

Comparable Directional Muon Suppression in Contrasting Thunderstorm Environments

Pranaba K Nayak^{1*}, Rupraj Biswasharma², Akshay S. Patil², P.K. Mohanty¹, S.K. Gupta¹, Y. Hayashi³, S. Kawakami³, S.R. Dugad¹, S. D. Pawar², A. Jain¹, A. Oshima⁴, P. Jagadeesan¹, B. Hariharan¹, M. Rameez¹, K. Ramesh¹, Adarsh K. Kamra², Daniel Rosenfeld⁵, Sibaji Raha⁶

¹Tata Institute of Fundamental Research, Mumbai 400 005, India; *email: pranaba@hotmail.com

²Thunderstorm Dynamics, IITM, Ministry of Earth Sciences, Pune-411008, India

³Graduate School of Science, Osaka Metropolitan University, Osaka-5588585, Japan

⁴College of Engineering, Chubu University, Kasugai-4878501, Japan

⁵The Hebrew University of Jerusalem, Jerusalem-9190401, Israel

⁶Bose Institute, EN 80, Sector V, Bidhannagar, Kolkata-700091, India



Why GRAPES-3?

- World's largest tracking muon telescope (560 m²)
- Directional capability: 169 bins → 9 sectors
- Continuous operation since 2000
- Multi-instrument synergy: EFM, ILLN, INSAT-3DR, ERA5

Science Question

Can thunderstorms with **markedly different** electrical and meteorological evolution nevertheless produce **nearly identical** directional muon responses?

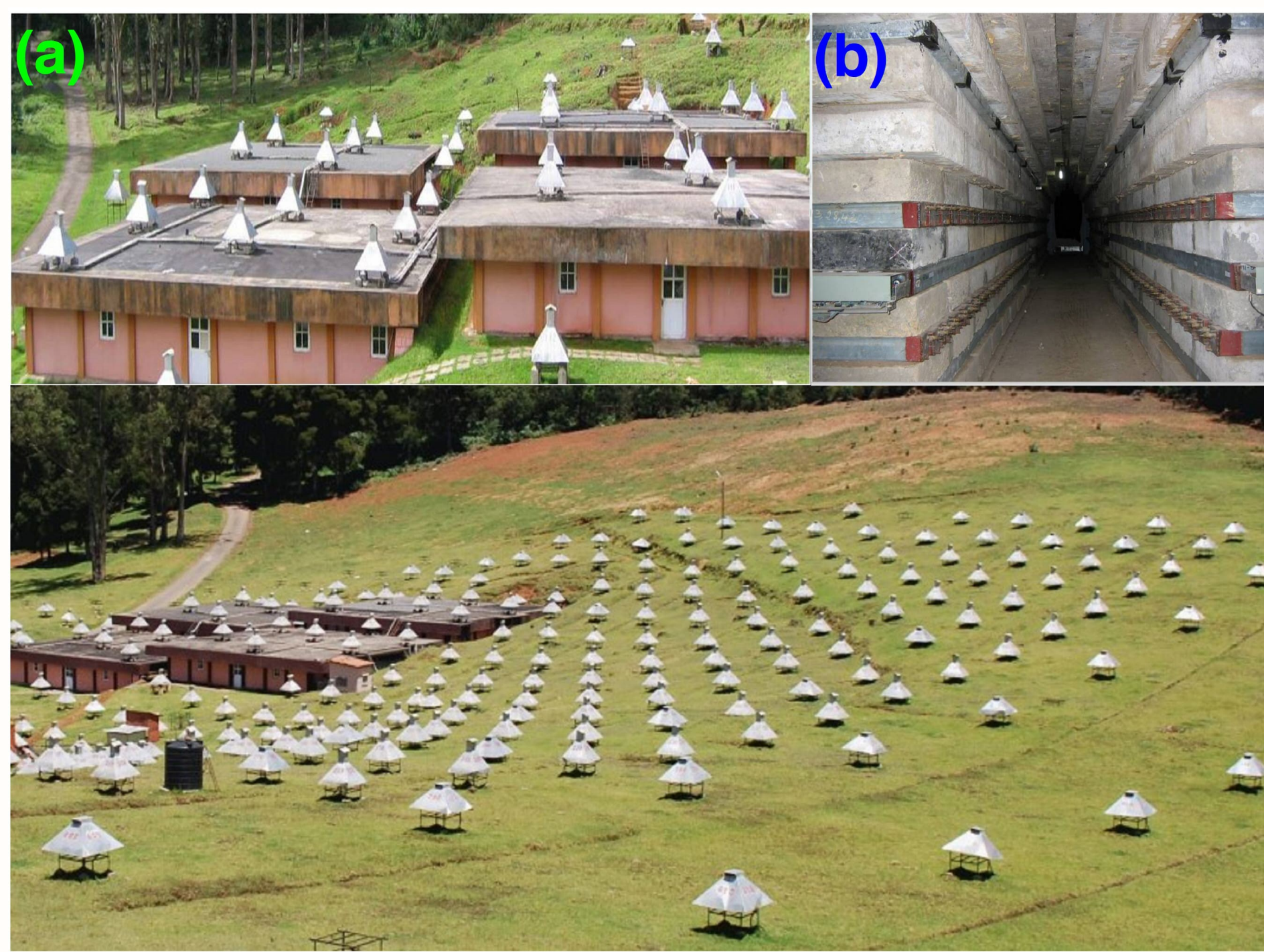


Figure 1: The GRAPES-3 Experiment at Ooty and module details: (a) super-module exterior, (b) module interior [1].

