

Space Weather's Climate Forcing

A graded review of the candidate pathways — galactic cosmic rays, the global electric circuit, energetic-particle precipitation — by which the Sun may influence weather and climate beyond Total Solar Irradiance.

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Scope & evidence classes. This report grades every claim it surveys: **ESTABLISHED** — replicated, broad peer-reviewed consensus; **CONTESTED** — real evidence, but disputed or mixed; **HYPOTHESIS** — a proposed mechanism with limited or no confirmation. It reviews the candidate pathways by which the Sun and the wider space environment — beyond the simple heating of Total Solar Irradiance — may influence Earth's weather and climate, and it deliberately shows the constraining and null evidence alongside the supporting work. It is a graded review of the published literature, *not a forecast and not a rejection of mainstream climate science*. The scientific consensus (IPCC 2021) assesses the total solar contribution to industrial-era warming as small — an effective radiative forcing near $+0.01 \text{ W/m}^2$ — next to the dominant anthropogenic forcing of roughly $+2.7 \text{ W/m}^2$. Throughout, this report separates *weather* (individual storms, a single winter's circulation) from *climate* (decadal-to-centennial radiative forcing); the weather- and seasonal-scale claims are, in general, considerably better supported than the climate-scale ones.

1. Introduction: Beyond the Irradiance Paradigm

ESTABLISHED Earth's climate is driven primarily by the radiative balance between incoming sunlight and outgoing thermal radiation, modulated by greenhouse gases, aerosols, ocean circulation, and internal variability. The Sun's direct radiative lever is Total Solar Irradiance (TSI), which varies by only about 0.1% over the 11-year cycle — roughly 1 W/m^2 at the top of the atmosphere before geometric and albedo factors reduce it to a few tenths of a W/m^2 of effective forcing. The mainstream assessment is that this direct TSI variation is too small to dominate decadal-to-centennial climate change (Gray et al. 2010; Lockwood 2012; Tinsley 2023).

ESTABLISHED Crucially, "the Sun affects climate only through TSI" is *not* the mainstream position, and this report does not treat it as a straw man to overturn. Modern climate models already include solar influences beyond bulk irradiance: spectrally-resolved ultraviolet variations that modulate stratospheric

ozone and drive a "top-down" dynamical response, and — increasingly — energetic particle precipitation. Both are part of the standard solar-forcing recommendation for the CMIP6 generation of climate models (Matthes et al. 2017). The genuine scientific frontier is not *whether* the Sun-climate link exceeds TSI, but *how large* the additional, particle- and field-mediated pathways are, and whether any of them rises to the level of a climate forcing rather than a modulator of weather and seasonal circulation.

CONTESTED The pathways reviewed here — galactic-cosmic-ray (GCR) cloud nucleation, the Global Electric Circuit (GEC), energetic particle precipitation (EPP), solar-wind-driven vorticity, and geomagnetic excursions — are sometimes presented as a unified "energetic coupling" framework that rivals greenhouse forcing. A recurring rhetorical move underlies that framing: because particle fluxes and electromagnetic inputs vary by far larger *fractions* than TSI, they are assumed to be climatically decisive. This inference does not hold on its own. A large fractional change in a tiny energy reservoir can still be a negligible radiative forcing; the relevant question is the absolute magnitude of the resulting change in Earth's energy budget, in W/m^2 , measured against the other terms. This report therefore grades each pathway on its demonstrated magnitude and reproducibility, not on the size of its fractional variability.

ESTABLISHED The structure follows the proposed coupling routes: cosmic rays and clouds (§2), the global electric circuit (§3), energetic particle precipitation and the polar vortex (§4), solar wind and vorticity (§5), and geomagnetic excursions in deep time (§6). Section 7 places these candidates against the mainstream radiative-forcing budget, and §8 synthesizes what is solid, what is contested, and what evidence would change the grades.

