A New Tool for Forecasting Solar Drivers of Severe Space Weather

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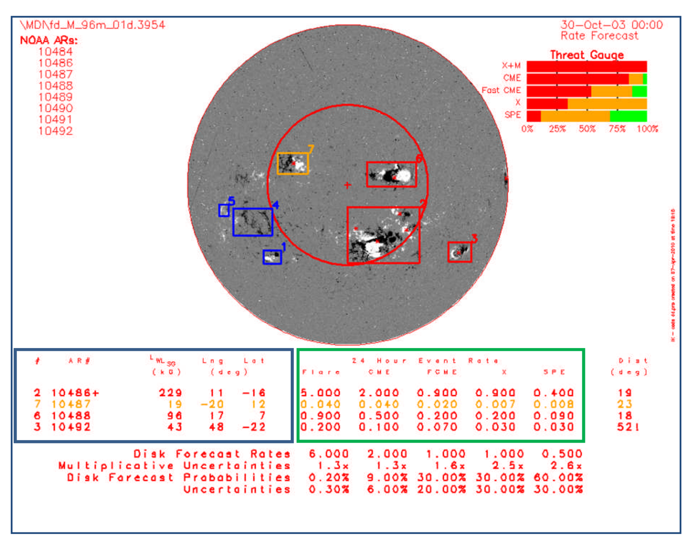
Motivation

▶Most severe space weather is driven by Solar flares and CMEs – the strongest of these originate in active regions and are driven by the release of coronal free magnetic energy

▶There is a positive correlation between an active region's free magnetic energy and the likelihood of flare and CME production – this positive correlation is the basis of our empirical space weather forecasting tool

▶The new tool takes a full disk MDI magnetogram, identifies strong magnetic field areas, identifies these with NOAA active regions, and measures a free-magnetic-energy proxy. It uses an empirically derived forecasting function to convert the free-magnetic-energy proxy to an expected event rate. It adds up the expected event rates from all active regions on the disk to forecast the expected rate and probability of each class of events – X-class flares, X&M class flares, CMEs, fast CMEs, and solar particle events (SPEs)

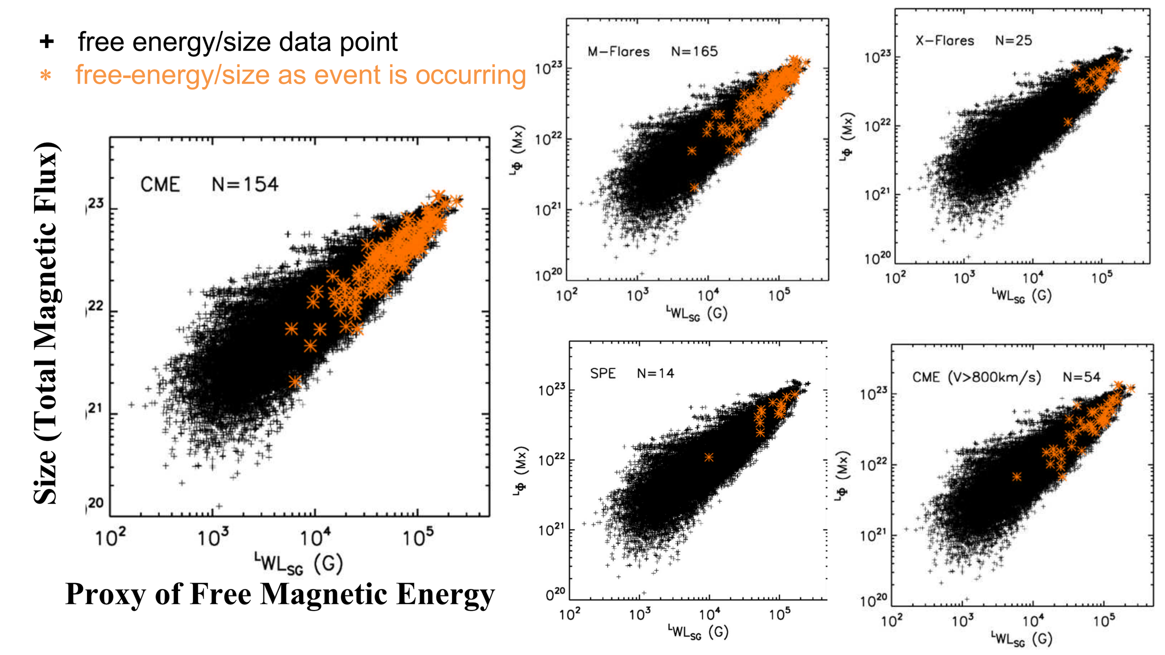
Sample Forecast Output



- The tool starts with a full-disk MDI magnetograms, identifies and encloses all strong magnetic field areas.
- Each strong magnetic field area is numbered and identified with one or more NOAA active regions. The active regions magnetogram is extracted and the proxy of the free magnetic energy is measured ($^{L}WL_{SG}$). **(Blue Box)**
- The proxy of the free magnetic energy is converted to expected rates of events **(Green box).** Threat level of each active region is color coded, based on expected M and X flare rate.
- Full disk expected event rates and All Clear probabilities are given below the blue and green boxes.
- A threat gauge shows the forecasted chance of event, yellow spanning the uncertainty range of the forecast rate.

