Does Quantifying the Evolution of the Photospheric Magnetic Field Lead to Improved Solar Flare Prediction?

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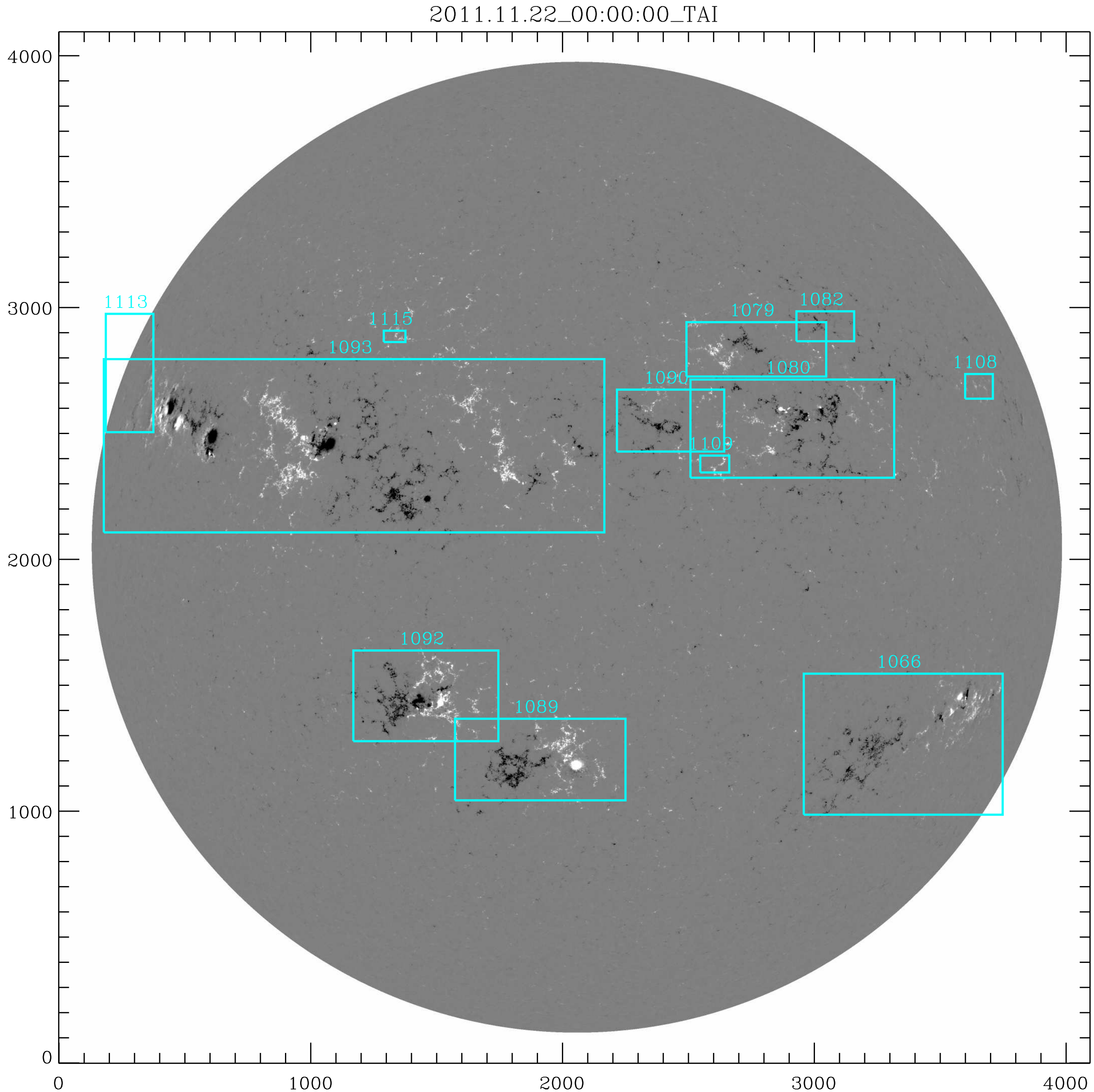
Overview

Make flare forecasts once per day over the course of a year (2011.08.01 to 2012.07.30) from SDO/HMI vector magnetograms.

