Geometric AI for Climate-Resilient Heritage

Riemannian Trajectory Learning for Predictive Monitoring

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01 • Research Problem

Climate-driven deterioration emerges from **coupled and nonlinear interactions** among moisture, heat, pollution, vegetation and terrain. Conventional Euclidean sequence models often learn each stressor independently and therefore miss the geometry of their joint evolution.

Objective: Forecast a 12-month ***Environmental Degradation Pressure Index (EDPI)*** for heritage sites across Greece.

Core idea: Represent environmental change as a trajectory on the manifold of **Symmetric Positive Definite (SPD) matrices**.

Decision value: Detect acceleration in latent stress before visible damage or threshold exceedance.

02 • Multi-Sensor Data Fusion

Monthly Earth-observation features are harmonized for **49 cultural heritage sites** (in 12 distinct regions) using Google Earth Engine.

- **Sentinel-1 SAR**: surface moisture and backscatter dynamics.
- **Sentinel-2 optical**: NDVI, NDBI and spectral condition indices.
- **Sentinel-5P**: tropospheric NO_2 exposure.
- **ERA5-Land**: temperature, precipitation and moisture anomalies.
- **NASA DEM**: elevation, slope and terrain context.

Model input

Site-level sequences $X_{1:T} \in \mathbb{R}^{T\times d}$ are standardized by sensor and aligned to a common monthly timeline.

03 • Geometric Representation

A recurrent encoder produces hidden states h_t. Each state is mapped to a symmetric matrix M_t and projected onto the SPD manifold through the matrix exponential:

$$S_t = \tfrac{1}{2}(M_t + M_t^\top),\ P_t = \exp(S_t) \in \mathrm{Sym}_n^+.$$

The Log-Euclidean distance between successive states is:

$$d_{\mathrm{LE}}(P_t, P_{t-1}) = \|\log P_t - \log P_{t-1}\|_F .$$

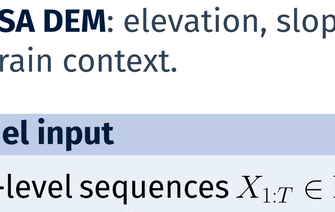

Figure 1. Environmental states form a temporally ordered trajectory on Sym_n^+.

04 • Primary Result: Geodesic Riemannian Velocity

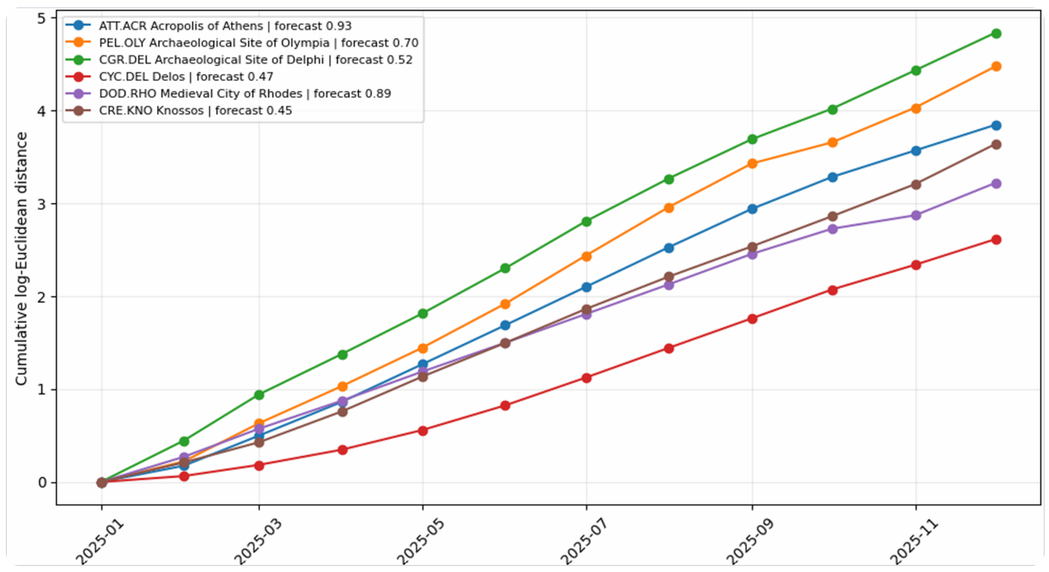

Figure 2. Cumulative geodesic distance acts as a latent measure of accumulated environmental stress. Urban sites such as the Acropolis diverge from lower-exposure controls. Steeper curves indicate faster change in the model's latent environmental state

One-year-ahead forecasting
12-month horizon
evaluated on sites held out from model training.

