Solar flare forecasting service by INAF-Catania Astrophysical Observatory

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Dataset

USSPS 31405 JJHHH aaabc ddAAA QXXYY t1t2t3SS

We use 5 parameters (see Ternullo et al., 2006 and Zirin 1998 for more details):

- Number of sunspots and pores (SS)
- Projected area (AA)
- Type of penumbra of the main sunspot (t1)
- Relative importance between leading spot and density of the sunspot population (t2)
- Group type according to Zurich classification (t3)

```
USSPS 31405 22085 20232  78010 35808 21302
                         86014 42205 31316
                         88257 21413 58695
                         89006 25412 21304
                         90001 33312 0/101
                         91001 31410 0/101
                         92001 10113 0/102
                         93003 18008 2/901
INAF-CATANIA ASTROPHYSICAL OBSERVATORY
```

The dataset is formed by daily observations of INAF-Catania Astrophysical Observatory (INAF-OACt) from January 2002 up today, when the weather conditions permit.

We also use the daily informations of the sunspot groups contained in the **Solar Region Summary** provided by NOAA.

Forecasting method

For each parameter, k, we compute the flare rate, FR, by the ratio between the number of sunspot groups which hosted at least a flare and characterized by a specific value of that parameter, $N_f(x_k)$, and the total number of sunspot groups characterized by the same value of that parameter $N(x_k)$:

$$FR_k(x_k) = \frac{N_f(x_k)}{N(x_k)}$$

The average among the flare rates for all parameters:

$$FR = \frac{FR_{SS}(x_{SS}) + FR_{AA}(x_{AA}) + FR_{t1}(x_{t1}) + FR_{t2}(x_{t2}) + FR_{t3}(x_{t3})}{5}$$

provides an estimation of the capability of hosting flares for sunspot groups characterized by a particular configuration, size and fragmentation (see Contarino et al., 2009).

Assuming that the flare event frequency follows the Poisson statistic, the event probability is given by: $p_f = 1 - \exp(-FR)$.
We compute the flare probability for three different samples of flare energies: for C1.0 GOES class and greater (C1.0+), for M1.0 GOES class and greater (M1.0+), for X1.0 GOES class and greater (X1.0+).

Forecasting method

```
Catania Ussps

USSPS 31405 06068 14232   46091 33308 55445
                          47073 41814 54627
                          49001 37909 0/101
                          50001 13419 0/101
                          51001 40517 0/101
                          52006 14011 25407
INAF-CATANIA ASTROPHYSICAL OBSERVATORY
```

NOAA/Solar Region Summary

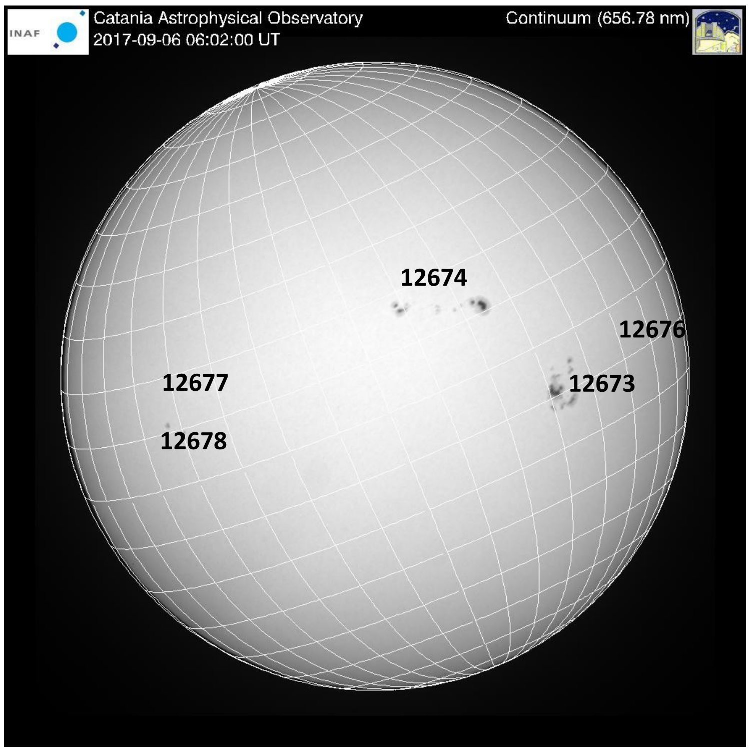
Nmbr	Location	Lo	Area	Z	LL	NN	Mag Type
2673	S09W30	119	0880	Dkc	09	33	Beta-Gamma-Delta
2674	N14W14	103	0680	Fhi	19	23	Beta
2675	S07W82	171	0010	Bxo	05	01	Beta
2676	S09W76	165	0030	Bxo	07	02	Beta
2677	N18E39	050	0020	Axx	01	01	Alpha
2678	N11E45	044	0010	Bxo	04	02	Beta

