Ionospheric Disruption Outlasts Solar Storm Conditions

1 in 6 Storms Continue Disruption 4-6 Days

Space Weather News Research Note from internal GrokBot Team 002

Across 119 major storms (GFZ Kp ≥ 6−, 2014–2025), mid-latitude TEC (50° geomagnetic N+S) stayed outside its quiet band for a median 24 hours after Kp went quiet. 17% were still disturbed at 96 hours (4 days). Ring current (SYM-H) was still about −24 nT when TEC recovered.

Figure 1 — Still disturbed after Kp says quiet

Kaplan–Meier fraction of storms whose band-mean TEC is still outside its quiet-day range vs hours after t0 (Kp ≤ 4+ for ≥ 6 h). Geomagnetic 30° / 50° / 70° bands (N+S mean bold; N dashed, S dotted) — the same bands as the SWN Storm-Time Corrections graphic. Grey band = 24–96 h window. Dash-dot = Schumann single-site TEC preview (58 h).

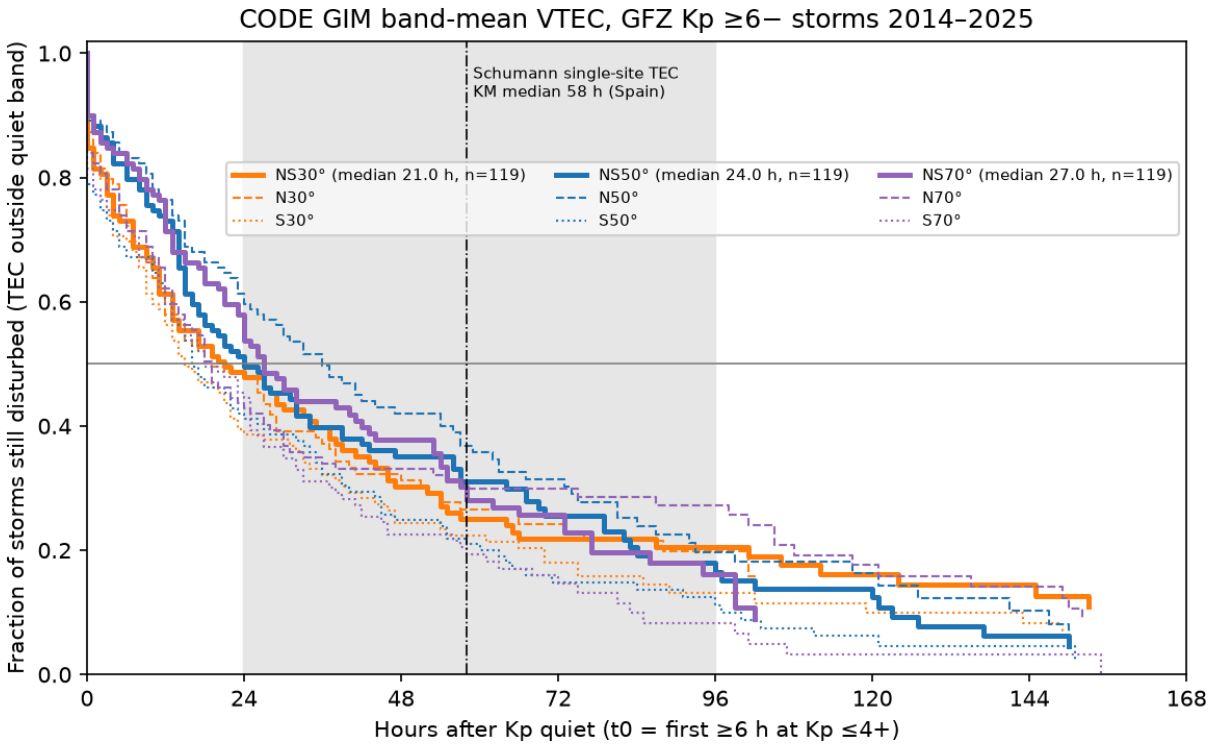
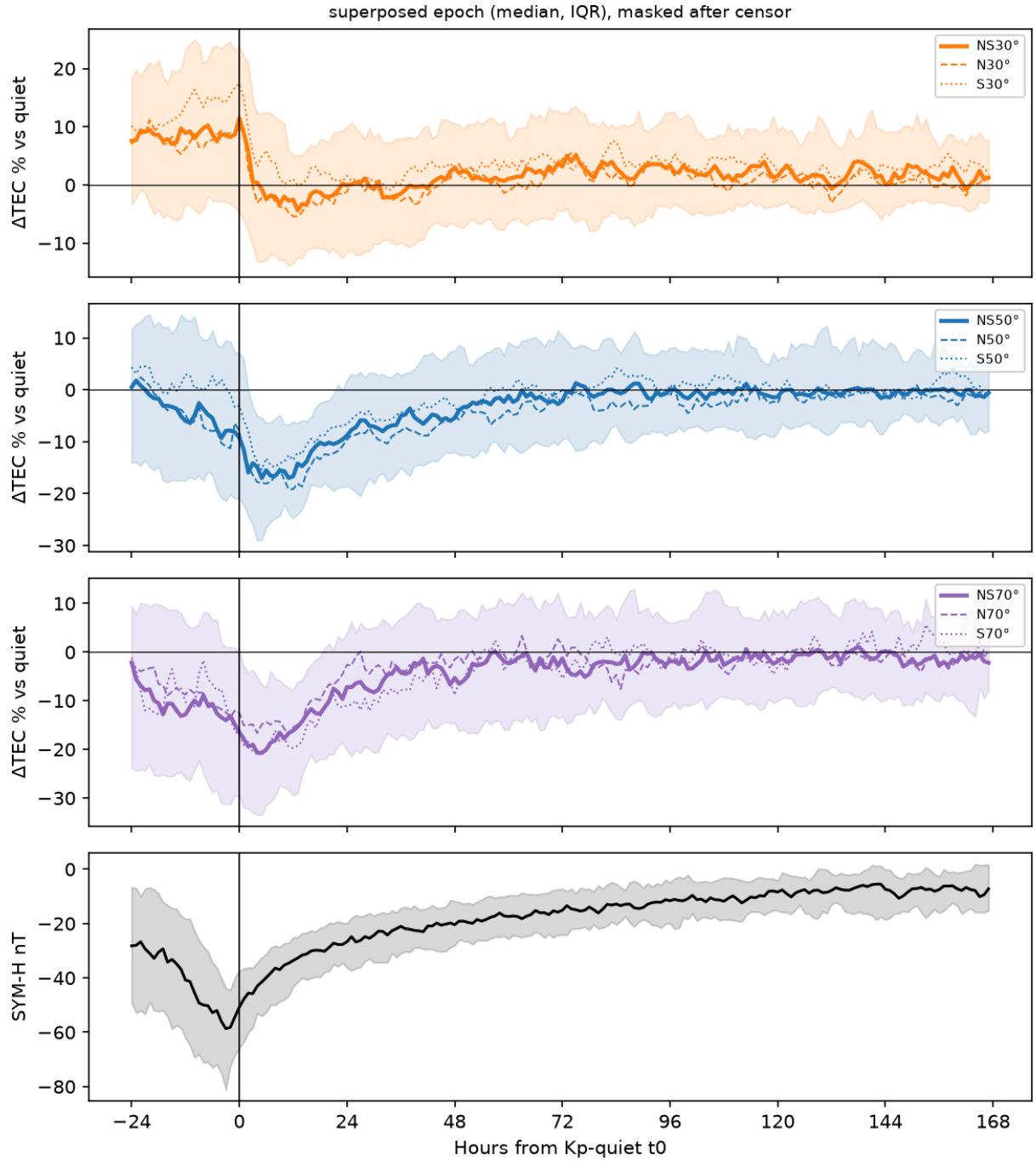


Figure 2 — What the lingering looks like

Superposed epoch t0 − 24 h → t0 + 167 h: median (IQR) ΔTEC % vs each storm's same-UT quiet median at 30° / 50° / 70°, plus OMNI SYM-H, masked after any new storm.



