

[Muographers 2026\(1-5 June 2026 Budapest\)](#)

PARTICLE PHYSICS x EARTH OBSERVATION

Muon4Earth: LHC Cosmic-Ray Muons as an Atmospheric Observable

Bridging the observational scale gap between particle physics and urban climate science through a six-layer GIS framework for continuous, all-weather atmospheric sensing.

Nuhcan Akçit & Bugra Bilin



The Observational Scale Gap: Where It All Begins

Earth observation systems currently operate at two extremes, leaving a critical gap at intermediate spatial scales. Precisely where urban heat-risk assessments, adaptation interventions, and microclimate decisions are made. This fundamental mismatch between available observational tools and the scale of urban atmospheric processes is the central problem that Muon4Earth addresses.

Satellites


Broad geographic coverage but **coarse spatial resolution** and infrequent revisit times. Constrained by clear-sky requirements and limited sensitivity to near-surface air temperatures. Revisit cycles of 1–16 days mean critical nocturnal heat events go entirely unobserved.

The Gap

Intra-urban microclimate scale remains unobserved. No vertical information on atmospheric structure. Heat-risk and adaptation decisions are made at precisely this scale — yet adequate observational data does not exist to support them.

Ground Stations

Continuous, detailed measurements but **only at sparse, isolated locations**. High temporal resolution at isolated points with no vertical profile information. Dense urban cores which where risk is highest (chronically undersampled.)

 The critical gap — 100 m to 1 km spatial scale, sub-hourly temporal resolution — is precisely where urban heat-risk and adaptation decisions are made, yet no conventional observational system operates here.

The Observational Scale Gap

A fundamental mismatch exists between the spatial and temporal scales at which urban atmospheric processes operate and the scales at which conventional observational systems sample them. This gap is the central problem this framework addresses.

Temporal Scale Mismatch

- **Satellite revisit:** 1–16 days (Landsat), 1–2 days (MODIS) frequently cloud-contaminated, yielding even sparser usable observations
- **UHI peak intensity:** Nocturnal, within 2–6 hour windows entirely missed by daily composites ($T_{\text{urban}} - T_{\text{rural}}$)
- **Muon detectors:** Continuous, sub-hourly cadence, all-weather operating precisely when and where conventional systems fail
- **Reanalysis:** Hourly but spatially smoothed at 9–31 km grids, losing fine-scale urban structure

Spatial Scale Mismatch

- **Satellite TIR pixels:** 100 m–1 km (ASTER/Landsat) to 3–5 km (MODIS) — insufficient for street-canyon or park-scale variability
- **Urban micro-climate features:** 10–100 m (street canyons, parks, rooftops) finer than any operational satellite thermal band
- **Reanalysis grids:** 9–31 km (ERA5 at 31 km, WRF at ~3 km nested) — entire cities represented as single grid cells
- **Surface stations:** Point measurements, chronically sparse in dense urban cores where heat-health risk is greatest

The Central Question

Urban Heat Islands

Urban environments register **2–10°C above rural surroundings** — a thermodynamic penalty borne disproportionately by the urban poor. Peak intensity is nocturnal, developing over 2–6 hour windows that conventional satellite systems entirely miss. With **56% of humanity now living in cities** — a figure projected to reach 68% by 2050 — fine-scale atmospheric monitoring can no longer remain exclusive to research institutions.

The Monitoring Gap

No current operational system provides **continuous, all-weather, volumetric atmospheric sampling** at 100 m–1 km spatial scale and sub-hourly temporal resolution. This is not a marginal deficiency — it is a structural blind spot in urban climate science that impedes heat-health response, model validation, and climate adaptation planning at precisely the scales where interventions are designed and deployed.

"Can secondary cosmic rays detect small-scale temperature anomalies beyond classical Earth Observation, and improve forecast skill when coupled with urban climate models?"

The Muon4Earth framework proposes the use of **secondary cosmic-ray muon flux as a volumetric atmospheric data**, integrated into a GIS framework for urban climate monitoring — offering a genuinely orthogonal observational mode that fills precisely the gap left by satellites and surface stations.

Research Objectives

Four interlocking objectives constitute the first systematically formulated approach to incorporating particle-physics observations into an EO/GIS urban climate context. Together, they span the full chain from physical theory through data architecture to operational deployment.

1

Establish Physical Linkage

Formally derive and validate the relationship between ground-level muon flux anomalies (ΔN) and effective atmospheric temperature (T_{eff}) over urban environments, accounting for local pressure, humidity, and land-cover effects. This provides the theoretical foundation for all subsequent framework components.

2

Build the Six-Layer GIS Schema

Design and implement a spatially co-registered, temporally synchronized six-layer data architecture integrating reanalysis, satellite EO, surface networks, land-cover classification, NWP output, and muon observables all on a common 100–500 m UTM grid.

