

Schumann Resonance Frequency Increase Following Recurrent Solar Wind Stream Onsets

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Key Points

- Threshold-defined solar-wind stream proxy onsets are followed by a repeatable increase in first-mode Schumann resonance frequency.
- The first-mode frequency increase appears at three high-latitude stations and is largest at the highest-latitude polar site.
- First-mode frequency-response magnitude tracks geomagnetic disturbance more clearly than solar-wind speed alone.

Abstract

Recurrent high-speed streams and corotating interaction regions (HSS/CIRs) are common solar-wind drivers, but their influence on Schumann resonance (SR) frequencies remains poorly quantified. We analyzed 173 threshold-defined HSS/CIR proxy onsets using superposed epoch composites, bootstrap uncertainty, and a month-matched random-epoch null model. At the polar Hornsund station (corrected geomagnetic latitude 74.16°N), the apparent first-mode SR frequency exhibits a positive response on days 0 to +1 relative to onset and is unlikely under the month-matched random-epoch null. A similar positive response appears at the high-latitude Ivalo (65.14°N) and Rovaniemi (63.69°N) stations, with the same ordering under matched-support restriction. Event-level scaling with baseline-relative K_p , AE, and V_{sw} impulses shows the clearest organization by K_p , consistent support from AE, and a positive but less diagnostic relation with V_{sw} . The K_p /AE organization strengthened after excluding ICME-overlap events. Overall, HSS/CIR proxy onsets are followed by a small but repeatable first-mode SR response that is statistically supported, reproducible across high-latitude stations, and organized more clearly by geomagnetic coupling than by solar-wind speed alone.

Plain Language Summary

High-speed solar wind streams return every few weeks as the Sun rotates and often disturb Earth's magnetic environment. We asked whether these recurring space weather events also change the Schumann resonances, the natural electromagnetic waves trapped between Earth's surface and the lower ionosphere. Using 173 event onsets identified from daily solar wind speed data, we found a small but repeatable increase in the first Schumann resonance frequency at the Polish Polar Station in Hornsund, Svalbard. The same positive response also appears at two other high-latitude stations

in Finland, while the response is largest at Hornsund and smaller at the two Finnish stations. The response varies more clearly with the level of geomagnetic activity than with solar wind speed alone, and that pattern becomes stronger when events overlapping interplanetary coronal mass ejections (ICMEs) are removed. This pattern is consistent with recurrent solar-wind forcing acting through geospace coupling and changes in lower-ionospheric conductivity or effective boundary height that modify the Earth-ionosphere waveguide, rather than through solar-wind speed alone.

1. Introduction

Schumann resonances (SR) arise from global lightning excitation of the Earth-ionosphere cavity and provide continuous information on both excitation-source distribution and the state of the lower ionospheric boundary. Because the cavity boundary is dissipative rather than perfectly conducting, modal frequency, damping or Q-factor, and intensity are distinct observables and should not be interpreted interchangeably. The first-mode frequency (F1) is especially useful as a cavity diagnostic because it is less directly tied to source strength than intensity. However, measured peak frequencies are apparent quantities: they can respond to changes in the effective lower-ionospheric cavity boundary, such as conductivity or effective-height changes, which modify Earth-ionosphere waveguide properties. They can also depend on source-observer geometry and path-dependent propagation effects, including source-to-station path sensitivity and local waveguide or surface-condition differences (Jones, 1969; Sentman and Fraser, 1991; Satori, 1996; Williams and Satori, 2007; Bozoki et al., 2021; Satori et al., 2024).

Solar and geospace disturbances can perturb SR parameters, but the existing evidence is concentrated in intense events, individual stations, or solar-cycle-scale variability. Solar X-ray bursts can increase F1, whereas solar proton events can decrease it, consistent with different ionization depths in the lower ionosphere (Roldugin et al., 2001, 2004; Singh et al., 2014; Satori et al., 2016; Zhou and Qiao, 2015). High-energy particle precipitation and relativistic electrons have also been linked to SR frequency or damping changes and to magnetosphere-atmosphere coupling (Schlegel and Füllekrug, 1999; Baker et al., 1990), while geomagnetic-storm, CME, and solar-cycle studies report station-scale or long-term SR changes (Gonzalez-Esparza et al., 2024; Salinas et al., 2016; Pazos et al., 2019; Bozoki et al., 2021). This motivates a population test of a common recurrent driver: high-speed streams and corotating interaction regions (HSS/CIRs).

HSS/CIRs are well suited to this test because they recur over solar rotations, are common during declining solar-cycle phases, and can be geoeffective without extreme solar-wind speed. An onset-centered composite can therefore test repeated driver forcing rather than persistent cavity memory from a single event. HSS/CIRs regularly enhance AE and related geomagnetic activity, with geoeffectiveness controlled by stream properties and coupling conditions (Grandin et al., 2019; Verbanac et al., 2011), and HSS-driven storms can enhance tens-of-keV electron precipitation over broad local-time sectors (Meredith et al., 2011; Asikainen and Ruopsa, 2016; Laitinen et al., 2024). The interpretation remains indirect: solar-wind plasma does not simply penetrate to the D region, but energetic particle precipitation is associated with D-region absorption by 10-100 keV electrons near 60-90 km, and relativistic precipitation can produce bremsstrahlung reaching deeper layers (Kilpua et al., 2026; Nesse et al., 2026). These processes are consistent with SR sensitivity to high-energy precipitation and to the effective ionospheric boundary (Schlegel and Füllekrug, 1999; Mushtak and Williams, 2002; Williams and Satori, 2007; Satori et al., 2016). We therefore separate

HSS/CIR forcing from ICMEs, which are distinct heliospheric structures and are treated separately from stream-interaction regions in modern catalogs (von Steiger and Richardson, 2006; Nguyen et al., 2025b).

Because recurrent solar-wind forcing, geomagnetic indices, and SR time series are autocorrelated, conventional tests can overstate lag structures when the null model ignores autocorrelation (Edvartsen et al., 2022). We therefore combine explicit event-validity rules with non-event timing null models and targeted sensitivity checks.

This study addresses three questions. First, is threshold-defined HSS/CIR proxy onset followed by a reproducible F1 response? Second, does that response persist across multiple stations? Third, is the event-to-event magnitude of the frequency change ($\Delta F1$) organized by baseline-relative onset impulses in Kp, AE, and solar wind speed? This matters for ionosphere/waveguide physics because it tests whether SR observations contain a small but repeatable, statistically supported response consistent with recurrent geospace influence on the effective lower-ionospheric boundary and the associated Earth-ionosphere waveguide response, extending earlier case studies to an event-population result.

2. Data and Methods

The analysis used daily solar-wind speed (V_{sw}), and the geomagnetic activity indices AE, and Kp on a common UTC grid. We identified 173 threshold-defined HSS/CIR proxy onsets between 3 November 2005 and 18 June 2024, with the date range set by the availability of SR measurements. We use the term HSS/CIR proxy because the event list captures HSS/CIR-type solar-wind arrivals from daily V_{sw} -based criteria, but it is not a formal solar-wind structure catalog. Candidate onsets were selected from a 3-day moving median of V_{sw} . An onset was accepted when the smoothed V_{sw} was at least 500 km/s, the increase relative to two days earlier was at least 80 km/s, and the candidate was separated by at least 20 days from any previously accepted onset. Kp and AE were not used to define the events; they were used only as measures of the realized geomagnetic response to the solar-wind forcing.

Schumann resonance data were obtained from three high-latitude stations: Hornsund, Svalbard (HRN, geographic: 77°N, 15.60°E; corrected geomagnetic latitude 74.16°N), Ivalo, Finland (IVA, geographic: 68.55°N, 27.28°E; corrected geomagnetic latitude: 65.14°N), and Rovaniemi, Finland (ROV, geographic: 66.78°N, 25.94°E; corrected geomagnetic latitude: 63.69°N). At HRN, first-mode frequency (F1), first-mode Q-factor (Q1), and first-mode intensity (I1), were obtained from spectral decomposition using 4-parameter Lorentzian fitting (Bozóki et al., 2023; Dyrda et al., 2014; Kulak et al., 2006). The Lorentz-fit products are shown in Figure 2. For the three-station comparison in Figure 3, F1 was estimated with the weighted-average first-mode frequency method at HRN, IVA, and ROV (Bozóki et al., 2021; Nickolaenko et al., 2015). This estimator difference is necessary because the Finnish station records are narrowband: although sampled at 40 Hz, their 3-dB cutoff is near 10 Hz, which limits reliable Lorentz-fit estimation of resonance peaks and widths. The HRN overlap between Lorentz-fit and the weighted-average method allows us to evaluate how the two spectral estimators affect the inferred onset response. The weighted-average F1 estimator is described in Text S1. Briefly, it is a power-spectral-density-weighted apparent first-

mode frequency computed over 6.5-9.5 Hz from 12-min Welch spectra (Welch, 1967) and then averaged to daily means before the event analysis.

