A multi-station analysis of cloud modification by successive Canadian wildfire smoke intrusions over Europe

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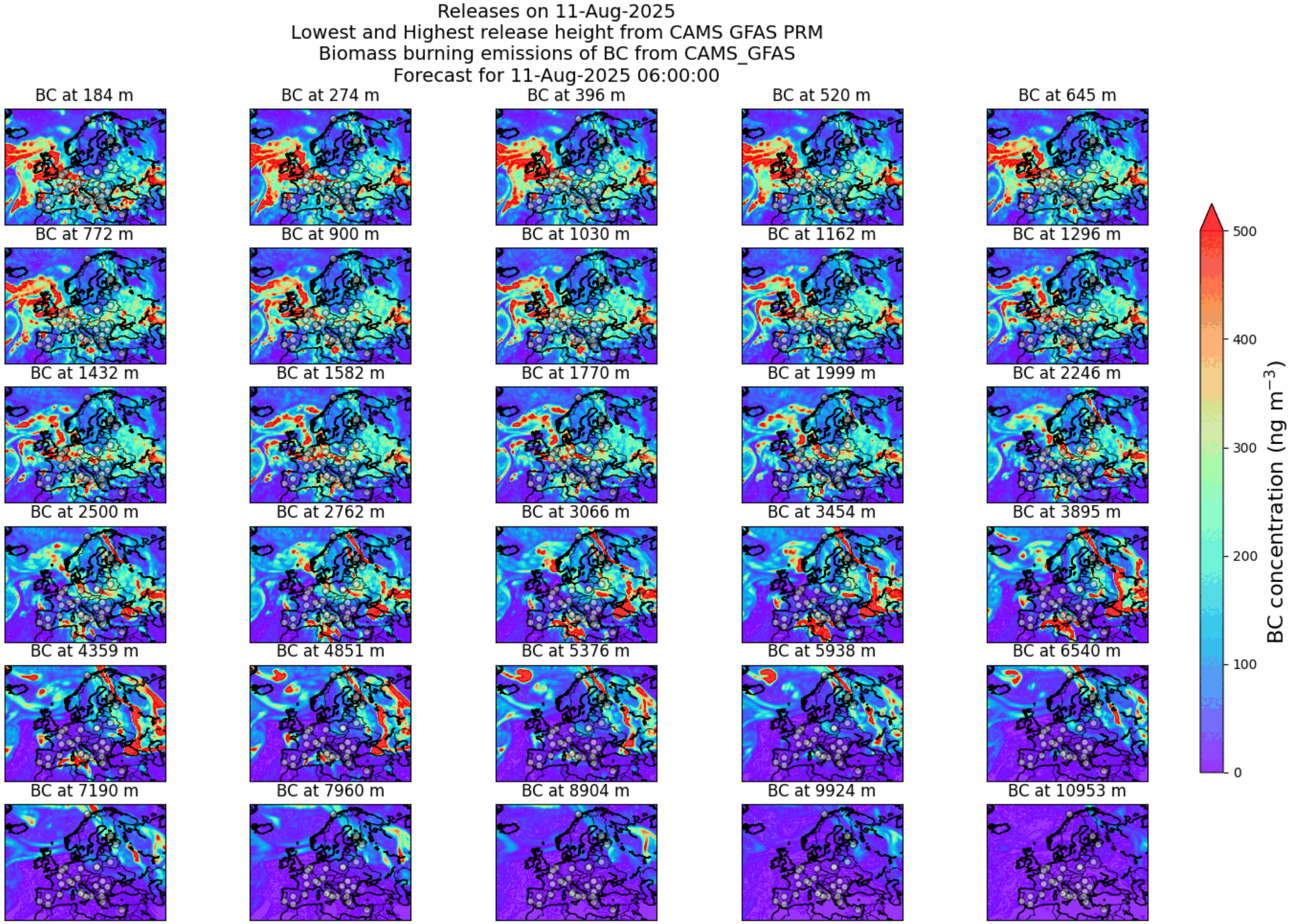
Introduction

- **Aerosols** remain among the **largest uncertainties in climate projections**; their **direct** (radiation) and **indirect** (cloud modification) effects are **poorly constrained**, making accurate characterization critical for weather forecasting and climate modelling
- By acting as **CCN** and **INPs**, aerosols control **droplet size**, **cloud lifetime, optical depth** and **precipitation efficiency**; with far-reaching consequences for the hydrological cycle
- Intensifying **wildfires** inject massive quantities of biomass-burning aerosol into the free troposphere, enabling **long-range transport thousands of kilometers** from the source and making them a globally relevant forcing agent
- The **Summer 2025 Canadian wildfires** exemplify this teleconnection: successive smoke waves crossed the North Atlantic, delivering measurable aerosol loading over Europe and providing a natural experiment for studying **dose-dependent cloud responses** far from the emission source

Methodology



Developed by N. Evangeliou (ne@nilu.no), E. Sollum and S. Eckhardt (sec@nilu.no) (NILU) supported by AMAP/Arctic Council, fire emissions were generated using Copernicus Atmosphere Monitoring Service Information 2024

The forecasts are based on GFS meteorological data and are provided in the frame of NILU's project FLEXPART

