EARTH SYSTEMS · RESEARCH REVIEW

Space Weather’s Earth Systems Influence

A graded synthesis of Earth as an electrodynamically coupled, open system — from the global electric circuit and the NAO to LAIC, seismicity, and geomagnetic jerks.

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Scope & evidence classes. This report synthesizes the case that Earth behaves as an electrodynamically coupled, open system, and grades each major 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 evidence is strongest in the atmosphere — where space weather plausibly acts as a continuous *driver* — and weakest in the solid Earth, where at most it could act as a *trigger* of energy already stored internally. The grade on each claim reflects where it actually sits in the literature, not how dramatic it sounds. *This is a graded review of the published science — not a forecast, and not a prediction of any event.*

1. Introduction: The Integrated Planetary System

CONTESTED This report's central proposition — that Earth is an electrodynamically coupled, *open* system responsive to space weather across all of its layers — is genuine but unevenly supported, and is graded domain by domain below rather than asserted as a whole.

The Earth sciences have historically treated the solid Earth, the atmosphere, and the geomagnetic field as systems driven mainly by internal dynamics — radiogenic heat, gravitational differentiation, and terrestrial meteorology. A growing body of work asks whether this picture is incomplete, and whether the boundaries between the heliosphere, magnetosphere, atmosphere, and lithosphere are more permeable to energy transfer than the classical view allows.

The proposed external driver is — the variable conditions in the solar wind, the Interplanetary Magnetic Field (IMF), and the flux of Galactic Cosmic Rays (GCRs). The interaction between these heliospheric inputs and Earth's magnetosphere is partly a shielding process and partly an active one: energy delivered by Coronal Mass Ejections (CMEs), Solar Energetic Particles (SEPs), and high-speed solar-wind streams can penetrate the magnetopause, modulate the Global Electric Circuit (GEC), and alter upper-atmosphere chemistry.

CONTESTED Where this report's unifying thesis is concerned, the honest summary is that the *strength* of coupling falls off sharply with depth into the Earth. Atmospheric electrical and dynamical responses to space weather are physically grounded and, in places, measured; the proposition that space weather meaningfully influences earthquakes, volcanoes, or the geodynamo is far more speculative and is rejected by mainstream seismology and geomagnetism on energy-budget grounds. This report keeps each domain — the GEC, the North Atlantic Oscillation, lithosphere-ionosphere coupling, seismicity, volcanism, and the deep interior — and grades each claim on its own evidence rather than carrying the confidence of the strongest domain across to the weakest.

A recurring distinction organizes the whole survey, and is developed in §8: in the atmosphere, solar inputs act as that continuously shape a system's state; in the solid Earth they could at most act as that nudge a system already poised at failure. The two require very different standards of proof, and conflating them is the most common error in this literature.

2. The Global Electric Circuit and Solar Modulation

The Global Electric Circuit (GEC) is the planetary-scale electrical system linking the ionosphere to the surface. ESTABLISHED Global thunderstorms and electrified shower clouds act as generators (current sources) that charge the ionosphere to a potential of roughly 250 kV relative to the ground; this potential drives a small downward vertical current density (Jz) through the atmosphere in fair-weather regions, which completes the circuit through the conductive Earth (Rycroft et al. 2012; Williams & Mareev 2014).

ESTABLISHED The modern quantitative picture is modest in magnitude, and the numbers are worth stating plainly because they bound everything that follows. The total global conduction current is on the order of ~1 kA (roughly 1,000–1,800 A), the total (global) resistance of the atmospheric circuit is ~220–250 Ω, and the *total electrical power* dissipated by the DC circuit is on the order of a few hundred — not gigawatts (Baumgaertner et al. 2013; Rycroft 2025). That is a small budget: two to three orders of magnitude below the ~10^{11} W of quiet-time magnetospheric energy input, and far below the power dissipated in geomagnetic storms. The GEC is therefore interesting as a *coupling channel and a sensor*, not as an energy source.

ESTABLISHED Atmospheric conductivity is not constant. Above the planetary boundary layer the dominant ionizing agent is the GCR flux, so when solar activity modulates GCRs it modulates the resistance of the atmospheric column and therefore Jz. CONTESTED What that modulation does to weather and climate is the contested part, addressed below.