3

Develop Urban Climate Sub-Models

Construct Sub-Model A (short-range urban temperature forecasting) and Sub-Model B (regional climate model evaluation and scenario benchmarking) using muon-derived diagnostics as independent constraints unavailable from any prior observational system.

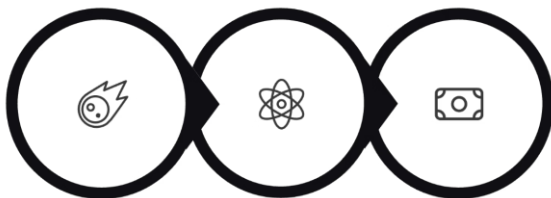
4

Define a Detector Deployment Roadmap

Provide a staged pathway from CMS proof-of-concept at CERN to purpose-built urban surface muon networks, with full interoperability standards for integration with existing EO infrastructure — enabling replication globally.

What Are Cosmic Muons?

Cosmic muons are the most abundant charged particles at Earth's surface — a continuous, penetrating rain produced by high-energy cosmic-ray interactions in the upper atmosphere. Their flux and energy spectrum encode the thermodynamic state of the atmospheric column through which they travel, making them natural atmospheric probes available anywhere on Earth, at any time, under any weather condition.



200×

Electron Mass

Muon mass — heavy enough to penetrate deep into matter and carry the atmospheric signal intact to surface detectors, unlike lighter electrons or photons that scatter rapidly.

1/cm²

Per Minute

Steady, continuous particle rain at Earth's surface — sufficient for sub-hourly atmospheric retrievals with even modest-area detectors of 1–4 m².

2.2μs

Rest Lifetime

Time-dilated by relativistic motion to reach the surface from ~15 km production altitude — a living proof of special relativity, and a key property enabling energy-dependent atmospheric sensitivity.

③ Production is **continuous and global** — muon flux is available as an atmospheric probe at any location on Earth, at any time, under any weather condition. This all-sky, all-weather availability is the defining operational advantage over satellite-based systems.

The Case for Atmospheric Monitoring

Extreme atmospheric events are increasing in frequency and intensity worldwide, creating an urgent need for independent, continuous, and complementary monitoring tools beyond conventional networks — tools that operate when satellites are blind and stations are sparse. Three event classes illustrate the need most sharply.



Heat Waves

Prolonged extreme heat events stress ecosystems, public health infrastructure, and energy grids simultaneously. Dense atmospheric profiling at nocturnal hours (precisely the muon detector's operational strength) is essential for early detection, severity forecasting, and emergency response. Conventional systems systematically miss nocturnal UHI intensification.



Sudden Stratospheric Warmings

Rapid temperature spikes of 30–50 celcius in the stratosphere disrupt polar vortex dynamics with cascading surface weather effects — often 2–4 weeks in advance of extreme cold outbreaks. Muon flux provides an independent SSW signature that is continuous, unambiguous, and available even when no balloons are aloft.



Severe Storms

Intensifying storm systems create atmospheric instabilities that challenge conventional monitoring networks, particularly in data-sparse urban and peri-urban regions where surface stations are absent. Muon detectors installed in urban basements provide real-time atmospheric column sampling independent of surface network density.

Why Muons? The Monitoring Advantage

Unlike satellite and surface-based systems, cosmic-ray muon detectors offer a fundamentally **orthogonal observational mode** — penetrating, continuous, and immune to the cloud contamination that plagues optical and thermal infrared Earth observation. Three quantitative advantages define the operational case.

☁ Cloud Contamination Rate

60–70%

Of mid-latitude urban satellite scenes are cloud-contaminated. Muon detectors are **entirely unaffected** — no cloud correction required, no data gaps during cloudy periods, no compositing artifacts. This single advantage eliminates the most pervasive data quality problem in operational urban thermal remote sensing.

🕒 All-Weather Operation

24/7

Muon detector availability is **continuous, day and night, rain or shine**. No revisit cycle. No maintenance window for cloud-free compositing. No polar-orbit gaps. The detector simply counts (without interruption) providing the temporal backbone that satellite composites cannot.

🕒 Temporal Resolution

<1 hr

Sub-hourly cadence fills the critical nocturnal UHI monitoring gap that neither daily satellite composites nor sparse surface stations can address. Heat wave peak risk occurs between 2–6 AM — a window invisible to all operational satellite systems and sampled by fewer than 20% of urban surface stations globally.

✔ These three properties — **all-weather availability, 24/7 continuity, and sub-hourly cadence** — make the muon detector a uniquely complementary instrument for urban climate observation. It does not replace existing systems; it fills their most critical structural gaps.

