Characterization of Subsurface Flow Dynamics for Forecasting of Solar Activity

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Evolution of large-scale magnetic field structures in the solar photosphere and corona is controlled by motions beneath the visible surface of the Sun. Subsurface plasma flows play a critical role in formation and evolution of active regions and their activity. We analyze subsurface flow maps provided by the local helioseismology pipeline from the Helioseismic and Magnetic Imager (HMI) data on board the Solar Dynamics Observatory, and investigate links between flow characteristics and magnetic activity. The primary goal is to determine flow descriptors, which can improve solar activity forecasts. In particular, by employing machine learning classifiers, we test how the flow helicity and velocity shear descriptors can improve the prediction of anation of flares and CME eruptions.

Motivation

The primary goal of our study is to improve characterization and physical understanding of the prediction of solar transient events by utilizing data and physical descriptors from Magnetographs and Subsurface Flow Maps obtained by local helioseismology.

The processes, by which the magnetic energy is stored, entering, and leaving of solar active regions, are critically linked to the flow patterns in active regions. Large-scale organized flows develop spontaneously in subsurface layers due magnetic flux emergence and its interaction with the existing magnetic field of active regions. This process forms stressed magnetic configurations that trigger solar eruptions.

Subsurface Flow Dynamics During Emergence and Evolution of Active Regions

We used the GONG/HMI time-distance helioseismology pipeline (http://sun.stanford.edu) to derive 3D subsurface flow maps during the emergence and evolution of Active Regions. The travel times are used for reconstruction of subsurface flows in 8 subsurface layers in the depth ranges: 0-1, 1-3, 3-5, 5-10, 10-13, 13-17, and 17-23 Mm, and with the horizontal spatial sampling of 0.12 degrees (1.5 Mm).

The horizontal flows for AR12675 in the depth range of 1-2 Mm are shown by arrows. The background color images are the corresponding photospheric magnetograms.

Time-distance pipeline data flow chart

Measurements of Subsurface Flows by Time-Distance Helioseismology

• The computational pipeline for studying the subsurface dynamics of active regions takes the Carrington coordinates of active regions from the Solar Region Summary (SRS) database, compiled by the NASA Space Weather Prediction Center (SWPC), and uses these coordinates as the central points of degree areas tracked for 10 days during their passage on the solar disk.
• This setup allows us to follow the evolution of active region areas even before the magnetic flux emergence and after the decay. The 3D subsurface flow maps are calculated from the tracked Dopplergrams that are remapped onto the heliographic coordinates using the Poisson’s projection (transverse cylindrical projection that preserves the distance along great circles).
• Each tracked, 6-hour long, database consists of 640 Dopplergrams of pixels with the spatial resolution of 0.06 degree/pixel, and 45-sec time cadence. The tracked databases are processed through the Time-Distance Helioseismology Pipeline (Zhao et al., 2012), and the output represents acoustic travel-time maps calculated with 0.12-deg sampling for the whole tracked areas (pixels).

Measurements of Acoustic Travel Times

The travel times are calculated by two different methods: 1) the Gabor wavelet fitting (Kosovichev and Duvall, 1997) and 2) a cross-correlation with a reference (Usoskin & Birch, 2002).

Travel Time Inversion

The travel times are used to infer the 3D maps of subsurface flows by solving an inverse problem. It is formulated as the set of linear integral equations whose kernels are calculated by using the ray-path theory and the first Born approximation.

The flow maps reveal strong (v>1 km/s) shearing flows beneath the active region, and, in particular, in the area of the Polarity Inversion Line (PIL), which was the source of several flares including the X9.3 flare of Sept. 6, 2017.

Correlation of Flow Characteristics with Flare Productivity

We define the flare productivity of the active region as $F = \frac{N_F}{t} + \frac{N_X}{t} + \frac{100}{N_{reg}}$, where $N_F$, $N_X$, and $N_{reg}$ are the total number of C-class, M-class, and X-class GOES flares happened in the AR within 24 or 48 hours from the considered moment. The flare productivity is used for correlation analysis with the AR magnetic and flow descriptors.

We analyze correlations of the derived descriptors with the flare productivity of the parent active region within the next 24-hour window. In addition to classically-used Pearson’s correlation coefficients which check for linear dependence between the set of pairs of parameters, we plan to analyze non-parametric Kendall’s tau-correlation coefficient defined as

$$\tau = \frac{1}{\sqrt{n}n} \sum (x_i - \bar{x})(y_i - \bar{y})$$

where the $x_i$ and $y_i$ are the values of the considered pair of parameter, sgn is a sign operator; $n$ is the number of data points. Kendall’s tau ranges between -1 and 1, and its value is expected to be 0 for independent data sets.

Summary

Heliocentric flow maps reveal links between subsurface flows and formation of the sheared magnetic structure with long Rayleigh Inversion (RI) which became a source of substantial flaring activity. In particular, the helioseismic data reveal correlation of increased flow convergence with flare productivity of active regions. We plan to incorporate the flow descriptors in the machine-learning flare prediction tools.