A central correction to older popular accounts is that solar-wind modulation of the circuit is a single lumped effect. The modern treatment (associated chiefly with Brian Tinsley) resolves it into three distinct channels (Tinsley 2022; Tinsley 2024; Lam & Tinsley 2016):

sets the bulk column resistance (and is itself solar-cycle modulated).

adds ionization at high latitudes (Mironova et al. 2015).

adds a high-latitude contribution to the ionospheric potential (Vi), distinct from the ~250 kV thunderstorm-driven potential and typically much smaller (tens of kV in quiet conditions).

CONTESTED A crucial boundary on the climate claims must be drawn here, because two different GCR pathways are routinely conflated. The route in which GCRs seed aerosol *nucleation* and thereby change cloud cover was tested directly by the CERN CLOUD experiment and found to be negligible for the present-day climate: variations in cosmic-ray intensity do not appreciably affect climate through nucleation today (Dunne et al. 2016; Pierce 2017). That verdict closes the *nucleation* route. It does automatically close the distinct GEC *Jz* route (electroscavenging, §2.2), which acts on already-existing droplets rather than forming new particles — but it does mean any GEC-climate mechanism must be argued on its own evidence and not on the discredited GCR-nucleation link.

CONTESTED A further caution comes from the polar branch. Claimed correlations between IMF-By (the Mansurov effect) and surface pressure largely fail once autocorrelation is handled properly, and in reanalysis a "significant" signal can appear *before* the forcing — a sign of artifact rather than causation (Edvartsen et al. 2022; Edvartsen et al. 2023). The polar-cap-to-troposphere channel is therefore weaker and less certain than older work implied.

2.1 The May 2024 Superstorm: A Transient-Modulation Case Study

CONTESTED The May 2024 geomagnetic superstorm — the most intense in two decades — offers a natural experiment in which two opposing space-weather effects coincided. A occurs when a CME's enhanced magnetic field deflects GCRs, reducing tropospheric ionization and conductivity; by Ohm's law, if the source potential is steady, falling conductivity raises the local electric field needed to drive Jz. A is the opposite: relativistic solar protons reach the lower atmosphere and *increase* ionization, especially at high latitudes.

One high-altitude station on the Qinghai-Tibet Plateau (Gar) recorded extreme volatility in the atmospheric electric field during the storm, including rapid inversions of sign as the FD and the particle precipitation traded dominance (Fu et al. 2025). This is a useful single-event illustration that during a superstorm space weather can briefly dominate the local surface field over ordinary meteorological control. It is , not a general law; the systematic, multi-event quantification of how Forbush decreases move the GEC comes from broader statistical work (Tacza et al. 2024), which finds real but small responses.

2.2 Electroscavenging: The Proposed Microphysical Link to Clouds

HYPOTHESIS The mechanism most often invoked to connect the tiny GEC power budget to the large energy of weather systems is (Tinsley 2022; Lam & Tinsley 2016). Clouds are relatively poor conductors because droplets scavenge the small ions that carry the current; as Jz crosses a cloud boundary, space charge accumulates on aerosols there. When those aerosols are charged, an electrical image force increases their collision efficiency with droplets, which can enhance the scavenging of cloud-condensation and ice-forming nuclei and, in supercooled clouds, promote contact ice nucleation. Because the rate scales with Jz, solar modulation of the GEC would, in this picture, modulate cloud microphysics.

CONTESTED The observational support is suggestive rather than conclusive. Day-scale changes in storm vorticity (e.g., the Vorticity Area Index) have been reported following solar-wind sector-boundary crossings, consistent with Jz-modulated latent-heat release. But no climate model has yet reproduced a robust, quantified electroscavenging effect at the global scale, the magnitude of any climate-relevant response is unconstrained, and — per §2 — the superficially similar GCR-nucleation route has been ruled out for the present-day climate. Electroscavenging should be read as a physically motivated hypothesis under active study, not a settled forcing.

3. Atmospheric Dynamics: Top-Down Forcing of the NAO

CONTESTED The North Atlantic Oscillation (NAO) governs winter storm tracks and temperature anomalies across the North Atlantic. It is an internal mode of atmospheric variability, but a substantial literature argues that its phase is modulated by the solar cycle through "top-down" stratospheric forcing. The signal is real in several analyses but small, and its robustness across records and models is debated — so this domain sits firmly in the contested-but-grounded middle, well above the lithospheric claims that follow.