BC Concentration over Europe — 2025-06-01 03:00 UTC

BC Concentration over Europe — 2025-07-09 03:00 UTC

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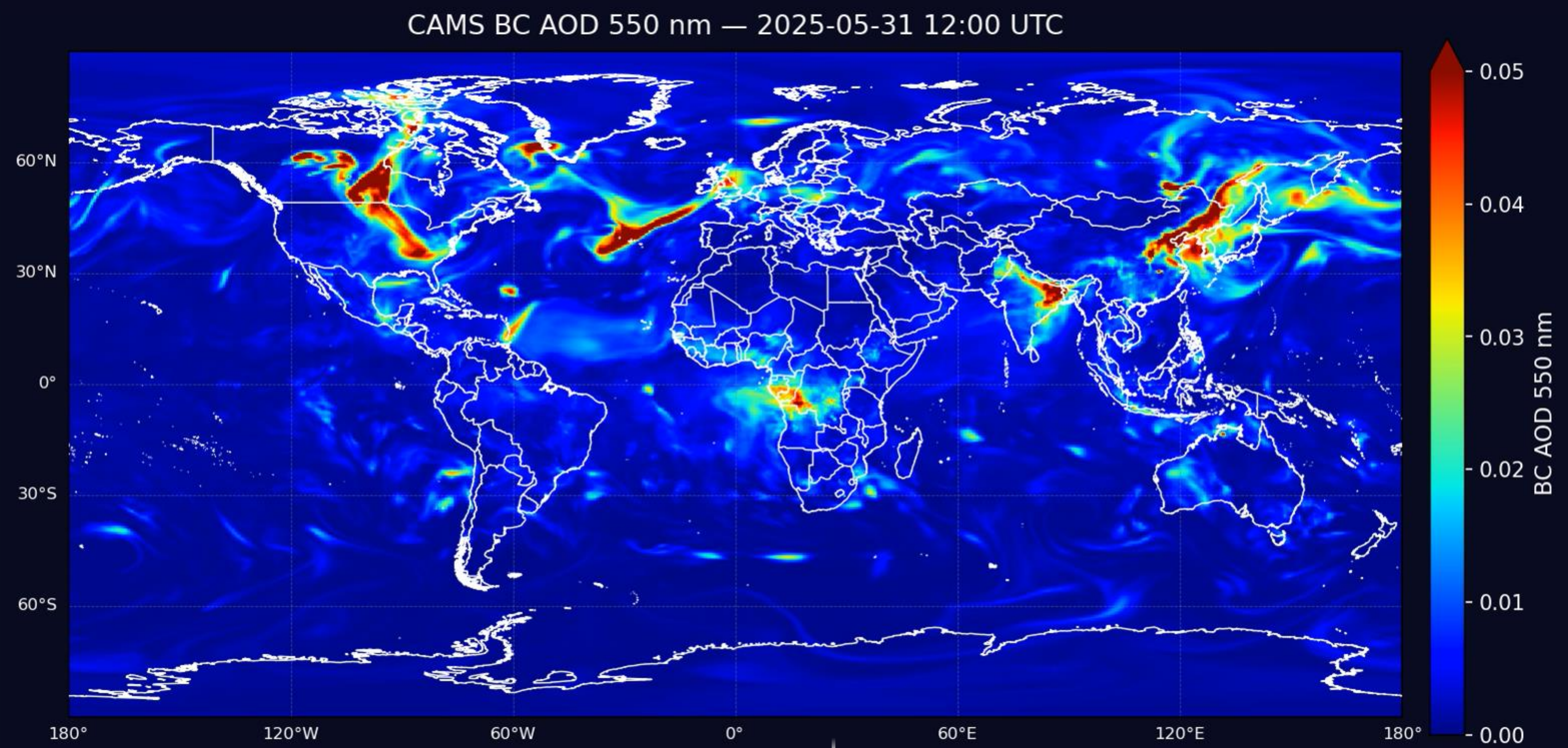
CAMS BC AOD 550 nm — 2025-05-31 12:00 UTC
60°N
30°N
0°
30°S
60°S
180°
120°W
60°W
0°
60°E
120°E
180°
0.05
0.04
0.03
0.02
0.01
0.00
BC AOD 550 nm