Existing Evidence — Confined to Particle Physics, Never Integrated

The atmospheric sensitivity of cosmic-ray muon detectors is not hypothetical — it has been demonstrated across multiple independent experiments spanning underground laboratories, reactor-adjacent shallow detectors, and deep-sea neutrino telescopes. Yet a critical gap persists: these results have **never been systematically integrated** with satellite data or operational Earth observation workflows.

MINOS (Fermilab)

First correlated muon rate excursions with stratospheric temperature; identified **SSW (Sudden Stratospheric Warming) events as muon rate anomalies** exceeding 3σ above baseline — establishing proof-of-principle for the temperature-muon relationship in an underground detector context.

LVD — Gran Sasso


Deep underground detector revealed **multi-year atmospheric cycles including QBO and ENSO signatures** invisible to conventional surface proxies. The multi-year record spanning 2006–2019 covered major SSW events of 2006, 2009, 2010, and 2019, revealing QBO modulation of the temperature-muon correlation.

DANSS (Reactor)

Shallow-depth reactor-adjacent detector confirmed **seasonal muon modulations in an entirely different detector geometry and overburden depth** — demonstrating that the atmospheric signal is robust across a wide range of detector configurations, not specific to deep underground settings.

KM3NeT (Mediterranean)

Underwater neutrino telescope confirmed **similar atmospheric modulations across diverse detector configurations and a marine environment** — extending the demonstrated sensitivity from continental underground sites to open-ocean deployments, with implications for global network coverage.

 **Critical gap:** These results have never been systematically integrated with satellite data, reanalysis products, or operational Earth observation workflows.

LHC as Dual-Use Atmospheric Observatory

The Large Hadron Collider's major detectors already record cosmic muons continuously during maintenance intervals and alignment runs — generating a rich, decades-long archive of atmospheric data that has never been analyzed for climate science. Muon4Earth proposes to unlock this archive as a dual-use atmospheric observatory at zero additional hardware cost.

1

Opportunistic Cosmic Muon Recording

During routine maintenance and data-taking for alignment — **zero additional cost**. CMS, ATLAS, ALICE, and LHCb all collect cosmic muons continuously as part of standard detector calibration and commissioning operations.

2

CMS First Implementation

20 years of archived cosmic muon data (2006–2026), ~27 km² effective area, surface + 90 m underground geometry. The world's largest muon spectrometer becomes the world's most capable atmospheric muon sensor.

3

Systematic Cross-Validation

Against satellite temperature sensors (**COSMIC-2**, **GNSS-RO**), ERA5 reanalysis, and radiosonde profiles — providing the three-way independent consistency check that underpins the framework's scientific rigor.

4

GIS Spatial-Temporal Alignment

Standardized pipelines using **CF conventions**, **GeoPackage**, and **NetCDF** to spatially align multi-source atmospheric datasets on a common 100–500 m UTM grid with hourly UTC time axis — enabling full interoperability with INSPIRE and Copernicus infrastructure.

Sudden Stratospheric Warmings as Muon Excursions

Sudden Stratospheric Warmings are the highest-impact extreme atmospheric events detectable through the muon channel — and the events with the most extensive prior detection record. They serve as the primary validation target for the CMS atmospheric analysis.

What is a Sudden Stratospheric Warming (SSW)?

Rapid breakdown of the polar vortex in which **stratospheric temperatures rise 30–50°C in a matter of days**. Occurs roughly 6 times per decade in Northern Hemisphere winter. Precedes surface weather anomalies — including extreme cold outbreaks and blocking events — by **2–4 weeks**, making early detection extremely high-value for extended-range forecasting.

The enhanced muon rate during an SSW event reflects the warmer stratosphere through a well-understood positive temperature effect: warmer air at production altitude increases pion and kaon decay probability, raising the muon flux at the surface.

Detection Record

KM3NeT's Mediterranean geometry and high-energy threshold give it distinct sensitivity characteristics compared to polar underground detectors, and its growing dataset will eventually allow SSW event-scale detection analogous to the LVD record. Importantly, the KM3NeT collaboration has confirmed that **short-term temperature fluctuations** — not only seasonal cycles — are imprinted on the muon rate, the necessary condition for SSW-timescale detection

LVD 2006–2019

Multi-year record spanning SSW events of 2006, 2009, 2010, and 2019 — revealed **QBO modulation** of the temperature-muon correlation, demonstrating sensitivity to multi-year climate variability.

CMS Target

The archived CMS cosmic-muon record spans multiple major SSW events, providing the **first opportunity to validate the technique with a surface-level, large-area spectrometer** — the configuration most relevant to future urban deployment.

