Investigating the Efficacy of Topologically Derived Time Series for Flare Forecasting.

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Motivation: The accurate forecasting of solar flares is considered a key goal within the solar physics and space weather communities. There is significant potential for flare prediction to be improved by incorporating topological fluxes of magnetogram data sets, without the need to invoke three-dimensional magnetic field extrapolations. Topological quantities such as magnetic helicity and magnetic winding have shown significant potential toward this aim and provide spatiotemporal information about the complexity of active region magnetic fields.

Aim: To develop publicly-available time series that are derived from the spatial fluxes of magnetic helicity and magnetic winding that show significant potential for solar flare prediction.

Introduction: A recent international collaboration performed a systematic comparison of existing flare forecast methods (as well as developing the statistical and methodological tools for this comparison; Leka et al. 2019). These methods are based on analyzing photospheric magnetograms, which provide information on the structure of the Sun's magnetic field as it passes from the interior into the solar atmosphere. The efficacy of the results is briefly summarized by the following text from Leka et al. (2019):

"*Regarding the results, generally speaking, no method works extraordinarily well; but we demonstrate that a fair number of methods consistently perform better than various no-skill measures, meaning that they do show definitive skill across more than one metric.*"

In short, what these studies reveal is that while significant progress has been made, there is still room for improvement.

Active Region Topology Code: Or ARTop (Alielden et al.2023), is an open-source tool for studying the input of topological quantities into solar active regions at the photospheric level. ARTop utilizes vector magnetograms from the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory in the form of Space-Weather HMI Active Region Patches (SHARP) to create maps, time series, and other metrics derived from input rates of magnetic helicity and magnetic winding fluxes (see Prior & MacTaggart 2020).

The flux of magnetic helicity has long been considered an important quantity in the study of active regions and solar flares (Pevtsov et al. 2003; Liu et al. 2023), the winding is a relativity novel quantity, which has been shown to have additional predictive efficacy (Prior & MacTaggart 2020; Aslam et al. 2024).

Our publication (Williams et al., 2025) presents 144 SHARP regions that have been analysed alongside 3 example regions in which we delve into more detail. However, this poster only focuses upon a sampled result from the three example regions.

Results: In Fig. 1 we present $\delta L'_c$ time series data for three example regions over a 72-hour period. In all three examples, we have highlighted several spikes (where the $\delta L'_c$ signal (blue) exceed a 2σ running mean envelope (grey)) in magenta that are not followed by flares (dashed vertical lines). The corresponding (shaded grey) periods in Fig. 2 reveal that these spikes in $\delta L'_c$ - highlighted in magenta - correspond to periods where the accumulated magnetic winding (blue) and helicity (orange) have not built up a sufficient reservoir of topology for new incoming flux at the photospheric level to disrupt and cause a potential magnetic reconnection event. During later periods of Fig. 1, it is shown that spikes in $\delta L'_c$ typically precede flaring with an almost one-to-one correspondence. This may be attributed to the fact that sufficient complex magnetic topology has since been inputted through the photosphere, which newly emerging structures can disrupt.