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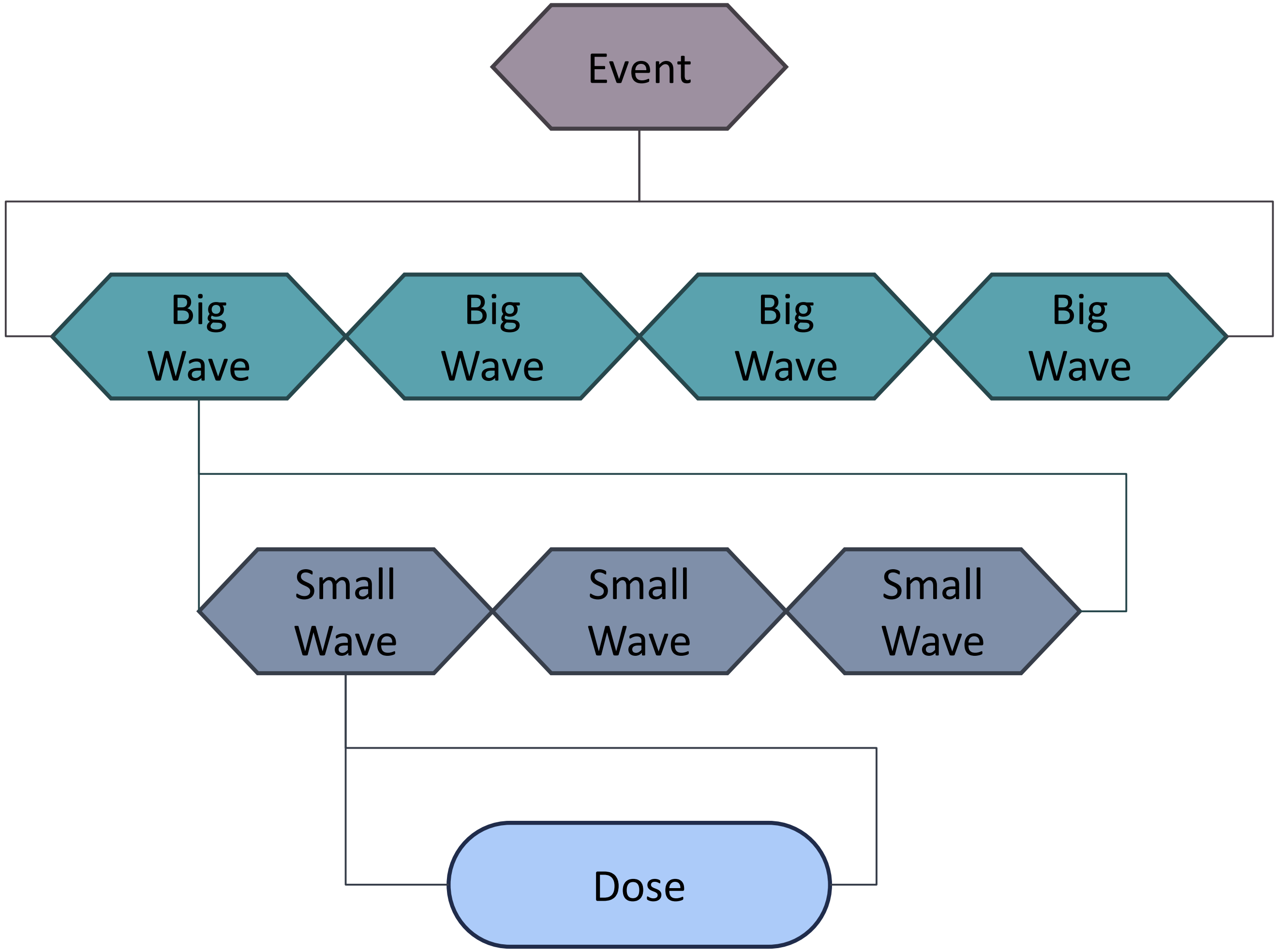