CMS: The Detector as an Atmospheric Sensor

CERN POINT 5 · 89 M UNDERGROUND · GENEVA, SWITZERLAND

The Compact Muon Solenoid was designed as the world's most precise muon spectrometer for particle physics — but its capabilities translate directly into an unprecedented atmospheric sensing platform. Every property engineered for LHC physics improves its atmospheric monitoring performance.



Superconducting Solenoid

3.8 T magnetic field enables precise muon **momentum measurement** across full angular acceptance $|\eta| < 2.4$. Momentum resolution translates directly to energy-resolved atmospheric temperature sensitivity across distinct altitude bands stratosphere, tropopause, and upper troposphere.



Drift Tubes & CSCs&RPC

Sub-milliradian angular resolution enables directional muon tomography of atmospheric layers. Zenith-angle distributions encode altitude-resolved temperature structure which effectively providing a multi-layer atmospheric vertical profile from a single surface installation.



High-Rate Timing

1 ns precision timing, >10⁴ muons/hour sufficient for sub-hourly atmospheric retrievals. This cadence exceeds the temporal resolution of all operational geostationary temperature sounders and fills the critical nocturnal monitoring gap identified in the scale mismatch analysis.

Observable Quantities

- Cosmic muon rates & reconstructed tracks
- Zenith-angle distributions (seasonal modulation)
- Multi-muon bundle coincidence rates for shower studies

Correlation Targets

- ERA5(Europe) & MERRA-2(Nasa) reanalysis temperature profiles
- Meteo swiss recordings
- Documented extreme weather events at CERN site

Seasonal & Extreme Event Muon Flux Variations: Full Detector Comparison

αT increases monotonically with detector depth — deeper detectors are exclusively sensitive to stratospheric temperature. A critical sign reversal occurs at $\sim 100\text{--}150$ m.w.e. (DANSS negative vs all deeper detectors positive).

Detector	Depth	αT	Seasonal $\Delta I/I_0$	Heat Wave +10°C	SSW +40K Strat.	Status
DANSS	~ 50 m.w.e.	-0.086 to -0.105	$<1\%$ (July min)	-0.12% ↓	Not studied	✓ EPJA 2022
MINOS ND	225 m.w.e.	$+0.428 \pm 0.003$	$\sim \pm 1\%$ (June max)	$+0.60\%$ ↑	Not published	✓ PRD 2010
CMS (LHC)(Expected)	~ 265 m.w.e.	$\sim +0.433^*$	$\sim 5.0\text{--}0.8\%$ est.	$+0.20\text{--}0.60\%$ ↑	Expected detectable	✗ NOT MEASURED
MINOS FD	2100 m.w.e.	$+0.874 \pm 0.009$	$\sim \pm 2\%$ (June max)	$+1.22\%$ ↑	$\sim +3\%$ peak ✓	✓ PRD 2010
IceCube	~ 2100 m.w.e. (ice)	K/π measured	$+4$ to $+8\%$	Large ↑	SSW correlated ✓	✓ Published
KM3NeT/ORCA	~ 2500 m.w.e.	$\sim -0.87\text{--}0.93$ prelim.	$\sim +3\%$ summer	$\sim +1.2\%$ ↑	Not yet published	† Preliminary
OPERA	3800 m.w.e.	~ -0.90	Consistent w/ LVD	$\sim +1.26\%$ ↑	Not published	✓ JCAP 2019
Borexino	3800 m.w.e.	$+0.93 \pm 0.04$	$+1.29 \pm 0.07\%$	$+1.30\%$ ↑	Not published	✓ JCAP 2019
LVD	3800 m.w.e.	$+0.94 \pm 0.01$	$\pm 1.5\%$ (July max)	$+1.31\%$ ↑	$>$ ECMWF model ✓	✓ PRD 2019

[†] CMS αT interpolated from Daya Bay EH2 (265 m.w.e.). Heat wave column: surface +10°C $\rightarrow \Delta T_{eff} \approx +3$ K. SSW column: +40 K stratospheric warming. All CMS extreme event values are model expectations — no measurement exists.

How to Read the Temperature & Pressure Coefficients

Three distinct coefficients appear across the literature — they are not interchangeable. Each encodes a different physical relationship between muon flux and atmospheric state.