Daily superposed-epoch analyses were constructed over lags from day -15 to day $+20$ relative to each accepted proxy onset. The analyses were performed for the HRN Lorentz-fit products and for the three-station weighted-average F1 records. For compact figure labels, the north-south and east-west magnetic components are denoted NS and EW, and their component average is denoted AVG. In the text, however, we use component average rather than repeating AVG. At each lag, the component-average response was computed as the mean of the NS and EW superposed-epoch responses. Each Schumann resonance response was baseline-subtracted using the pre-event interval from day -15 to day -5 . The solar-wind and geomagnetic driver curves shown in the superposed-epoch figures were not baseline-subtracted, so that their absolute onset evolution remains visible.

An event was included in a given composite when the full lag window existed on the common daily grid, at least six finite baseline days were available, and at least one response value existed over days 0 and $+1$. The primary response statistic was the onset response, $R_{0:1}$, defined a priori as the mean baseline-subtracted response over days 0 and $+1$. Unless a magnetic component is specified, $R_{0:1}$ refers to the component-average onset response. The compact label D01 is used only in figure captions and panel labels to denote this same day 0 to day $+1$ response window. Composite means were calculated from valid events, and 95% bootstrap percentile intervals were obtained from 5,000 event-resampling replicates. Statistical support was assessed with 5,000 month-matched random-epoch composites drawn from non-event days while applying the same lag window, baseline interval, validity rules, event count, and onset-response statistic as the observed composites. The resulting random-epoch envelopes and global maximum-absolute threshold define the null reference for Figures 2 and 3; AR(1), circular-shift, and matched-support details are given in Text S2.

For event-level scaling, we used the valid common daily-onset subset of the three-station weighted-average dataset. The response variable was event-specific $\Delta F1$, averaged over days 0 and $+1$ after subtracting the days -15 to -5 baseline. Baseline-relative K_p , AE, and Vsw impulses were calculated over the same day 0 to $+1$ window, and ordinary least-squares fits were used only as descriptive onset-phase association tests, not as causal or predictive models. Because K_p , AE, and Vsw have different units and physical meanings, slope magnitudes were not compared directly across drivers. ICME-overlap sensitivity was tested using the Nguyen et al. (2025a) catalog with ± 1 day padding to account for daily timing uncertainty; full-sample and ICME-excluded Pearson, Spearman, Benjamini-Hochberg-adjusted, and Theil-Sen statistics are reported in Table S1.

3. Results

The main result is a repeatable, event-timed positive F1 response after threshold-defined HSS/CIR proxy onset. Here $R_{0:1}$ refers to the baseline-subtracted mean response over days 0 and $+1$, as defined in Section 2. Unless otherwise stated, $R_{0:1}$ denotes the component-average response, computed from the north-south and east-west magnetic components. We first illustrate the solar-rotation context of the selected events, then test the response statistically at HRN using Lorentz-

fit F1, extend the analysis to three stations using weighted-average F1, and finally compare event-level F1 changes with Kp, AE, and Vsw impulses relative to the pre-event baseline.

Figure 1 provides the rotation-scale context for the event selection. It shows daily HRN F1, solar-wind speed, AE, and Kp from November 2005 to January 2006, covering the first four accepted proxy onsets over about three solar rotations. The figure is not used as a statistical test; rather, it illustrates why an onset-centered composite is appropriate for this class of repeating solar-wind structures.

Figure 2 establishes the HRN result using the Lorentz-fit spectral products. Under the final validity rules, 120 events contributed to the HRN composites. The component-average F1 response rises sharply near onset, with an onset response of $R_{0:1} = 0.0586$ Hz. The component-average onset response corresponds to approximately 0.75% of the local pre-event baseline. The component-specific responses were similar in timing but not identical in magnitude, with $R_{0:1}=0.0619$ Hz for the north-south component and $R_{0:1}=0.0552$ Hz for the east-west component, equivalent to about 0.80% and 0.71%, respectively.

The same HRN Lorentz-fit composite also shows supporting changes in Q1 and I1. The component-average Q1 onset response was $R_{0:1}=0.194$, approximately 4.28% of baseline. The component-average I1 onset response was $R_{0:1} = 0.0465$ pT^2/Hz , or approximately 14.64% of baseline. These quantities are not treated as coequal primary response variables. Q1 provides supporting information on damping or effective cavity losses, whereas I1 is treated as exploratory because intensity mixes source and cavity effects more directly than frequency. Accordingly, the following analyses focus on F1 as the primary response variable, with Q1 and I1 maintained only as secondary HRN Lorentz-fit diagnostics.

Having established the HRN response with Lorentz-fit F1, we next test whether the frequency response is also present in the three-station weighted-average data. Figure 3 shows that the F1 response extends beyond HRN and is organized across stations. Using the same HSS/CIR proxy onset dates at all three stations, the common-forcing composites included 120 valid events at HRN, 157 at IVA, and 165 at ROV. The component-average onset response was $R_{0:1}= 0.0248$ Hz at HRN, 0.0126 Hz at IVA, and 0.00977 Hz at ROV. These increases correspond to approximately 0.317%, 0.163%, and 0.126% of the local pre-event baseline, respectively. Thus, the largest weighted-average F1 response is observed at HRN and the smallest at ROV. Given the station geomagnetic latitudes, this ordering is consistent with stronger coupling into the higher-latitude polar region sampled by HRN, although it is not by itself a formal between-station test.

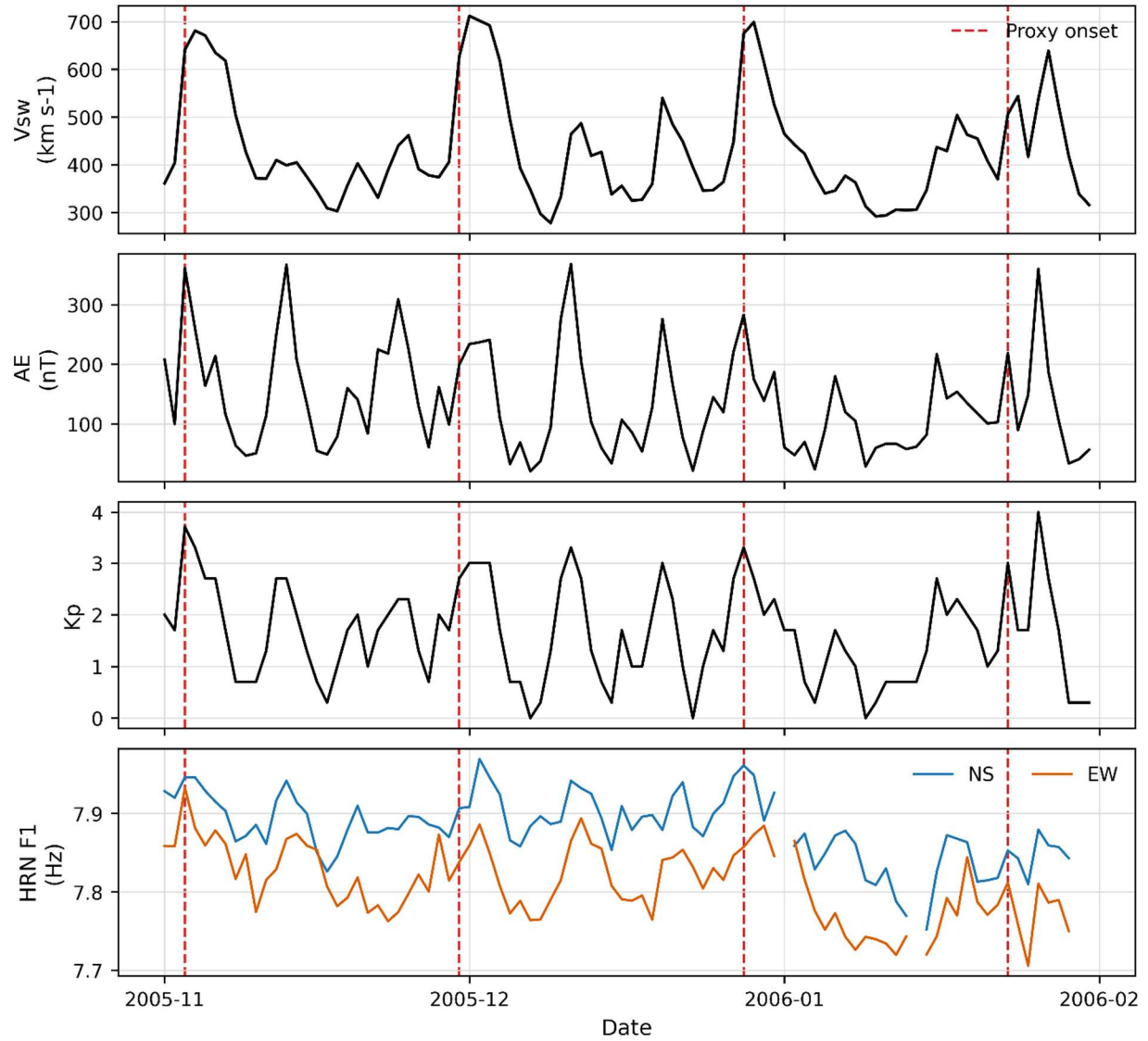


Figure 1. Representative HSS/CIR proxy interval. Panels show daily solar-wind speed, AE, Kp, and HRN Lorentz-fit first-mode Schumann resonance frequency for the north-south and east-west components from November 2005 to January 2006. Red dashed lines mark accepted threshold-defined proxy onsets.