- Extract HMI Active Region Patches (HARPS) from vector magnetograms.
- Parameterize the magnetic field once per hour for six hours per day.
- Characterize the value and rate of change of the parameters.
- Classify the HARPs using Discriminant Analysis, including bootstrap and cross-validation.
- Quantify the ability of each variable to distinguish flaring regions using skill scores.
- Answer the questions “does quantifying the evolution of the photospheric magnetic field lead to improved solar flare prediction?”

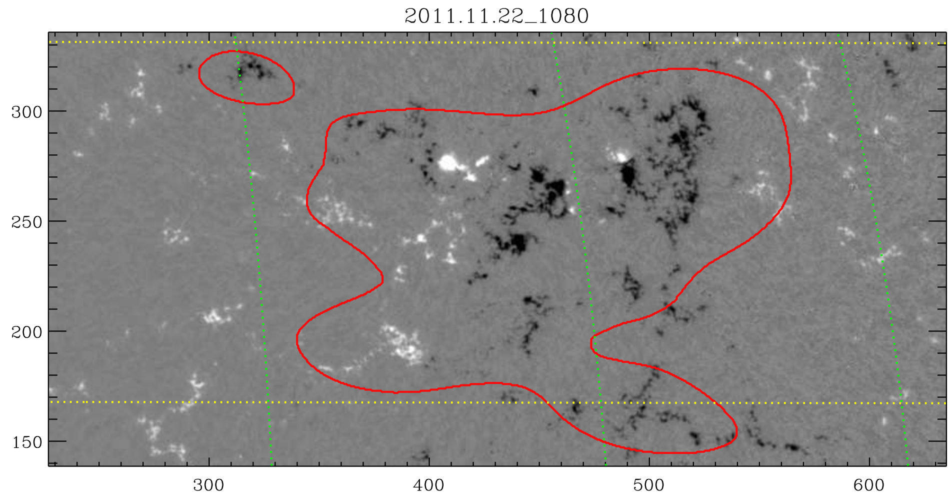
HMI Data

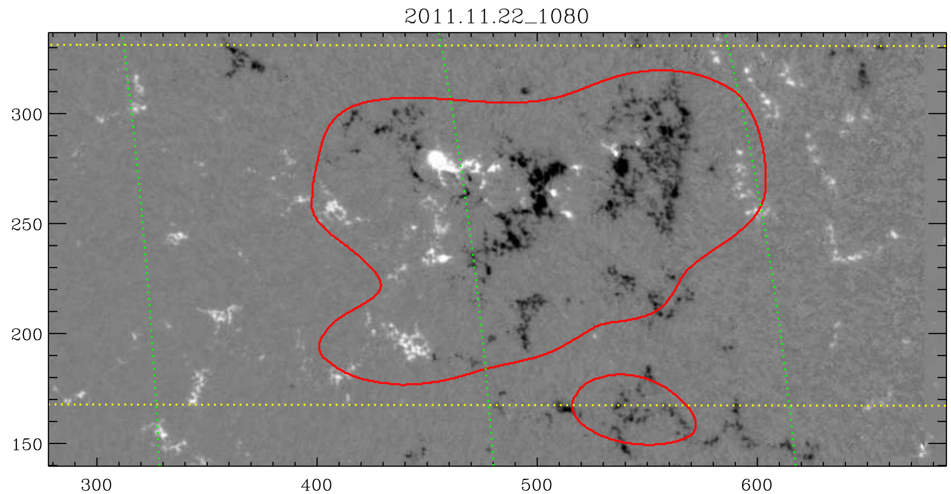


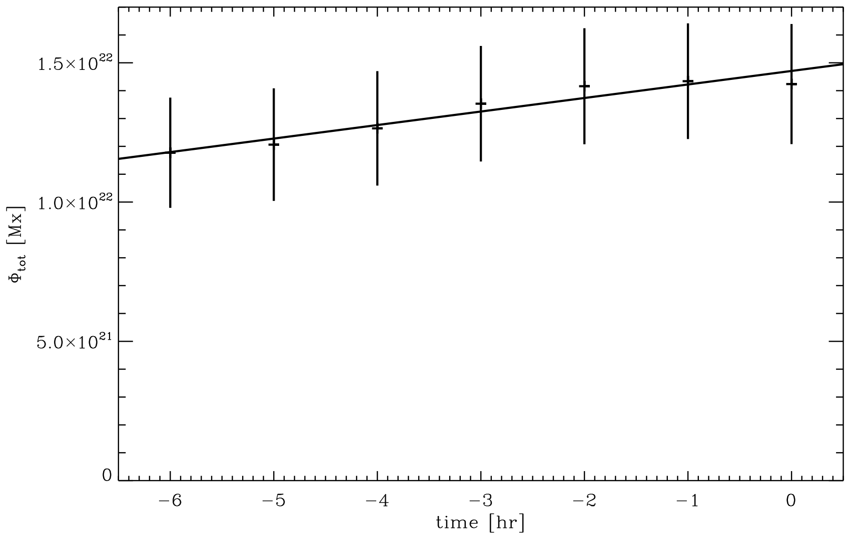
An example HMI magnetogram, with boxes enclosing HARPs.

- 3339 (not unique) HARPS
- 93 produced at least one M1.0 or larger flare within 24 hr
- 484 produced at least one C1.0 or larger flare within 24 hr

HARP Data







Example of the radial component of the magnetic field for HARP 1080 at the start (top, left) and end (bottom, left) of the time interval. The red contour outlines the active pixels in the HARP. This results in the flux shown above. The intercept and slope of the linear fit are used as the flare-forecasting parameters.