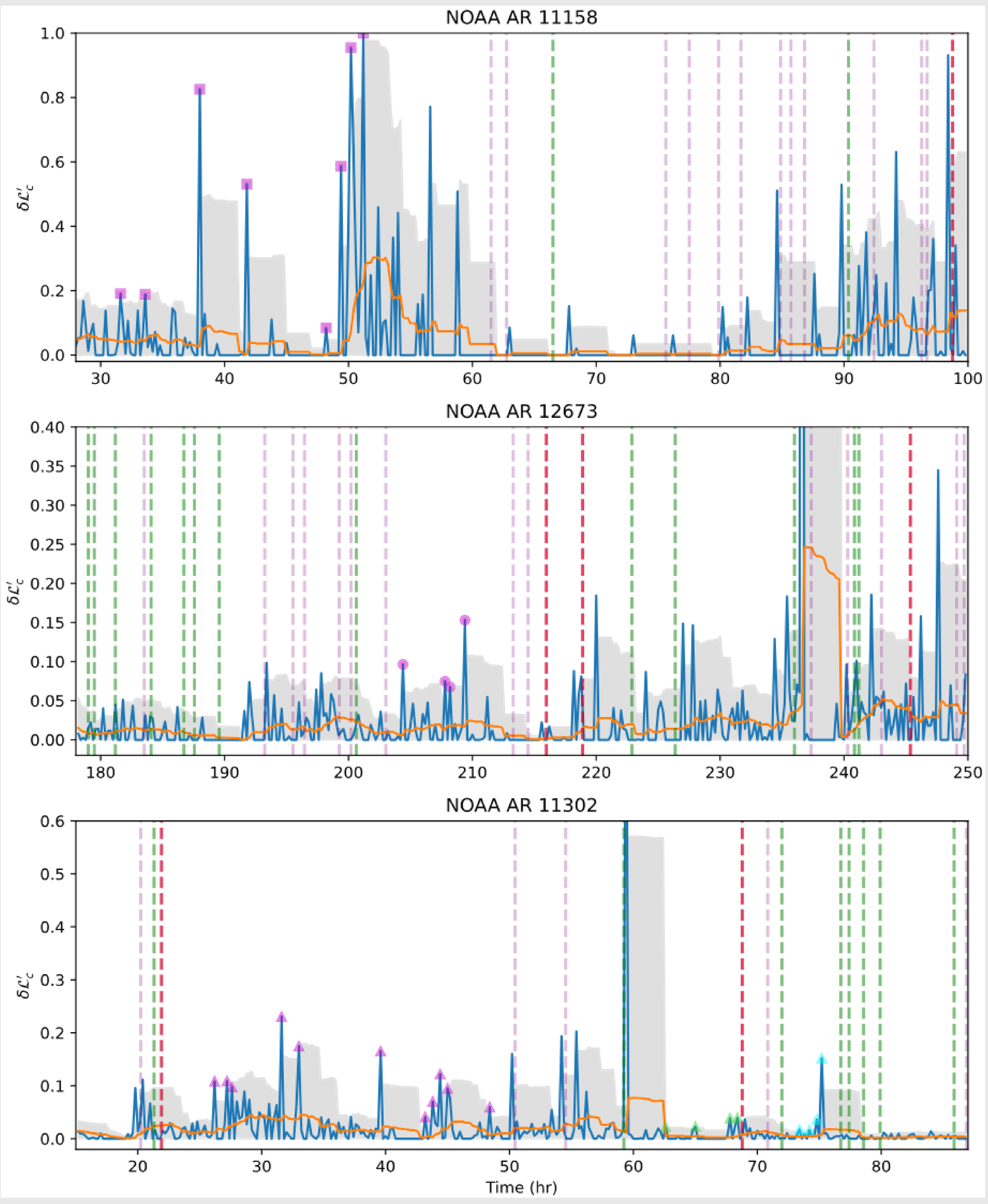

Fig. 1: Time-series plots for $\delta L'_c$ (blue) with a running mean of 3 hr (orange) and 2σ envelope (grey) for three SHARP regions preceding M- (dashed green) and X-class (dashed red) solar flares. For context, C-class flares are also shown (dashed pink). Each plot is normalized with respect to the maximum spike in the time series.