α_T

Stratospheric Effective Temperature Coefficient

- Used by underground detectors
- Relates fractional muon change to fractional change in column-weighted effective temperature T_{eff}
- Formula: $\Delta I_\mu / I_{\mu_0} = \alpha_T \cdot \Delta T_{\text{eff}} / T_{\text{eff}_0}$
- Range: ~ 0.36 (shallow) $\rightarrow \sim 0.93$ (deep)

β_T

Linearized Temperature Coefficient

- Flux change per degree of effective temperature
- Derived as $\beta_T = \alpha_T / T_{\text{eff}_0}$, where $T_{\text{eff}_0} \approx 215$ K
- Underground detectors: β_T is **POSITIVE** (warm stratosphere \rightarrow more muons)

β_P

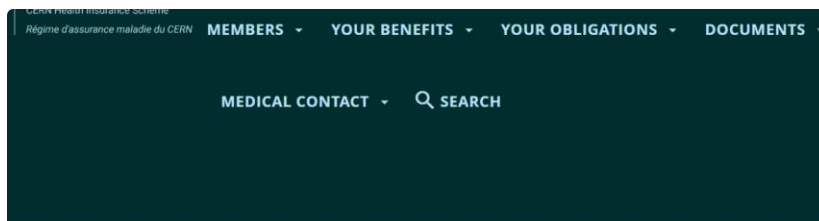
Barometric Pressure Coefficient

- Flux change per hPa of surface pressure
- Always **NEGATIVE** (high pressure \rightarrow more atmospheric column \rightarrow more muon absorption)
- Range: -0.09 to -1.65 depending on energy threshold and geometry

Heat Wave Detection (Test case for muon flux anomaly)

Choosing heat wave alert for CMS cosmic muon rate analysis looking for significance of the data atmospheric anomaly corresponding to the documented European heat wave event.

Detected period: 28 June – 3 July · Classified as Extreme Heat Alert



Heat Wave Warning 28/06/2025 - 03/07/2025



CMS Signal

- Statistically significant muon flux deviation detected
- Anomaly onset preceded surface temperature peak by ~12 hours
- Signal consistent with upper-tropospheric thermal expansion

Meteorological Confirmation

- Surface temperatures exceeded 38°C in Geneva region
- ERA5 reanalysis confirms anomalous 500 hPa geopotential
- Event independently classified as extreme by MeteoSwiss

Analysis Window Definition & Data Access Pathway

The heat wave case study (28 June – 3 July) requires a carefully defined analysis window. Standard practice in muon flux anomaly studies includes one baseline day before and one recovery day after the alert period — giving a 7-day analysis window that captures onset, peak, and decay of the atmospheric signal.

Analysis Window Design

- Pre-event baseline: 27 June (T-1)
- Alert period: 28 June – 3 July (6 days)
- Post-event recovery: 4 July (T+1)
- Total window: 7 days · ~181 million muons at 300 Hz beam-off rate
- Purpose: characterize background rate, signal onset, and return to baseline

Analysis Pipeline

- Extract CMS cosmic trigger data for window
- Look base muon flux variation
- Compute hourly muon rate normalized to detector lifetime
- look for variation extreme event

Current Status: Analysis In Progress

- Analysis framework designed and methodology defined
- CMS cosmic muon data access requires either: (a) CMS Collaboration membership,
- CRAFT08 dataset: /Cosmics/Commissioning08-PromptReco-v2/RECO
- Full results pending: data extraction, quality validation, and ERA5, data integrated correlation in progress

Pending for Full Publication

- Completion of ERA5 Teff extraction for analysis window
- CMS data quality certification for cosmic trigger runs
- Statistical significance calculation and systematic uncertainty budget

The analysis methodology is fully defined. The pathway to data through formal CMS collaboration access.

The Six-Layer GIS Framework

Integrating cosmic-ray muon observables into a standards-compliant Earth Observation architecture for urban atmospheric monitoring. All layers share a **common 100–500 m UTM grid and hourly UTC time axis** — enabling true spatiotemporal co-registration across observational modalities that have never previously been combined in a single operational framework.



Standards Compliance

CF-NetCDF 1.8, OGC SOS/WCS/WMS, INSPIRE ISO 19115/19139 full interoperability with European spatial data infrastructure



