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COMESEP

Historical analysis of Sun-Earth connections in the context of extreme space weather events

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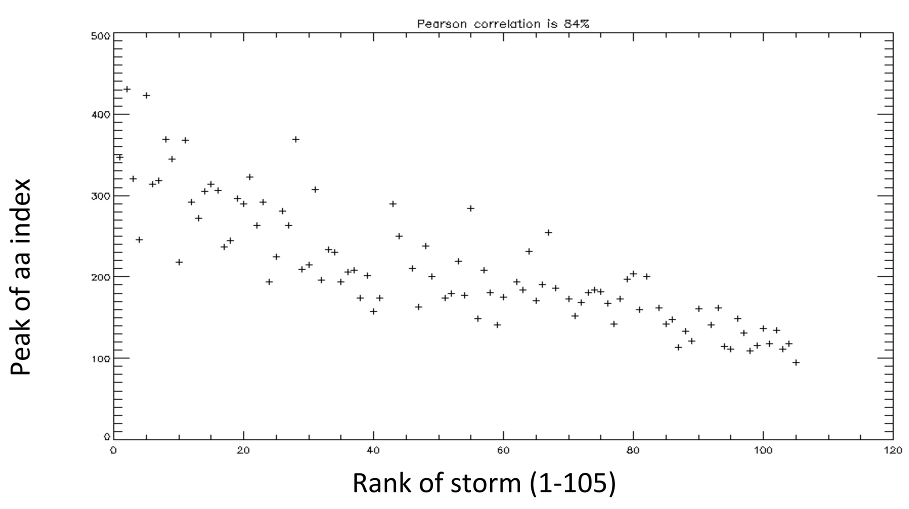
We present an historical analysis of Sun-Earth connections in the context of the most extreme space weather events of the last 150 years. To identify the key-factors leading to these extreme events, we have selected a sample of the most important geomagnetic storms based on the well-known aa index. Here we focus on characterizing the active regions most probably responsible for these major geomagnetic storms.

For this purpose, we use detailed sunspot catalogs (Lefèvre & Clette, 2012) as well as solar images and drawings. For geomagnetic events during the SOHO era, vast amounts of detailed solar data is readily available and thus solar terrestrial connections easy to access through various detailed studies. Events posterior to the 1940s are still relatively easy to study because mainly of the availability of flare data and numerous solar drawings. However, back to the beginning of the aa index in 1868, solar data from catalogs become scarce as well as sunspot drawings. In this study, we have systematically gathered the most interesting sunspot parameters back to 1868, going as far as hunting solar drawings from the old Greenwich archives, and extracting the parameters ourselves.

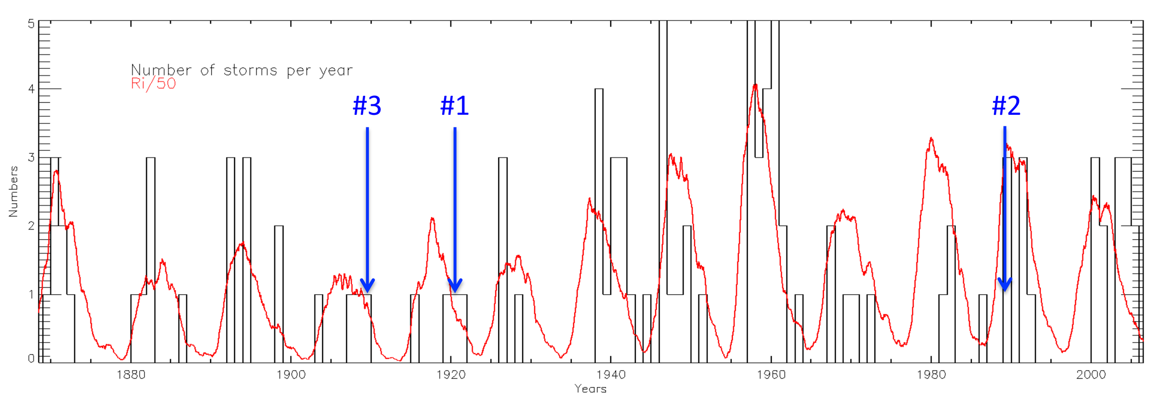
Here we present a detailed statistical analysis of the active region parameters relative to the flare/geomagnetic parameters, which will lead to a few interesting clues on how to characterize future storms from just these sunspot parameters.

