Temporal Clustering is Universal in Environmental Data: A Cross-Domain Inter-Event Time Analysis

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We apply the coefficient of variation (CV) of inter-event times to 12 environmental event streams spanning seismology, space weather, radiation monitoring, air quality, hydrology, and oceanography. Using 229,876 events from government and scientific data sources, we find that **every domain exhibits temporal clustering** ($CV > 1.0$), rejecting the homogeneous Poisson null hypothesis across all tested metrics. Clustering strength varies by two orders of magnitude, from mild (earthquakes $M4+$, $CV = 1.17$) to extreme (radiation measurements, $CV = 238$). Space weather events show consistently strong clustering ($CV = 17$–61), while seismic events show the weakest clustering ($CV = 1.2$–1.3). Higher event severity thresholds produce stronger clustering across all domains, suggesting that extreme events share common drivers that produce sequences. These findings challenge the independence assumptions underlying many environmental hazard models.

INTRODUCTION

The assumption that environmental hazard events occur as a homogeneous Poisson process — randomly and independently in time — is foundational to many risk assessment frameworks [1]. Under this assumption, the inter-event times follow an exponential distribution with coefficient of variation $CV = 1.0$. Deviations indicate temporal clustering ($CV > 1$) or quasi-periodic behavior ($CV < 1$).

While temporal clustering has been extensively studied in seismology through aftershock analysis and the Epidemic-Type Aftershock Sequence (ETAS) model [2, 3], and in solar physics through flare waiting-time distributions [5], systematic cross-domain comparisons using a unified methodology are absent from the literature. This paper applies the same inter-event time analysis to 12 event streams across six environmental domains, creating a "clustering atlas" that enables direct comparison of temporal structure across disciplines.

DATA

All data are sourced through the TerraPulse climate intelligence platform (`https://terrapulse.info`), which ingests and normalizes observations from government and scientific APIs including USGS, NOAA SWPC, NASA DONKI, Safecast, and Open-Meteo. The platform maintains over 6 million observations across 83 data sources. Table I summarizes the 12 event streams analyzed.

TABLE I. Event streams analyzed, defined by metric-specific thresholds.

Event Stream	N	**Source**
Earthquakes $M \geq 4.0$	82,189	USGS
Earthquakes $M \geq 5.0$	9,836	USGS
Earthquakes $M \geq 6.0$	836	USGS
Kp storms ($Kp \geq 4$)	12,804	NOAA SWPC
Kp major ($Kp \geq 5$)	5,914	NOAA SWPC
CME events	9,043	NASA DONKI
Fast CMEs ($v \geq 500$ km/s)	1,787	NASA DONKI
Solar flares ($\geq$ M-class)	874	NASA DONKI
Radiation (≥ 50 CPM)	92,412	Safecast
AQI unhealthy (≥ 100)	869	Open-Meteo
High streamflow ($\geq$ 10K cfs)	11,266	USGS Water
High waves ($\geq$ 3m)	1,066	Open-Meteo

METHOD

For each event stream of n events with ordered timestamps $\{t_1, t_2, \ldots, t_n\}$, we compute the inter-event times $\Delta t_i = t_{i+1} - t_i$ and the coefficient of variation:

$$CV = \frac{\sigma_{\Delta t}}{\mu_{\Delta t}} \tag{1}$$

For a homogeneous Poisson process, $CV = 1.0$ exactly [1]. As a complementary test, we compute the dispersion index $D = s_n^2/\bar{n}$ of daily event counts, which follows approximately χ^2_{N-1} under the Poisson null.

RESULTS

All 12 event streams show $CV > 1.0$ (Table II, Fig. 1). No domain exhibits Poisson-like or regular temporal structure.

Seismic events show the weakest clustering ($CV \approx 1.2$–1.3), consistent with Omori-law aftershock sequences [4] superimposed on quasi-random background seismicity. CV increases with magnitude threshold, indicating that larger events cluster more strongly.

FIG. 1. Coefficient of variation (CV) of inter-event times across 12 environmental event streams, grouped by domain. The dashed line marks $CV = 1.0$ (Poisson). All streams show $CV > 1.0$, indicating universal temporal clustering. Color indicates domain: red = seismic, orange = space weather, purple = radiation, gray = air quality, teal = hydrology, blue = ocean.

TABLE II. Temporal clustering results. All streams show $CV > 1.0$.

Event Stream	CV	D	Class
Earthquakes $M4+$	1.17	30	Mild
Earthquakes $M5+$	1.30	25	Mild
Earthquakes $M6+$	1.32	22	Clustered
Kp storms (≥ 4)	60.6	1336	Strong
Kp major (≥ 5)	55.8	903	Strong
CME events	21.5	800	Strong
CME fast	20.1	110	Strong
Solar flares (M+)	17.1	72	Strong
Radiation (≥ 50)	238	542	Extreme
AQI unhealthy	5.0	42	Clustered
High streamflow	10.7	280	Strong
High waves ($\geq$ 3m)	3.9	43	Clustered

Space weather events exhibit strong clustering (CV = 17–61) driven by solar active region persistence across multiple 27-day rotation periods [5]. The Kp index shows the strongest clustering ($CV = 60.6$) due to its bimodal distribution between quiet and storm states.

Radiation measurements ($CV = 238$) show extreme clustering driven by observational rather than physical factors — citizen-science volunteers collect dense measurements during campaigns, creating temporal bursts. This represents a methodological caution: extreme CV values may indicate sampling bias.

Atmospheric and oceanic events (CV = 4–11) show moderate clustering consistent with synoptic weather pattern persistence on 3–7 day timescales.

DISCUSSION

The universality of temporal clustering has practical implications for environmental risk assessment. Models that assume event independence — including standard return-period calculations — systematically underestimate the probability of event sequences [6]. The CV provides a simple, interpretable diagnostic that should be routinely reported alongside event catalogs.

The two-order-of-magnitude range in CV values reflects fundamentally different clustering mechanisms: tectonic stress transfer (seismic), active region evolution (space weather), weather pattern persistence (atmospheric/oceanic), and measurement campaign structure (radiation). Distinguishing physical from observational clustering is essential for correct interpretation.

CONCLUSION

Temporal clustering is universal in environmental data. Across 12 event streams in 6 domains, totaling 229,876 events, no metric follows a homogeneous Poisson process. We recommend that environmental hazard assessments routinely report the CV of their event catalogs as a minimal diagnostic of temporal structure. All data and analysis code are available at `https://terrapulse.info` and `https://github.com/isenbek/terrapulse`.

Data sourced from USGS, NOAA SWPC, NASA DONKI, Safecast, and Open-Meteo via the TerraPulse platform. Built with Python, SciPy, Polars, and Plotly.

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