Tracking Performance

- 4 layers → 2 orthogonal projection planes
- 50 cm layer separation
- Angular accuracy < 4° per plane [1, 2, 3]
- Energy threshold: 1 GeV (vertical muons)

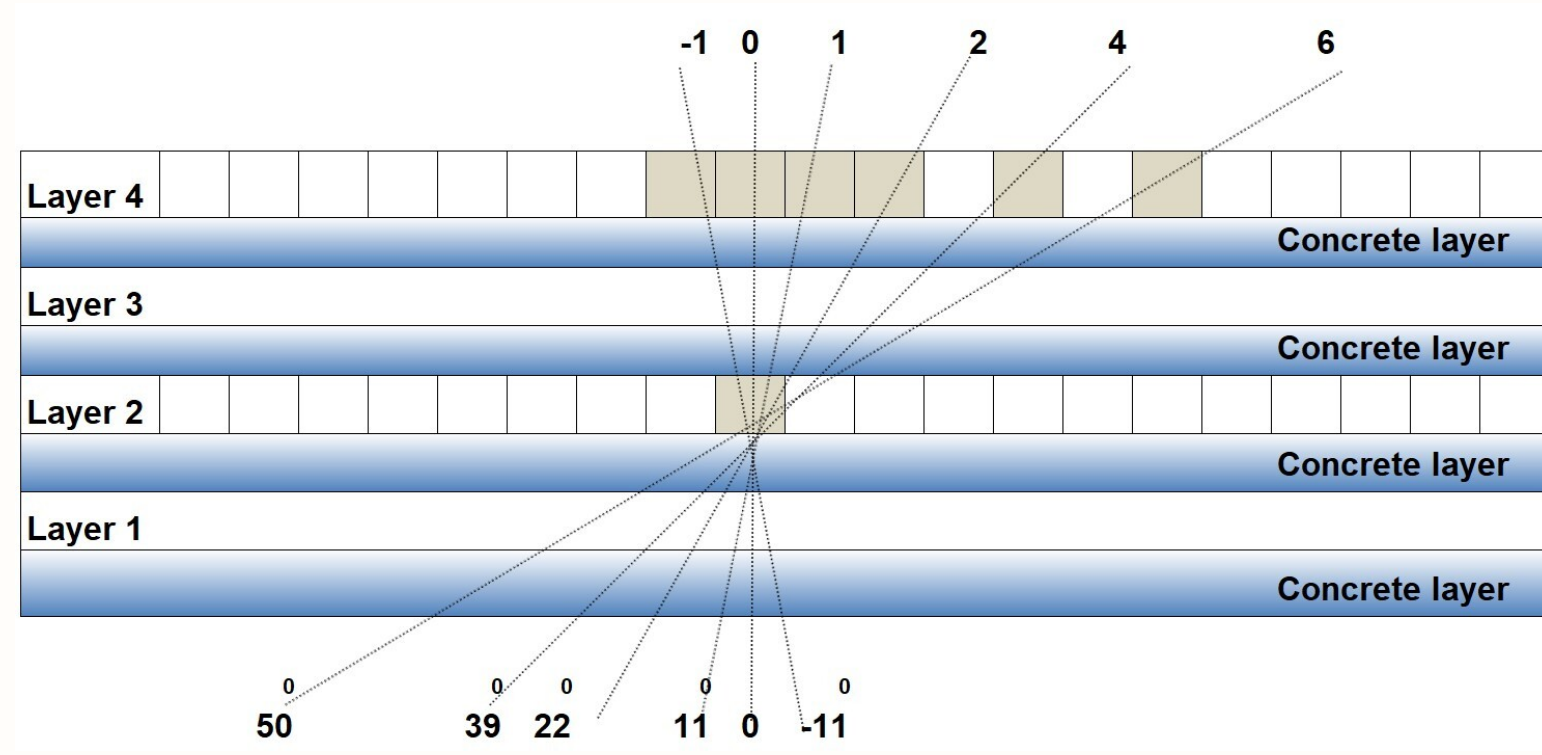


Figure 2: Muon direction reconstruction in one projection plane from PRC geometry, using triggered PRCs in the lower and upper layers [2].

