Subsurface flow properties of flaring versus flare-quiet active regions

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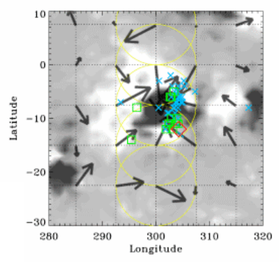
Introduction:

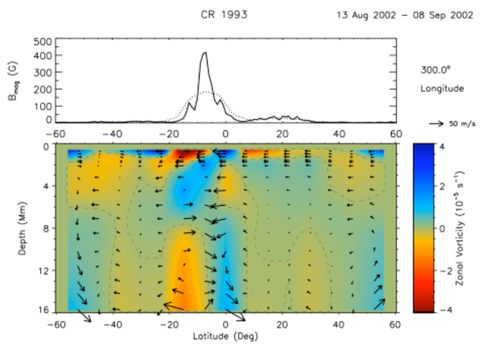
Previous studies have shown that the flare activity of active regions is intrinsically linked with the vorticity of subsurface flows on temporal and spatial scales comparable to the size and lifetime of active regions. We begin to address the question whether the measured vorticity of subsurface flows associated with active regions can help to improve flare forecasting. For this purpose, we apply statistical tests based on discriminant analysis to several subsurface flow parameters with the goal to differentiate between flaring and non-flaring active regions.

Data Collection:

We use a ring-diagram analysis of Global Oscillation Network Group (GONG+) data to derive synoptic maps of vorticity and kinetic helicity density measurements at 16 different depths, ranging from 0.6 Mm to 16 Mm. The GOES satellite provides flare intensity data, including class, intensity, and location. NSO Kitt Peak synoptic charts give magnetic information.

Right: Ring-Diagram technique example for AR 10069. Yellow circles show dense pack regions, black arrows show horizontal flow vectors at 7 Mm, colored symbols show C, M, and X class flare activity, and the background shows magnetic flux.





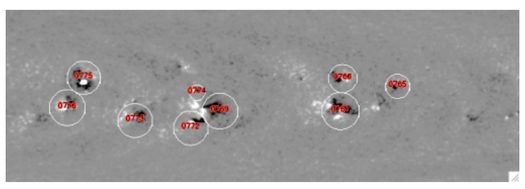
Left-Top: Magnetic field strength as a function of latitude.

Left-Bottom: Zonal vorticity as a function of latitude and depth.

Active Region Statistics:

As in Mason et al. (2006) active regions (AR's) are identified in magnetograms using the NOAA active region numbers. Circular masks are then drawn on the magnetic synoptic maps to fully enclose each AR and calculate the associated radius of the mask, flux, vorticity, and helicity. We also derive a so-called structure component of vorticity (ω_s) to quantify the dipolar structure of the zonal and meridional vorticity components of the active regions. Our data consists of Carrington Rotations (CR's) 1979-2022 from (Mason et al.) with an updated set of CR's 2023-2059, giving total of 1009 AR's.

Magnetic synoptic map for Carrington Rotation 2030



Summary:

- Potential to improve flare forecast
- Subsurface flow characteristics improve the ability to distinguish between flaring and non-flaring AR's.
- Maximum Flux plus flow characteristics best for C-class flares
- Total Flux plus flow characteristics best for M-class flares
- X-class flares important, but too infrequent for reliable results
- The structure vorticity (at 11 Mm) is among the 5 best performing parameters.
- Future work: Look at subsurface flows on shorter timescales, as active regions evolve

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References:

Leka, K.D. and Barnes, G. 2007 ApJ, 656, 1173

Mason, D., Komm, R., Hill, F., Howe, R., Haber, D., and Hindman, B.W. 2006 ApJ, 645, 1543

Discriminant Analysis (DA):

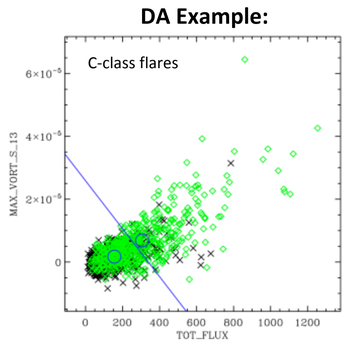
The technique's purpose is to classify a new object as belonging to at least one of two mutually exclusive populations in order to maximize the correct classification rate. It can consider multiple variables simultaneously and help determine which factors are the most important (Leka and Barnes, 2007).

Our two populations are Active Regions that either produce or don't produce a flare during their disk passage.