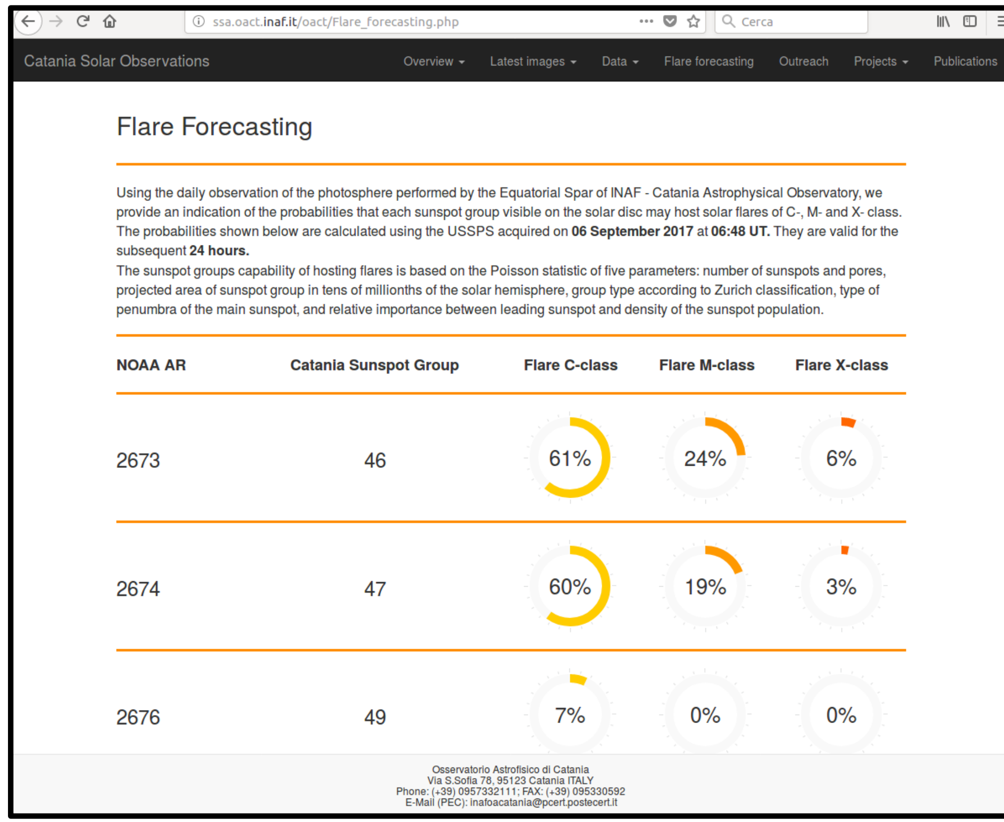
Hour	Min.	CC	NOAA	t1	t2	t3	Area	SS
06	48	46	2673	5	5	4	091	45
06	48	47	2674	5	4	6	073	27
06	48	49	2676	0	/	1	001	01
06	48	50	2677	0	/	1	001	01
06	48	51	NNNN	0	/	1	001	01
06	48	52	2678	2	5	4	006	07

		Flare probability (%)		
NOAA	CC	C+	M+	X+
2673	46	61	24	5
2674	47	60	19	3
2676	49	7	0	0
2677	50	7	0	0
NNNN	51	7	0	0
2678	52	26	5	1