Methods at a Glance

Dataset	Resolution	Role
Muon (GRAPES-3)	4 min	Directional TIMES
E-field (EFM-100)	20 Hz	Near-ground E-field
Lightning (ILLN)	~200 m, ms	IC/CG flash rates
INSAT-3DR	4 km, 30 min	Cloud-top BT
ERA5	0.25°, 1 h	LWC/IWC, thermodynamics

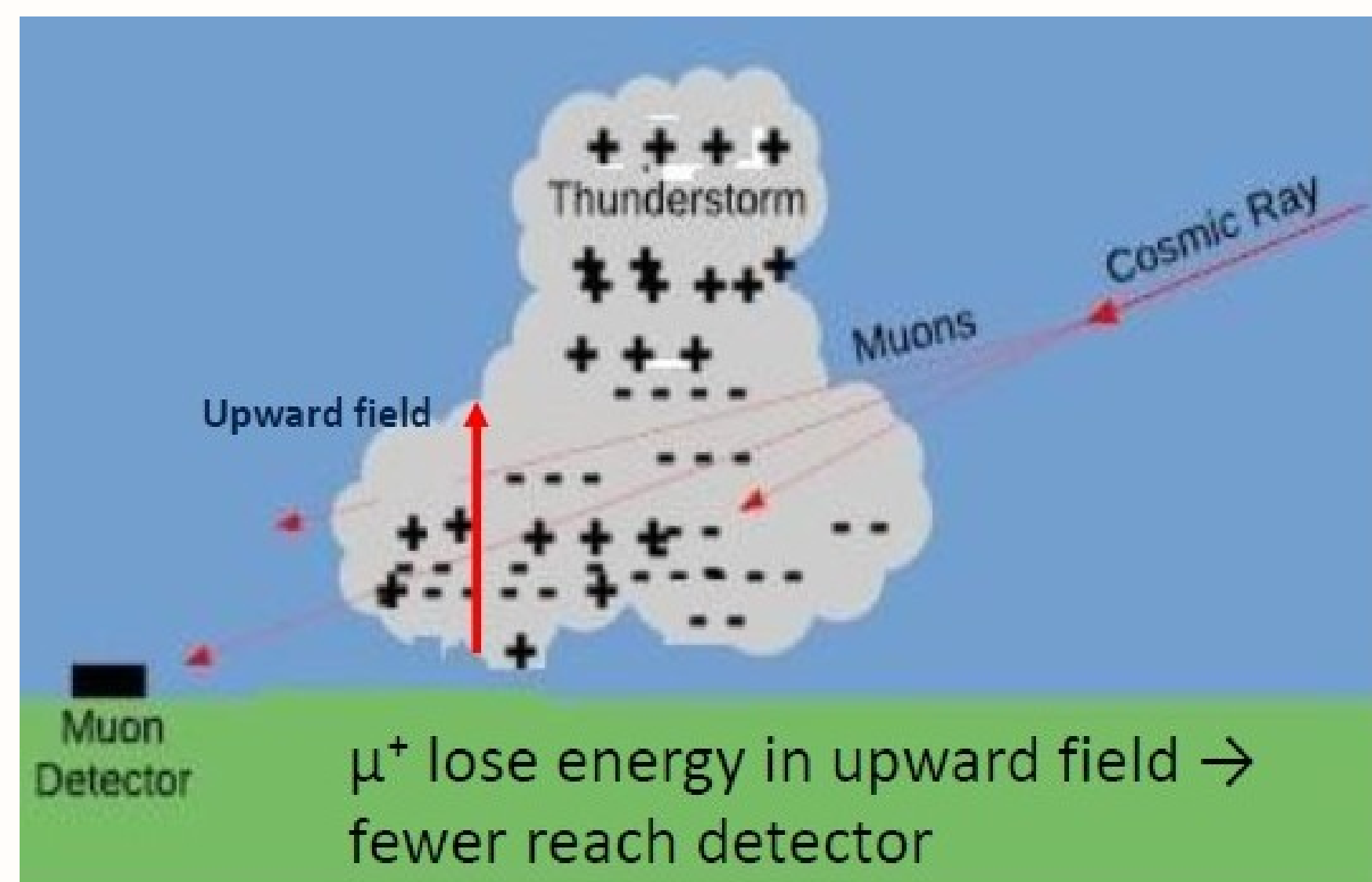


Figure 3: μ^+ deceleration in upward E -fields → muon deficit at the detector.

Key Physics

- Upward E -field → μ^+ lose energy → flux deficit
- Effect $\propto$ field strength $\times$ path length
- Directional signature** → probes storm charge geometry
- Charge-dependent response → directional asymmetry