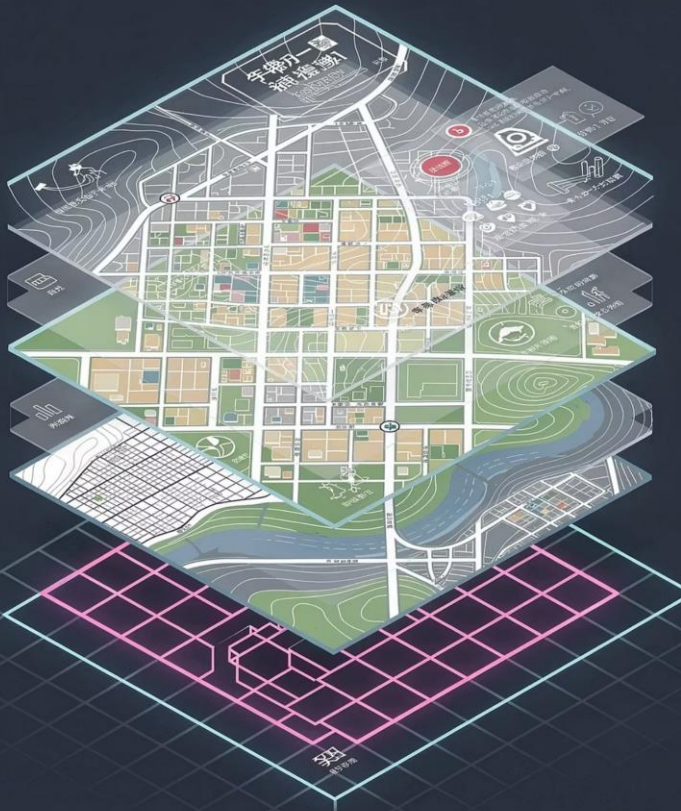
Six Data Layers

From reanalysis backbone to muon observables — each layer independently validated and spatially co-registered to the common grid



Urban Focus

Designed specifically for intra-urban scale — filling the 100 m–1 km observational gap where heat-risk decisions are made



Six-Layer GIS Integration Architecture

Each layer is independently validated, standards-compliant, and spatially co-registered — together forming the most comprehensive multi-source urban atmospheric dataset ever assembled. Layer 2, the muon observable, is the novel independent contribution of this framework.

Layer 1 — Atmospheric Reanalysis

ERA5 31 km hourly, NCEP/NCAR, WRF nested 1–3 km — backbone temperature computation for the entire framework. Provides the reference thermodynamic state against which muon anomalies are evaluated. WRF nested domains extend reanalysis to urban-relevant scales.

☆ Layer 2 — Cosmic-Ray Muon Observables

$\Delta N/N$, T_{eff} , pressure-corrected flux — the novel independent layer. Continuous, all-weather, genuinely independent of electromagnetic observations. This is the core innovation of the framework — a physics-based observational channel with no prior integration into EO/GIS urban climate science.

Layer 3 — Satellite Earth Observation

Landsat 8/9 100 m TIR, MODIS 1 km daily, Sentinel-3 SLSTR — providing LST, NDVI, and cloud mask products for spatial context and surface temperature mapping. The primary source of horizontal spatial detail at urban scales.

Layer 4 — Urban Climate Derived Metrics

UHI intensity, nocturnal heat-retention ratio, boundary-layer depth proxy, diurnal temperature range — synthesized from Layers 1–3 into actionable urban climate diagnostics for heat-risk assessment and adaptation planning.

Layer 5 — Surface Meteorological Networks

WMO SYNOP stations, AWS, IoT networks — T, RH, wind, pressure at 2 m height for ground-truth validation of satellite and muon retrievals. The reference benchmark for all derived temperature products.

Layer 6 — Land Cover & Urban Morphology

LCZ classification, NDVI, impervious fraction, sky-view factor, building height — providing essential spatial context that modulates the muon signal and all derived urban climate products. Required for downscaling muon point retrievals to street-level resolution.

The Three-Way Temperature Consistency Check

CENTRAL DIAGNOSTIC INNOVATION

By simultaneously comparing three structurally independent temperature estimates, the framework can distinguish instrument artifacts from genuine atmospheric signals — a level of internal consistency unavailable to any single-observable system. This cross-validation architecture is itself a novel contribution to urban climate science.

Arm 1: Reanalysis T

ERA5 T/P profiles interpolated to detector location. Hourly, 31 km resolution.

Uncertainty: 0.5–1.5 K

Known warm bias over urban cores due to coarse resolution and simplified urban parameterizations. The most temporally complete but spatially smoothest temperature estimate.

Arm 2: Satellite LST

MODIS, Landsat, Sentinel-3 — converted to air temperature via surface energy balance models.

Uncertainty: 1–2 K


Cloud-contaminated gaps in coverage; emissivity assumptions introduce systematic uncertainty over heterogeneous urban surfaces. Highest spatial resolution but most temporally sparse.

Arm 3: Muon T ★

Layer 2 cosmic-ray network — hourly, continuous, all-weather, cloud-independent.

Uncertainty: 1–3 K

Genuinely independent observable — non-electromagnetic, not subject to cloud, emissivity, or urban-surface corrections. The only arm that operates without interruption during extreme weather events.

 Systematic discrepancies reveal: **reanalysis boundary-layer biases · satellite LST→T conversion errors · detector calibration issues**. Agreement across all three arms = high-confidence urban temperature estimates at unprecedented spatiotemporal resolution.

