EARTHQUAKES · RESEARCH REVIEW

Space Weather and Earthquakes

A graded review of whether the Sun–Earth environment can trigger earthquakes or leave detectable pre-seismic signatures — and why the strongest global statistical tests are null.

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> **Operational note — Blot Echo runtime (2026-02).** Carrington's in-app Blot Echo layer draws a single forecast zone from each slab-relative deep-focus earthquake, with each zone's intensity decaying on a 48-hour half-life; a qualifying shallow earthquake inside an active zone is shown as a confirmed-hit marker. It is an experimental research layer.

Scope & evidence classes. This report surveys the hypothesis that the Sun-Earth environment can trigger earthquakes or leave detectable pre-seismic signatures, and grades each claim so the reader can separate robust physics from frontier speculation: ESTABLISHED — replicated, broad peer-reviewed consensus · CONTESTED — real evidence, but disputed or mixed · HYPOTHESIS — a proposed mechanism with limited or no confirmation. The honest summary up front: mainstream seismology does not accept space weather as a validated earthquake trigger, and the most rigorous global statistical tests are null (Love & Thomas 2013; Akhoondzadeh & De Santis 2022). The physics by which the Sun perturbs the magnetosphere, ionosphere, and global electric circuit is real; whether those perturbations add usable earthquake-forecasting information after ordinary seismicity is modelled is the open question this review weighs. *This is a graded review of the published literature — not a forecast, a prediction, or advice for emergency planning. For official earthquake information, consult the USGS and your local civil authorities.*

1. Introduction: The Geocosmic Open-System Paradigm

The study of earthquake genesis is dominated, correctly, by tectonic loading, fault friction, mantle dynamics, and stress transfer inside the Earth. ESTABLISHED Space-weather research asks a narrower question: whether the Sun-Earth environment can modulate the *timing* or *observability* of rupture in faults that are already close to failure, and whether ionospheric or electromagnetic measurements can add useful probability information after ordinary seismicity baselines are known. This report surveys that hypothesis space across heliophysics, atmospheric electricity, geomagnetism, ionospheric remote sensing, and rheology.

The aim is not to catalogue statistical coincidences but to separate three roles that are often conflated: space weather as a candidate external , space weather as a of ionospheric precursor claims, and space weather as a in probabilistic forecasting. We examine the interaction between solar drivers (Coronal Mass Ejections, high-speed solar-wind streams, solar flares) and terrestrial responders (the magnetosphere, ionosphere, atmosphere, and lithosphere). Frameworks such as the reverse-piezoelectric hypothesis, planetary resonance, Lithosphere-Atmosphere-Ionosphere Coupling (LAIC), Schumann-resonance analysis, and satellite missions (Swarm, DEMETER, CSES) define the research perimeter, but their inclusion does not imply validation.

ESTABLISHED The mainstream verdict must frame everything that follows. The official position of agencies such as the United States Geological Survey is that reliable short-term earthquake *prediction* is not currently possible (U.S. Geological Survey, n.d.), and the strong-skeptic argument that earthquakes are effectively unpredictable was made influentially in *Science* by Geller et al. (1997). Two systematic critical reviews of the entire precursor field — one for space-based observations, one for ground-based — concluded that most reported precursors suffer from retrospective selection, undefined alarm windows, and unreported false-alarm rates (Picozza, Conti & Sotgiu 2021; Conti, Picozza & Sotgiu 2021).

CONTESTED Against that backdrop, a parallel literature reports correlations between solar-terrestrial activity and seismicity, and physical mechanisms that could in principle support them. The strongest single test of the headline claim is negative: Love & Thomas (2013) found solar-terrestrial triggering of earthquakes once the global catalogue is treated properly, and Akhoondzadeh & De Santis (2022) showed that the ~33 % "anomaly-before-quake" rate reported for solar-geomagnetic indices is reproduced by 100 time-randomized catalogs — i.e., it is what chance produces. This review therefore treats space-weather triggering as an open, mostly unconfirmed research question, and pairs each supportive claim with its skeptical counterpart.