2. Galactic Cosmic Rays and Cloud Formation

CONTESTED The hypothesis that galactic cosmic rays influence cloud cover — "cosmoclimatology," associated chiefly with Henrik Svensmark — is the most debated of the candidate pathways. GCRs are the dominant ioniser of the lower troposphere, and their flux is anti-correlated with solar activity (a stronger heliospheric field during solar maximum shields the inner solar system). The proposal is that this ionisation modulates aerosol nucleation, cloud condensation nuclei (CCN), cloud albedo, and ultimately temperature. The underlying microphysics is real and measurable; the contested step is whether it scales up to a detectable *climate* forcing. Three claims must be kept separate: (a) ion-induced nucleation can occur; (b) the freshly nucleated particles grow to climate-relevant CCN sizes; and (c) the resulting CCN change produces a measurable global radiative forcing. Evidence weakens markedly from (a) to (c).

ESTABLISHED Ion-induced nucleation (IIN) itself is well-demonstrated: ions lower the thermodynamic barrier to forming molecular clusters, and this is observed both in the laboratory and in the field. A historic objection — the "growth bottleneck," in which 1–2 nm clusters are scavenged by larger pre-

existing aerosols before reaching CCN size (~50–100 nm) — was addressed by chamber work reporting that ions also accelerate the *growth* of clusters via electrostatic interactions (Svensmark et al. 2017).

CONTESTED The reach of that result is disputed. The chamber demonstrates a mechanism under controlled conditions; translating a percent-level modulation of nucleation into a change in cloud cover and albedo over the real, aerosol-rich atmosphere is the unproven step. In most of the present-day atmosphere, CCN concentrations are buffered by abundant non-ion sources (sulfuric acid, organics, sea salt), so the marginal effect of GCR-modulated ions is small (Gordon et al. 2016; Gordon et al. 2017).

CONTESTED Forbush decreases — abrupt, days-long drops in GCR flux when a coronal mass ejection sweeps cosmic rays away from Earth — are used as natural experiments that isolate the ionisation signal from changes in irradiance. Some compositing studies report a small reduction in cloud or aerosol properties days after the strongest events (Svensmark et al. 2021); others, using independent satellite cloud datasets and larger event samples, find (Calogović et al. 2010; Laken et al. 2012; Krissansen-Totton & Davies 2013). The result is sensitive to event ranking, the compositing window, satellite calibration, and multiple-comparison control, and the field has not converged.

CONTESTED A specific number from this literature deserves careful handling. One analysis of the five strongest ionisation-decreasing events reported a transient change in net radiative balance of approximately (median 1.2) (Svensmark et al. 2021). This is a , and the authors do not scale it to a sustained climate forcing. Placing it beside the sustained ~2 W/m² forcing from industrial-era CO₂ — as popular summaries sometimes do — is an apples-to-oranges comparison: a transient, regional, multi-day pulse is not equivalent to a persistent, global radiative imbalance.

ESTABLISHED The GCR-cloud hypothesis is the rare climate question with a purpose-built laboratory test: CERN's CLOUD experiment. Its results constrain the hypothesis rather than confirm it. CLOUD established that ions assist nucleation but that, across most of the atmosphere, vapours such as sulfuric acid, ammonia, amines, and biogenic organics dominate particle formation, and that the ion contribution to global particle formation is modest (Kirkby et al. 2011; Dunne et al. 2016; Kirkby et al. 2023). Quantitatively, modelling anchored to CLOUD chemistry finds that the solar-cycle modulation of CCN is only of order — far too small to drive a meaningful change in cloud radiative forcing (Gordon et al. 2017).

ESTABLISHED Independent analyses reach the same conclusion from other directions: the CCN response to GCR changes is estimated to be one-to-two orders of magnitude too small to matter for climate (Pierce & Adams 2009), and reconstructions of solar activity cannot account for late-20th-century warming through any cosmic-ray channel (Sloan & Wolfendale 2013; Gray et al. 2010). Recent

reanalysis-based work continues to find at most regional, second-order GCR/cloud associations consistent with these limits (Kumar et al. 2023). A GCR-cloud section that omits CLOUD and this null literature is not a balanced review; included, they place the pathway at

HYPOTHESIS On geological timescales, the cosmoclimatology programme proposes that Earth's passage through regions of high supernova activity modulated GCR flux, cloudiness, and even marine biodiversity over the Phanerozoic (Svensmark 2022; Svensmark 2023). These correlations are intriguing and actively published, but they rest on reconstructed deep-time proxies with large uncertainties and contested causal direction, and they are not independently established. They are best read as a stimulating hypothesis, not as confirmation of the modern GCR-climate link.