3.1 Stratospheric Coupling Mechanisms

The proposed link runs through the stratosphere via two agents:

- Total solar irradiance varies only ~0.1% over a cycle, but the UV band varies far more (several percent). UV is absorbed by stratospheric ozone; at solar maximum, enhanced UV strengthens the equator-to-pole temperature gradient and, by thermal-wind balance, the stratospheric polar vortex — favoring a positive NAO at the surface (Guttu et al. 2021).
- On the cycle's declining phase, recurrent storms precipitate energetic electrons that generate reactive nitrogen (NOx) and odd hydrogen (HOx); NOx descending inside the winter polar vortex catalytically destroys ozone, cooling the polar stratosphere and further strengthening the vortex. This gives the solar wind a route — distinct from irradiance — to reinforce the positive NAO phase.

3.2 The Lagged Response and Ocean Memory

CONTESTED A long-standing puzzle is that the surface NAO response often peaks 2–4 years *after* solar maximum. Coupled ocean-atmosphere modeling attributes the delay to the Atlantic acting as a memory reservoir: the stratospheric signal propagates down, imprints a sea-surface-temperature "tripole," and the ocean's thermal inertia re-emerges that anomaly in subsequent winters, extending and amplifying the solar signal (Thiéblemont et al. 2015). Recent work adds synergistic dependence on the Quasi-Biennial Oscillation, whose phase gates the efficiency of the EPP pathway (Salminen et al. 2019), and on ENSO. These are plausible, partially modeled mechanisms; the amplitude of the surface effect, and its stationarity over the historical record, remain disputed.

4. Lithosphere-Atmosphere-Ionosphere Coupling (LAIC)

CONTESTED The LAIC framework asks how processes in earthquake preparation zones might communicate with the upper atmosphere — and, conversely, how space weather might modulate that channel. The most-developed version (associated with Pulinets and Ouzounov) proposes that micro-fracturing before a large earthquake releases radon, whose alpha decay ionizes near-surface air, seeding ion-induced water condensation (and latent-heat / thermal anomalies), changing near-surface conductivity, perturbing the local GEC field, and ultimately producing ionospheric Total Electron Content (TEC) anomalies (Pulinets & Davidenko 2014). An "electrically active lithosphere" is itself defensible — telluric currents have many well-catalogued generation mechanisms (Helman 2014) — but the full pre-seismic LAIC chain is far from established.

CONTESTED Recent satellite missions have produced observations interpreted as pre-seismic. The China Seismo-Electromagnetic Satellite (CSES-01), with the Swarm constellation, has been reported to show small plasma-density irregularities 1–5 days before some large events, including anomalies around the January 2024 Central Asia earthquakes (Lukianova et al. 2024; Li et al. 2024). These are intriguing case reports; none establishes causality, and they coexist with a large body of negative results.

CONTESTED Two structural objections must be stated alongside the positive reports:

- Systematic re-analyses find that the apparent pre-seismic TEC rise is largely an artifact of analysis choices and of the *post*-seismic ionospheric depletion biasing reference-curve fitting; the often-cited universal "~40-minute" onset is physically implausible; and over large catalogs there is no significant pre-earthquake TEC signal (Kamogawa & Kakinami 2013; Masci & Thomas 2015; Thomas et al. 2017; Ikuta et al. 2020; Eisenbeis & Occhipinti 2021). A pro-precursor satellite-statistics literature does exist (De Santis et al. 2019; Marchetti et al. 2022), but it remains methodologically contested (Picozza et al. 2021).
- DC atmospheric electricity couples most directly to the *lower* ionosphere (the D region), whereas GNSS-TEC anomalies are dominated by the *F* region. A claim that lower-atmosphere electrical changes explain TEC therefore requires an additional transport mechanism and strict control for geomagnetic activity — which is exactly the confound the skeptical re-analyses identify.

CONTESTED The radon pillar is similarly weaker than often presented: a meta-analysis of more than 90 radon studies finds strong publication bias, and long continuous series show fewer than one "anomaly" per year, undercutting radon as a reliable precursor (Woith 2015).