Variables included (both total and maximum, except for radius):

Overall:	Flux, Radius of the mask
Depth-Dependent:	Vorticity-x, Vorticity-y, Vorticity-z, Structure Vorticity, Enstrophy, Helicity, Helicity-z

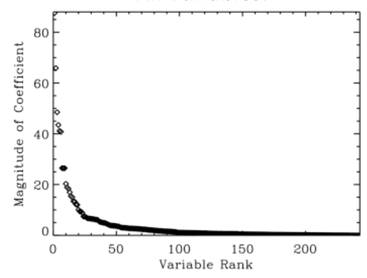
DA Example:



Left: Example plot using two variables. Diamonds are flaring regions, X's are non-flaring regions. AR's above the line are predicted to flare, AR's below are not.

Right: Relative strength of each individual variable when running DA using all 243 variables for C-class flares. Only a very few rise above the rest.

All Variables:



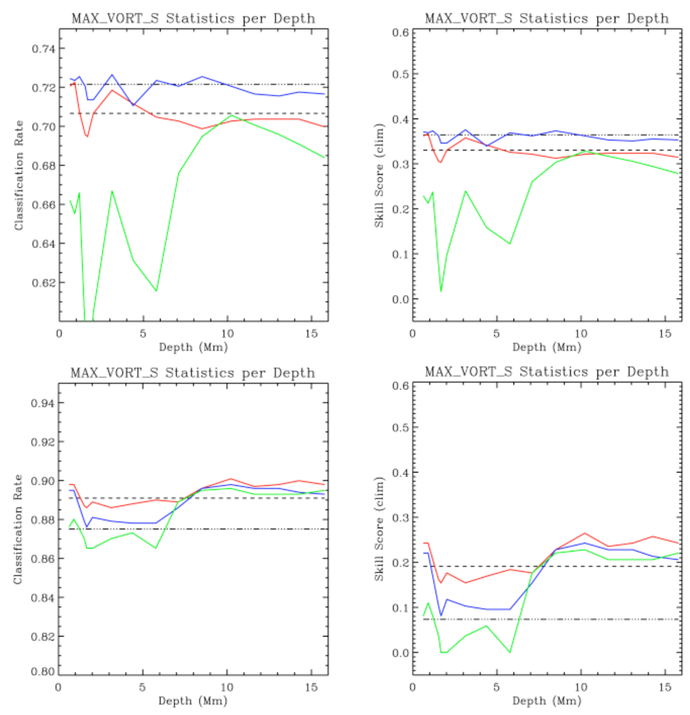
Depth Analysis:

We examine how well vorticity and helicity combined with maximum flux and total flux perform at different depths, to see where the greatest improvement occurs. For C-class flares, combining vorticity and helicity with maximum flux works best, while for M-class flares, combining them with total flux works best. In M-class flares, the improvement from including flow measurements is clear at depths greater than 8 Mm. For C-class flares the results are less apparent.

Classification Rate:
Percentage of correct flaring or non-flaring predictions.

Heidke Skill Score (climatology):
Measures improvement over a null-forecast.

Classification Rate: **Skill Score:**



C-Class Flares

M-Class Flares

DA Results:

The following tables show the results of various runs with DA, in order to determine how successful vorticity and helicity are separating flaring and non-flaring AR's.

Combinations:

(depth plots) – Flux and mask radius plus the combination of the best individual depth from each depth dependent variable (see above plots).

(all variables) – Best depths determined from 15 variable coefficients of DA run using all variables

with flux – Best depths calculated while including flux (red and blue lines in the depth plots)

All Variables – Using a large number of (correlated) variables is a bad idea

C-Class Flares

Combination	Classification Rate (%)	Heidke Skill Score (climatology)
Best Depths with Max Flux (depth plots)	75.1239	0.432127
Best Depths with Total Flux (depth plots)	74.4301	0.416290
Best Depths (depth plots)	73.9346	0.404977
Max Flux	72.1506	0.364253
Best Depths (all variables)	71.3578	0.346154
Total Flux	70.6640	0.330317
All Variables	67.6908	0.262443
Null-Hypothesis	56.1943	0.000000

M-Class Flares

Combination	Classification Rate (%)	Heidke Skill Score (climatology)
Best Depths with Total Flux (depth plots)	90.1883	0.272059
Best Depths (depth plots)	90.2874	0.279412
Best Depths with Max Flux (depth plots)	89.8910	0.250000
Total Flux	89.0981	0.191176
Best Depths (all variables)	88.2061	0.125000
Max Flux	87.5124	0.0735294
Null-Hypothesis	86.5213	0.000000
All Variables	85.1338	-0.102941