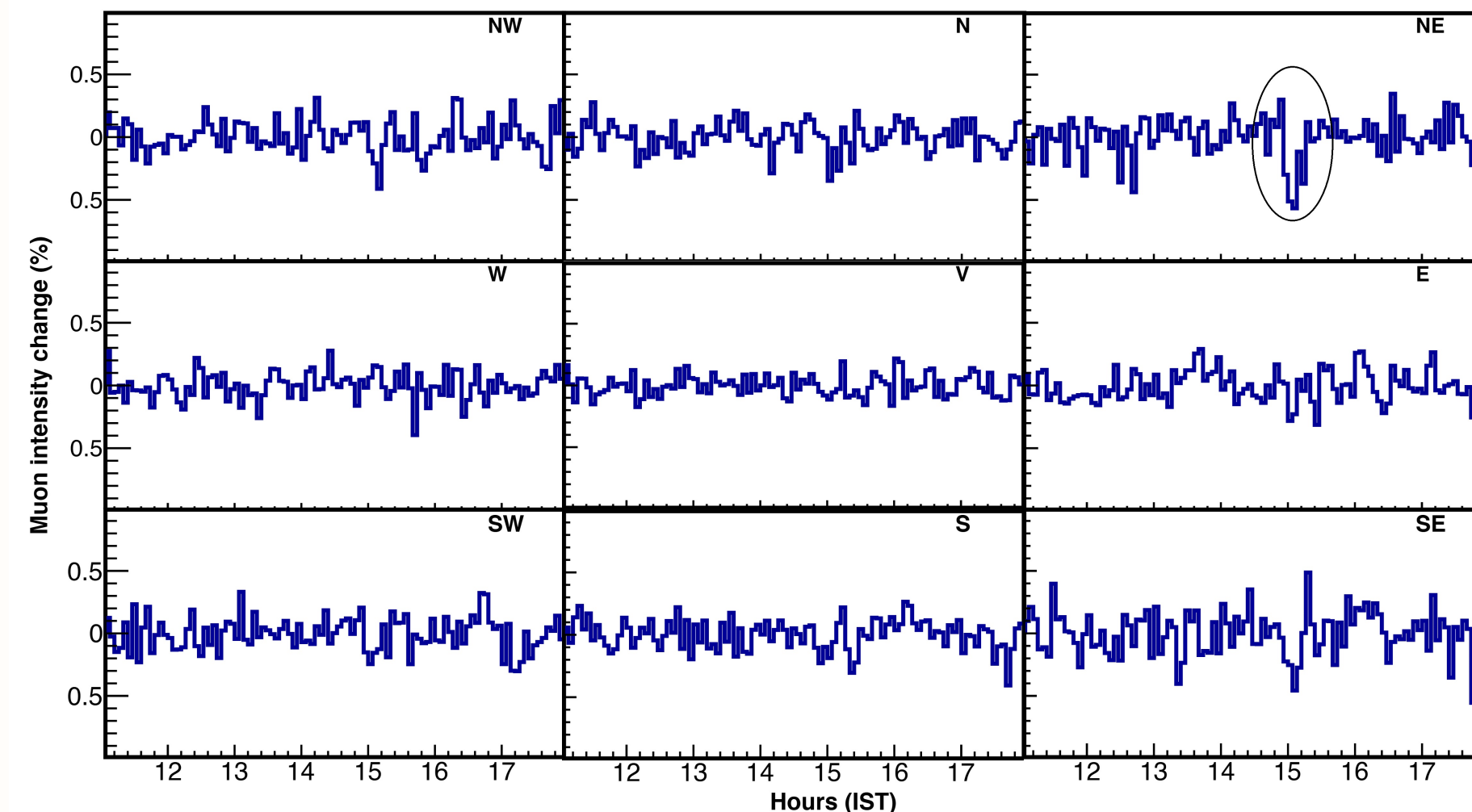


Figure 4: Fully corrected muon intensity in the nine viewing directions on 8 April 2020. A $(0.59 \pm 0.02)\%$ (5.1σ) suppression appears **only in the NE sector** near 15:00 IST; all other directions show statistical fluctuations.