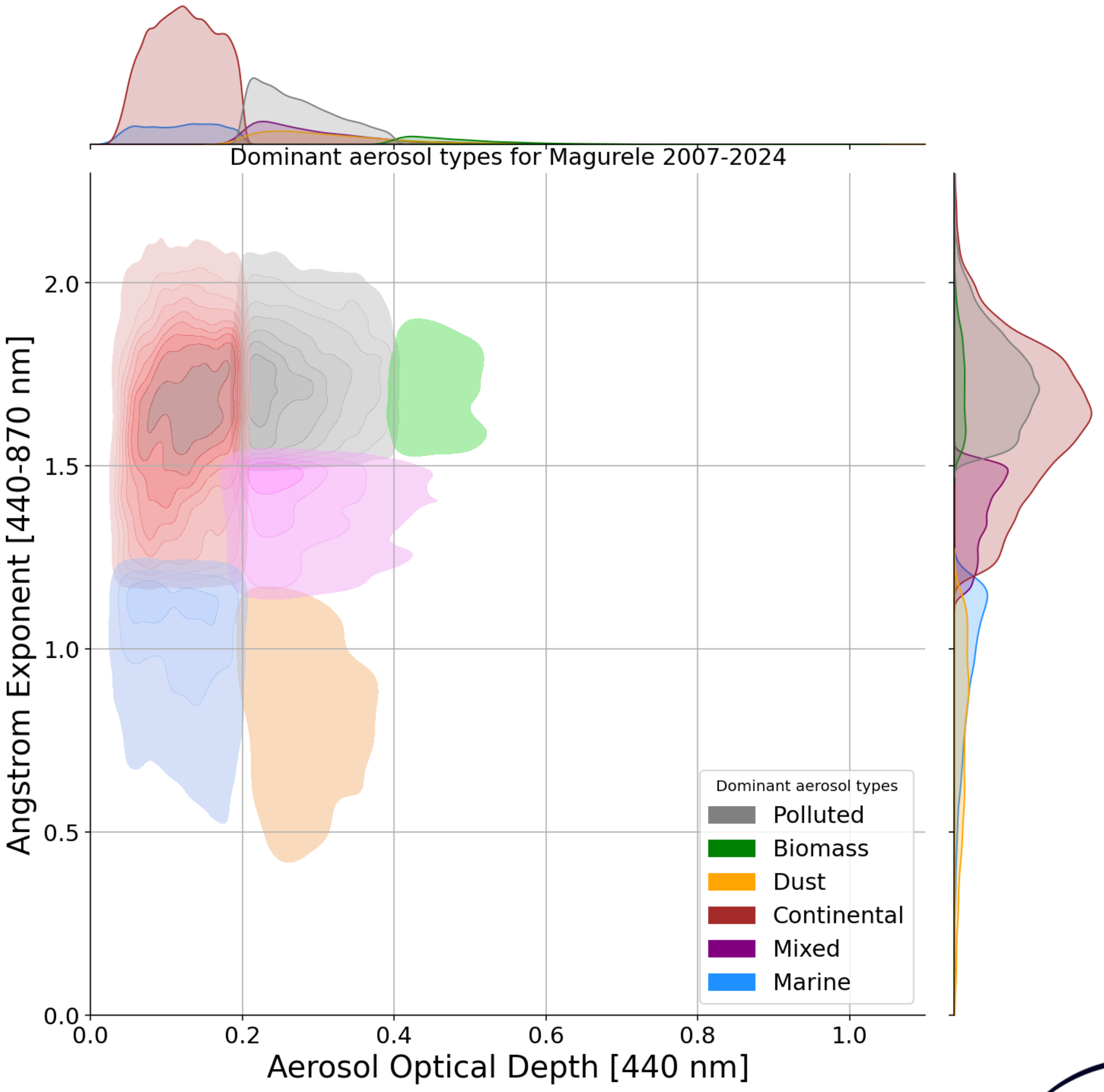
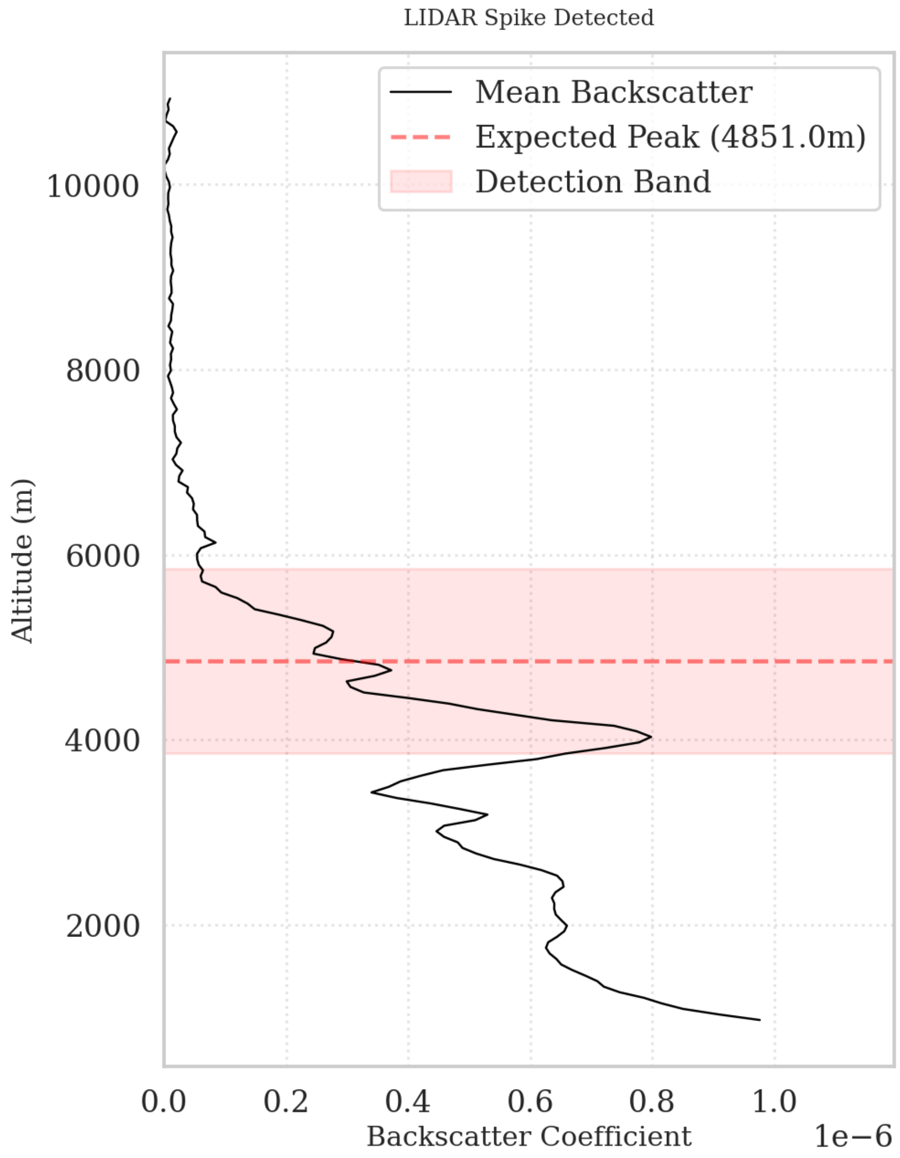
Dose Calculation