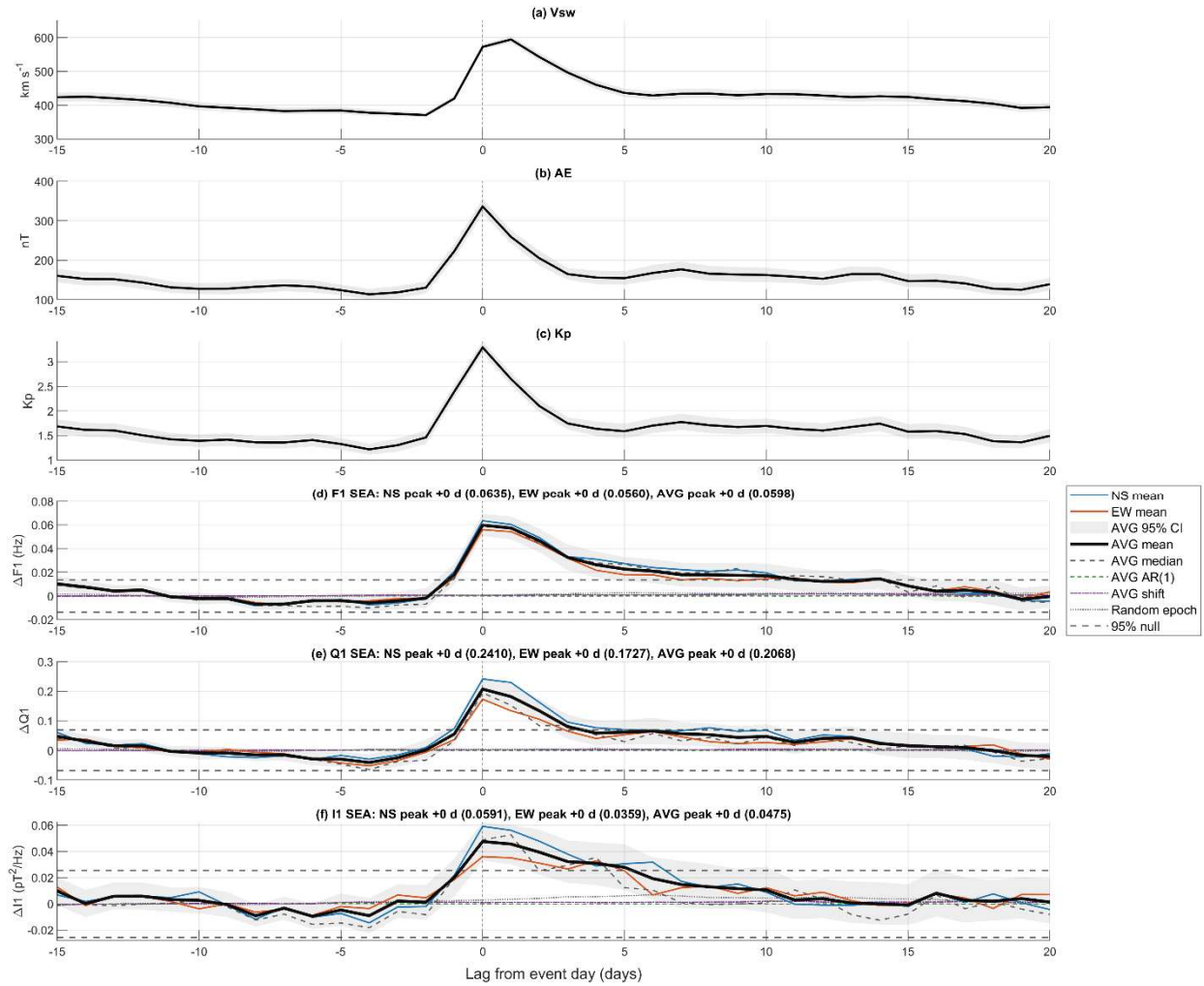


Figure 2. Hornsund (HRN) superposed epoch response to 173 threshold-defined high-speed-stream/corotating-interaction-region (HSS/CIR) proxy onsets. Panels show solar-wind speed (Vsw), auroral electrojet index (AE), planetary K index (Kp), and baseline-subtracted Lorentz-fit first-mode frequency (F1), Q factor (Q1), and intensity (I1) for north-south (NS), east-west (EW), and component-average (AVG) magnetic-field products. Shading gives the AVG 95% bootstrap interval; dashed thresholds mark the two-sided 95% global random-epoch limit. Composites use 120 valid HRN events and days -15 to -5 baselines; $R_{0:1}$ values reported in the text are the mean response over days 0 to +1.

To verify that the station ordering was not caused by unequal data support, we repeated the component-average comparison using only the 106 onsets with valid component-average F1 data at all three stations. This common-event subset preserved the same ordering, with $R_{0:1} = 0.0246$ Hz at HRN, 0.0122 Hz at IVA, and 0.00969 Hz at ROV, equivalent to approximately 0.315%, 0.157%, and 0.125% of baseline, respectively. Supplementary Figure S1 shows the corresponding weighted-average F1 random-epoch null envelopes and global-threshold reference for HRN, IVA, and ROV in the north-south, east-west and component-average products. The station ordering is therefore not produced by unequal component-average data support alone.

Because the Lorentz-fit and weighted-average analyses use different spectral estimators, we compared both F1 products at HRN to test whether the onset-scale behavior was preserved across methods. Supplementary Figure S2 addresses this estimator comparison. On the same 120-event subset valid for both HRN estimators, the weighted-average F1 preserves the positive onset-scale sign of the Lorentz-fit F1 response in the north-south, east-west, and component-average products. The Lorentz-fit component-average response gives $R_{0:1} = 0.0586$ Hz and peaks at day 0, whereas the weighted-average component-average response gives $R_{0:1} = 0.0248$ Hz and peaks at day +1. The same pattern holds in the directional components: Lorentz-fit north-south and east-west responses peak at day 0, whereas weighted-average north-south and east-west responses peak at day +1, but all components remain positive over the onset interval. This comparison supports the use of weighted-average F1 for the multi-station analysis by preserving sign and onset-scale timing, while also showing that the two spectral methods are not magnitude-equivalent.

Figure 4 places the station response in a coupling context. Within this threshold-defined HSS/CIR proxy class, Vsw defines the upstream event class, whereas Kp and AE characterize the realized downstream geomagnetic disturbance. Event-level $\Delta F1$ was positively associated with all three baseline-relative driver impulses, but Kp provided the clearest organization, with full-sample Pearson correlations of $r = 0.318$ - 0.452 across stations and components. AE gave consistent support, while Vsw remained positive but less diagnostic. Expanded statistics, including Benjamini-Hochberg-adjusted q values, Theil-Sen slopes, and ICME-excluded sensitivities, are reported in Table S1. Excluding ICME-overlap events strengthened the Kp/AE organization without changing the basic result, supporting the interpretation that the F1 response is organized more clearly by realized geomagnetic disturbance than by upstream solar-wind speed alone.