Photospheric Magnetic Field Parameters

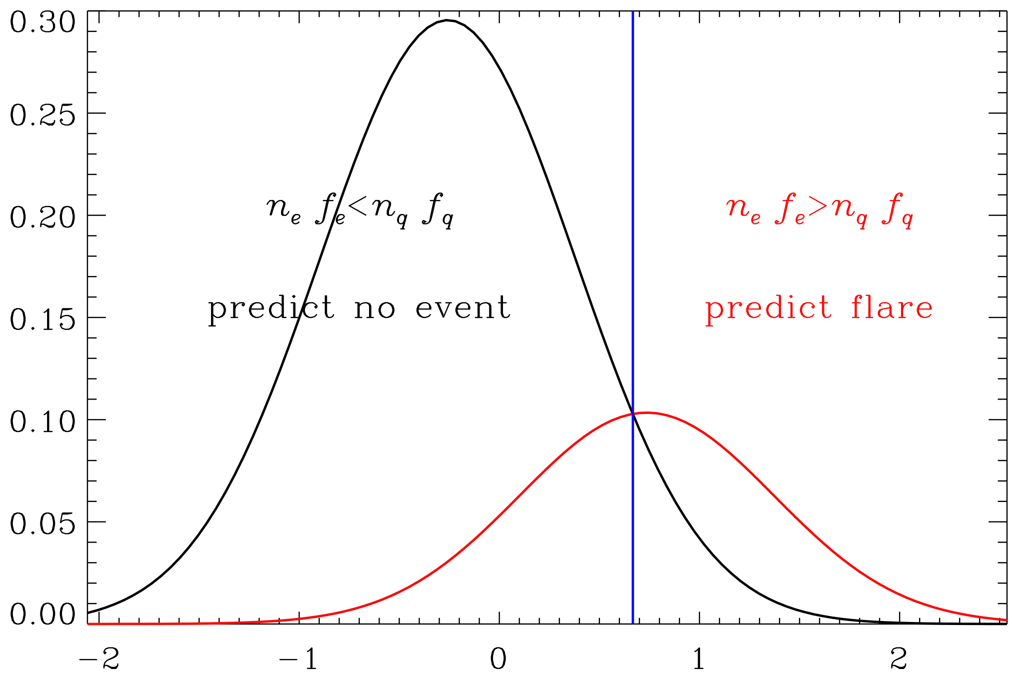
Description	Formula	Variable
Distribution of Magnetic Fields		
moments of vertical magnetic field	$B_z = \boldsymbol{B}\cdot\boldsymbol{e}_z$	$\mathcal{M}(B_z)$
total unsigned flux	$\Phi_{\rm tot} = \sum \lvert B_z \rvert \, dA$	$\Phi_{\rm tot}$
absolute value of the net flux	$\lvert\Phi_{\rm net}\rvert = \lvert \sum B_z \, dA \rvert$	$\lvert\Phi_{\rm net}\rvert$
moments of horizontal magnetic field	$B_h = \sqrt{B_x^2 + B_y^2}$	$\mathcal{M}(B_h)$
moments of inclination angle	$\gamma = \tan^{-1}(B_z/B_h)$	$\mathcal{M}(\gamma)$
Distribution of Horizontal Gradients of the Fields		
moments of total field gradients	$\lvert\boldsymbol{\nabla}_h B\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B\rvert)$
moments of vertical field gradients	$\lvert\boldsymbol{\nabla}_h B_z\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B_z\rvert)$
moments of horizontal field gradients	$\lvert\boldsymbol{\nabla}_h B_h\rvert$	$\mathcal{M}(\lvert\boldsymbol{\nabla}_h B_h\rvert)$
Distribution of Vertical Current Density		
moments of vertical current density	$J_z = C(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y})$	$\mathcal{M}(J_z)$
total unsigned vertical current	$I_{\rm tot} = \sum \lvert J_z \rvert \, dA$	$I_{\rm tot}$
absolute value of the net vertical current	$\lvert I_{\rm net}\rvert = \lvert \sum J_z \, dA \rvert$	$\lvert I_{\rm net}\rvert$
Distribution of Force-free Parameter		
moments of force-free parameter	$\alpha = C J_z / B_z$	$\mathcal{M}(\alpha)$