5. Seismicity and Geomagnetism: The Trigger Hypothesis

ESTABLISHED The mainstream position must come first, because it is the consensus: no causal link between geomagnetic activity and earthquakes has been demonstrated. The U.S. Geological Survey states that space weather is not known to cause earthquakes (U.S. Geological Survey, n.d.); the foundational skeptical literature holds that earthquakes cannot be reliably predicted from precursors (Geller et al. 1997); and the post-L'Aquila ICEF review concluded that the search for diagnostic precursors has not produced a successful short-term prediction scheme (Jordan et al. 2011). The energy-scale disparity is the core difficulty: the electromagnetic energy a storm deposits in the crust is negligible against the elastic energy of a fault.

Against that backdrop, a 2020–2025 literature proposes physical mechanisms by which space weather could act not as an energy *source* but as a *trigger* for faults already at criticality. These are best read as HYPOTHESIS-grade proposals.

5.1 The Reverse Piezoelectric Effect

HYPOTHESIS Rapid geomagnetic-field fluctuations induce telluric currents in the conductive crust (Faraday's law); fault zones with fluids and fractured rock can concentrate them; and an applied electric field mechanically deforms piezoelectric minerals (quartz) — so, in a fault locked near failure, the induced stress might in principle overcome static friction (Marchitelli et al. 2020). The hypothesis predicts maximum sensitivity where field lines are near-horizontal (the intertropical zone). The objection is straightforward: the induced stresses are minute, and the mechanism only "works" by assuming the fault was already at the point of rupture — in which case the trigger is essentially incidental.

5.2 Electroosmosis and Fluid Dynamics

HYPOTHESIS A related idea holds that storm-induced telluric currents drive electroosmotic flow of crustal fluids, raising pore pressure and reducing the effective normal stress that clamps a fault shut. This would predict sensitivity concentrated in shallow (<30 km), fluid-rich settings. As with §5.1, the mechanism is physically conceivable but unquantified at the scale required, and the supporting statistics are contested (§5.3).

5.3 Statistical Evidence: The Proton-Flux Correlation

CONTESTED The empirical case rests largely on a reported correlation between solar proton flux and large ($M \geq 7$) earthquakes worldwide, with a ~1-day lag, over two decades of data (Marchitelli et al. 2020). A separate analysis reports a higher probability of large, shallow earthquakes in the days after intense geomagnetic storms (Chen et al. 2020). The central methodological dispute is : standard practice removes aftershocks to satisfy the Poisson-independence assumption, and critics argue that failing to do so manufactures spurious correlations whenever a solar event happens to coincide with an active aftershock sequence — a Monte-Carlo re-test concludes the apparent solar-seismic correlation is consistent with a "casual artifact" (Akhoondzadeh & De Santis 2022). Proponents counter that if external forcing triggers *global* clusters, then de-clustering would remove the very signal of interest, and they point to the persistence of the correlation in raw catalogs (Marchitelli et al. 2020, Frontiers). Both readings are on the table; independent replication on de-clustered catalogs is what would settle it, and that has not been convincingly achieved.

6. Volcanic Activity: Muon-Induced Nucleation

HYPOTHESIS A parallel proposal links explosive volcanism to GCRs via secondary muons. Silica-rich (viscous) magmas can sit in a metastable, volatile-supersaturated state because high viscosity and surface tension inhibit the first bubbles (nucleation). By analogy to a particle-physics bubble chamber, a highly penetrating cosmic-ray muon traversing such a chamber could ionize the melt and seed nucleation; once bubbles form, exsolution raises pressure and can drive an eruption (Ebisuzaki et al. 2011).

CONTESTED The supporting statistic is a small sample: of 11 eruptions from silica-rich Japanese volcanoes over ~306 years, 9 fell during solar minima (high GCR flux), with a stated chance probability below ~3.3%, and the correlation is reported to be absent for low-viscosity basaltic systems. A sample of 11 is fragile, and the result has not been independently replicated on a global eruption catalog. The standing physical objection is muon penetration: muon flux attenuates steeply with depth, so at the multi-kilometer depth of a typical magma chamber it is most likely too low to trigger a chamber-wide event. Proponents reply that nucleation need only begin in the shallow, higher-flux roof of the conduit and then propagate a decompression wave downward, and recent laboratory work shows that mechanical shear can itself nucleate bubbles in magma, priming the system further (Roche et al. 2025). Treat the muon trigger as an unconfirmed hypothesis with a suggestive but underpowered statistical basis.