05 • Predictive Performance

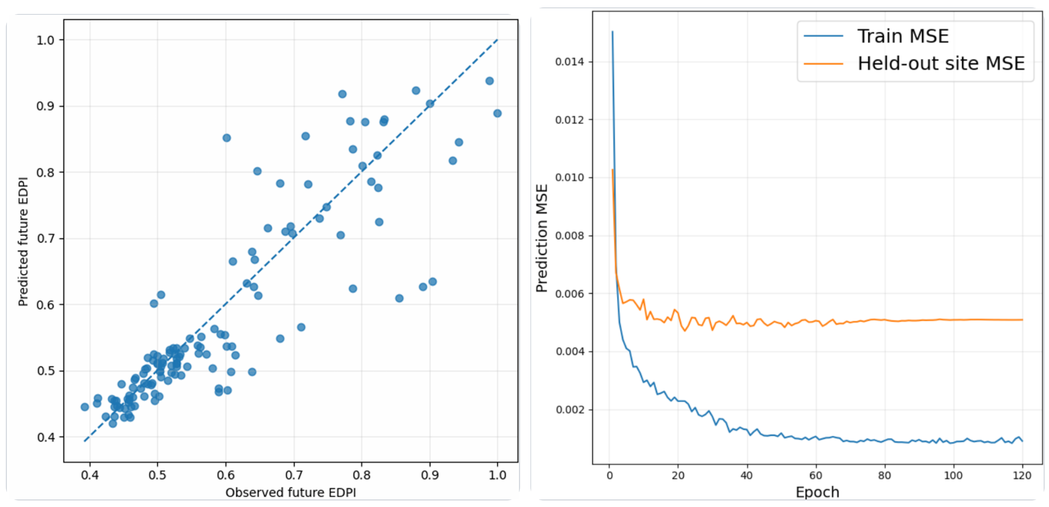

Figure 3a. Observed versus predicted future EDPI for held-out sites.

Figure 3b. Training and held-out-site prediction MSE across epochs.

Key finding: Forecasts were most reliable at low-to-moderate EDPI, while high-pressure episodes produced the largest errors.

49	$R^2 = 0.753$	0.045	0.071
sites	held-out fit	test MAE	test RMSE

06 • Stressor Attribution

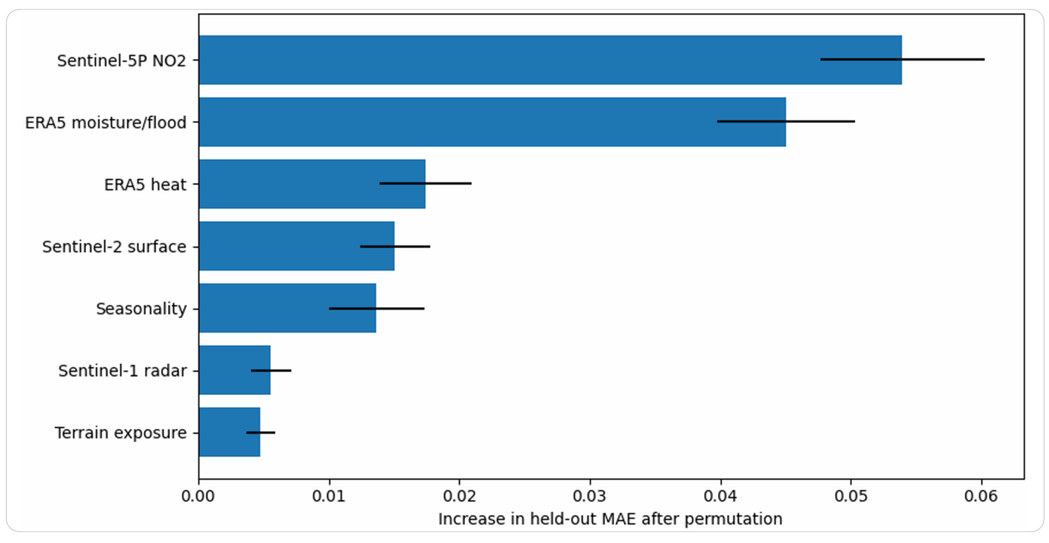

Figure 4. Permutation importance identifies the variables most responsible for forecast degradation when perturbed.