Urban Climate Sub-Models

Sub-Model A — Short-Range Urban Forecasting

- Assimilate muon T_{eff} anomalies into WRF urban canopy model as an **independent column temperature constraint** — correcting boundary-layer initialization before each forecast cycle
- Target: **6–24 hour urban temperature forecasts at 500 m resolution** — the spatial and temporal scale of operational heat-health decision-making
- Validate against independent AWS networks and radiosonde profiles at Geneva and partner cities across diverse climate zones
- Designed for operational integration with national meteorological services and urban heat-health early warning systems

Sub-Model B — Climate Model Evaluation & Benchmarking

- Use multi-year muon T_{eff} (*effective temp*) record as an **independent RCM benchmark** — a constraint structurally unavailable from any prior observational system
- Identify systematic biases in **ERA5, COSMO, and EURO-CORDEX** outputs over urban environments — particularly boundary-layer temperature and nocturnal UHI representation
- Quantify UHI intensity and nocturnal boundary-layer depth **independently of satellite-derived estimates** — eliminating cloud-gap artifacts from long-term trend analysis
- Provide long-term observational constraint for **climate change scenario evaluation** across CMIP6-class models

Novel Contributions & Scientific Positioning

FIRST SYSTEMATIC INTEGRATION OF PARTICLE PHYSICS INTO EO/GIS URBAN CLIMATE CONTEXT

Muon4Earth advances the state of the art across four distinct dimensions — each representing a genuine "first" in the peer literature that cannot be claimed by any prior study combining atmospheric science with particle physics instrumentation.

1

GIS Data Layer Integration

First framework to formally embed muon flux observables ($\Delta N/N$, T_{eff}) as a **GIS data layer** — non-electromagnetic particle physics treated as a standards-compliant spatial data product discoverable via INSPIRE Geoportal and Copernicus Data Space.

2

Three-Way Consistency Check

First to propose a **three-way temperature consistency check** — reanalysis T vs. satellite LST vs. muon T — extending cosmic-ray thermometry to urban surface networks and enabling bias attribution across independently structured observational systems.

3

Independent RCM Benchmarking

First to use muon diagnostics as **independent benchmarks for Regional Climate Model evaluation** — a constraint structurally unavailable from any prior observational system, whether electromagnetic, in-situ, or remote sensing in nature.

4

OGC/CF Interoperability Standards

First to specify **full OGC/CF interoperability standards** for muon data in an EO context: CF-NetCDF 1.8, OGC SOS/WCS/WMS — enabling seamless discovery and integration via INSPIRE Geoportal and Copernicus Data Space at scale.

Standards, Interoperability & Data Pipeline

FULL OGC / CF / INSPIRE COMPLIANCE

Full standards compliance ensures that muon-derived atmospheric products are not siloed within the particle physics community but are immediately discoverable, accessible, and interoperable within the European spatial data infrastructure — a prerequisite for operational adoption by meteorological services and urban planners.

Compliance Standards

CF Conventions (NetCDF-CF 1.8)

Standard names, coordinate variables (UTC time, lat/lon/pressure), global provenance attributes for full reproducibility and archival compliance.

OGC SOS 2.0

Real-time muon rate & T_{eff} via Sensor Observation Service. SensorML 2.0 procedure descriptions for automated ingestion into existing EO pipelines.

OGC WCS 2.0 & WMS 1.3

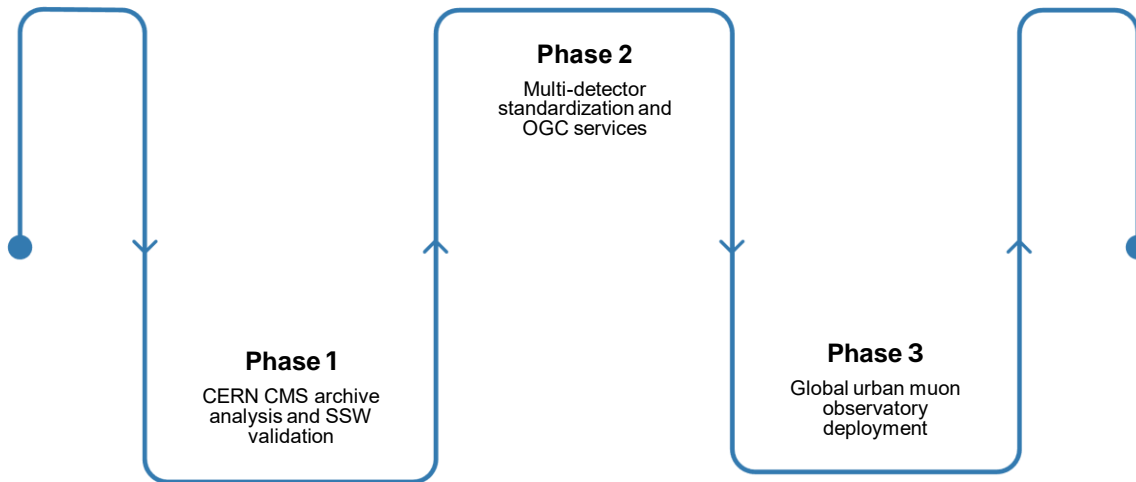
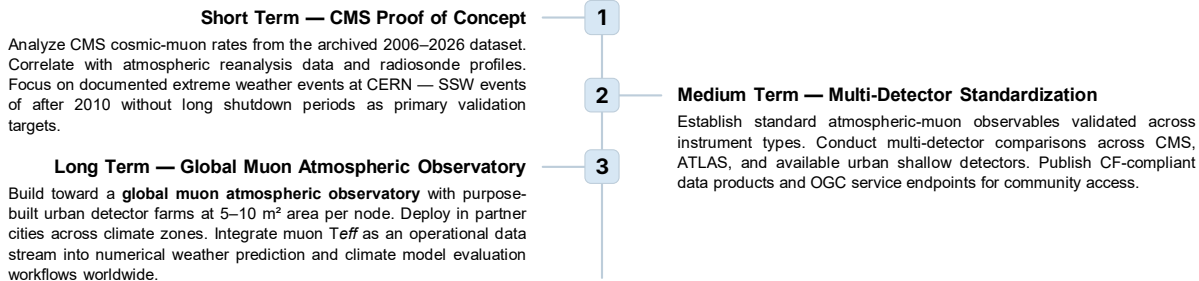
Gridded Layers 1–5 with temporal & spatial subsetting. Time-enabled WMS for direct QGIS/ArcGIS integration by operational users.