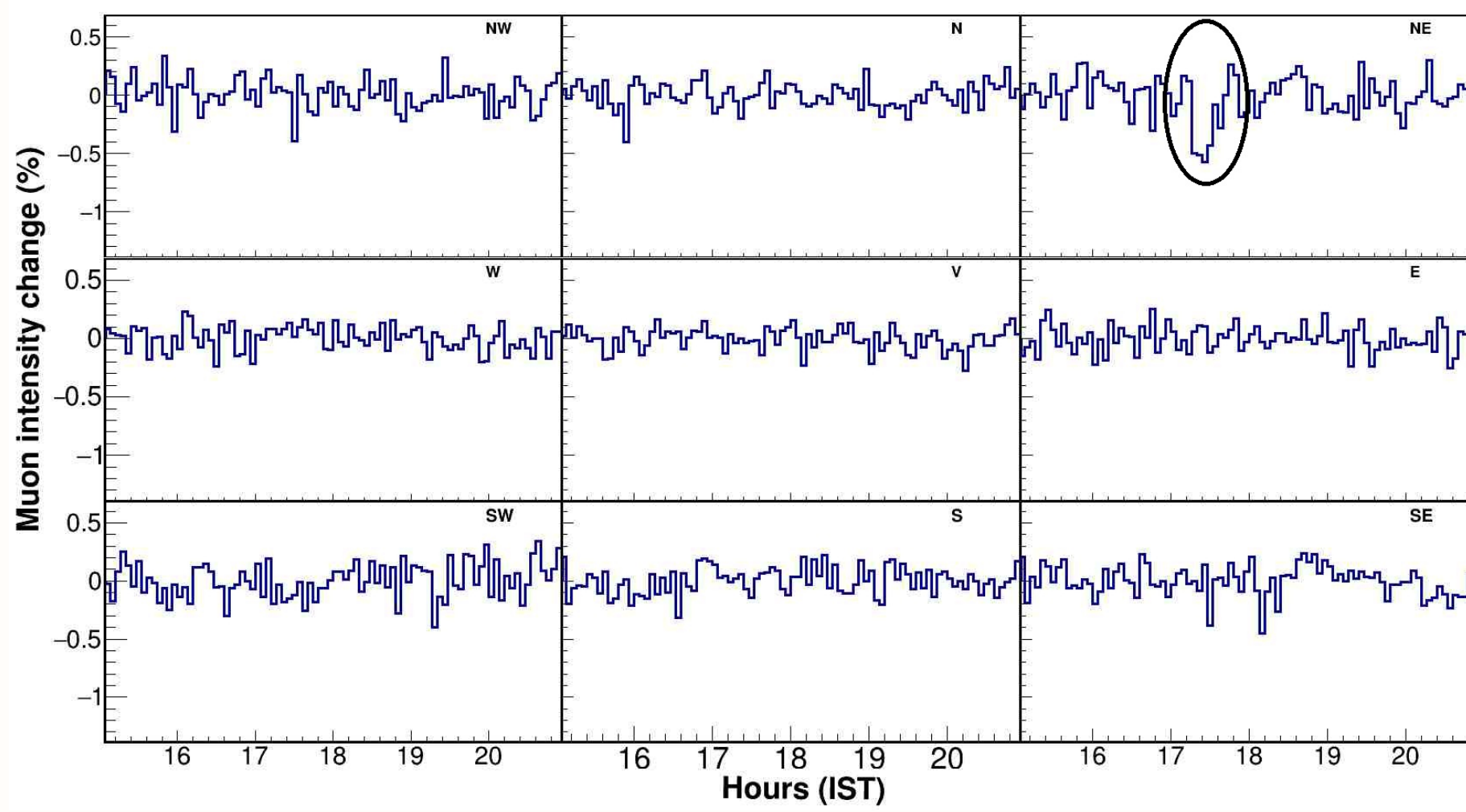


Figure 5: Muon intensity in the nine viewing directions on 17 May 2020. The suppression is confined to the NE sector near 17:20 IST.