best fit force-free parameter	$\boldsymbol{B} = \alpha_{\rm ff} \boldsymbol{\nabla}\times\boldsymbol{B}$	$\lvert\alpha_{\rm ff}\rvert$

Photospheric Magnetic Field Parameters

Description	Formula	Variable
Distribution of Current Helicity		
moments of current helicity	$h_c = CB_z(\partial B_y/\partial x - \partial B_x/\partial y)$	$\mathcal{M}(h_c)$
total unsigned current helicity	$H_c^{\rm tot} = \sum \lvert h_c \rvert \, dA$	$H_c^{\rm tot}$
absolute value of net current helicity	$\lvert H_c^{\rm net} \rvert = \lvert \sum h_c \, dA \rvert$	$\lvert H_c^{\rm net} \rvert$
Distribution of Shear Angles		
moments of 3-D shear angle	$\Psi = \cos^{-1}(\boldsymbol{B}^p \cdot \boldsymbol{B}^o / B^p B^o)$	$\mathcal{M}(\Psi)$
area with shear $> \Psi_0, \ \Psi_0 = 45^\circ, \ 80^\circ$	$A(\Psi > \Psi_0) = \sum_{\Psi > \Psi_0} dA$	$A(\Psi > \Psi_0)$
moments of neutral-line shear angle	$\Psi_{\rm NL} = \cos^{-1}(\frac{\boldsymbol{B}^p_{\rm NL} \cdot \boldsymbol{B}^o_{\rm NL}}{B^p_{\rm NL} B^o_{\rm NL}})$	$\mathcal{M}(\Psi_{\rm NL})$
length of neutral line with shear $> \Psi_0$	$L(\Psi_{\rm NL} > \Psi_0) = \sum_{\Psi_{\rm NL} > \Psi_0} dL$	$L(\Psi_{\rm NL} > \Psi_0)$
moments of horizontal shear angle	$\psi = \cos^{-1}(\boldsymbol{B}^p_h \cdot \boldsymbol{B}^o_h / B^p_h B^o_h)$	$\mathcal{M}(\psi)$
area with horizontal shear $> \psi_0$	$A(\psi > \psi_0) = \sum_{\psi > \psi_0} dA$	$A(\psi > \psi_0)$
Distribution of Excess Magnetic Energy		
moments of excess magnetic energy	$\rho_e = (\boldsymbol{B}^p - \boldsymbol{B}^o)^2 / 8\pi$	$\mathcal{M}(\rho_e)$
total excess magnetic energy	$E_e = \sum \rho_e \, dA$	E_e