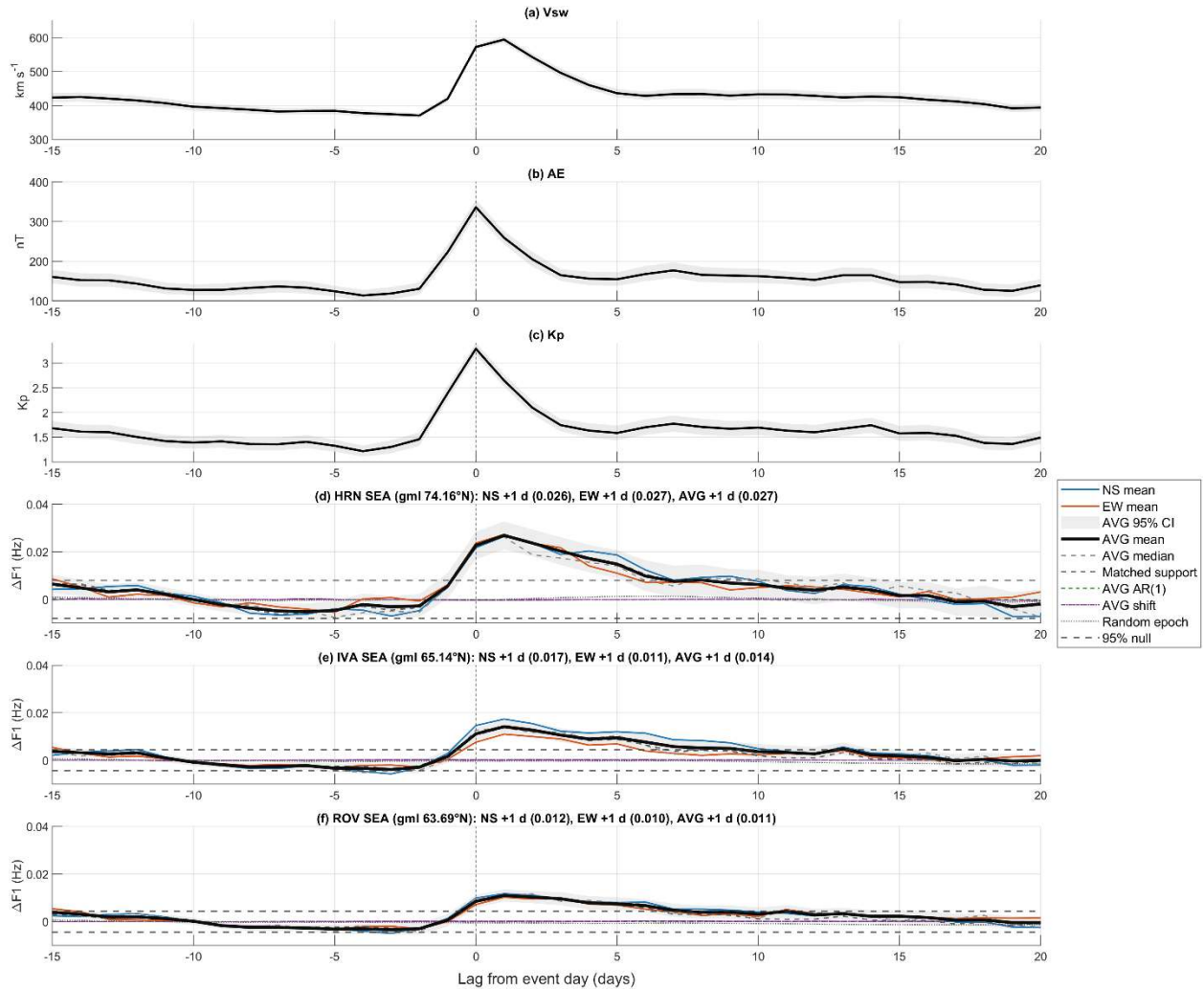


Figure 3. Three-station weighted-average first-mode Schumann resonance frequency (F1) response to the same threshold-defined high-speed-stream/corotating-interaction-region (HSS/CIR) proxy onsets. Panels show solar-wind speed (Vsw), auroral electrojet index (AE), planetary K index (Kp), and baseline-subtracted F1 at Hornsund (HRN), Ivalo (IVA), and Rovaniemi (ROV). Blue and orange curves show north-south (NS) and east-west (EW) magnetic-field components; black curves show the component average (AVG). Shading gives the AVG 95% bootstrap interval; additional curves show control and matched-support composites. Valid-event counts are 120, 157, and 165 for HRN, IVA, and ROV; $R_{0:1}$ values reported in the text are mean responses over days 0 to +1.

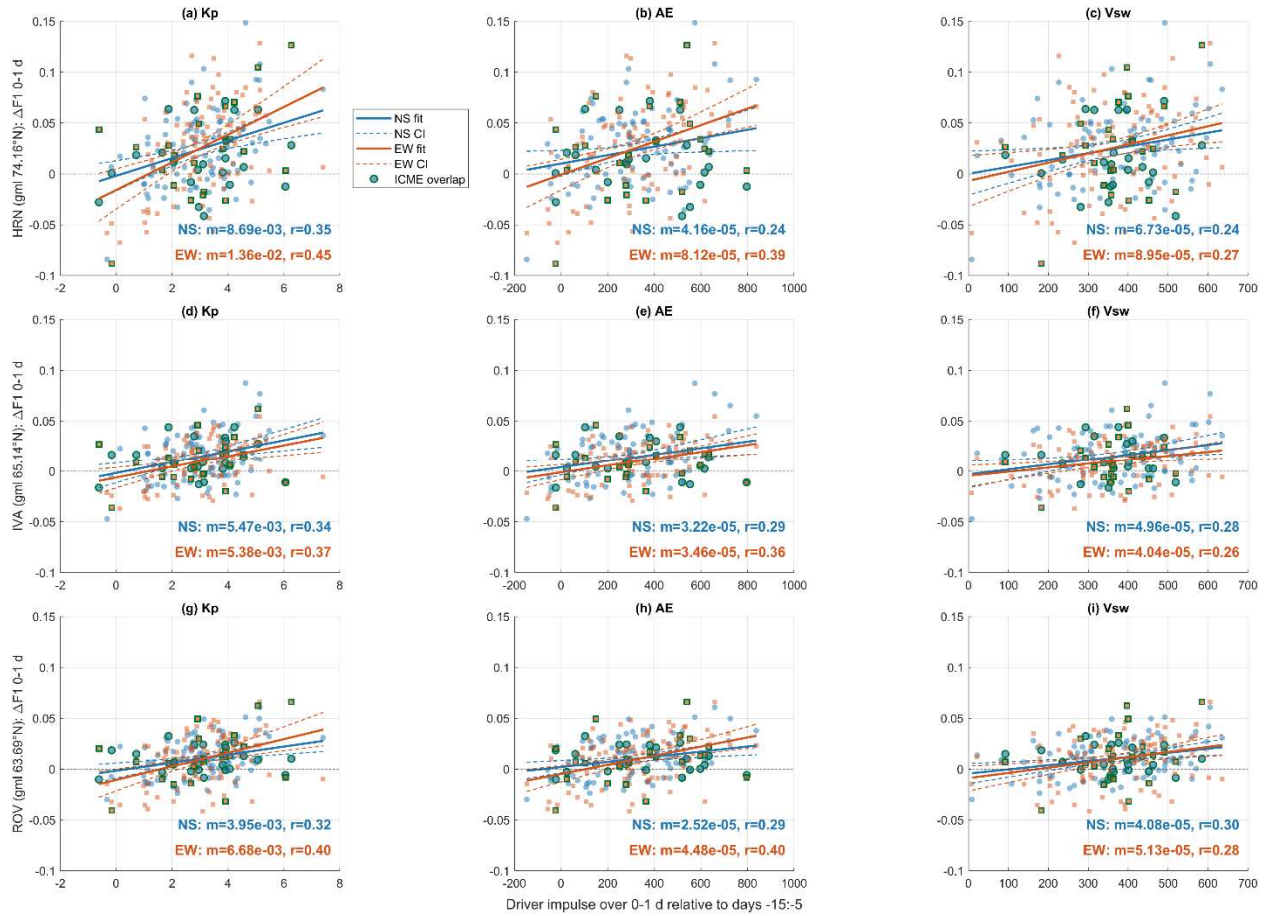


Figure 4. Event-level scaling of weighted-average first-mode frequency change ($\Delta F1$) against geomagnetic and solar-wind driver impulses. Rows show Hornsund (HRN), Ivalo (IVA), and Rovaniemi (ROV); columns show planetary K index (Kp), auroral electrojet index (AE), and solar-wind speed (Vsw) impulses over days 0 to +1 relative to the days -15 to -5 baseline. Blue circles and orange squares show north-south (NS) and east-west (EW) component responses; green outlines mark interplanetary coronal mass ejection (ICME) overlaps. Lines show full-sample ordinary least-squares fits with 95% bootstrap bounds; expanded and ICME-excluded statistics are in Table S1.

4. Discussion

The importance of the F1 result lies in its repeatability, timing, and physical organization, not in the absolute frequency shift alone. The HRN Lorentz-fit component-average onset response, $R_{0.1} = 0.0586$ Hz, corresponds to about 0.75% of the local pre-event baseline. This small fractional change becomes geophysically meaningful because it occurs in the predefined day 0 to +1 onset window, exceeds the global random-epoch threshold near the principal peak, remains larger than the secondary controls around that peak, and appears within a broader three-station pattern organized by geomagnetic coupling.