SAMPLE SELECTION



We select geomagnetic events starting in 1868, at the beginning of the aa index (Cliver, 2000). We rank events according to different criteria but ranking is strongly correlated to aa index as can be seen from the figure on the left.

The sample contains 105 storms with aa > 300nT. Below are represented storms numbers 1, 2 and 3.



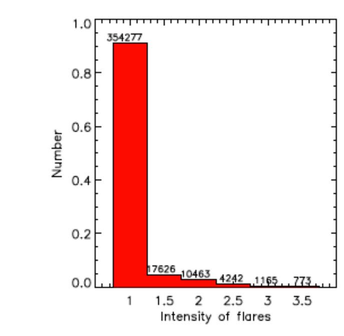
AVAILABLE PARAMETERS

Different elements enable linking geomagnetic events to an active region on the Sun.

- Earth: geomagnetic indices
- Interplanetary : CMEs
- Sun: Flares, Sunspot details

Before 1966		1-	1	1+	2-	2	2+	3-	3	3+	
From 1966	S	1F	1N	1B	2F	2N	2B	3F	3N	3B	4
Numerical scale	1	1	1	1.5	2	2	2.5	3	3	3.5	3.5

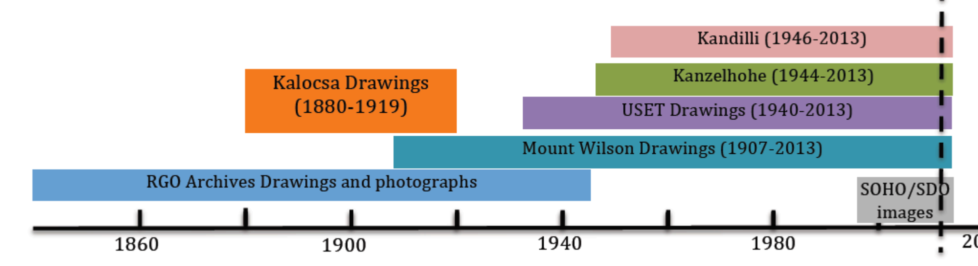
This table shows how the standards in flare indices have varied over time since the official beginning of the Flare Patrol in 1938.



This figure shows the number of flares in each intensity class that were seen by the Flare Patrol since 1938.

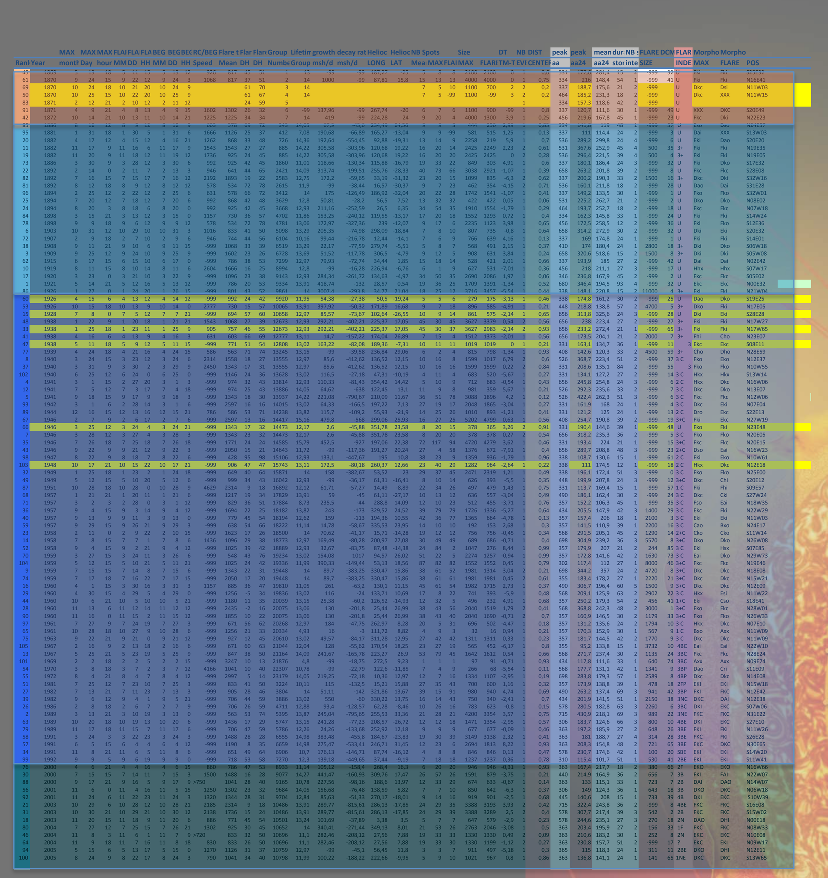
However, their availability is limited in time.