Solar flare forecasting service

When weather conditions permit, we provide daily an indication of the probabilities that each sunspot group visible on the solar disc may host solar flares of C1.0+, M1.0+ and X1.0+ class at: **http://ssa.oact.inaf.it/oact/Flare_forecasting.php.**





Flare Forecasting

Using the daily observation of the photosphere performed by the Equatorial Spar of INAF - Catania Astrophysical Observatory, we provide an indication of the probabilities that each sunspot group visible on the solar disc may host solar flares of C-, M- and X- class. The probabilities shown below are calculated using the USSPS acquired on **06 September 2017** at **06:48 UT.** They are valid for the subsequent **24 hours.**
The sunspot groups capability of hosting flares is based on the Poisson statistic of five parameters: number of sunspots and pores, projected area of sunspot group in tens of millionths of the solar hemisphere, group type according to Zurich classification, type of penumbra of the main sunspot, and relative importance between leading sunspot and density of the sunspot population.

NOAA AR	Catania Sunspot Group	Flare C-class	Flare M-class	Flare X-class
2673	46	61%	24%	6%
2674	47	60%	19%	3%
2676	49	7%	0%	0%

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They are valid for the subsequent **24 hours**

Forecasting performance measures

Hour	Min.	Inst.	Class	NOAA
06	17	G15	C1.6	2673
07	29	G15	C2.7	2673
11	53	G15	X9.3	2673
15	51	G15	M2.5	2673
19	21	G15	M1.4	2673
08	57	G13	X2.2	2673

CC	NOAA	t1	t2	t3	Area	SS	#Flare C	M	X
46	2673	5	5	4	091	45	2	2	2
47	2674	5	4	6	073	27	0	0	0
49	2676	0	/	1	001	01	0	0	0
50	2677	0	/	1	001	01	0	0	0
51	NNNN	0	/	1	001	01	0	0	0
52	2678	2	5	4	006	07	0	0	0

NOAA	CC	Flare probability (%) C+	M+	X+
2673	46	61	24	5
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2677	50	7	0	0
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2678	52	26	5	1

To evaluate the performance of our forecasting method we compare our **flare probablities** with the the flare records obtained by the GOES satellites and saved in the **Space Weather Prediction Center Reports**.

Forecasting performance measures

To quantify the performance of binary, categorical forecasts, contingency tables and a variety of skill scores are used (see Barnes et al., 2016 for details).

Table 2
Example Contingency Table

	Predicted	
Observed	Event	No Event
Event	True Positive (TP, hit)	False Negative (FN, miss)
No Event	False Positive (FP, false alarm)	True Negative (TN, correct negative)

The **Rate Correct** provides a first estimation of the forecast performance: $A_{for} = \frac{(TP+TN)}{N}$, where N is the total number of forcasts (N = TP + FP + FN + TN).
However, this measure of accuracy can be miseleading for very unbalanced event/no event ratio!

To avoid this issue it is better to normalizie the performance to a reference forecast by using a **skill score**: $\text{Skill} = \frac{A_{for} - A_{ref}}{A_{per} - A_{ref}}$, where A_{per} and A_{ref} are the accuracy of a perfect forecast and of a reference method, respectively.

Skill = 1 ⟺ Perfect performance
Skill = 0 ⟺ No improvement over a reference forecast
Skill < 0 ⟺ Worse performance than the reference

Forecasting performance measures

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We used 2 different skill scores (with 2 different A_{ref}):

- **Appleman's Skill Score (ApSS):**

$$A_{for} = \frac{(TP+TN)}{N} \qquad A_{ref} = \frac{(TN+FP)}{N} \qquad A_{per} = 1$$