- **Small wave dose** is calculated as the time-integral of the peak BC concentration (0–10 km) over the small wave duration, using the trapezoidal rule
- A higher dose means the station was exposed to either a stronger plume, a longer-lasting one, or both


Dominant aerosol types for Magurele 2007-2024
Angstrom Exponent [440-870 nm]
Aerosol Optical Depth [440 nm]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
Dominant aerosol types
Polluted
Biomass
Dust
Continental
Mixed
Marine


LIDAR Spike Detected
Mean Backscatter
Expected Peak (4851.0m)
Detection Band
Altitude (m)
10000
8000
6000
4000
2000
0.0
0.2
0.4
0.6
0.8
1.0
Backscatter Coefficient
1e−6

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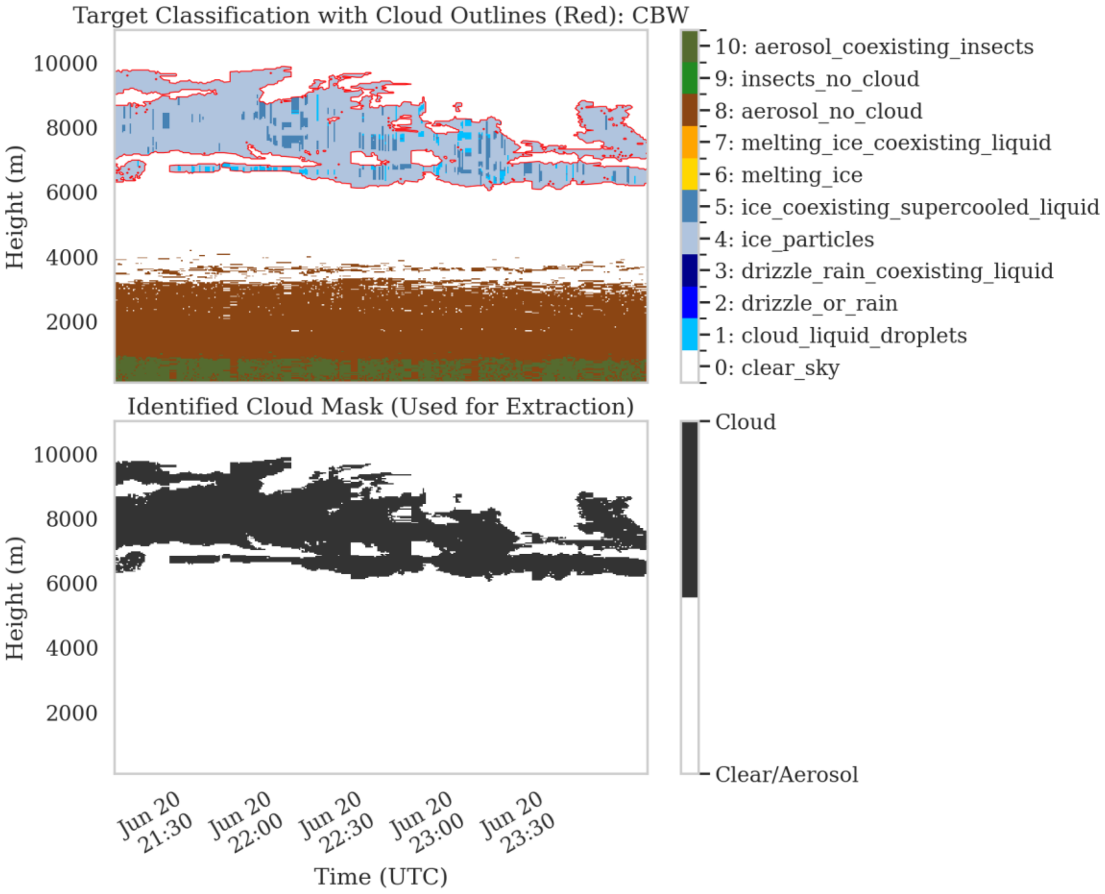
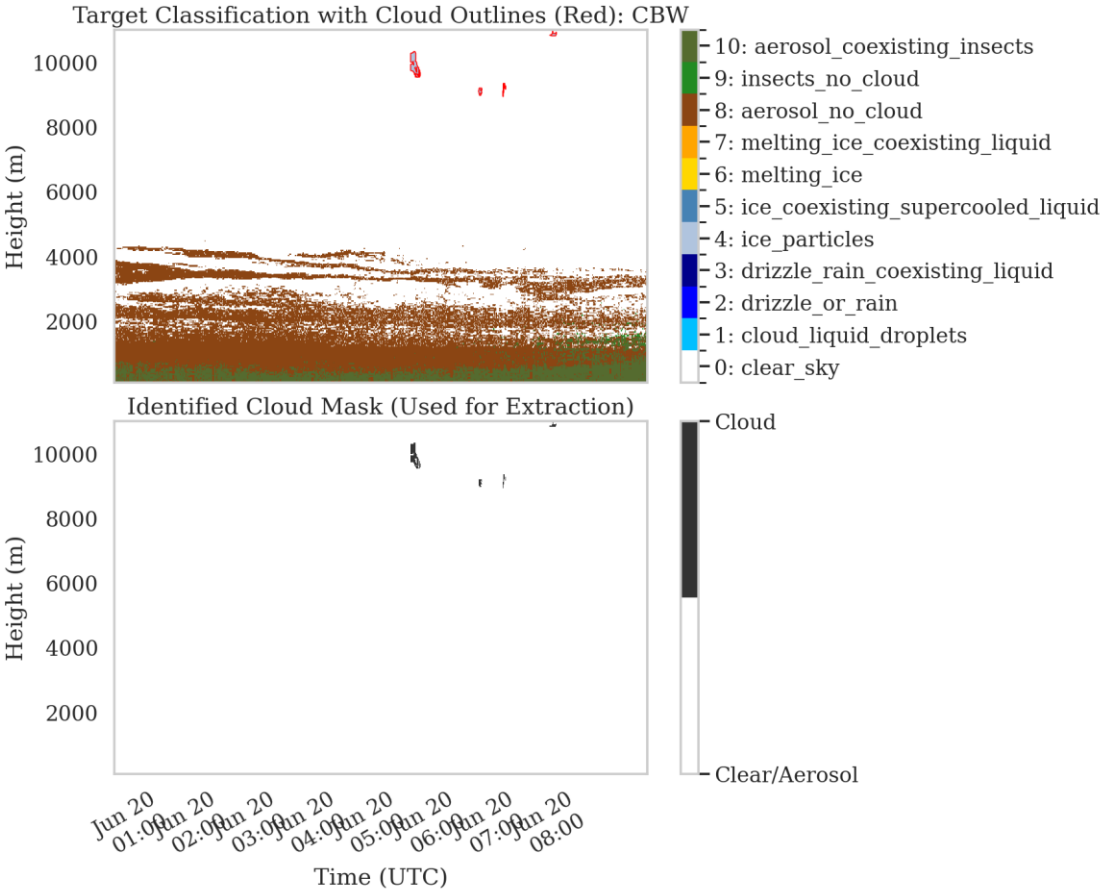