- Geomagnetic indices: aa (1868), *Kp*, (1932), *Dst (1957), am (1959)*
- CME information: SOHO era mainly
- Flares: 1938, first flare patrol at Mount Wilson at the beginning of the 20th Century + Newton (1943, 1944)
- Detailed Sunspot data: reconstruction back to 1876 (RGO catalog+ complementary information) + data extracted from archives and images for older data



NAME	SOHO Era	H_α Patrol	RGO Era	Pre-RGO Era
DATE	2005-1996	1996-1926	1926-1876	1876-1868
EVENTS (105)	13	63	22	7
AA	*************	*************	*************	*************
CME	*************	*******		
H_α	*************	*************		
USET	*************	*********		
USAF	*************	*******		
DPD	*************	*******		
RGO		*******	*************	
DRAWINGS	*************	*************	*************	*************

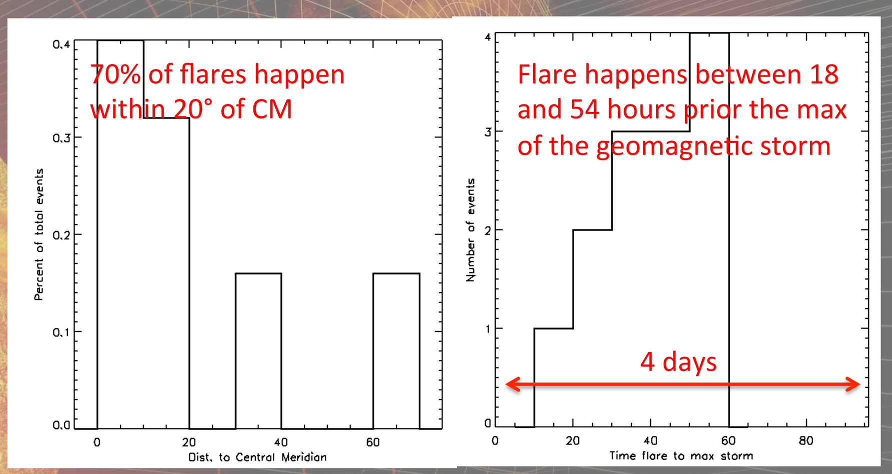
The figure above shows sources of drawings and images of the Sun used in this study. The figure on the right shows the availability of different types of data over time.



As our sample of geomagnetic storms spans almost 150 years, the data and its subsequent analysis present a strong dependency on time period: the type of data available and the time-coverage varies a lot, so we divided this study in four sections, corresponding to the four different time periods described in the table. We start from the most recent events for which all kinds of data are available (SOHO era) to the oldest events for which very few information exists and time coverage is partial at best.