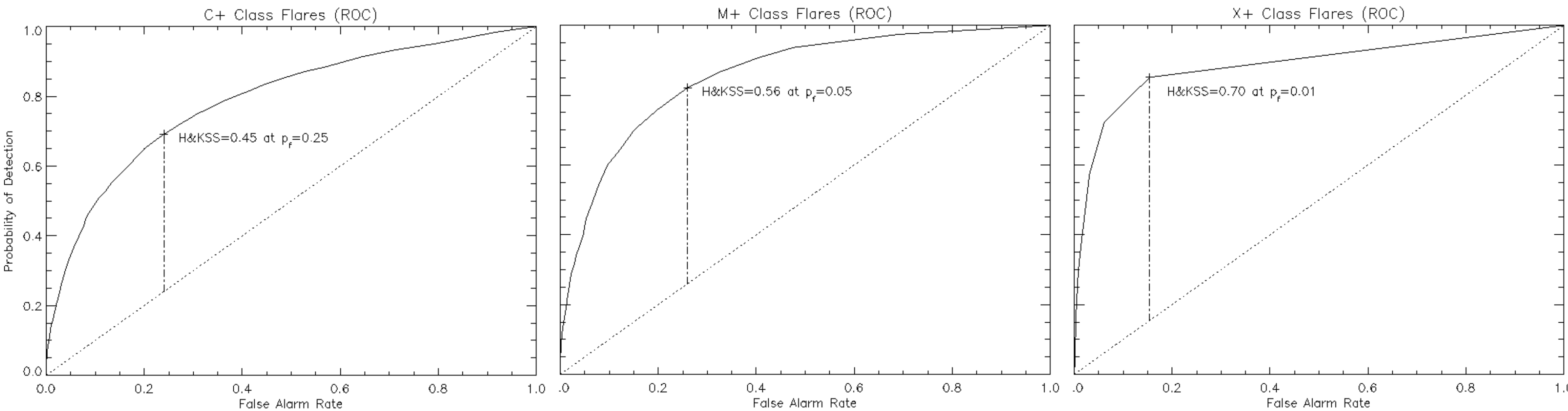
- **Hanssen & Kuipers' Discriminant (H&KSS):**

$$A_{for} = \frac{(TP+TN)}{N} \qquad A_{ref} = \frac{TP}{TP+FN} - \frac{FP}{FP+TN} = POD - FAR \qquad A_{per} = 1$$

where *POD* is the probability of detection and *FAR* is the false alarm rate

Forecasting performance measures

Receiver Operating Characteristic (ROC) curves for C1.0+, M1.0+ and X1.0+



p_f indicates the **threshold probability** for genereting the binary categorical classification to maximize the H&KSS.
Any forecast probability over the threshold was considered to be a forecast for an event, and anything less was considered to be a forecast for non-event.

The *FAR = POD* line corresponds to the peformance of the reference forecast method.

Forecasting performance measures

Our flare forecasting method predicts the probability of a flare of a given class rather than a binary, cetegorical forecast.
Therefore, a measure of accuracy for a probabilistic forecast is the mean square error (MSE):

$$A_{for} = MSE(p_f, o) = < (p_f - o)^2 >$$

where p_f is the forecast probability, and o is the observed outcome (o=0 for no event, o=1 for an event). In this case $A_{per} = 0$

Using the climatological event rate as a reference forecast with a corresponding accuracy:

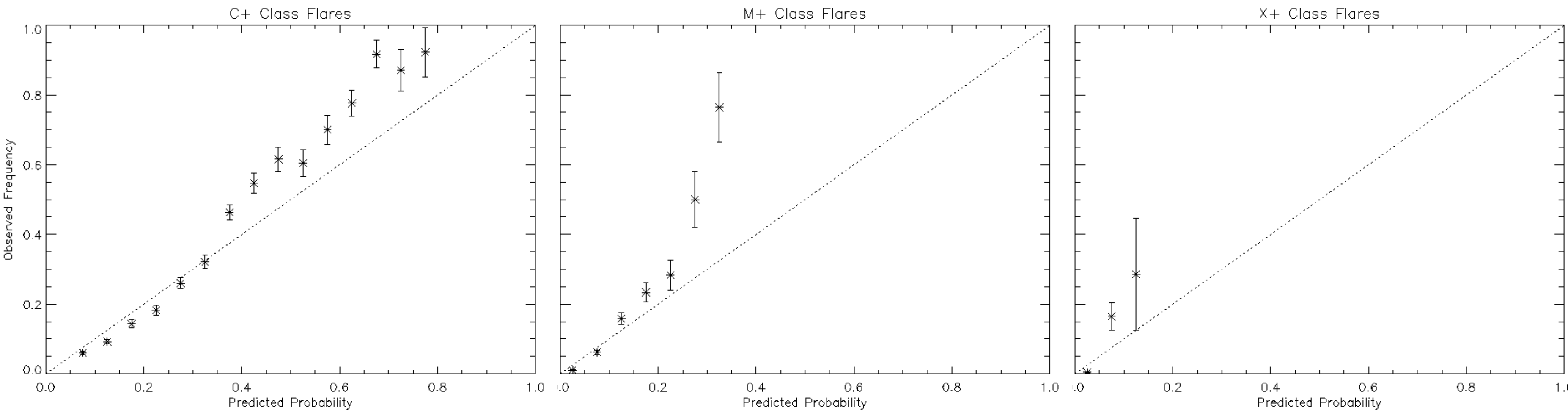
$$A_{ref} = MSE(< o >, o) = < (< o > - o)^2 >$$

We compute the **Barier Skill Score (BSS):**

$$BSS = \frac{MSE(p_f, o) - MSE(< o >, o)}{0 - MSE(< o >, o)}$$

Forecasting performance measures

Reliability plots for C1.0+, M1.0+ and X1.0+



Perfect reliability occurs when all points lie on the *x=y* line.

When points lie under the *x=y* line there is a tendency to over prediction.

When points lie over the *x=y* line there is a tendency to under prediction.

Forecasting performance measures

Parameters	C+ class flares	M+ class flares	X+ class flares
Active region	8598.00	8598.00	8598.00
Active region with flares	1841.00	347	47
$\langle p_f \rangle$	0.214	0.040	0.005
$\langle o \rangle$	0.214	0.040	0.005
Median p_f	0.160	0.020	0.002
σ_{p_f}	0.144	0.049	0.010
σ_o	0.410	0.197	0.074
$\langle p_f \| o = 1 \rangle$	0.337	0.127	0.036
$\langle p_f \| o = 0 \rangle$	0.136	0.037	0.005
Median $p_f \| o = 1$	0.337	0.107	0.035
Median $p_f \| o = 0$	0.136	0.018	0.002
SD $p_f \| o = 1$	0.170	0.085	0.023
SD $p_f \| o = 0$	0.112	0.043	0.009
MAE(p_f, o)	0.281	0.070	0.010
MSE(p_f, o)	0.134	0.034	0.005
Linear association	0.469	0.364	0.232
SS(p_f, o)	0.206	0.119	0.044

Flare class	H&KSS	ApSS	BSS
C 1.0 +	0.45 (0.25)	0.16 (0.40)	0.20
M 1.0 +	0.56 (0.05)	0.04 (0.27)	0.12
X 1.0 +	0.70 (0.01)	-	0.04

Summary

- The solar flare forecasting sevice is available at:
  http://ssa.oact.inaf.it/oact/Flare_forecasting.php.
- Our forecasting method assumes that the flare event frequency follows the Poisson statistics.
- We predict the probability that a flare occurs in a sunspot group distinguishing three different energy ranges: C1.0+, M1.0+ and X1.0+.
- We measured the performances of our forecasting method using 3 different Skill Scores.
- Almost all scores shows values corresponding to performance better than the considered reference forecasts.
- The present method seems more accurate at predicting stronger events, which are more important for their Space Weather effects.

Reference:

- Barnes, G., Leka, K. D., Schrijver, C. J., et al., ApJ, 829 (2016) 89;
- Contarino, L., Zuccarello, F., Romano, P., et al., Acta Geophysica, 57 (2009) 52;
- Ternullo, M., Contarino, L., Romano, P., & Zuccarello, F., Astronomische Nachrichten, 327 (2006) 36;
- Zirin, H., The Astrophysics of the Sun, edited by H. Zirin (Cambridge University Press) 1998, 198 pp.