Events in Phase Space

Flares, CMEs, and SPEs tend to originate from active regions with the most free energy



Skill Scores

The first four scores are based on yes/no forecast, with a forecasted event rate of 0.5/day or greater being counted as a yes forecast, while an event rate of less than 0.5 events/day is counted as a no forecast. The quadratic (Brier) score and SS are a comparison between the forecasted rates (f_i) and the observed flare rate (σ_i), while QR* is the quadratic score if the average flare rate is used (Balch, 2008, Spaced Weather Vol 6).

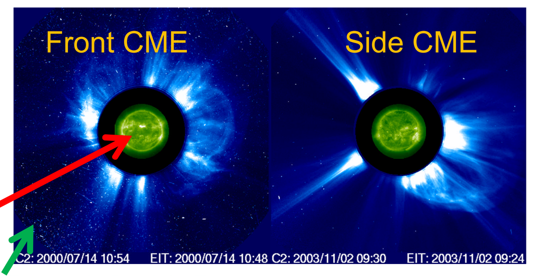
	Expression	"Free Energy"	"McIntosh"	Best Possible Score
Probability of Detection	A/(A+C)	0.45	0.26	1
False Alarm Rate	B/(A+B)	0.49	0.70	0
Percent correct	(A+D)/N	0.95	0.93	1
Heidke Skill	(A+D-E)/(N-E)	0.45	0.24	1
Quadratic Score	$1/N)\sum(f_i-\sigma_i)^2$	0.14	0.16	0
SS	(QR*-QR)/QR*	0.20	0.06	1

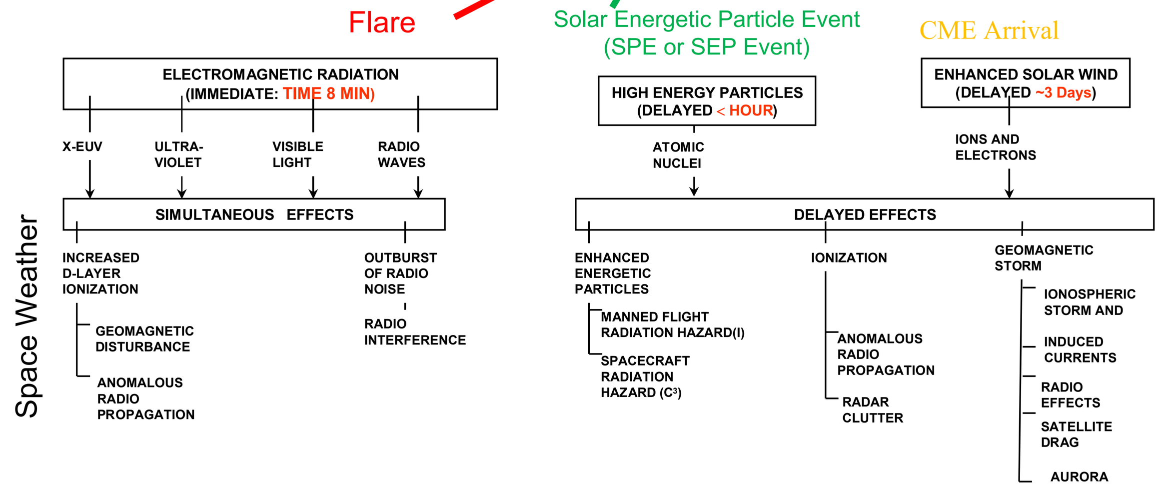
$E=((A+B)(A+C)+(B+D)*(C+D))/N$ $QR^*=(1/N)\sum(\sigma-\sigma_i)^2=0.17$

Our skill scores are always significantly better than McIntosh skill scores.