Target Classification with Cloud Outlines (Red): CBW
10000
8000
6000
4000
2000
Height (m)
10: aerosol_coexisting_insects
9: insects_no_cloud
8: aerosol_no_cloud
7: melting_ice_coexisting_liquid
6: melting_ice
5: ice_coexisting_supercooled_liquid
4: ice_particles
3: drizzle_rain_coexisting_liquid
2: drizzle_or_rain
1: cloud_liquid_droplets
0: clear_sky
Identified Cloud Mask (Used for Extraction)
Cloud
Clear/Aerosol
Jun 20 21:30
Jun 20 22:00
Jun 20 22:30
Jun 20 23:00
Jun 20 23:30
Time (UTC)


Target Classification with Cloud Outlines (Red): CBW
10000
8000
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Height (m)
10: aerosol_coexisting_insects
9: insects_no_cloud
8: aerosol_no_cloud
7: melting_ice_coexisting_liquid
6: melting_ice
5: ice_coexisting_supercooled_liquid
4: ice_particles
3: drizzle_rain_coexisting_liquid
2: drizzle_or_rain
1: cloud_liquid_droplets
0: clear_sky
Identified Cloud Mask (Used for Extraction)
Cloud
Clear/Aerosol
Time (UTC)

Results

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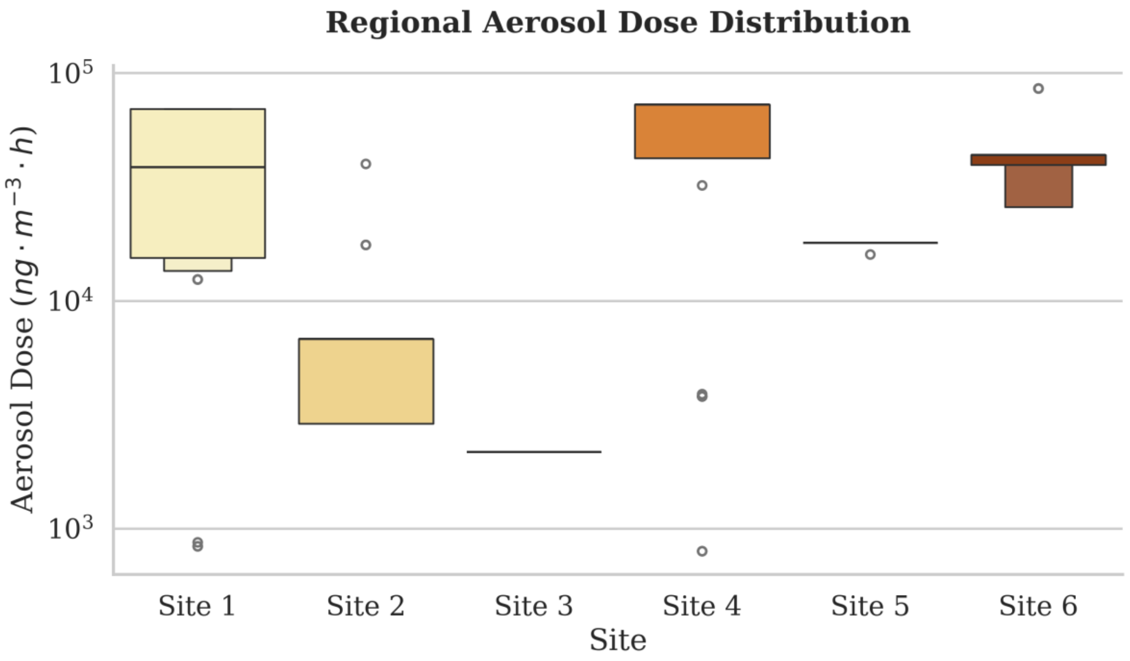
Results

- **Aerosol dose varies** by nearly two orders of magnitude across sites (log scale spans ~10^3–10^5 ng·m^{-3}·h)
- **Sites 4** and **6** received the **highest** and most **consistent** smoke loading; **Sites 3** and **5** were **minimally** impacted
- **Site 1** shows **the largest IQR**, reflecting variable exposure across successive smoke waves
- Isolated **low outliers** represent clean background periods between wave arrivals
- Site-to-site variability reflects differences in **transport pathway geometry**, not just distance from source