3. The Global Electric Circuit and Cloud Microphysics

HYPOTHESIS A second proposed route, developed chiefly by Brian Tinsley, concerns not the *creation* of CCN but the *fate* of aerosols and droplets within clouds, mediated by the Global Electric Circuit (GEC). The circuit is real and quantified; its coupling to weather and climate is the unproven part.

ESTABLISHED The Earth-ionosphere system behaves as a leaky spherical capacitor. Global thunderstorm and electrified-cloud activity charges the ionosphere to roughly relative to the surface, driving a fair-weather vertical conduction current of order down through the atmosphere (Rycroft et al. 2012; Rycroft 2025). This current is modulated both by the solar wind (via the cross-polar-cap potential) and by GCRs (which set the air's conductivity), so a space-weather signal can in principle reach cloud altitudes through the circuit.

HYPOTHESIS Tinsley's "electro-scavenging" mechanism proposes that space charge accumulating at cloud boundaries enhances the rate at which droplets collect aerosol and ice-forming particles, altering precipitation, cloud lifetime, and — through latent-heat release — storm dynamics. Parameterization studies report that even weak cloud electrification can measurably increase the rate at which droplets collect aerosol and ice-forming particles (Zhang, Tinsley & Zhou 2018).

CONTESTED The leap from microphysical enhancement to climate forcing is not supported, and the strongest cautions come from the pathway's own literature. Tinsley's own assessment characterises the resulting cloud and surface-pressure responses as — a modulation, not a driver (Tinsley 2022). Direct laboratory measurement of electro-scavenging finds the collection efficiency what the theory predicts (Dépée et al. 2021). And the statistical signatures often cited as evidence (e.g. day-of-sector-crossing changes in vorticity) weaken or vanish once

atmospheric autocorrelation is handled correctly (Edvartsen et al. 2022). The GEC is therefore graded as a weather influence — and not established as a climate forcing.

4. Energetic Particle Precipitation and the Polar Vortex

ESTABLISHED Energetic particle precipitation (EPP) — solar protons and magnetospheric electrons entering the polar atmosphere — is the of the non-irradiance pathways, and the one most clearly entering mainstream models. Its chemistry is well-established; its surface-climate reach is real but conditional.

ESTABLISHED When energetic particles ionise the polar mesosphere and stratosphere, they generate odd nitrogen (NO_x) and odd hydrogen (HO_x). EPP is a major source of reactive odd nitrogen (NO_y) in the polar winter middle atmosphere — in active seasons contributing up to ~40% of the polar NO_y budget (the older claim that EPP supplies "~10% of *global* stratospheric NO_x" is not well-traceable to a primary figure and is not used here). During polar night, this NO_x is shielded from photodissociation, descends inside the vortex, and catalytically destroys ozone — the "EPP indirect effect," producing upper-stratospheric ozone losses of order 10–15% after strong events and persisting for months (Szeląg et al. 2022; Nesse et al. 2026).

CONTESTED Model fidelity is itself an active issue: the CMIP6 solar-forcing dataset under-represented energetic-particle ionisation — a gap the CMIP7 solar-forcing effort is explicitly intended to close — which implies that model-based EPP impacts to date are, if anything, conservative rather than exaggerated (Funke et al. 2024).

CONTESTED The chemical chain has a dynamical consequence: ozone loss cools the polar stratosphere, strengthens the polar vortex, and — via downward wave–mean-flow coupling — favours the positive phase of the Northern Annular Mode and the North Atlantic Oscillation (NAO), nudging a given winter's European weather. Fast pathways from EPP through mesospheric ozone to surface weather have been demonstrated on weekly timescales (Seppälä et al. 2025), and the EPP–climate literature is reviewed comprehensively by Nesse et al. 2026.