This interpretation must remain within the apparent-frequency framework. Measured SR peak frequencies are not source-free eigenfrequencies; they can depend on effective Earth-ionosphere waveguide conditions, including lower-ionospheric conductivity or boundary-height changes, and

on source-observer geometry, including the distance, azimuth, and relative weighting of dominant lightning regions (Jones, 1969; Sentman and Fraser, 1991; Williams and Satori, 2007; Bozoki et al., 2021; Nickolaenko et al., 2025a,b). The same-sign onset response across stations and magnetic components supports a reproducible event-timed signal, but station ordering and north-south/east-west differences cannot be interpreted uniquely as a uniform cavity-height change. The component diagnostic confirms this limitation: daily component offsets are present and a detectable differential contribution occurs at IVA, although the onset-timed response is mainly common to both horizontal components after baseline subtraction (Text S3; Table S2). Thus, source geometry may contribute to apparent F1 variability, but it does not by itself explain the HSS/CIR-timed response.

The supporting HRN Lorentz-fit Q1 and I1 changes place the F1 response in context but are not coequal evidence. The Q1 increase is compatible with altered modal damping or effective cavity losses, whereas I1 is harder to interpret because SR intensity mixes source strength, propagation, and cavity effects (Bozoki et al., 2021; Satori et al., 2016). Consistent with the source-receiver caution raised by Pechony and Price (2006), we therefore treat I1 as exploratory and do not use it as direct evidence of lower-ionospheric height change.

Within these limits, the three-station comparison remains important because it shows that the onset-timed F1 response is not confined to HRN. The largest weighted-average response occurs at HRN, with smaller responses at IVA and ROV, and this ordering survives matched-support restriction. This pattern is compatible with stronger high-latitude geospace coupling at the polar station, but it is not diagnostic of a purely latitude-dependent ionospheric effect. The HRN estimator comparison further reduces the possibility that the multi-station result is an artifact of method choice: weighted-average F1 preserves the positive sign and onset-scale timing of Lorentz-fit F1 in both components and their average, but with smaller magnitude and a day +1 rather than day 0 peak (Figure S2). The two estimators therefore support the same qualitative response while remaining non-equivalent in magnitude.

The event-level scaling supports an indirect geospace interpretation. Kp provides the clearest organization of event-level $\Delta F1$, AE gives consistent support, and Vsw remains positive but less diagnostic. This ordering is physically meaningful because Vsw is an upstream speed perturbation, whereas Kp and AE measure the realized downstream geomagnetic disturbance. The strengthening of the Kp/AE organization after excluding ICME-overlap events further suggests that the relation is not produced by ICME contamination. A plausible pathway is therefore HSS/CIR-type forcing that enhances geomagnetic and auroral electrodynamic disturbance, increases energetic particle precipitation and ionization, and modifies lower-ionospheric conductivity or effective Earth-ionosphere waveguide conditions (Baker et al., 1990; Schlegel and Füllekrug, 1999; Meredith et al., 2011; Asikainen and Ruopsa, 2016; Laitinen et al., 2024; Kilpua et al., 2026; Bozoki et al., 2021). This is a magnetosphere-ionosphere pathway, not direct penetration of solar-wind plasma into the D region.

Two timing limitations follow from this interpretation. First, the analysis does not determine whether the response is associated mainly with the CIR compression region, the early HSS interval, or the combined geoeffective interval

around daily-scale arrival. Second, the several-day response duration reflects daily averaging, stream-arrival timing, geomagnetic coupling, and waveguide response time; it should therefore be interpreted as recurrent solar-wind forcing, not as a measurement of solar-source angular width.

The observed frequency shift can still be compared with an order-of-magnitude ionospheric-height scale. Using the Mushtak and Williams (2002) knee-model scaling, with $h_m^* = 96.5 \text{ km}$, $F1 \approx 7.7 - 7.8 \text{ Hz}$, and the HRN Lorentz-fit response $R_{0:1} = 0.0586 \text{ Hz}$, gives an apparent magnetic-characteristic-height decrease of about 1.4-1.5 km. The smaller weighted-average responses at HRN, IVA, and ROV correspond to apparent changes of roughly 0.6, 0.3, and 0.2 km, respectively. These values are physically plausible and of order one kilometer, but they are model-dependent scale estimates, not an inversion of $\Delta F1$ into D-region height.

Finally, we note that the amplitude of the HSS/CIR composite response is smaller than reported for direct solar-flare forcing. Shvets et al. (2017) reported flare-related weighted-average Schumann resonance frequency increases that can reach about 0.1-0.2 Hz for moderate to X-class flares, and Surkov (2025) modelled an X6.9 flare case with an approximately 0.44 Hz increase. The smaller HSS/CIR response is physically reasonable because HSS/CIR forcing develops over days and acts indirectly through geomagnetic coupling in a limited spatial domain, unlike direct dayside X-ray ionization during solar flares.

5. Conclusions

This study supports three main conclusions. First, threshold-defined HSS/CIR proxy onsets are followed by a reproducible positive apparent first-mode Schumann resonance frequency response at HRN. The response occurs within the a priori onset window and is unlikely under the month-matched random-epoch null. Second, the positive response is also present in the three-station weighted-average analysis. It is largest at HRN and smaller at IVA and ROV, with the same ordering under matched-support restriction. Because measured SR peak frequencies are apparent frequencies, this station ordering should be interpreted as spatial organization of the observed response rather than as a unique latitude-dependent ionospheric-height change. Third, event-level scaling shows that the response magnitude is organized most clearly by Kp, consistently by AE, and positively but less diagnostically by Vsw. The Kp/AE organization strengthens after excluding ICME-overlap events. Together, these results show that first-mode SR frequency contains a small but statistically detectable apparent response to recurrent geospace influence on the Earth-ionosphere waveguide, while separation of waveguide changes from source-observer geometry and estimator effects will require future source-geometry modeling and broader station coverage.

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Open Research

Solar wind speed, Kp, and AE data were obtained from the NASA Space Physics Data Facility OMNI database through OMNIWeb (Papitashvili & King, 2020). The ICME-overlap flags used for the noICME sensitivity analysis were derived from the Interplanetary Solar Events Catalogs dataset (Nguyen et al., 2025a). The Hornsund, Ivalo, and Rovaniemi Schumann resonance products, together with the HSS/CIR proxy onset list, are permanently archived in the Finnish Fairdata repository (Raita et al., 2026).

Conflict of Interest Disclosure

The authors declare there are no conflicts of interest for this manuscript.