Discriminant Analysis and Probability Forecasts

Use discriminant analysis to turn parameter values into a forecast.



The probability density function, f_j, is defined by

$$P(x_a < x < x_b) = \int_{x_a}^{x_b} f_j(x)\,dx$$

where P is the probability that an observation falls between x_a and x_b.

Forecast a region to flare whenever the probability density estimate for flaring regions exceeds the probability density estimate for nonflaring regions:

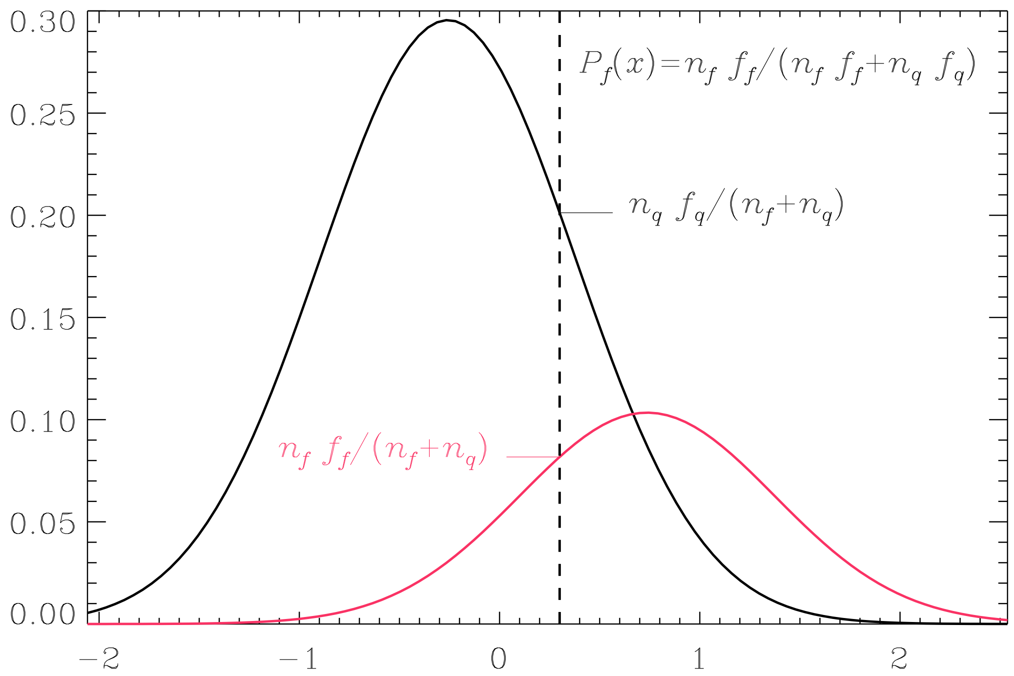
$n_f f_f(x) \geq n_n f_n(x) \;\Rightarrow$ predict a flare.

$n_f f_f(x) < n_n f_n(x) \;\Rightarrow$ predict flare quiet.

where n_j is the prior probability of belonging to population j, estimated as the sample size of population j.