CONTESTED The surface signal is . The clearest EPP–NAO response appears essentially only in winters with an easterly phase of the Quasi-Biennial Oscillation, which gates the downward coupling (Maliniemi et al. 2016). It is a regional, seasonal modulation of winter circulation — a *weather/seasonal* effect — not a global radiative forcing.

ESTABLISHED EPP's maturity is reflected in its move toward operational seasonal forecasting and its inclusion in the CMIP solar-forcing recommendation (Matthes et al. 2017; Nesse et al. 2026).

CONTESTED Even so, its demonstrated effect is a conditioning of regional winter variability of a magnitude comparable to other internal modes — important for seasonal prediction, but not a re-writing of the global energy budget. This is the honest ceiling of the best-supported pathway.

5. Solar Wind, Vorticity, and the Wilcox Effect

HYPOTHESIS In 1973 John Wilcox reported a brief dip in Northern-Hemisphere tropospheric vorticity a day or so after Earth crossed a heliospheric-current-sheet (sector) boundary. The "Wilcox effect" implies a rapid atmospheric response to the interplanetary magnetic environment.

CONTESTED The effect has been revisited with modern reanalyses and reported to persist in both hemispheres (Prikryl et al. 2009), and the same group has extended it to the influence of solar-wind high-speed streams on extratropical cyclones and heavy precipitation (Prikryl & Rušin 2023). The central caution is : the modern positive results come predominantly from a single research group, and there is little independent confirmation of the solar-wind/vorticity link. Where the related Mansurov/sector-boundary signals have been re-examined with proper treatment of autocorrelation and effective degrees of freedom, the apparent significance is much reduced — and in at least one analysis a putative response appears *before* the sector crossing, pointing to an artefact (Edvartsen et al. 2022; Edvartsen et al. 2023).

HYPOTHESIS The proposed mechanism is that solar-wind disturbances drive Joule heating in the auroral ionosphere, launching atmospheric gravity waves that propagate down to the troposphere and trigger conditional symmetric instability, intensifying cyclones (Prikryl 2024). The chain is physically plausible and there is independent evidence that the lower atmosphere can respond rapidly to solar-wind/GEC changes (Harrison & Lockwood 2020). But as a *weather trigger* rather than a *climate forcing*, and absent broad independent replication, it remains a hypothesis.

6. Geomagnetic Excursions and Climate

CONTESTED Earth's magnetic field gates the particle inputs discussed above; when it weakens during an excursion, those inputs intensify. The geophysics of such events is sound; the catastrophist *climate-and-extinction* narrative attached to them is what the literature has pushed back on.

ESTABLISHED The Laschamps excursion (~41,000 years ago) is a real, well-dated event in which the geomagnetic field weakened dramatically and briefly reversed, leaving a clear spike in cosmogenic-

isotope (^{14}C , ^{10}Be) production. A high-profile reconstruction tied this interval to environmental and biological change and named its onset the "Adams Event" (Cooper et al. 2021).

CONTESTED The strong climate-and-extinction interpretation drew immediate, formal rebuttal. Two Technical Comments in *Science* challenged the dating, the magnitude of field collapse, and the causal links to megafaunal extinction and human behaviour (Hawks 2021; Picin et al. 2021), with a published author Response (Cooper et al. 2021, Response). Independent records also indicate that major cooling the excursion, undercutting a simple field-collapse-causes-climate-shift story (Albert & Sirocko 2023). Modelling further shows that the largest ozone losses require a weak field an extreme solar proton event, not field weakening alone (Arsenović et al. 2024). Laschamps is therefore best understood as an of geomagnetic variability — informative about the upper bound of particle forcing — not as a template for normal climate variability.