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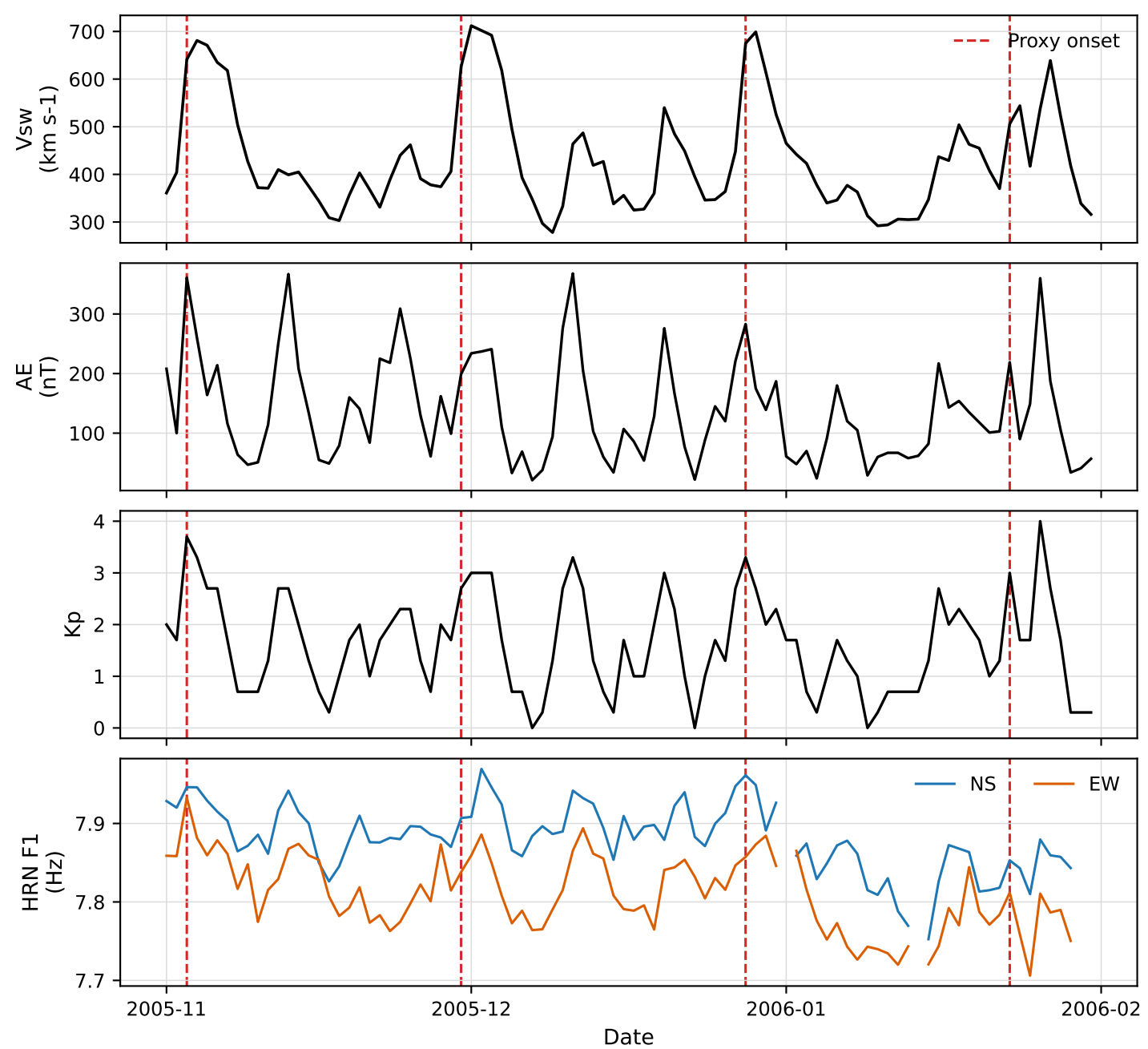
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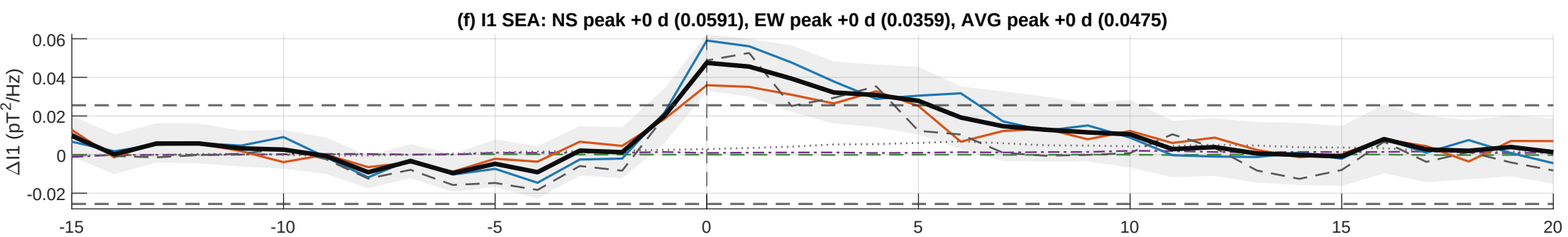
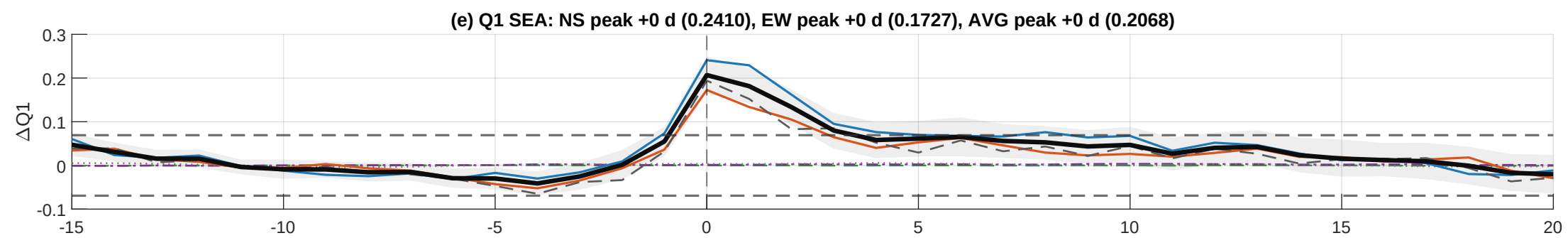
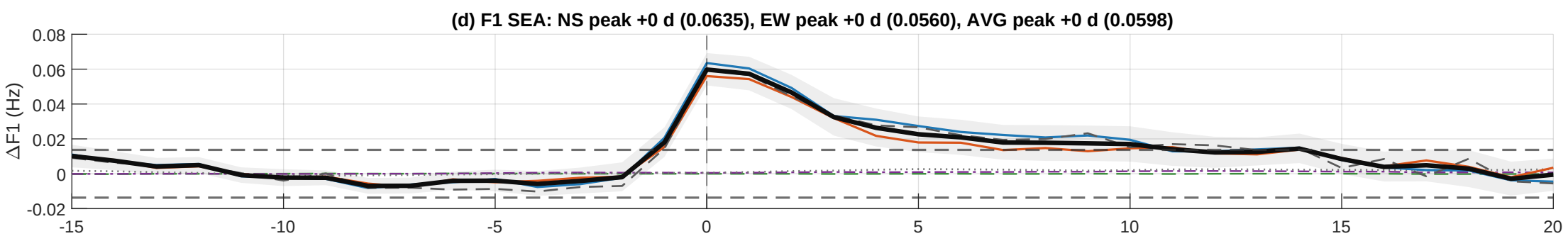
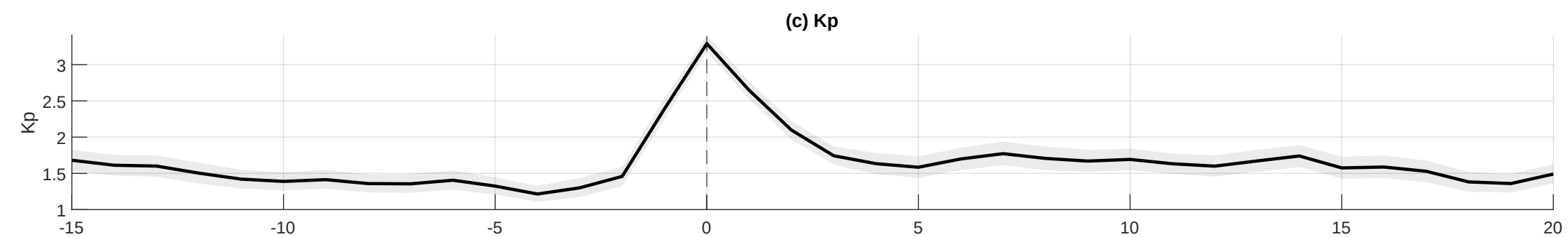
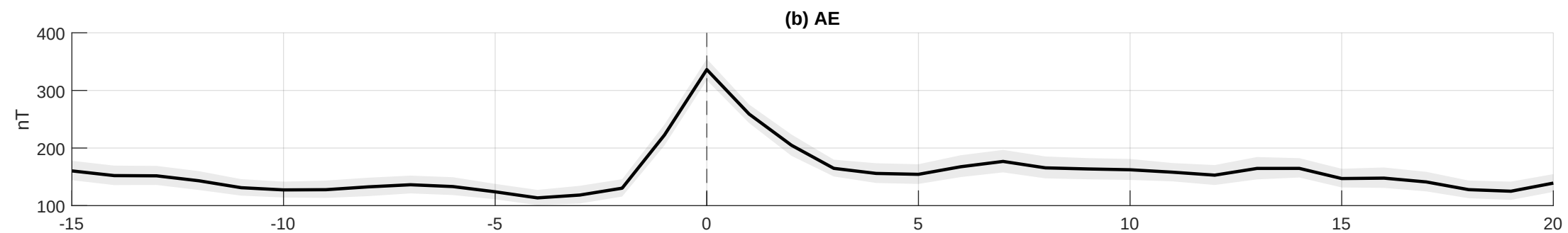
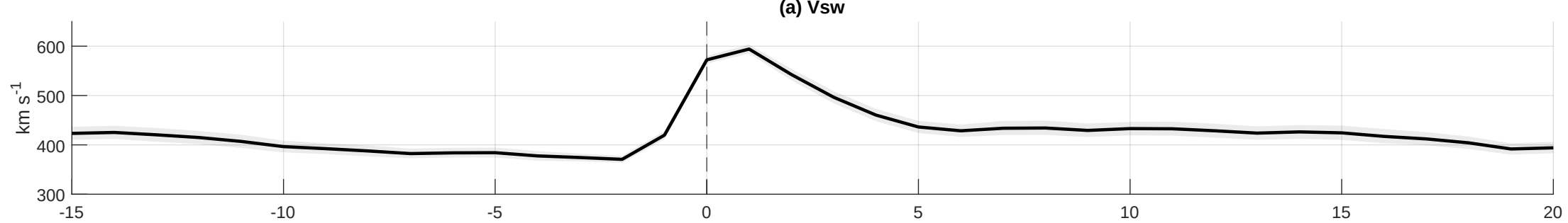
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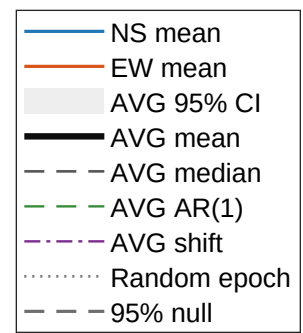
Figure_1.