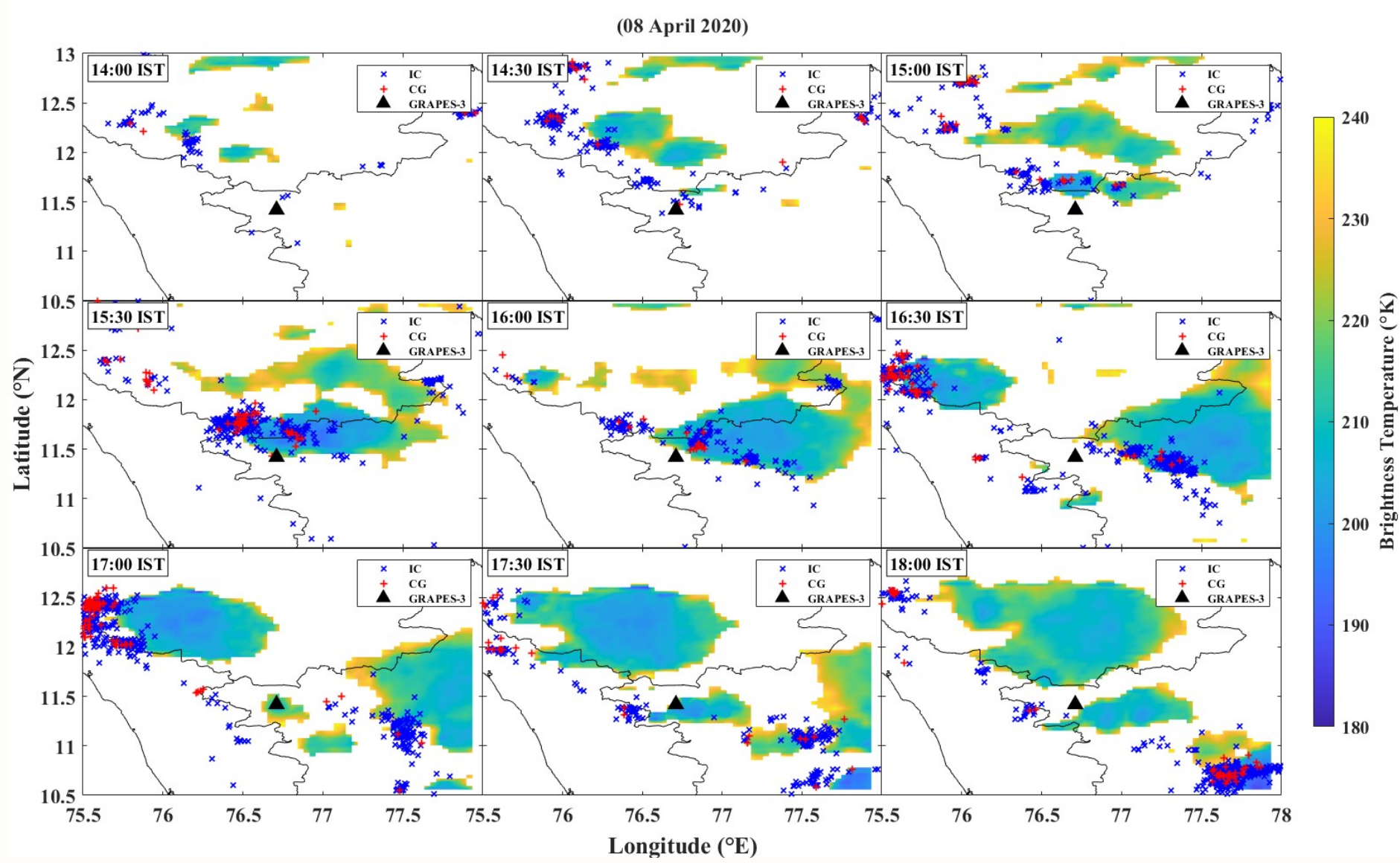


Figure 6: INSAT-3DR brightness temperature and ILLN lightning (IC: blue; CG: red) for 8 April 2020. Convection develops over GRAPES-3 (black triangle) during the muon suppression.

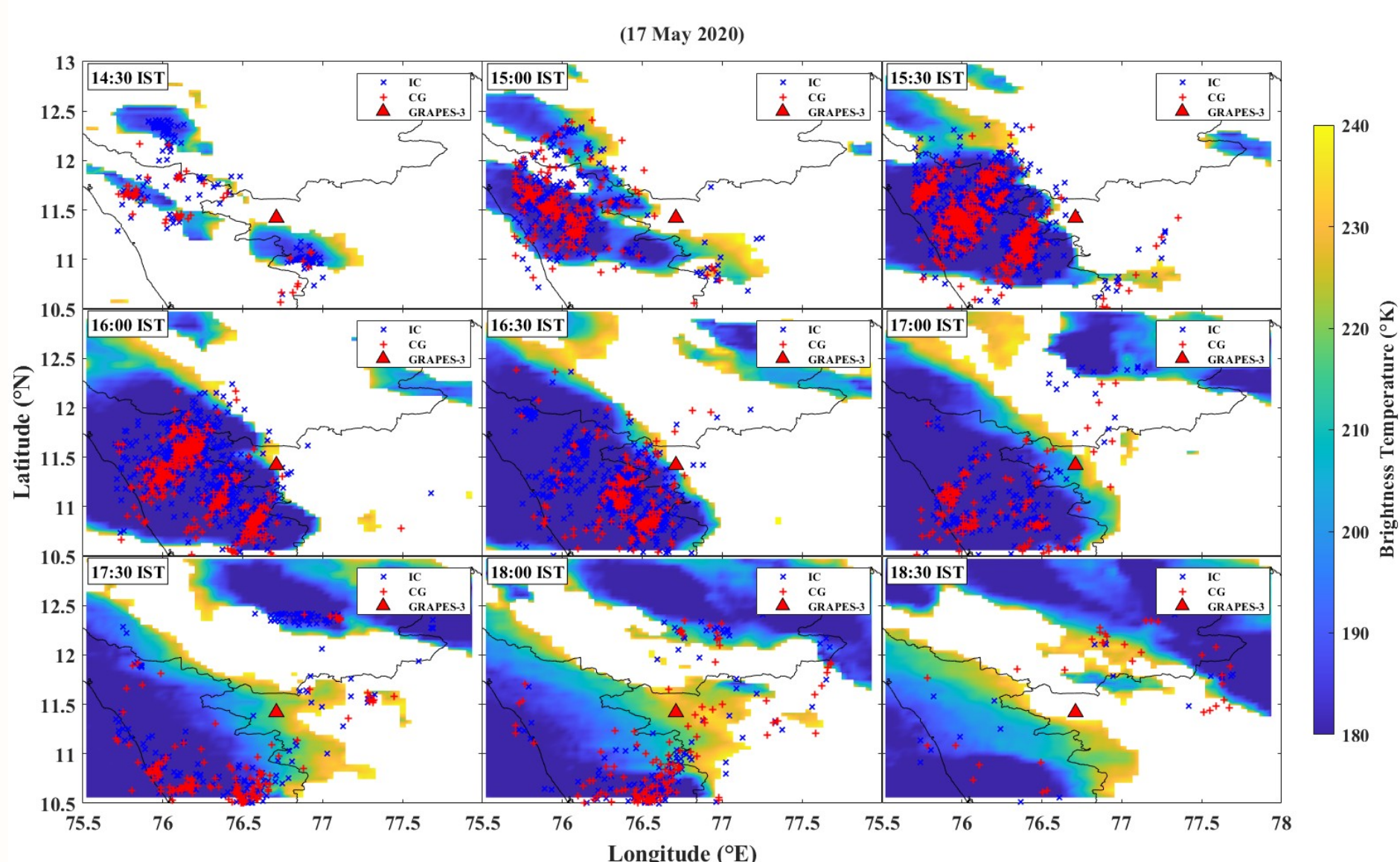


Figure 7: INSAT-3DR brightness temperature and ILLN lightning (IC: blue; CG: red) for 17 May 2020. The organized system passes with GRAPES-3 (red triangle) near its periphery.