Claims

1. **119 storms, 12 years.** Every GFZ Kp ≥ 6− storm from 2014 through 2025 (n = 119; 52 in 2014–2019, 67 in 2020–2025) was followed for up to 7 days after Kp returned to quiet, using CODE global ionosphere maps (100% daily coverage, 4,383 days).
2. **Half the storms keep the mid-latitude ionosphere disturbed ~1 day after Kp is quiet.** At 50° geomagnetic (N+S), the Kaplan–Meier median time for TEC to get back inside its quiet band and stay there 12 h is **24 h** (n = 119; 100 recovered, 19 censored).
3. **A long tail runs to 4 days and beyond.** At 50°, **35%** of storms are still disturbed at 48 h, **26%** at 72 h and **17% (≈1 in 6)** at 96 h after Kp quiet. 3 storms never re-entered the band in a full 7-day window.
4. **It is a depletion.** At 50°, median TEC sits **17% below quiet** 5 h after Kp quiet, **−9%** at 24 h, **−5%** at 48 h and back to ≈0 by ~96 h (n = 117 → 80). 99 of 119 storms had a negative median 50° ΔTEC in the first 24 h.
5. **All three graphic bands linger about a day.** KM medians: **30° = 21 h**, **50° = 24 h**, **70° = 27 h** (each n = 119). 70° shows the deepest early depletion (−21% at +5 h).
6. **The ring current is not done either.** When 50° TEC finally recovers, SYM-H is still at a median **−24 nT** (IQR −40 to −15, n = 100); on the same clock, SYM-H is −51 nT at t0 and −27 nT at t0 + 24 h.
7. **Same answer with a stricter quiet-day rule.** Re-selecting quiet days with the Schumann-locked global exclusion gives 50° = **27 h** (vs 24 h); daytime-only (LT 10–16) band means give 50° = **23 h**.
8. **Single-site preview fits.** The Schumann note's one TEC grid point over Spain (42 storms, 2013–2017) had a 58 h median; global band means average over longitudes and both hemispheres, and land at ~1 day with a multi-day tail.

Methods

Storms and "Kp quiet." A storm is any GFZ definitive 3-hour Kp value ≥ 6− from 2014 through 2025. **t0** is the start of the first run of ≥ 6 h (two consecutive 3-hour bins) at Kp ≤ 4+ after the storm. A new Kp ≥ 5− onset less than 24 h after t0 is merged into the same storm and t0 moves to the end of it. Each storm is followed for 7 days (168 h) after t0, or until the next Kp ≥ 5− onset if one comes sooner. This gives **119 storms** (52 in 2014–2019, 67 in 2020–2025); 46 include a merge and 55 are cut short by a new storm within 7 days. Table: storm_inventory.csv.

TEC in the graphic's bands. Vertical TEC comes from CODE (AIUB) final global ionosphere maps, one file per day for all 4,383 days (2-hourly maps until 18 Oct 2014, hourly after). Each map point gets a geomagnetic latitude from the IGRF-14 dipole. A band is every point within ±2.5° of 30°, 50° or 70° geomagnetic latitude, north and south separately, averaged with cos(latitude) weights over all longitudes; the N+S band is the mean of the two. The headline band is **50° N+S (NS50)**. North and south are also kept separately; no season split is applied.

Quiet range. For each storm, up to 10 GFZ international quiet days within ±15 days of t0, nearest first, skipping days from 1 day before the storm start to 5 days after t0 (median 8 quiet days per storm). At each UT hour the quiet range is the 2.5–97.5 percentile of quiet-day TEC at that same hour (pooled over all hours when fewer than 5 quiet samples exist). Tables: quiet_days_selected.csv, quiet_band_envelopes.csv.

Recovery time. T_rec is the first time after t0 at which band TEC stays inside its quiet range for ≥ 12 consecutive hours (a missing map breaks a run). Storms that never get there are censored at the end of their follow-up. Kaplan–Meier curves give the fraction of storms still disturbed at each hour; the median is where that fraction first reaches 50%. The superposed-epoch strip is the median across storms of ΔTEC % = 100 × (TEC − quiet median at the same UT) / quiet median, from t0 − 24 h to t0 + 167 h, with SYM-H (NASA OMNI, hourly means of 5-min values) on the same clock.