HYPOTHESIS The proposal that smaller, centennial-scale "archaeomagnetic jerks" modulated Holocene climate is weaker still. Regional, non-dipole field spikes do not substantially change *global* cosmogenic-isotope production, so the proposed GCR-mediated climate link lacks a global mechanism (Nilsson et al. 2024). Notably, the originators of the jerk-climate idea themselves described the connection as "intriguing but tenuous" (Courillot et al. 2007). Some geological case studies report field-weakening/climate associations while explicitly calling their own mechanism hypothetical (Kitaba et al. 2017; Hyodo et al. 2022).

7. The Mainstream Climate Context

ESTABLISHED Placing these candidates against the assessed radiative-forcing budget is what keeps the review honest. The IPCC AR6 assessment finds the over the industrial era to be about (range roughly -0.06 to $+0.08$), and explicitly rates any cosmic-ray/cloud climate forcing as (IPCC 2021). For comparison, the effective radiative forcing from anthropogenic CO_2 alone is about , and total anthropogenic forcing about — two orders of magnitude larger than the assessed solar term.

ESTABLISHED This does not erase the pathways above. The mainstream already incorporates the better-supported solar routes — spectral-UV/ozone "top-down" coupling and, increasingly, EPP — in the CMIP solar-forcing datasets (Matthes et al. 2017). What the consensus does not support is the elevation of the *contested* GCR and GEC pathways to climate-forcing status, or the omission of their measured magnitudes. Independent audits that attempt to maximise the solar contribution to recent temperature trends still cannot reproduce observed warming without the dominant greenhouse term (Lockwood 2012), and even studies emphasising solar influence frame it as a modulation on top of stronger forcings (Connolly, Soon et al. 2021; Ineson et al. 2015).

8. Synthesis: What Is Solid, What Is Contested

The Sun-climate relationship is genuinely richer than TSI alone — but the strength of the evidence falls off sharply along the weather-to-climate axis:

ESTABLISHED EPP chemistry (NO_x production, polar ozone loss); **CONTESTED** EPP modulation of a given winter's NAO (conditional on the QBO); the existence and quantification of the Global Electric Circuit.

CONTESTED GCR → cloud → global temperature (mechanism real, climatic amplitude small per CLOUD and the null literature); GEC as a sustained climate forcing; geomagnetic excursions as routine climate drivers.

HYPOTHESIS the solar-wind/Wilcox vorticity link and its auroral-gravity-wave mechanism (single-group, autocorrelation-sensitive); the deep-time supernova-biodiversity correlation; archaeomagnetic-jerk climate effects.

The core, defensible insight is that solar influence operates through more than irradiance, via particle and electromagnetic channels — a view the mainstream shares for the UV/ozone and EPP routes. The overreach is to grant the contested GCR/GEC pathways equal standing with greenhouse forcing and to omit their measured, small magnitudes.

For the GCR pathway: a pre-registered, multi-group Forbush/SPE compositing analysis with a shared null model and explicit autocorrelation control. For the GEC and Wilcox pathways: independent (non-original-group) replication with specified controls (ENSO, QBO, volcanic aerosols, ozone). For EPP: continued reconciliation of the CMIP ionisation underestimate and out-of-sample seasonal-forecast skill. For all of them, the decisive test is the same — a demonstrated, reproducible signal that survives proper statistics and is quantified in W/m² against the other terms of the energy budget.

Limitations and Open Questions

This is a literature review compiled with AI assistance, not original analysis, and not a forecast. Evidence grades reflect the published balance of evidence as surveyed here and may shift as the field evolves.

Several pillars rest on **CONTESTED** results (the modern Wilcox-effect analyses; parts of the cosmoclimatology programme); broad independent replication is the missing ingredient, and its absence is itself a finding.

Magnitude, not mechanism, is the recurring gap. Many of these mechanisms are physically real at the process scale; what is unproven is that they integrate to a globally significant radiative forcing. The treatment of deep-time and geomagnetic claims depends on proxy reconstructions with large uncertainties and contested causal direction.

Where corpus papers were available only as metadata at the time of writing, claims were kept at the level the abstract and the secondary literature support; quote-level use awaits full-text ingestion.

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