Discriminant Analysis and Probability Forecasts

Use discriminant analysis to turn parameter values into a forecast.



The probability density function, f_j, is defined by

$$P(x_a < x < x_b) = \int_{x_a}^{x_b} f_j(x)\,dx$$

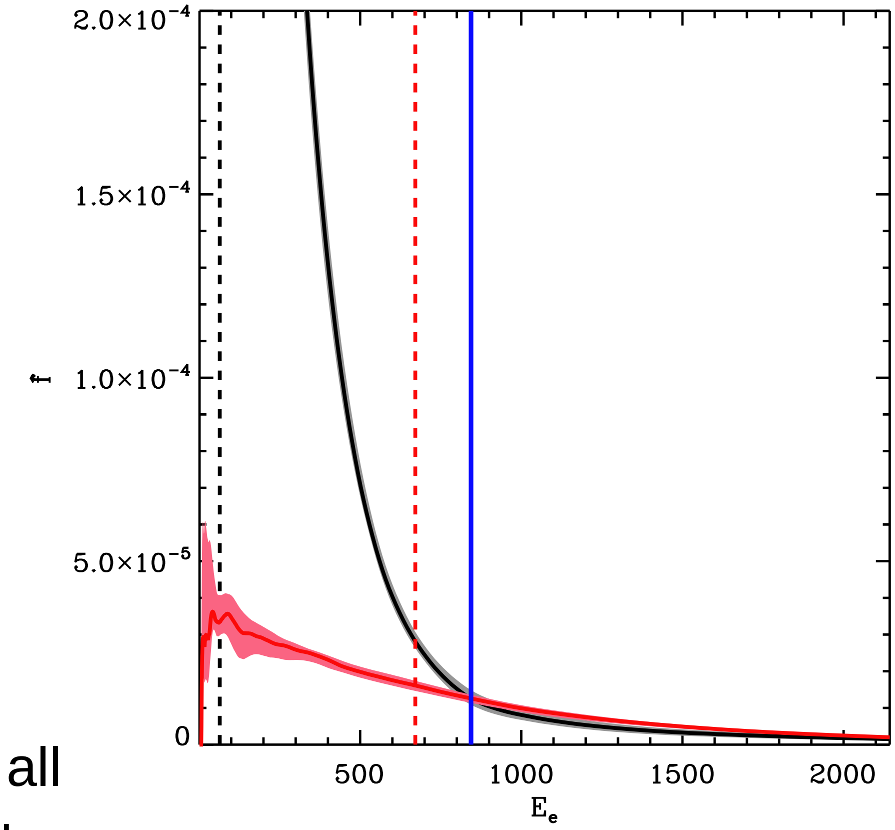
where P is the probability that an observation falls between x_a and x_b.

Alternatively, using Bayes' Theorem, estimate the probability of a flare occurring as

$$P_f(x) = \frac{n_f f_f(x)}{n_f f_f(x) + n_q f_q(x)}.$$

Results for M1.0 and above, 24 hr

variable	Brier SS
E_e	0.31 ± 0.05
$\lvert I_{\rm net}^{B_z<0}\rvert$	0.25 ± 0.04
$I_{\rm net}^{B_z<0}$	0.25 ± 0.05
$H_c^{\rm tot}$	0.24 ± 0.04
$I_{\rm tot}^{+}$	0.23 ± 0.04



The best performing variables all quantify the present state of the photospheric field.