Headline counts.

- NS50: n = 119, 100 recovered, 19 censored (16 by a new storm, 3 never back within 7 days), **Kaplan–Meier median 24 h**; still disturbed **35% at 48 h, 26% at 72 h, 17% at 96 h**.
- NS30: n = 119, 96 recovered, **21 h**. NS70: n = 119, 93 recovered, **27 h**.
- SYM-H when NS50 TEC recovers: median **−24.4 nT** (IQR −39.6 to −15.1, n = 100). On the epoch strip SYM-H is −51 nT at t0 and −27 nT at t0 + 24 h.
- Epoch strip, NS50: ΔTEC −17.0% at t0 + 5 h, −8.8% at + 24 h, −5.5% at + 48 h, ≈ 0 at + 96 h.
- Sensitivities: daytime-only band means (10–16 local time) → NS50 23 h; an alternative quiet-day rule (skip every listed storm's start-to-t0 + 5 d window) → NS50 27 h (n = 118).
- Single-site preview (cited, not re-run): the Schumann persistence note found a 58 h Kaplan–Meier median for CODE TEC at one grid point over Spain (42 storms, 2013–2017).

How to recreate the headline numbers.

1. Open storm_inventory.csv: count rows → 119; merge_count > 0 → 46; censor_time_utc filled → 55; solar_phase → 52 SC24_decline, 67 SC25.
2. Open recovery_times.csv and keep band = NS50 (119 rows). Compute the Kaplan–Meier estimator with time = T_rec_h and event = recovered (at each recovery time, multiply the running fraction by 1 − recoveries ÷ storms with T_rec_h ≥ that time). It first falls to ≤ 0.5 at **24 h**; read it at 48, 72 and 96 h → **0.352, 0.256, 0.165**. Count recovered = TRUE → 100; censor_reason → 16 re_onset, 3 no_recovery_within_168h.
3. Repeat step 2 for NS30 → **21 h** and NS70 → **27 h**.
4. Median of symh_at_recovery_nT over NS50 rows with recovered = TRUE → **−24.4 nT**.
5. Check steps 2–4 against km_summary.csv and the full curves (Figure 1) against km_curves.csv.
6. Figure 2 = sea_strip.csv: plot median with q25–q75 against hours_from_t0 for series NS30, NS50, NS70 (and N/S), and series SYMH.
7. Sensitivities: km_band_x_phase.csv rows with sector = day_LT10-16 and solar_phase = ALL (NS50 → 23 h); km_sens_qday_variants.csv (NS50 → 24 h vs 27 h). km_band_x_phase.csv also lists 2014–2019 vs 2020–2025 medians for recreation only; the note does not claim a difference between periods.
8. To rebuild the TEC bands themselves, download the daily CODE files listed below, compute geomagnetic latitude from the IGRF-14 dipole terms, and average as described above.

Derived data (Drive CSVs). Folder: https://drive.google.com/drive/folders/1-OjecC4Cz27L3XI5IRSVY1Lf_9sUqAjn — storm_inventory, quiet_days_selected, quiet_band_envelopes, recovery_times, km_summary, km_curves, sea_strip, km_band_x_phase, km_sens_qday_variants (plus MANIFEST.md and SHA256SUMS.txt).

Sources. GFZ Kp and international quiet days — Matzka et al. 2021, doi:10.5880/Kp.0001 (CC BY 4.0), https://kp.gfz-potsdam.de/en/ · CODE (AIUB) global ionosphere maps — https://www.aiub.unibe.ch/download/CODE/ · NASA OMNI high-resolution SYM-H — https://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni/ · IGRF-14 — https://www.ngdc.noaa.gov/IAGA/vmod/coeffs/ · Context: Mendillo 2006, Rev. Geophys. 44, RG4001 (doi:10.1029/2005RG000193).