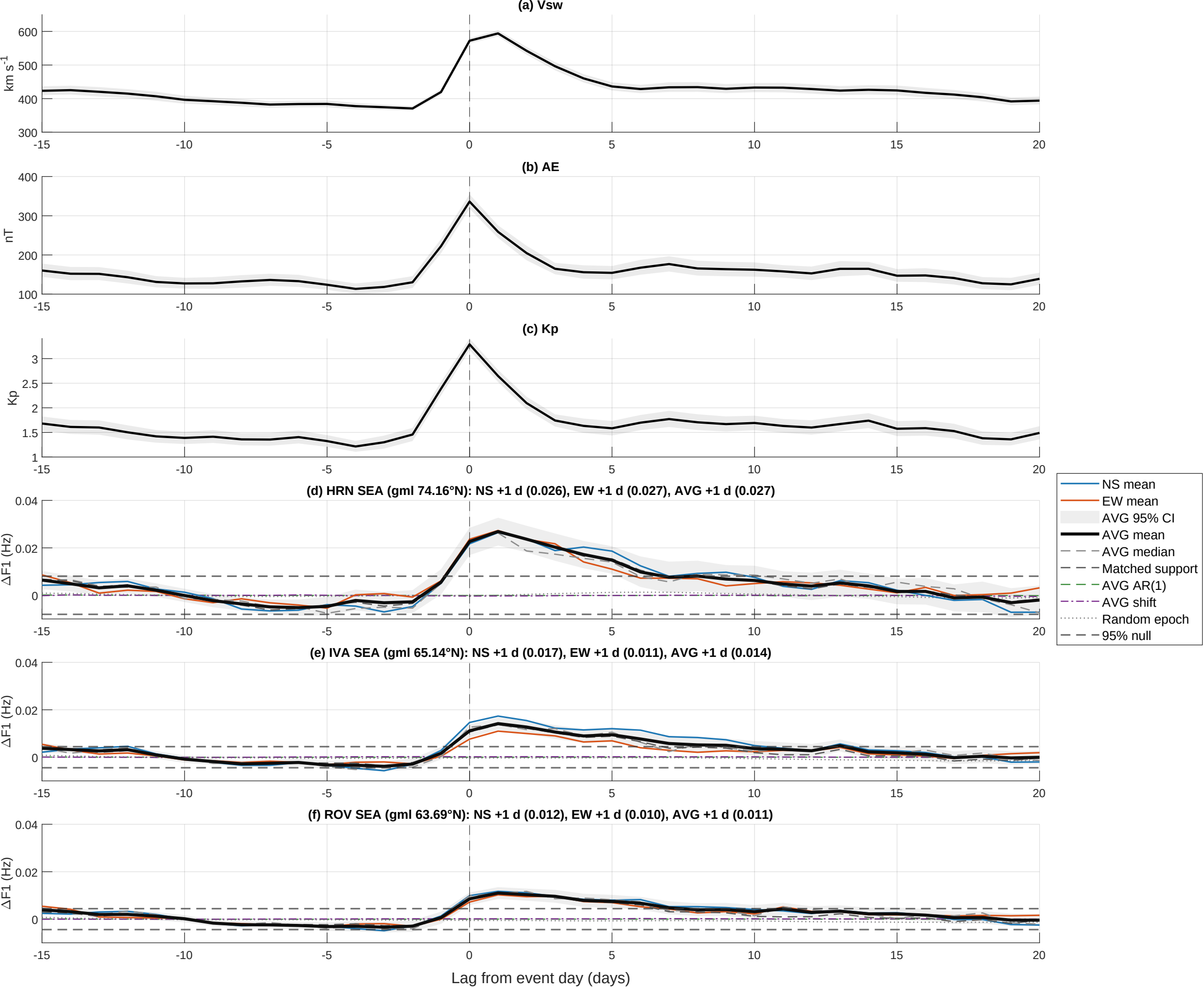
Figure_2.



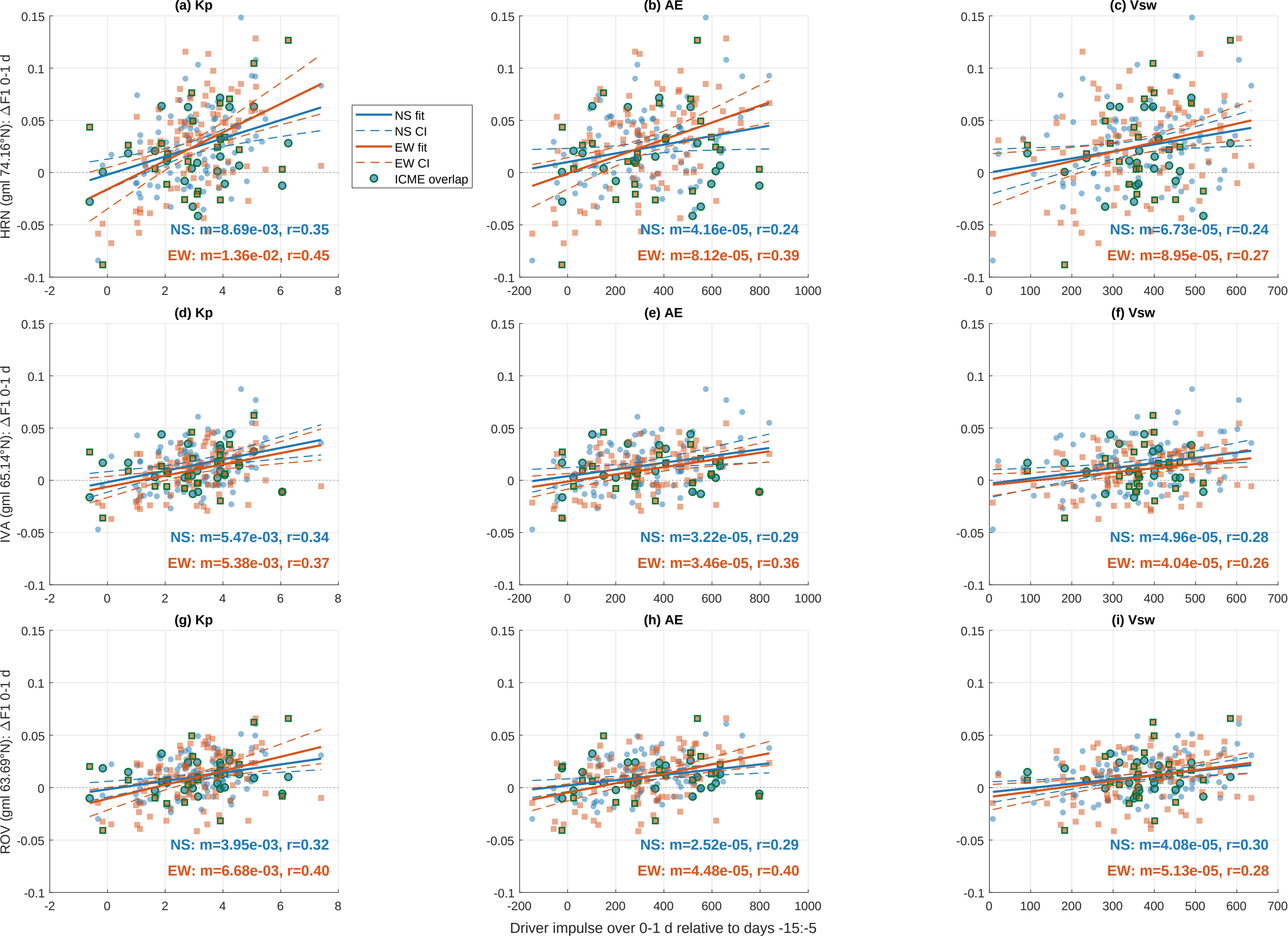
Lag from event day (days)