Results for M1.0 and above, 24 hr

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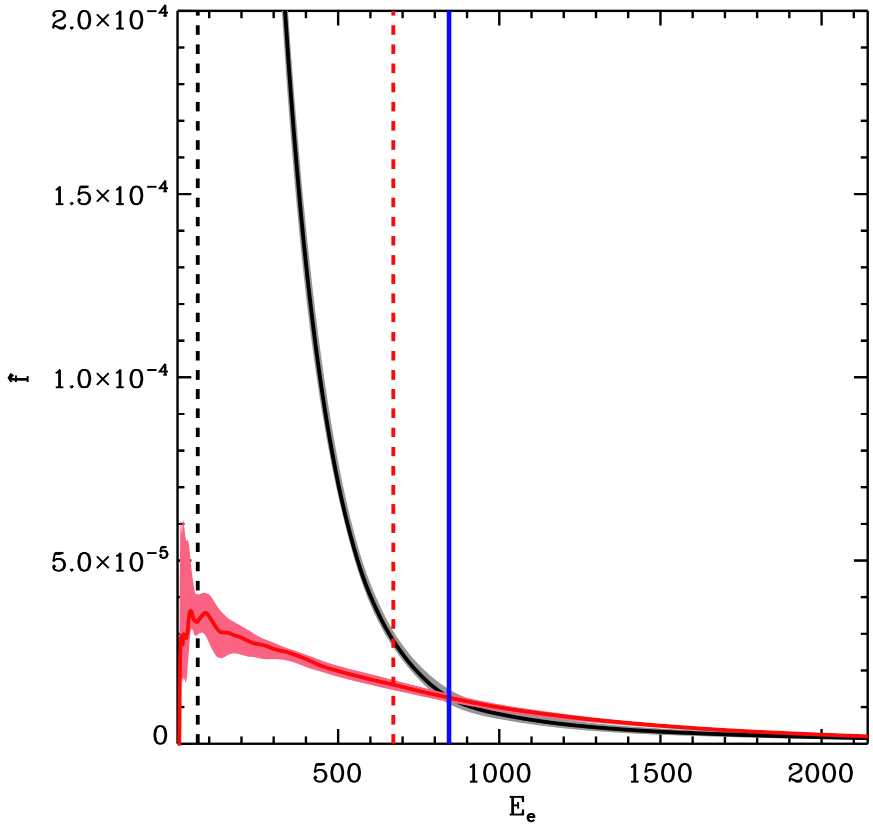
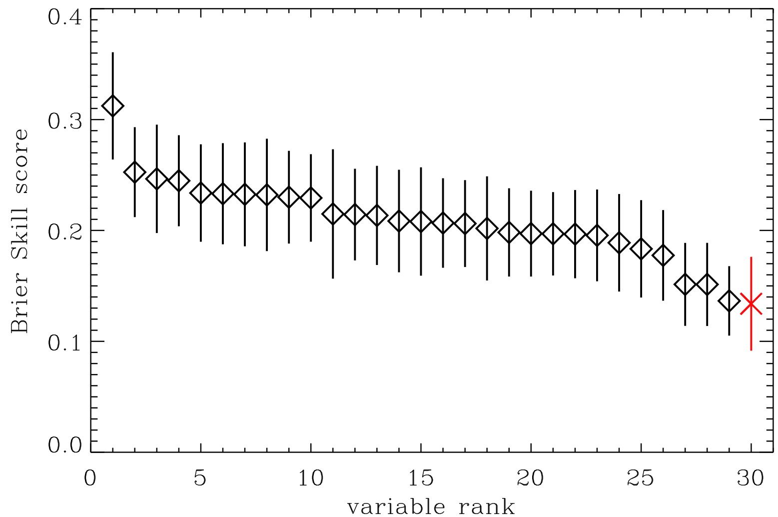
variable	Brier SS
$dH_c^{\rm net}/dt$	0.13 ± 0.04
$d\lvert H_c^{\rm net}\rvert/dt$	0.12 ± 0.04
$dA(\Psi > 80^\circ)/dt$	0.12 ± 0.05