7. Deep Earth Dynamics: The Core and Geomagnetic Jerks

ESTABLISHED The geodynamo — convection of molten iron in the outer core — generates the geomagnetic field, and this is fundamentally an *internal* process. The question this section weighs is whether any of its short-term variability is externally modulated — a claim that ranges from mainstream (§7.1) to fringe (§7.2).

7.1 Geomagnetic Jerks and Length of Day

ESTABLISHED Geomagnetic *jerks* — abrupt changes in the rate of secular variation — reflect sudden accelerations of core-surface flow, and decadal length-of-day (LOD) variations are driven by angular-momentum exchange between core and mantle. That core-mantle coupling controls decadal LOD is standard geophysics. CONTESTED More specific is the report of a statistically significant ~8.6-year oscillation in LOD that tracks the occurrence of geomagnetic jerks, attributed to fast equatorial magnetohydrodynamic waves propagating along the core surface (Duan & Huang 2020). The correlation is interesting and sits within mainstream core dynamics; its precise period and interpretation are still debated.

7.2 The External-Driven Quasidynamo Hypothesis

HYPOTHESIS — *Frontier, marginally published, not accepted.* A fringe proposal (the "Interplanetary External Driven Quasidynamo") suggests that the oscillating solar magnetic field induces currents in the conductive cores of the planets, including Earth, and that the resulting Lorentz-force perturbations manifest as geomagnetic jerks and length-of-day changes synchronized to heliospheric and planetary-alignment cycles (Lutephy 2018). We include it for completeness because it bears directly on this section's topic, but the reader should weigh it accordingly: it appears only in a very low-impact journal, it has not been independently replicated, and it is not accepted by the geomagnetism community — for which the standard explanation of jerks remains internal, buoyancy-driven core flow (§7.1). It is best read as an unverified frontier idea, not as evidence of external control of the core.

8. Synthesis and Comparative Analysis

CONTESTED The phenomena in this report share one thread — the response of Earth's non-linear systems to external electromagnetic forcing — but they do share a confidence level. The single most useful distinction is between drivers and triggers:

> Solar inputs supply a continuous source of energy and ionization that actively shapes the system's state; responses are quasi-linear, measurable, and lagged. These claims are CONTESTED but physically grounded, and several are partly measured.
>
> The energy of the event (tectonic stress, magmatic pressure) is internal and vast; any solar input is energetically negligible and could at most perturb a system already at criticality. This is why such correlations are statistical and probabilistic at best, why they are so vulnerable to de-clustering and selection artifacts, and why they remain HYPOTHESIS-grade. Mainstream seismology and geomagnetism do not accept them.

8.1 What Would Move These Claims

Turning correlation into mechanism requires monitoring, not more statistics on the same catalogs: simultaneous multi-altitude measurement of the electric field and Jz to close the Ohm's-law budget during storms; pre-registered event-and-null analyses on de-clustered catalogs for any seismic claim; and laboratory quantification of the proposed reverse-piezoelectric and muon-nucleation effects on realistic samples. Until then, the atmospheric coupling stands as a real if modest part of the Earth system, and the solid-Earth claims stand as open hypotheses to be tested — not findings to be relied upon.

Limitations & Open Questions

> For every solid-Earth claim, the external electromagnetic energy is negligible against the internal energy of the event. A trigger argument therefore *requires* a system already at failure, which makes the external input hard to distinguish from coincidence.
>
> De-clustering, selection effects, multiple comparisons, and autocorrelation each can manufacture an apparent signal; the seismicity and volcano correlations have not been convincingly replicated on properly de-clustered, global catalogs.
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> CERN CLOUD closed the GCR→nucleation→climate route for the present day (Dunne et al. 2016); the GEC Jz /

electroscavenging route is distinct and remains open but unquantified. Neither supports a large cosmic-ray climate forcing today.

The lower-atmosphere (D-region) electrical changes invoked by LAIC are not obviously connected to the F-region where TEC anomalies live; bridging them needs an explicit, controlled mechanism.

Core-mantle coupling and jerks are mainstream; external solar / planetary driving of the geodynamo (§7.2) is not, and has no credible support.

Single-event and small-N results (Gar-station fields, 11-eruption volcano statistics, individual CSES anomalies) are illustrative, not confirmatory.

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