SOHO ERA

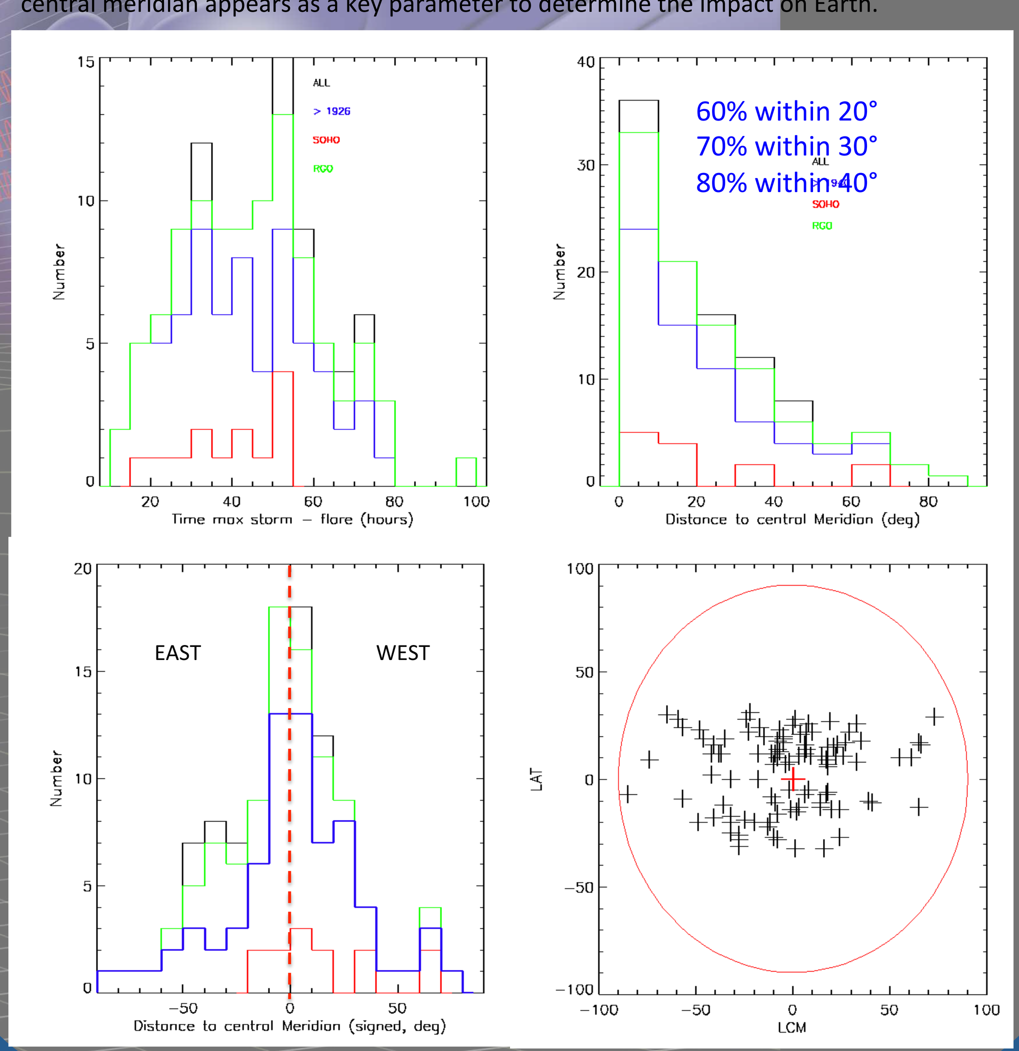
We choose a 4-day window before the geomagnetic storm as our most probable period for corresponding event(s) happening on the Sun. In this 4-day window, we choose the most extensive/intense flare, in terms of flare index, flare area or X-ray flux. Independent studies on the link between CME data and probable flares from Richardson & Cane (2010) confirm the date of the flare that is chosen with this method. The figure below shows that all of the associated flares happen within the selected window of 4 days.



We use the merged catalog (Lefèvre & Clette, 2012) based on Debrecen Photoheliographic Data (Gyori et al., 2011) and the SOON network data to derive the dynamical parameters of the region that was identified. We follow the variations of AR area and number of spots, as well as the morphological type. The area of the ARs seems to be affected by a phenomenon linked the associated flare(s): the area shows sudden changes (strong variations in growth or decay rate) in a window of ± 1 day around flare time. Strong changes are detected in 11 cases out of 13. When the change in area variation is not as evident, the number of spots appears more affected.
We use the confirmed results from each period as assumption for the next (older) periods and go backwards from there.