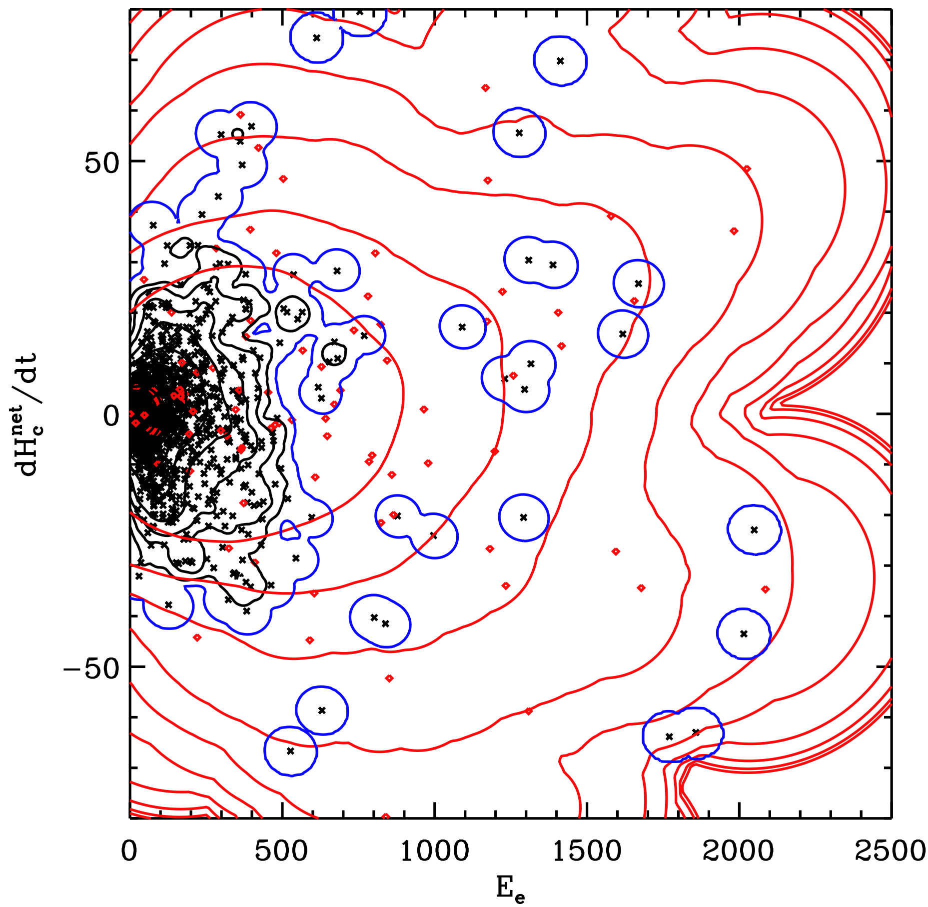




Variables quantifying evolution of the field have less ability to forecast flares.

Results for M1.0 and above, 24 hr

variable	variable	Brier SS
E_e	dH_c^{net}/dt	0.40 ± 0.06
$\lvert I_{\text{net}}^{B_z>0}\rvert$	E_e	0.39 ± 0.04
E_e	$d\lvert I_{\text{net}}^c\rvert/dt$	0.39 ± 0.07
$\sigma(B)$	E_e	0.39 ± 0.04
$< B_h >$	E_e	0.38 ± 0.04
$\kappa(\lvert\alpha\rvert)$	E_e	0.38 ± 0.07
$\sigma(\lvert J_z^c\rvert)$	E_e	0.37 ± 0.04
$A(\Psi > 80°)$	E_e	0.37 ± 0.05



- Combining variables quantifying the evolution of the field with its present state perform better than individual variables...
- but no more than combining variables quantifying the present state.
- The same holds true for other definitions of event (e.g., C1.0, 24 hr).

Conclusions

- Variables characterizing the evolution of the magnetic field do not by themselves result in better flare forecasts than simply characterizing the magnetic field at a given time.
- Combining evolution with the present state of the magnetic field performs better than either alone... but combinations of parameters characterizing the present state do just as well.
- This may not be the final answer!
  - The relevant timescales may be longer or shorter than the 6 hr used for this study. Fortunately, HMI is well suited to consider both shorter (cadence of 12 minutes) or longer (24 hr coverage) timescales.
  - We may not be considered the evolution of the right quantities, e.g., are photospheric flows useful?