A factual note on instrumentation: the field has migrated from the French DEMETER satellite (2004–2010) to the China Seismo-Electromagnetic Satellite (CSES-01, 2018–), and CSES-02 was launched on 14 June 2025 in a 180°-phased orbit with CSES-01 (Bartocci et al. 2026). Better instruments sharpen the measurements; they do not by themselves resolve the causal question.

2. Direct Electrodynamic Coupling: The Triggering Mechanism

HYPOTHESIS The most physically quantifiable vector for space weather to influence seismicity is electromagnetic induction. Unlike the quasi-static gravitational field, the geomagnetic environment is volatile, with rapid fluctuations (dB/dt) driven by the solar wind. This section examines the hypothesis that Geomagnetically Induced Currents (GIC) penetrate the crust and interact with faults via the reverse piezoelectric effect — and why the broad statistical tests do not yet support it.

2.1 Geomagnetically Induced Currents (GIC) in the Lithosphere

ESTABLISHED During a geomagnetic storm, the solar-wind–magnetosphere interaction produces rapid geomagnetic-field variations. By Faraday's law a time-varying magnetic field induces an electric field in conductive media, generating Geomagnetically Induced Currents that flow through the ground, oceans, and infrastructure. GIC are best known as a power-grid hazard, but they are genuine telluric currents that permeate the lithosphere; their magnitude and path are set by the geoelectric field and the conductivity structure of the crust.

CONTESTED Tectonic fault zones often show anomalously high conductivity relative to host rock, because fault gouge and brecciation raise porosity and admit saline fluids, and hydrothermal activity deposits conductive minerals. Fault zones can therefore act as conductive channels that concentrate telluric current. Pulinets & Khachikyan (2021) argue, within the global-electric-circuit framework, that storm-time current densities in the lithosphere can rise by orders of magnitude over the quiescent background. Whether such currents reach the levels needed to perturb a fault, and whether that perturbation matters against tectonic stress, remains unverified — the field-scale evidence is reviewed, with a generally cautious verdict, by Zeigarnik, Bogomolov & Novikov (2022).

2.2 The Reverse Piezoelectric Effect: Converting Current to Stress

HYPOTHESIS The presence of current does not by itself cause rupture; a transduction mechanism is required to convert electrical energy into mechanical stress. The reverse piezoelectric effect is the proposed bridge: applying an electric field to a non-centrosymmetric crystal (such as quartz, abundant in felsic continental crust) induces a mechanical deformation. Electro-seismic models — including the "Zarshenas Earthquake Prediction Theory" and similar proposals, which remain outside the peer-reviewed mainstream — posit a chain in which a solar-driven dB/dt induces crustal electric fields, those fields drive GIC through conductive fault gouge, and the field acts on quartz grains to produce a strain pulse that nudges a critically-loaded fault past failure.

CONTESTED Laboratory work shows that external electric and magnetic fields can modify rock friction and influence micro-fracture propagation, and that lab-scale electrical pulses can trigger weak acoustic emissions (Zeigarnik, Bogomolov & Novikov 2022). The gap between these laboratory effects and a natural earthquake is large: the energy a geomagnetic storm delivers to a fault is many orders of magnitude below the tectonic stress already stored there. This "energy-budget" objection is the standard mainstream reason for skepticism, and it is why the broad correlation tests below matter more than the mechanism's in-principle plausibility.

2.3 Penetration Depth and Deep-Focus Earthquakes

CONTESTED A frequent objection to electromagnetic triggering is the skin effect, which limits how deep high-frequency fields penetrate a conductor. The objection is weaker for the Ultra-Low-Frequency (ULF) band that dominates geomagnetic storms (periods of minutes to hours). Using the standard skin-depth approximation — depth scales as roughly 503 times the square root of resistivity (in ohm-metres)

divided by frequency (in hertz) — typical crustal resistivities and ULF frequencies give skin depths of tens to hundreds of kilometres, in principle reaching the seismogenic zone.

HYPOTHESIS On this basis, Pulinets & Khachikyan (2021) report that deep-focus earthquakes correlate with the global ionospheric potential, including a Universal-Time variation that tracks the diurnal Carnegie curve, and interpret it as the vertical global electric circuit reaching the deep interior. This is a single-group result in a frontier area; it has not been independently replicated with matched controls, and the systematic reviews of the field caution that exactly this kind of correlation is prone to retrospective selection (Picozza, Conti & Sotgiu 2021).