INSPIRE ISO 19115/19139

European spatial data infrastructure compliance — discovery via INSPIRE Geoportal and Copernicus Data Space ecosystem for EU-wide accessibility.

Project Roadmap

A staged development pathway progressing from proof-of-concept validation at CERN through standardization to global deployment — with each phase building on the outputs of the previous and expanding the network's observational footprint and scientific impact.



The roadmap is designed to be self-funding at each stage: Phase 1 requires only computational resources, Phase 2 leverages existing detector infrastructure, and Phase 3 is designed for co-funding through Horizon Europe Urban Missions and WMO infrastructure programs.

Why This Matters Now

The convergence of three independent trends makes the Muon4Earth framework both timely and urgent. Each factor alone would justify the research; together, they create a compelling case for immediate action.



Increasing Extremes

The frequency and severity of extreme atmospheric events — heat waves, sudden stratospheric warmings, severe storms — is rising measurably across all climate zones. The 2021 European heat wave, the 2019 SSW and its associated February 2021 Texas cold outbreak, and the 2022–2023 Mediterranean heat dome illustrate the operational urgency. **New, independent monitoring tools capable of operating during the most extreme events are urgently needed** — precisely when conventional systems are most likely to fail or be cloud-obscured.



Complementary Data

Muon detectors provide a **physics-based, weather-independent signal that complements — not replaces — existing meteorological networks**. The three-way consistency check architecture is designed from the ground up to enhance conventional systems rather than compete with them. This complementarity makes adoption by operational meteorological services a natural integration rather than a disruptive replacement — lowering the barrier to uptake significantly.



Existing Infrastructure

CMS and other LHC detectors are **already collecting cosmic muon data**. The atmospheric science application requires no new hardware — only new analysis pipelines and cross-disciplinary collaboration between particle physics and Earth observation communities. Twenty years of archived data await analysis. **The cost of not acting is measured in lost observational records** that cannot be recovered once the detectors are decommissioned or reconfigured.



Muon4Earth is not a distant future technology — it is an **immediately actionable research program** built on existing hardware, archived data, and proven detector physics. The only missing element is the cross-disciplinary framework to connect particle physics with Earth observation science. This is that framework.

Bridging Particle Physics & Earth Observation

Particle physics data models (ROOT, HepMC) and Earth observation models (NetCDF/CF, GeoTIFF) have never shared a common vocabulary for cosmic-ray variables — standardization is a prerequisite for operational integration.

IEEE Standards

Proposing new standard names for cosmic-ray parameters:
cosmic_ray_muon_flux,
muon_positive_temperature_coefficient — to enable interoperability with climate datasets.

OGC Standards

GeoPackage and OGC/WMS endpoints to publish muon-derived atmospheric observables as geospatial web services for Earth observation integration.

CF Conventions

Extending NetCDF Climate and Forecast metadata conventions to accommodate particle-physics-derived atmospheric variables in standard Earth observation workflows.





Take-Home Message

Cosmic muons are not only probes of matter — they are also continuous probes of the atmosphere, offering a novel pathway for monitoring and understanding extreme atmospheric events.

Physics

Muon flux encodes real-time information about atmospheric density, pressure, and temperature profiles.

Detector

CMS provides a unique, long-running, high-quality cosmic muon dataset ready for atmospheric analysis.

Vision

Towards global muon detector farms integrated with meteorological forecasting systems.