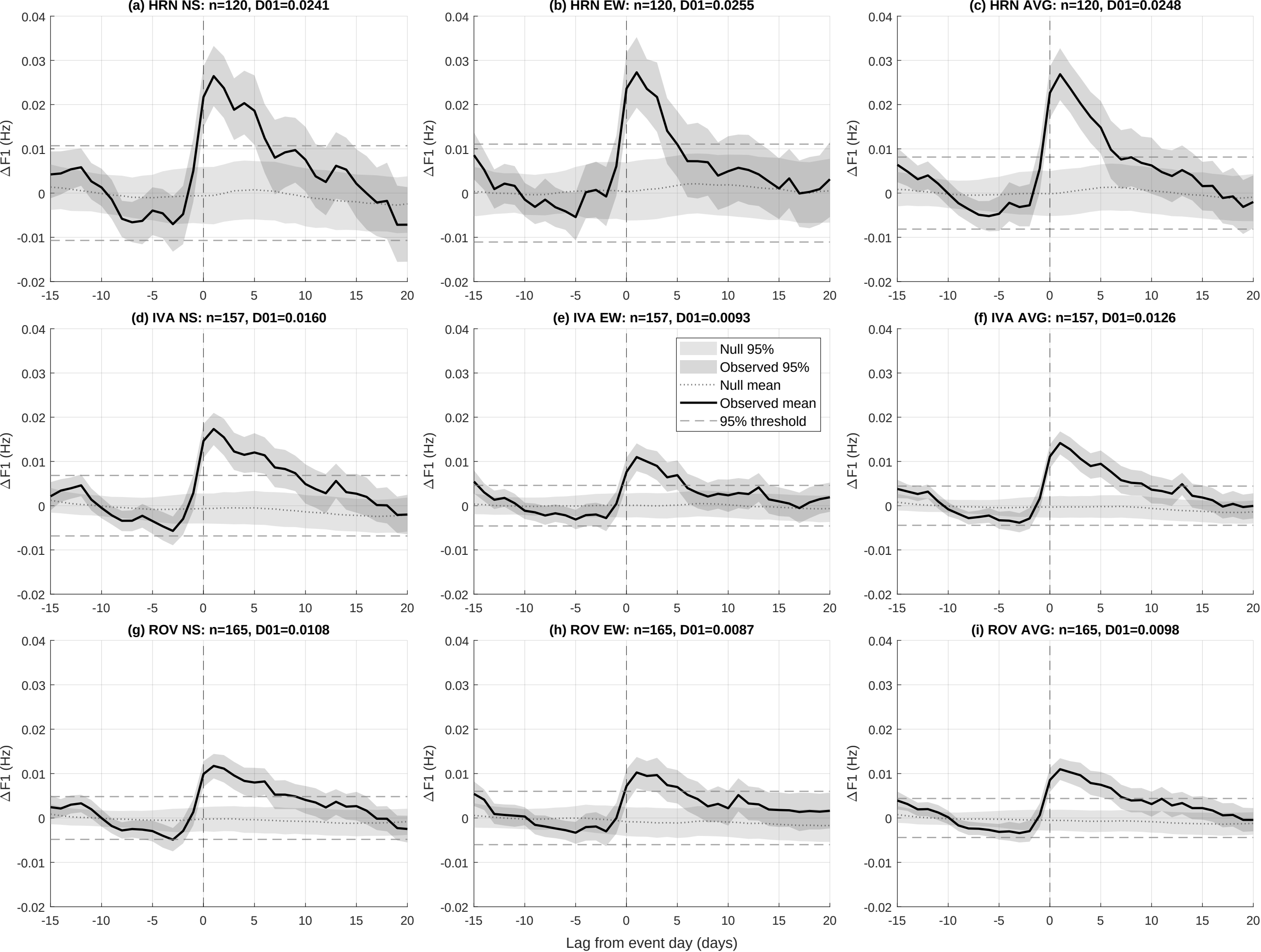
Figure_3.



Figure_4.

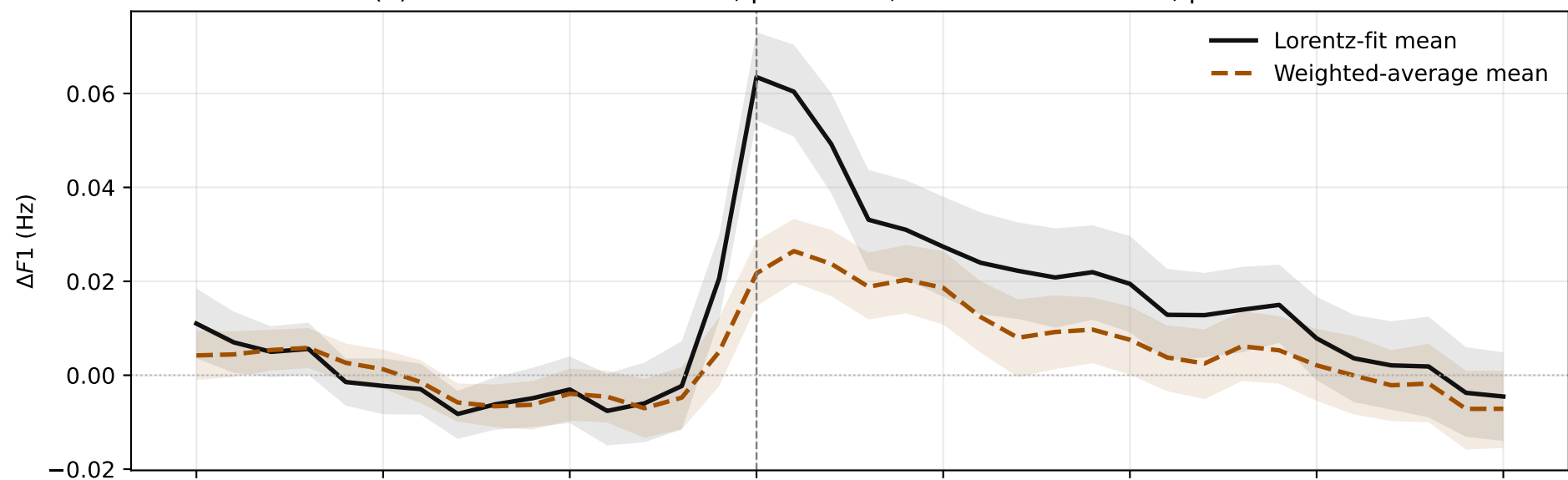


Figure_S1.

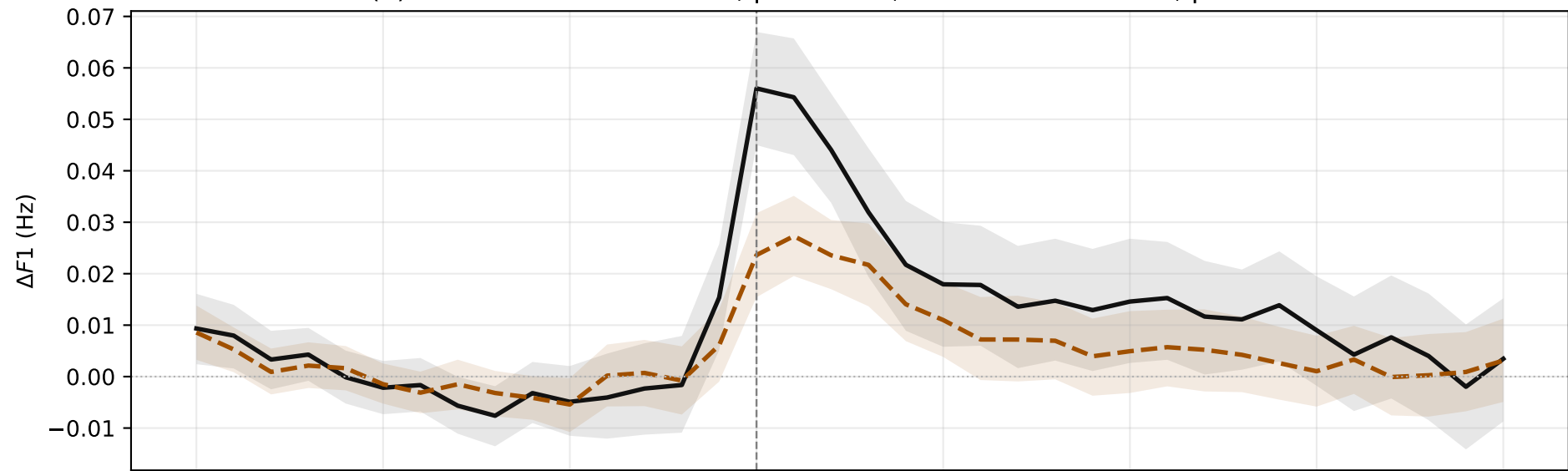


Figure_S2.

(a) NS: FIT D01=0.0619 Hz, peak +0 d; WA D01=0.0241 Hz, peak +1 d



(b) EW: FIT D01=0.0552 Hz, peak +0 d; WA D01=0.0255 Hz, peak +1 d



(c) AVG: FIT D01=0.0586 Hz, peak +0 d; WA D01=0.0248 Hz, peak +1 d