3. Atmospheric and Ionospheric Mediators: Indirect Coupling

HYPOTHESIS Beyond direct induction, space weather alters the atmosphere and ionosphere, and those changes could in principle feed back to the solid Earth through pressure loading and modulation of the Global Electric Circuit (GEC). The mechanisms in this section are individually plausible but collectively unproven as earthquake influences; each is graded accordingly.

3.1 The Global Electric Circuit (GEC) and Radon Ionization

ESTABLISHED The atmosphere behaves as a leaky capacitor between the conducting ground and the ionosphere, sustaining a ~250 kV potential difference and a downward fair-weather current — the Global Electric Circuit, reviewed by Siingh et al. (2023). Solar activity modulates the GEC: solar proton events increase polar ionization and conductivity, while Forbush decreases (drops in galactic-cosmic-ray flux during strong solar-wind conditions) reduce lower-atmosphere ionization.

HYPOTHESIS The proposed link to seismicity runs through radon: micro-fracturing in a fault's preparation zone is said to release radon, whose decay ionizes near-ground air and creates a column of enhanced conductivity that couples preferentially to the GEC during solar perturbations, with Joule heating or electro-migration then weakening the fault (Pulinets & Khachikyan 2021). The radon-precursor literature is itself contested: careful time-series work finds that meteorological noise dominates radon records and that pre-seismic anomalies do not separate cleanly from ordinary variability (İçhedef et al. 2025).

3.2 Atmospheric Pressure Loading: The "Unclamping" Idea

CONTESTED Surface air pressure varies by several hectopascals with weather, and a rapid pressure drop reduces the normal stress clamping a dipping fault, which can in principle ease slip. Tidal and surface-load triggering of *small* earthquakes has measurable support in the seismological literature (Cochran, Vidale & Tanaka 2004); extending it to large ruptures from solar-modulated pressure changes of a few hPa is far more speculative, and no controlled study establishes a solar→pressure→large-earthquake chain. The associated suggestion that solar activity sets the pressure changes (via Forbush-decrease pressure responses or jet-stream shifts) adds a second unverified link and is graded HYPOTHESIS.

3.3 The Cosmic-Ray–Cloud Connection

CONTESTED A long-running hypothesis links galactic cosmic rays to low-cloud cover via ion-induced nucleation, making heliophysics a candidate modulator of hydrology. The microphysical step is genuinely disputed: modelling indicates the cosmic-ray modulation of cloud-condensation-nuclei is too weak to matter climatically (Pierce & Adams 2009), and the broader debate is reviewed in the companion climate report. HYPOTHESIS The further step — that cosmic-ray-driven cloud changes redistribute water mass enough to modulate crustal stress and earthquake timing — is a speculative extension with no direct seismic confirmation, included here only to map the perimeter of the literature.

3.4 Ocean-Lithosphere-Atmosphere-Ionosphere Coupling (OLAIC)

HYPOTHESIS Extending LAIC to include the oceans, some case studies report that before coastal earthquakes deep water may upwell and diffuse thermal anomalies along plate boundaries, propagating a bottom-up perturbation from sea-surface temperature through air-sea heat flux and atmospheric gravity waves to the ionosphere (Xu, Wang & Chen 2023). These are uncontrolled retrospective case studies of individual events; they establish the *pattern* a coupling would produce, not that the coupling drove the earthquake, and they share the selection-bias weaknesses catalogued by Conti, Picozza & Sotgiu (2021).

4. Gravitational and Rotational Coupling: The "Planetary" Hypothesis

HYPOTHESIS The most radical proposals hold that solar activity and seismicity are co-symptoms of a gravitationally driven synchronization of the solar system — that planetary orbital dynamics modulate both the solar dynamo and Earth's geodynamics. This section is the most speculative in the review and is graded accordingly throughout.

