation of point estimates (confidence intervals). For this purpose, $-D_{\rm st}$ data sample is re-sampled and calculate its median x^* to compute differences $\delta^* = x^*_{\rm median} - x_{\rm median}$. Thus, our estimated 95% median bootstrap confidence interval is $\left[x_{\rm median} - \delta^*_{.0025}, x_{\rm median} - \delta^*_{.0975}\right]$.

Figure 2 shows histograms of binned maxima storm values. Left panel includes three different fits used over exceedances cumulative. A simple look lead us to believe that ML fit is a good representation of storms rate occurrence, specially for extreme events. In the others panels storm maxima data was separated by Solar Cycle or combinations of them.

A quick comparison with SC24 shows that all cycles have more activity than SC24. A comparison of median rate occurrence with 95% confidence interval of different set of data and events from SC24, listed on Tables 1 and 2, shows better accuracy from extreme events prediction, accompanied with less uncertainties.

4. Conclusions

Our results show that ML is the most accurate method to characterize $-D_{\rm st}$ PDF, specially for tail values that correspond to extreme events. Then, a revision of storm extrapolation with $100 < -D_{\rm st}$ lead us to conclude that this method tends to overestimate the rate occurrence of storms in comparison of number of events occurred during SC24,

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Table 1. Bootstrap and 95% Confidence Intervals for Maximum Exceedances for all events, SC20-21, SC20-22, SC20-2322 events, -Dst and comparison with number of events in SC24.

-Dst (nT)	All events	SC20-21	SC20-22	SC20-23	SC24
100	71.35 [65.75, 77.01]	58.70 [50.94, 66.80]	63.44 [55.16,71.81]	53.98 [46.80,61.28]	21
200	10.89 [8.55,13.21]	6.93 [3.98,9.66]	7.41 [4.39,10.25]	9.15 [6.26,12.12]	2
589	0.19 [0.00,0.32]	0.07 [−0.11,0.12]	0.06 [−0.09,0.10]	0.29 [−0.14,0.48]	0

Table 2. Bootstrap and 95% Confidence Intervals for Maximum Exceedances for all SC20-21, SC20-21, SC20-23 events, -Dst and comparison with number of events in SC24.

-Dst (nT)	SC20	SC21	SC22	SC23	SC24
100	42.63 [32.99, 51.73]	76.98 [63.79,90.43]	89.05 [74.72,103.20]	64.38 [53.74,75.16]	21
200	5.75 [2.64,8.82]	8.16 [3.15,12.70]	9.13 [3.70,13.83]	12.26 [7.73,17.15]	2
589	0.11 [−0.24,0.0.21]	0.04 [−0.19,0.09]	0.03 [−0.14,0.06]	0.49 [−0.32,0.90]	0

but as we move towards larger $-D_{\rm st}$ values, this difference tends to decreased. Regardless of what combination of solar cycles were used to predict SC24, the prediction always overestimate the number of storms that actually occurred. A possible explanation is the the fact that SC24 was the least active cycle in the past 200 years. Thus, it is possible that if the trend of weak solar cycles continues, using previous solar cycles data to forecast the next cycle would most likely be unreliable as it will keep overestimating the number of storms that will actually be recorded. We expect to increase the scope of the present work in a subsequent manuscript.

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