STATISTICS

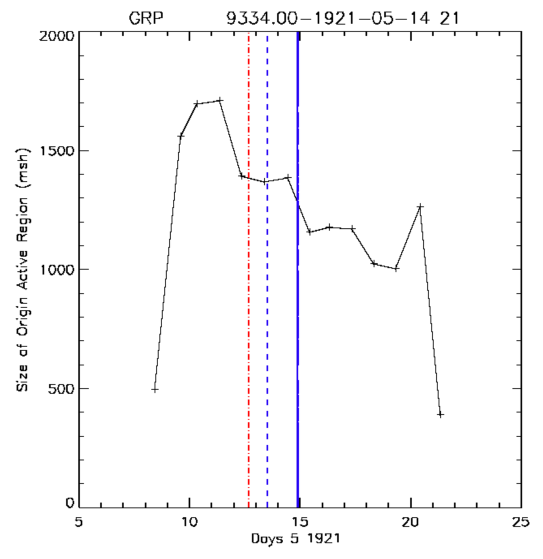
Here we show the time between the maximum of the storm and the flare on the Sun as well as the positions of the supposedly responsible Active Regions. Position relative to the central meridian appears as a key parameter to determine the impact on Earth.



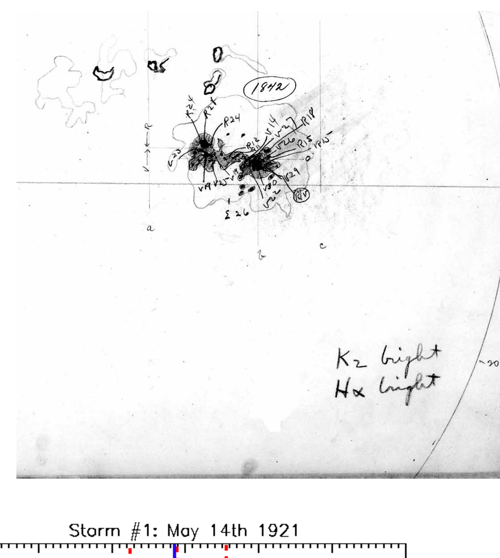
CONCLUSIONS

- The 4 day-window to look for responsible flare is adapted to our specific sample of extreme geomagnetic events.
- We note the importance of : size (complexity: 90% of AR at flare are D, E or F type) and position of the Active regions.
- There is no significant preference for Active Regions coming from east or west causing CME/storms.
- The large majority of flares causing these very severe geomagnetic storms happens close to the maximum size of the Active Regions involved.
- Flares seem to happen when the responsible Active Region experiences sudden variations in morphology: in size or in number of spots. In approximately 87% of cases you can find these sudden variations in the form of local maxima or minima. However, the causality is not so clear, as it appears the flare can happen in a window of +/- 1day, but it is impossible to say if the change causes the flare or the other way around (just like in modern studies).

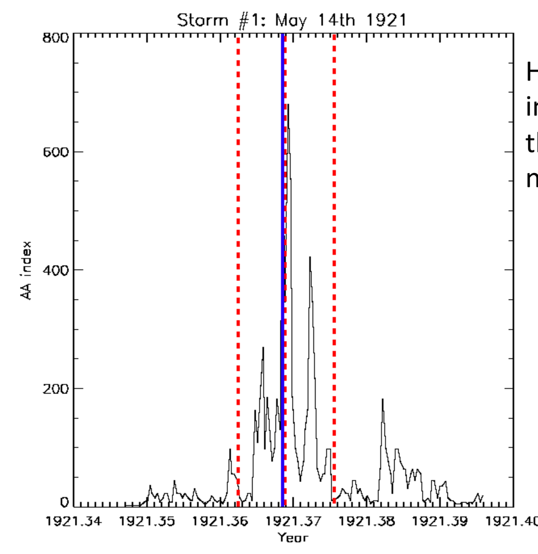
THE MAY 1921 STORM



This figure shows the variation in millionth of the solar hemisphere of the Active Region supposed to be responsible for the extreme event of May 1921. You can see this stair shape that suggests multiple sudden changes in area, probably linked to multiple flares and multiple geomagnetic events.



This figure shows the Active Region supposed to be responsible for this flare on the 12th of May 1921 on a drawing from Mount Wilson in California (cf. "K_2 bright" and "Hα bright" indications). This drawing is the only available information on the flare that caused Storm #1 since the Carrington event in 1859.



Here are the variations of the AA index in a window of 4 days before and after the event. You can clearly see that it is not a "simple" geomagnetic storm.

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This work has been conducted in the frame of the European Community's Seventh Framework Programme under grant agreement no. 263252 (COMESEP). We gratefully acknowledge the use of data from the Konkoly Observatory (DPD).