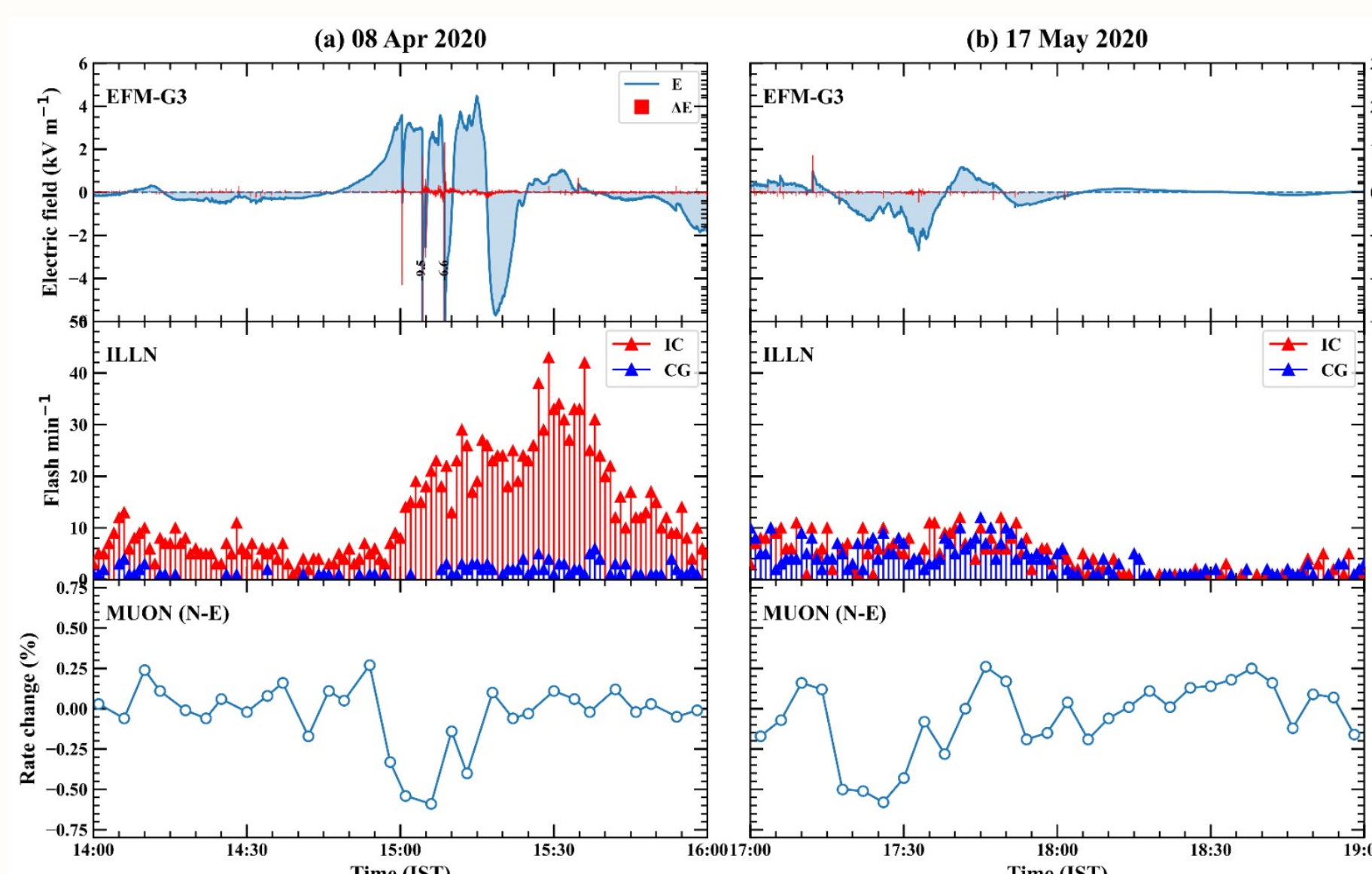


Figure 8: Surface E -field (EFM-G3), lightning flash rates, and NE-direction muon intensity for both events. Contrasting electrical evolution, comparable response.