4.1 Solar Wind and Length-of-Day (LOD) Variations

ESTABLISHED Earth's rotation rate fluctuates at the millisecond level (Length-of-Day variations) through angular-momentum exchange with the atmosphere, ocean, and core — that much is standard geophysics. HYPOTHESIS The speculative proposal here is that solar-wind drag and CME impacts exert an external torque that, via crustal heterogeneity, produces differential shear stress at plate boundaries. Statistical decompositions are said to report decadal periodicities (~11, ~14, ~30, ~60 yr) shared between seismicity, LOD, and solar indices. The robustness of those periodicities is the weak point: the spectral methods used to extract them are sensitive to analysis choices, shared periodicity is not evidence of a causal mechanical link, and the broader premise that an external cycle paces large-earthquake timing fails the direct test that global seismicity is statistically indistinguishable from a Poisson process (Ghazoui et al. 2026).

4.2 Planetary Resonance and Barycentric Motion

HYPOTHESIS Scafetta & Bianchini (2022) advance a planetary theory of *solar-activity* variability, in which the giant planets move the Sun about the solar-system barycentre and modulate the sunspot

cycle. Extending this to — that Earth's earthquake release is phase-locked to the same planetary beats — is a much stronger and less supported claim, made chiefly by a single research program (Dumont et al. 2025); that work is not an independent confirmation, and the implied forcing is acknowledged to be very weak.

ESTABLISHED The direct test of the underlying premise is negative. Ghazoui et al. (2026), in *Science Advances*, find that the occurrence of major earthquakes is statistically as random (Poisson) as that of smaller ones — a strong constraint that leaves little room for a deterministic external pacemaker of large-event timing. A separate, unreplicated 2026 analysis attributes any lunar-nodal (18.6-yr) signal to modulation of seismic *energy release*, not of event *rate* (Doglioni 2026) — a far weaker and more specific claim than planetary "synchronization."

5. Case Studies: Forensic Analysis and Its Limits

Individual events are where coupling hypotheses look most persuasive and are most easily over-read. Each case below pairs the reported correlation with the reason it does not, on its own, demonstrate causation. CONTESTED as a class: suggestive temporal alignment, no matched-control population.

5.1 The Tōhoku-Oki Earthquake (11 March 2011)

The M9.1 Tōhoku event is often cited as a solar-terrestrial sequence; in the usual retelling, M- and X-class flares on 7–8 March were followed by a CME impact on ~10 March that turned the IMF Bz strongly southward and drove a geomagnetic storm, with the mainshock at 05:46 UTC on 11 March, roughly 24 h after impact. CONTESTED The 24-hour "lag" is the problem as much as the appeal: with frequent space-weather activity and a single event, a one-day coincidence carries little inferential weight, and post-event geomagnetic changes are expected from the rupture itself rather than being its cause. The honest reading is an illustrative timeline, not evidence of triggering.

5.2 The Gorkha, Nepal Earthquake (25 April 2015)

The M7.8 Gorkha earthquake is frequently invoked for ionospheric precursors. Clear *co-seismic* TEC disturbances were measured after the rupture (Catherine et al. 2017); the contested claim is the separate one — that positive Total Electron Content (TEC) anomalies appeared over the epicentral region in the days *before* the mainshock, reported during the recovery phase of the March 2015 "St. Patrick's Day" storm — a storm whose purported global earthquake associations have themselves been examined directly, again without controlled comparison (Ouzounov & Khachikyan 2024). CONTESTED The interpretation is confounded at the root: the same storm that supposedly "enhanced" the precursor also produces large TEC variability unrelated to any earthquake. The general case for pre-seismic TEC has been challenged directly — Eisenbeis & Occhipinti (2021) show that the canonical pre-seismic TEC "enhancement" is an of reference-curve fitting plus a post-quake data hole, and Masci et al. (2015) refute the widely-cited "40-minute precursor" onset. Global analyses likewise find no consistent, spatially coherent pre-earthquake TEC signal (Cullen et al. 2024, a preprint). The Gorkha anomalies are real measurements; that they were *precursory* is not established.

5.3 The Chilean Earthquakes (Maule 2010, Illapel 2015)

Analyses of the Maule, Iquique, and Illapel events report rising ULF magnetic power spectral density and an accelerating "cumulative magnetic anomaly" beginning weeks before each rupture (Cordaro, Venegas-Aravena & Laroze 2021). CONTESTED Such ULF anomalies are also produced by global geomagnetic activity (PC5 pulsations driven by the solar wind), so disentangling a local crustal source from the space-weather background is exactly the discrimination problem the critical reviews flag. A disciplined skill assessment of ULF precursors using Molchan error diagrams finds they beat random only modestly, alarming on the order of ~20 % of targets (Han et al. 2016).