- Sentinel-5P NO_2 captures urban pollution exposure.
- ERA5-Land moisture captures wetting–drying cycles.
- Terrain modifies drainage, heat loading and local sensitivity.

07 • National Risk Forecast

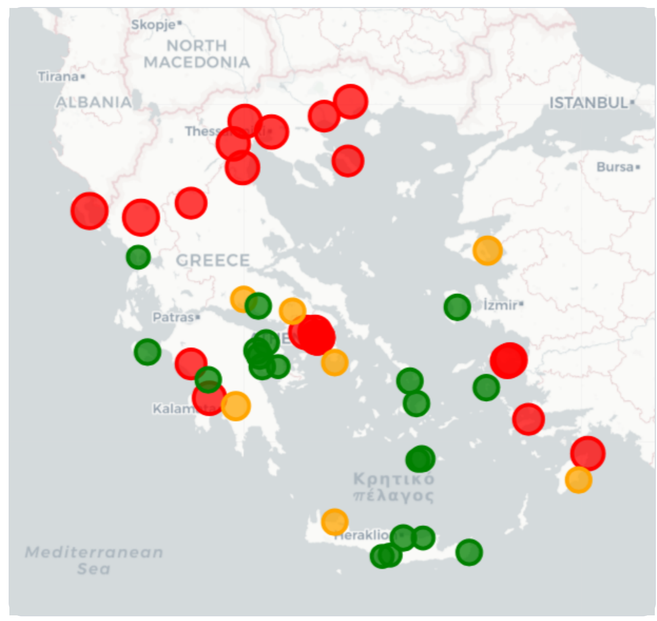

Figure 5. Greece-wide one-year-ahead predicted EDPI. Marker colour indicates the predicted environmental-pressure category, while marker size reflects forecast magnitude.

08 • Training Objective and Pipeline

Prediction accuracy is balanced with trajectory regularity:

$$\mathcal{L} = \mathcal{L}_{\mathrm{pred}} + \lambda_{\mathrm{geo}}\mathcal{L}_{\mathrm{smooth}},$$

$$\mathcal{L}_{\mathrm{smooth}} = \sum_{t=2}^{T-1} \|\log P_{t+1} - 2\log P_t + \log P_{t-1}\|_F^2 .$$



Low curvature indicates stable evolution; **high curvature** indicates a regime change; and **high velocity** signals rapid accumulation of coupled stress.

09 • Regional Context

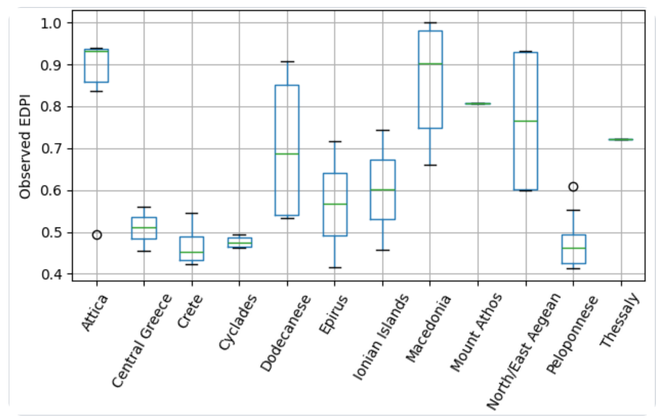

Figure 6. Distribution of the latest observed EO-derived EDPI across Greek regions. This figure describes regional environmental-pressure context, not direct material condition.

10 • Validation and Impact

- **Geometric advantage**: captures interaction stress missed by independent Euclidean features.
- **Operational scalability**: one harmonized workflow across 49 diverse Greek sites.
- **Preservation value**: supports inspections and transparent conservation priorities.

Take-home message

The **shape, speed and curvature** of a site's latent environmental trajectory provide an interpretable early-warning signal for climate-resilient heritage management.

Project Links

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Explore the preceding study and run the fully reproducible notebook.

Preceding Work

</> Colab Notebook