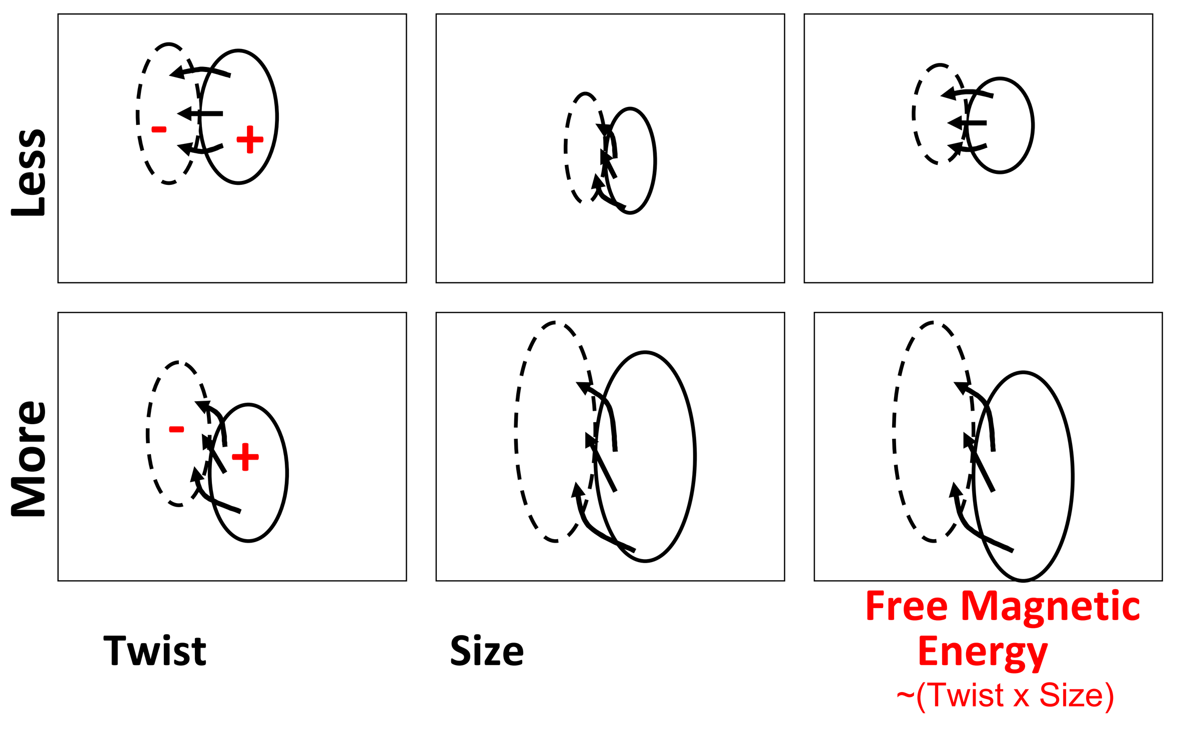
Flares, CMEs & Severe Space Weather

Right: A flare appears in both of the green SOHO/EIT, and in both cases a CME is seen in the blue SOHO/LASCO images. The front CME also produces a shock-wave that accelerates particles, producing a Solar Particle Event, also seen in the LASCO image.





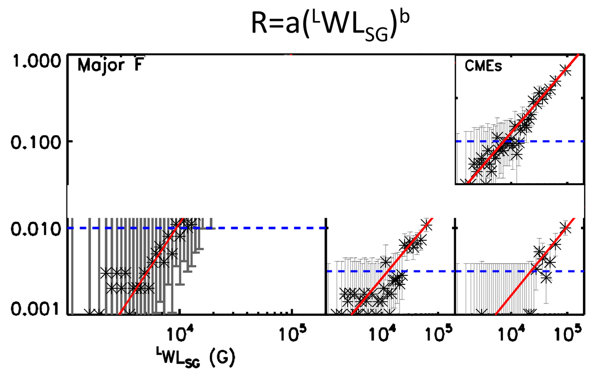
Active-Region's Magnetic Quantities



Empirical Forecasting Relation

- We bin our sample of 40,000 magnetograms, from 1,300 active regions into 40 equally populated bins based on our free magnetic energy proxy.
- For each bin we determine an average of the free magnetic energy proxy, an average event rate(*), and the statistical uncertainty of event rate (|).
- A power-law fit (red line) is done for all bins that have an event rate of greater than 0.01 events/day (left dashed blue line). This is the forecasting function, to convert any given free magnetic energy proxy measure to an empirical event rate. Each event type has its own forecasting function.

$R=a(^{L}WL_{SG})^b$



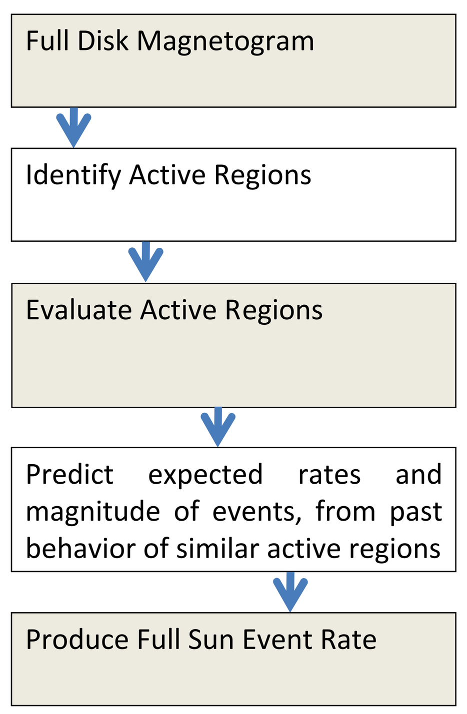
Power-Law Fits

Event Type	$\log_{10} a$	b	Reduced Chi-squared
X and M Flares	-9.75±0.03	1.95±0.14	0.21
X Flares	-10.77±0.11	2.00±0.58	0.39
CMEs	-7.81±0.04	1.50±0.16	0.31
Fast CMEs	-8.36±0.07	1.55±0.29	0.43
SPEs	-8.84±0.12	1.57±0.59	0.44