6. Second-Order Correlations and Rate-of-Change Framing

HYPOTHESIS Some of the more interesting proposals concern non-linear or rate-dependent relationships rather than absolute magnitudes. They remain hypotheses, but they are framed more carefully than the simple "more sunspots, more quakes" claims that broad tests reject.

6.1 The ”Gradient” Hypothesis: The S-Shape of Risk

HYPOTHESIS Simple linear correlations between solar activity and seismicity are weak or absent. The "gradient" idea is that the *rate of change* (dB/dt, dP/dt), not the peak, matters — implying elevated risk during the ascending and descending phases of the solar cycle, where the declining phase is dominated by recurrent high-speed streams from coronal holes that buffet the magnetosphere for days. This reframing is physically motivated but has not been tested prospectively, and it shares the multiple-comparisons hazard of all "which phase / which index" searches: with enough candidate windows, some will correlate by chance (Akhoondzadeh & De Santis 2022).

6.2 Schumann Resonance as a Candidate Sensor

HYPOTHESIS The Schumann Resonances (~~7.83 Hz and harmonics) are global electromagnetic standing waves in the Earth-ionosphere cavity, pumped by lightning. Because their frequency and Q-factor depend on the cavity's geometry and conductivity, the proposal is that large-scale pre-seismic ionization could shift the spectrum, making Schumann monitoring a global stress sensor. Individual case studies report anomalies before M~~7 events (Hayakawa et al. 2021). CONTESTED The most systematic test is skeptical: a five-year evaluation in the Greek area concluded that case studies the value of Schumann-resonance precursors and that the reliability of the signal is not confirmed (Tritakis et al. 2025). The honest status is a candidate sensor with suggestive single events and a negative multi-year assessment.

6.3 Biological and Behavioural Proxies

HYPOTHESIS A speculative cross-domain analogy holds that "biological sensors" (humans, animals) and "geological sensors" (faults) respond to the same environmental cues — barometric pressure drops and ULF electromagnetic emissions — and that this is why pressure-sensitive physiology (and folklore about animal premonition) appears to track seismic activity. There is no controlled evidence that animal or

human physiology forecasts earthquakes; this paragraph maps a frequently-raised idea rather than endorsing it, and it is graded at the lowest confidence tier.

6.4 Particle Precipitation and Spatial Correlations

HYPOTHESIS Some studies report that large earthquakes cluster near the geomagnetic footprints of energetic-particle precipitation, and machine-learning work has attempted to classify solar-linked seismic events from proton-density time series (Altaibek et al. 2024). CONTESTED Machine-learning skill claims in this area require special scrutiny: a 2026 review shows that random k-fold cross-validation leaks information and inflates reported accuracy, so headline ">95 % accuracy" figures are red flags rather than evidence (Jover-Alfaro et al. 2026). The spatial-correlation claims have not been validated against matched non-event controls — the same time-randomized-catalog standard that dissolves the broader solar-seismic correlation (Akhoondzadeh & De Santis 2022).

7. Synthesis: What Is Solid, What Is Contested

ESTABLISHED The defensible synthesis is a cautious, open-system research framing, not a validated trigger model:

> The strongest global statistical tests find no significant solar-terrestrial triggering of large earthquakes (Love & Thomas 2013; Akhoondzadeh & De Santis 2022), and major-event timing is statistically Poisson (Ghazoui et al. 2026). The supportive studies that exist — storm-to-earthquake lags (Sobolev 2021; Chen et al. 2020; Chen et al. 2025), flare triggering (Novikov et al. 2020; Sorokin & Novikov 2024), and the solar-activity correlation of Marchitelli et al. (2020) — are individually interesting but contested, often self-caveated (Chen et al. 2025 note their own random-series control reduces the significance), and not independently replicated.
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> Pre-seismic TEC, magnetic, and Schumann "anomalies" must be interpreted against local time, season, storm phase, solar flux, and geomagnetic indices, with shuffled or synthetic catalogs as controls. When that is done, the canonical TEC precursor dissolves into an artifact (Eisenbeis & Occhipinti 2021; Masci et al. 2015), and credibility assessments of TEC-based prediction are negative (Ikuta & Oba 2022; Ikuta et al. 2020; Thomas et al. 2017). Satellite-era work has not changed this: enhanced-analytics Swarm studies concede limited reliability (Harrigan et al. 2024), recent single-event Swarm case studies report pre-seismic magnetic anomalies without matched controls (Alimoradi et al. 2025), and the field's own critical reviews emphasise unreported false-alarm rates (Picozza, Conti & Sotgiu 2021; Conti, Picozza & Sotgiu 2021).
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> A space-weather or ionospheric signal matters operationally only if it improves calibrated scores beyond the established baselines — short-term clustering (ETAS) and precursory-scale seismicity (EEPAS; Rhoades & Evison 2004) — measured the way operational forecasting is measured (Jordan et al. 2011; Mizrahi et al. 2024). The most direct test of precursor value is sobering: adding non-seismicity precursors to a temporal ETAS

model yields only marginal per-event gains, and the seismicity clustering consistently outperforms them (Zhang et al. 2025). To date, no precursor-augmented model has cleared a fully prospective benchmark such as the CSEP experiments (Serafini et al. 2025; Han, Mizrahi & Wiemer 2025); reproducible-forecasting baselines remain ETAS plus seismic background (Mancini & Marzocchi 2023).

New instruments (CSES-02; Bartocci et al. 2026) and broader observations — solar wind, TEC maps, Schumann channels, ground ULF — are legitimate candidate features, and the mechanism literature is steadily improving (Hayakawa 2025; Li et al. 2020; Huang et al. 2026). But any such channel earns operational status only after it survives out-of-sample testing as a fixed feature over all monitored times and regions — including non-event days — against ETAS, EEPAS, and seasonal/catalog baselines. Until then, the appropriate framing is candidate-signal research, not prediction.

Data Table: Solar-Seismic Coupling Mechanisms — Status Summary

Coupling vector	Primary solar driver	Terrestrial mediator	Proposed mechanism	Evidence grade
Electrodynamic	CME / solar flare	Magnetosphere / GIC	Reverse piezoelectric stress	HYPOTHESIS
Atmospheric	Forbush decrease / SPE	Ionosphere / clouds	Pressure loading / unclamping	HYPOTHESIS (solar chain; tidal loading of *small* EQs separately CONTESTED)
Circuit	Solar proton event	Global Electric Circuit	Radon ionization / Joule heating	HYPOTHESIS
Rotational	Solar-wind drag	Angular momentum / LOD	Inertial torque / shear stress	HYPOTHESIS
Gravitational	Planetary alignment	Solar barycentre	Resonance / tidal forcing	HYPOTHESIS (timing is Poisson)
Ionospheric precursor	Storm-time TEC	Ionosphere	Pre-seismic TEC anomaly	CONTESTED (largely artifact)
Statistical correlation	Geomagnetic storms	Global seismicity	Storm→large-EQ lag	CONTESTED (null in strongest tests)

Limitations & Open Questions

Large earthquakes are rare and space-weather activity is common, so spurious "precursor before quake" coincidences are abundant. Any claim must be tested against

time-randomized catalogs; the one headline correlation tested that way did not survive (Akhoondzadeh & De Santis 2022).

Geomagnetic storms drive TEC, ULF, and Schumann variability directly. A signal that appears "before" a quake during a storm is more parsimoniously explained by the storm than by the fault.

Most positive case studies choose the event, window, station, and index after the fact; without pre-registered windows and reported false-alarm rates, their skill is unknown (Picozza, Conti & Sotgiu 2021).

Even where a coupling is physically real (GIC, GEC modulation), the energy delivered to a fault is minute against stored tectonic stress, and demonstrating a mechanism does not demonstrate forecasting value.

a precursor channel that, specified in advance, adds calibrated information over ETAS/EEPAS on a prospective CSEP-style benchmark across all monitored times and regions. None has yet done so.

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