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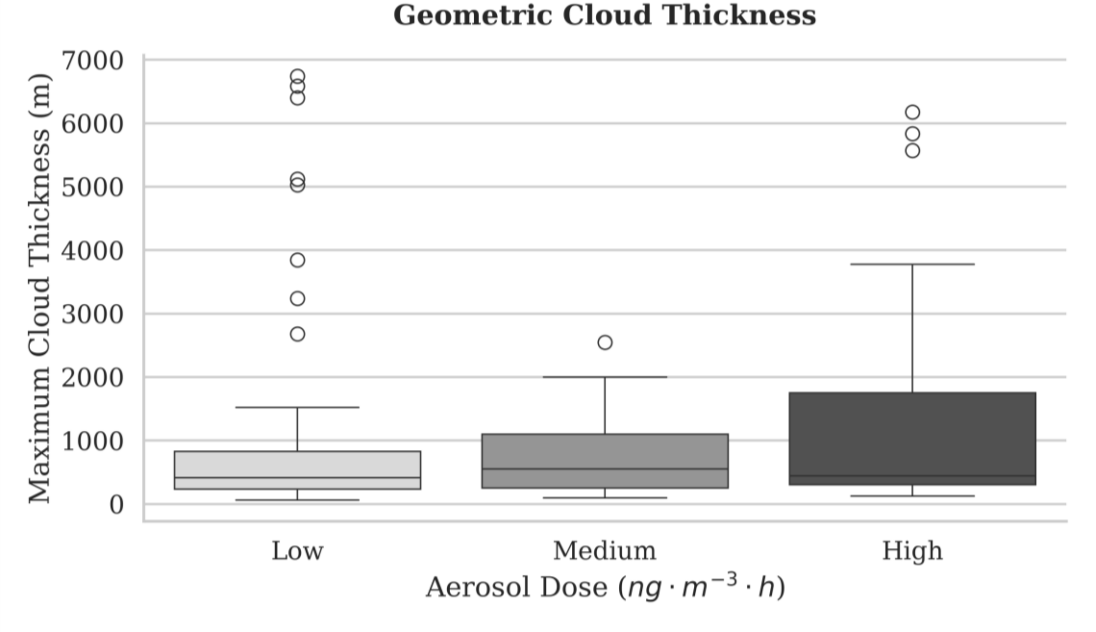
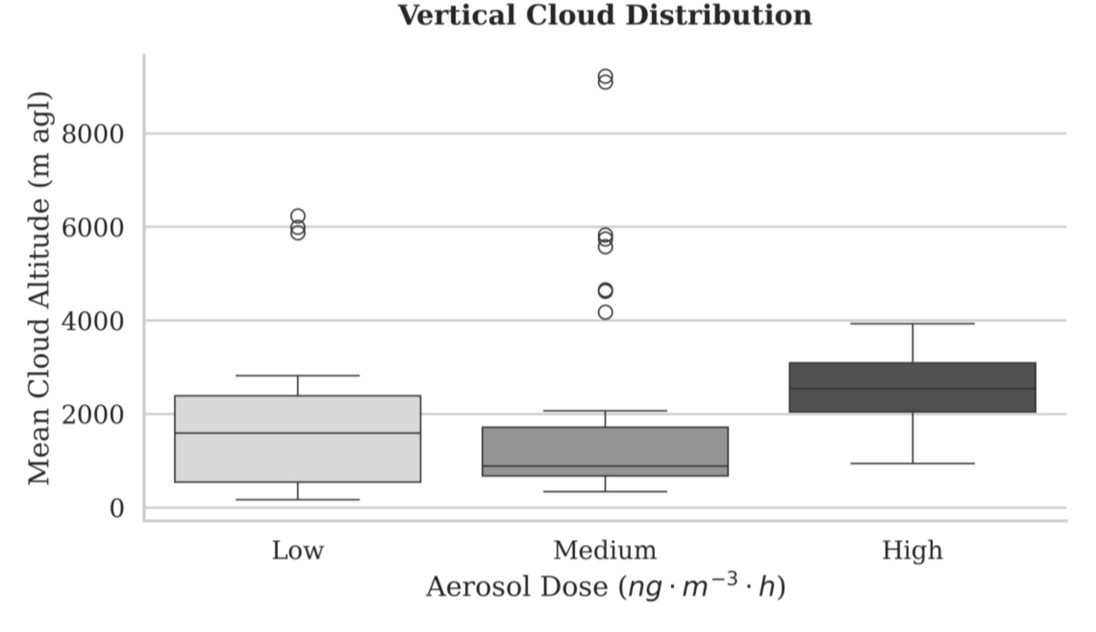