Observation Summary

Parameter	8 Apr	17 May
Muon decrease	$0.59 \pm 0.02\%$	$0.58 \pm 0.02\%$
Significance	5.1σ	4.9σ
Direction	NE	NE
Surface E -field	Bipolar	Negative
Lightning	Moderate	High
Storm type	Localized	Organized
Min BT ₁₁	200–210 K	190–200 K
Hydrometeor	LWC	IWC
Storm over site	Core	Periphery

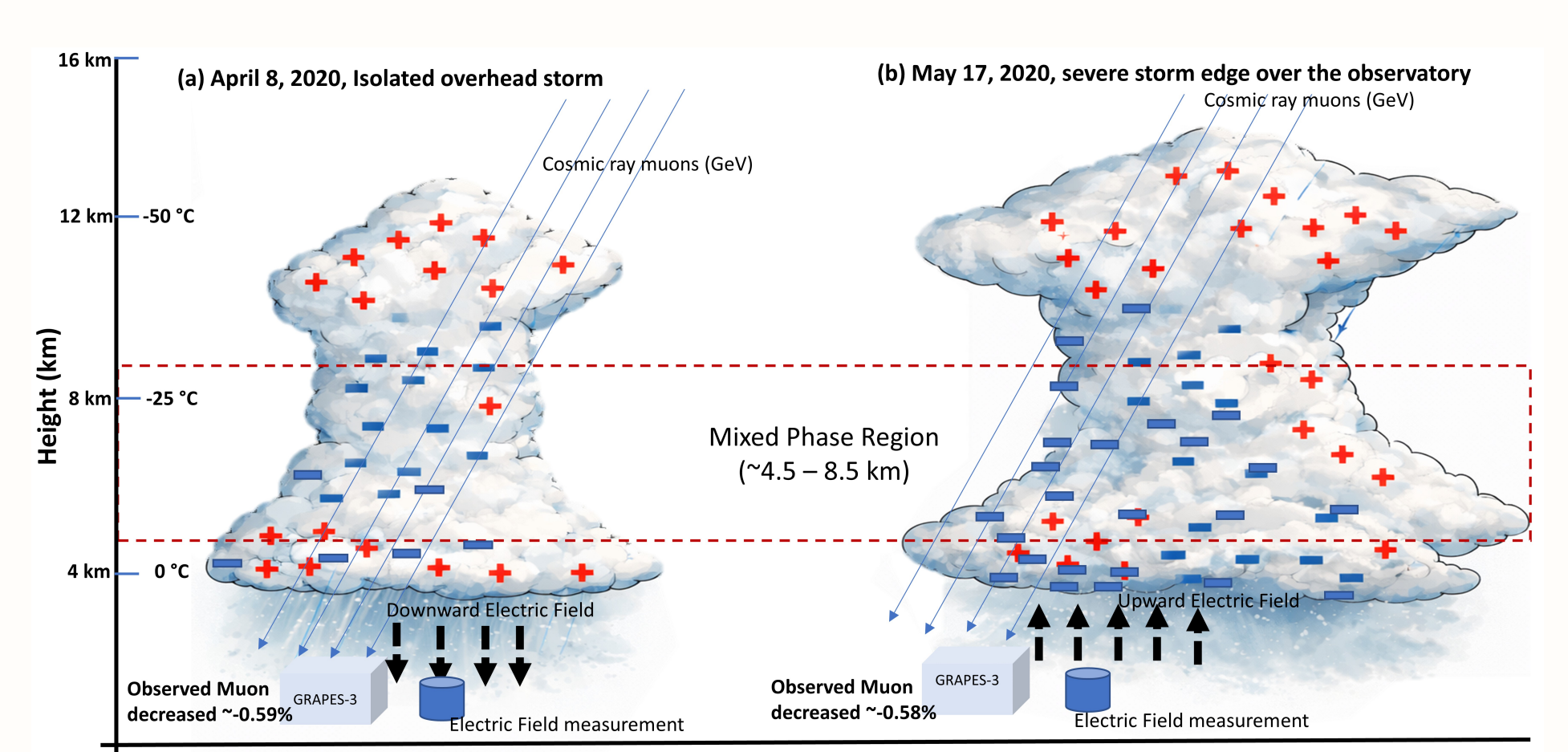


Figure 9: Conceptual illustration of the contrasting storm geometries inferred from the combined observations. (a) 8 April: a localized convective system positioned directly above or close to GRAPES-3. (b) 17 May: the observatory lies beneath the peripheral region of a larger organized storm. Despite these contrasting geometries, both events produced nearly identical directional muon suppressions. The shaded region denotes the mixed-phase layer (4.5–8.5 km). Schematic is qualitative and not to scale.

Conclusions

Same output:

$(0.59 \pm 0.02)\%$ (5.1σ) & $(0.58 \pm 0.02)\%$ (4.9σ), both in the **NE sector**.

Different inputs:

Bipolar vs. negative E -field; moderate vs. high lightning; 200–210 K vs. 190–200 K cloud tops; localized vs. organized; LWC- vs. IWC-dominant.

Key implication:

Atmospheric observables **do not uniquely determine** the muon response.

Physical picture:

Response depends on the **trajectory-integrated electric potential**.

Outlook:

Larger TIME samples; WRF-ELECT + CORSIKA modeling.

Takeaway

Different thunderstorm environments can produce remarkably similar directional muon suppressions — surface and atmospheric observables do not uniquely determine the muon response.

References

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