From Active Regions to Full Disk

- Event rates are additive, so we can add the forecasted event rates of all active regions on the disk.
- Forecasted event rates from poorly observed active regions (active regions near the limb) are less certain, because our proxy of free magnetic energy is more uncertain. These measurements will improve with SDO vector magnetograms. Active regions at the west limb could have forecast made based on previous history.
- Event rates for active regions or full disk can be converted to event (or All-Clear) probabilities
- All-Clear event probability: $Prob(t)=100\%(e^{-Rt})$

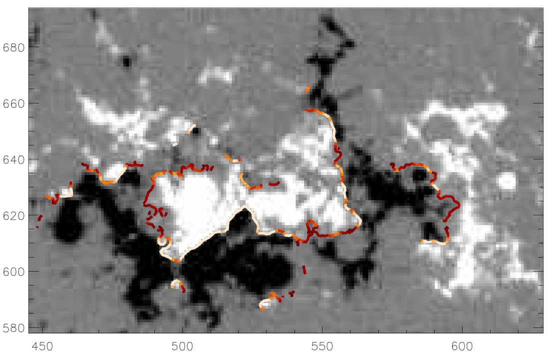
Outline of Method



NOAA presently classifies active regions by the McIntosh classification scheme, and then uses previous history of that class of active regions to forecast event rates, modified by observers experience.

Our method uses a measured proxy of an active region's free magnetic energy, and uses a forecasting curve determined from a sample of 40,000 magnetograms from 1,300 active regions with known event histories to convert the free magnetic energy proxy into the active region's expected event rate. All magnetograms are from SOHO/MDI and were of active regions observed during 1996-2004, during central disk passage.

Active-Region's Magnetic Measures



From SDO/HMI

➢ **Size:**

$\Phi=\int|B_z|\,da \quad (|B_z| >100G)$

➢ **Free Magnetic Energy:**

$WL_{SG}= \int(\nabla B_z)\,dl \quad (\text{potential } B_h>150G)$

where B_z is the vertical field,

B_h is the horizontal field, and the line integral is on the polarity inversion line.

In the line-of-sight approximation (MDI):

➢ B_z is replaced by the line-of-sight field and

➢ B_h is replaced by the potential transverse field which is calculated from the line-of-sight field

Performance of Forecasting Relation

- We bin our sample of 40,000 magnetograms, from 1,300 active regions into 40 equally populated bins based on our free magnetic energy proxy.
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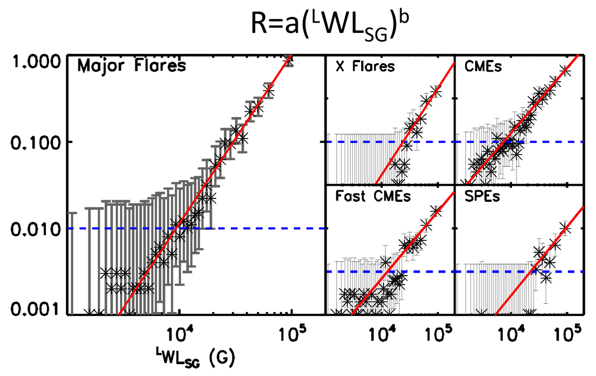

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Transition to SDO

▶ SDO\HMI will produce full-disk vector magnetograms, at higher cadence, higher resolution, and with less latency than MDI.

▶ The vector magnetograms will allow accurate assessment of our free magnetic energy proxy further from disk center than MDI line-of-sight magnetograms.

▶ The lower latency would allow forecasting with more recent observations.

▶ It will take a solar cycle to develop a database comparable to that available from MDI. To make forecasts based on HMI observations, in the meantime we will have to use the empirical conversion function determined from MDI.

▶ Since our free-magnetic-energy proxies is based on measuring gradients in the line-of-sight fields, where the line-of-sight field is approximately the vertical field, and MDI unlikely fully resolves these gradients, we will need to develop a conversion function, $f(WL_{SDO})$, using overlapping observations , magnetograms of the same active regions from both MDI and HMI

$$R=a\, f(WL_{SDO})^b$$

▶ We will likely use the SDO tiles for each active region, and thus eliminate the automated active region identification step.