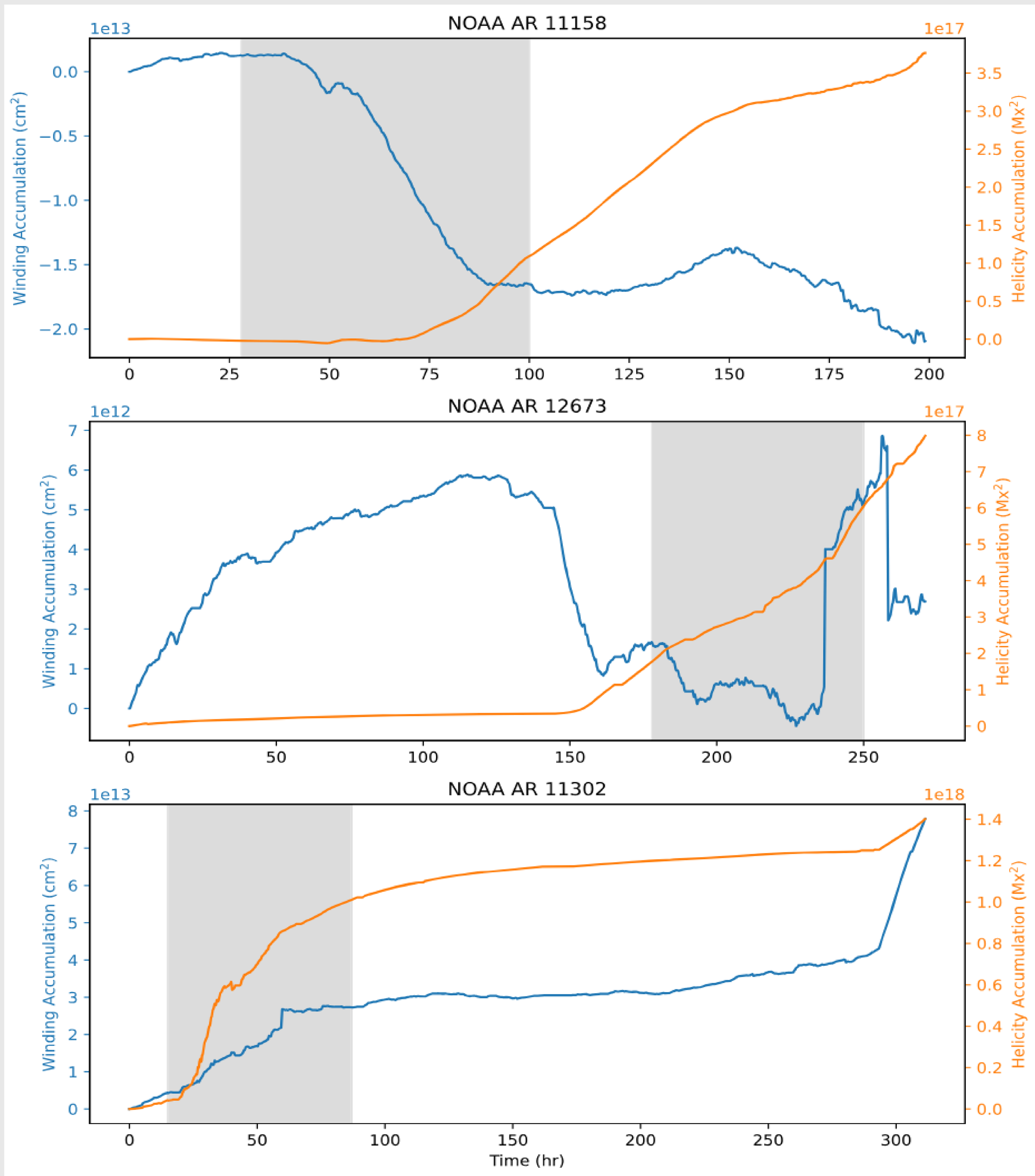

Fig. 2: The time-integrated quantities $\delta L'$ (blue) and $\delta H'$ (orange) calculated for active regions AR 11158, 11302, and 12673. The shaded gray regions indicate the 72hr observation windows shown in Fig. 1 for each region.

Quantity	X_s			N_s	X_f			N_f
	3 hr	6 hr	12 hr		3 hr	6 hr	12 hr	
$\delta\mathcal{L}'_c$	0.470	0.566	0.697	236	0.556	0.756	0.848	190
$\delta\mathcal{H}'_c$	0.380	0.502	0.653	166	0.371	0.549	0.737	190
$v_z\,\delta\mathcal{L}'_c$	0.383	0.494	0.652	163	0.383	0.608	0.790	190
$v_z\,\delta\mathcal{H}'_c$	0.356	0.518	0.648	156	0.349	0.574	0.749	190
$v_z\,\lvert B_z\rvert$	0.402	0.512	0.608	113	0.291	0.537	0.735	190
$\mathrm{Kurt}\,(\delta\mathcal{L}'_c)$	0.428	0.551	0.644	291	0.474	0.702	0.803	190
$\mathrm{Kurt}\,(\delta\mathcal{H}'_c)$	0.359	0.512	0.646	261	0.423	0.688	0.854	190
$\mathrm{Kurt}\,(v_z\,\delta\mathcal{L}'_c)$	0.470	0.600	0.669	265	0.401	0.721	0.842	190
$\mathrm{Kurt}\,(v_z\,\delta\mathcal{H}'_c)$	0.399	0.539	0.616	289	0.477	0.681	0.850	190
$\mathrm{Kurt}\,(v_z\,\lvert B_z\rvert)$	0.452	0.546	0.668	269	0.433	0.677	0.835	190

Table 1: Percentage of spikes preceding flares, X_s, and flares with spikes preceding them, X_f, across the three example regions. Values are shown for time-scales of 3, 6, and 12 hours, respectively. N_s and N_f are the total number of spikes and flares across all regions.

In Table 1 we present the relationship between spikes preceding flares (X_s) and flares with spikes preceding them (X_f) for various topological quantities and their kurtoses, for search-window timescales of 3, 6, and 12 hours, respectively. What is clear here is that i) $\delta L'_c$ is the quantity that shows greatest efficacy as a precursor to flaring and ii) whilst every spike seen is not always followed by a flare, up to 85% of flares are preceded by a spike in $\delta L'_c$ within a 12-hour period. This indicates that when sufficient complex topology has been inputted to the solar atmosphere (i.e., large accumulation of magnetic helicity), spikes in $\delta L'_c$ become meaningful and provide a potential early-warning that flaring may occur in the hours that follow.

Summary: Constructing time series composed of only the current-carrying-dominant parts of the δL and δH fluxes produced time series whose extremal values, spikes (those outside of two standard deviations from the running mean over a suitable window) show significant temporal correlation with the timing of flares. When these signals are only classified as meaningful if a significant amount of net current-carrying helicity δH has been accumulated in the region, this correlation improves significantly.

Across the parameter scans for the metrics investigated in this work, it seems that $\delta L'_c$ is the topological quantity with the greatest potential for forecasting flaring events on its own (based on spiking activity of the quantities examined during this study).

Full details and links to the complete topological dataset can be found in our publication: **Williams et al. (2025), ApJ, 980, 102**.

References: Alielden+ 2023, *RASTI*, **2**, 398; Aslam+ 2024, *MNRAS*, **534**, 444; Leka+ 2019, *ApJS*, **243**, 36; Liu+ 2023, *ApJ*, **942**,27; Pevtsov+ 2003, *ApJ*, **593**, 1217; Prior & MacTaggart 2020, *RSPSA*, **476**, 20200483.