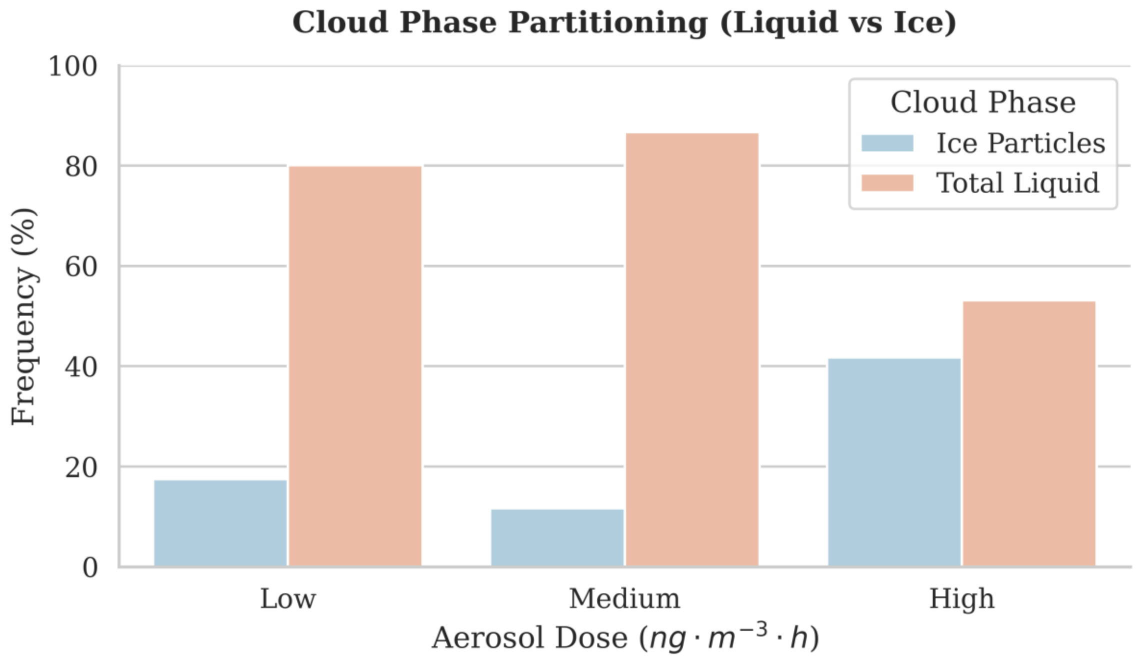


Results

- Cloud **altitude** shows **no strong trend with dose**, confirming **thermodynamics as the primary control on cloud height**; though High dose cases sample a wider range of vertical regimes
- Cloud **thickness** increases with aerosol dose at the median, consistent with **suppressed coalescence** allowing liquid water to accumulate before precipitation initiates
- **High dose** dramatically **widens the thickness IQR**, revealing divergent outcomes: some clouds grow anomalously deep while others remain thin
- **Deep convective outliers** (>5000 m thickness, >6000 m altitude) appear across all dose categories, indicating that strong thermodynamic forcing can override aerosol effects entirely
- **High aerosol** dose **does not simply** deepen or lift clouds uniformly; it widens the envelope of possible cloud states, explaining why dose-response relationships in aerosol-cloud studies are rarely linear

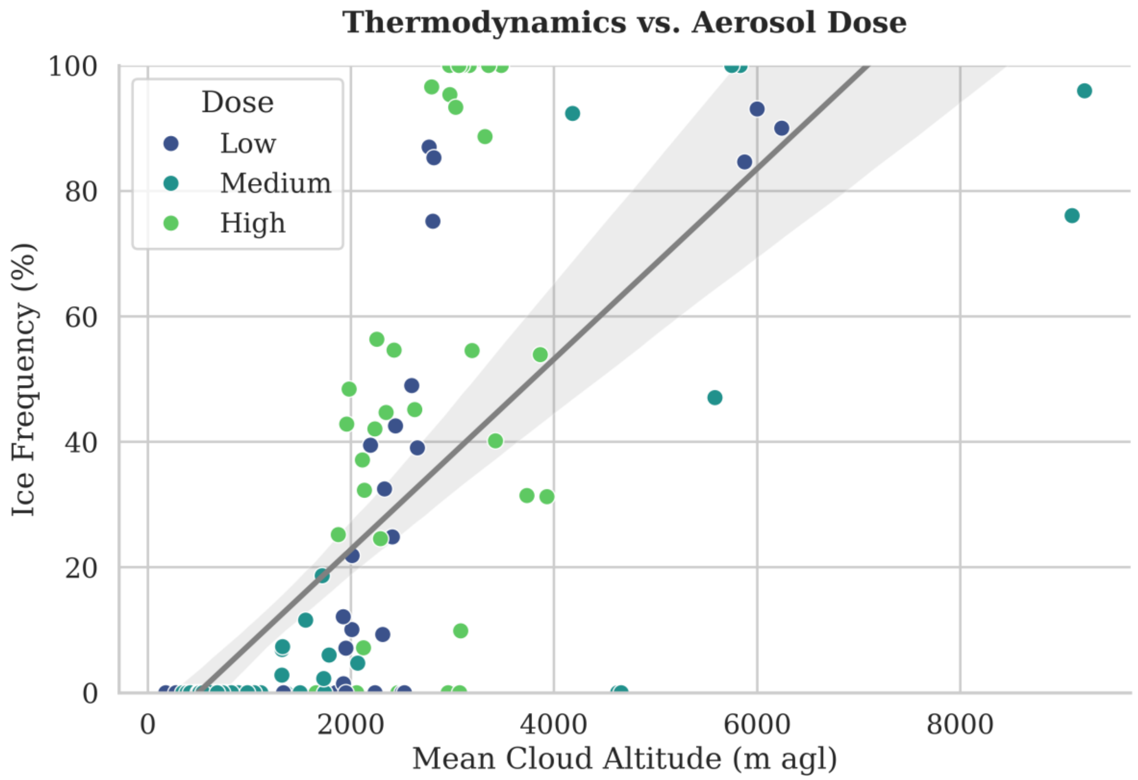
Results

- **Ice frequency** jumps sharply to ~42% under High dose, compared to ~11% at Medium and ~18% at Low
- **Liquid frequency** drops to ~53% at High dose
- **Medium dose** shows the **highest liquid frequency** (~87%), consistent with low-altitude warm clouds dominating that regime
- The **non-monotonic ice behavior** suggests aerosol-driven glaciation activates only above a loading threshold
- **Wildfire smoke at high concentrations** likely contributes ice-nucleating particles, promoting glaciation at warmer temperatures



Results

- **Ice frequency increases strongly with cloud altitude**, confirming temperature as the primary glaciation control
- The regression line and confidence band quantify this **thermodynamic baseline** for comparison
- At fixed altitudes (~2000–3000 m), some High dose points show **ice frequencies above the regression expectation**
- Dose categories do not cleanly separate above/below the regression line, indicating **aerosol is a secondary rather than dominant driver**



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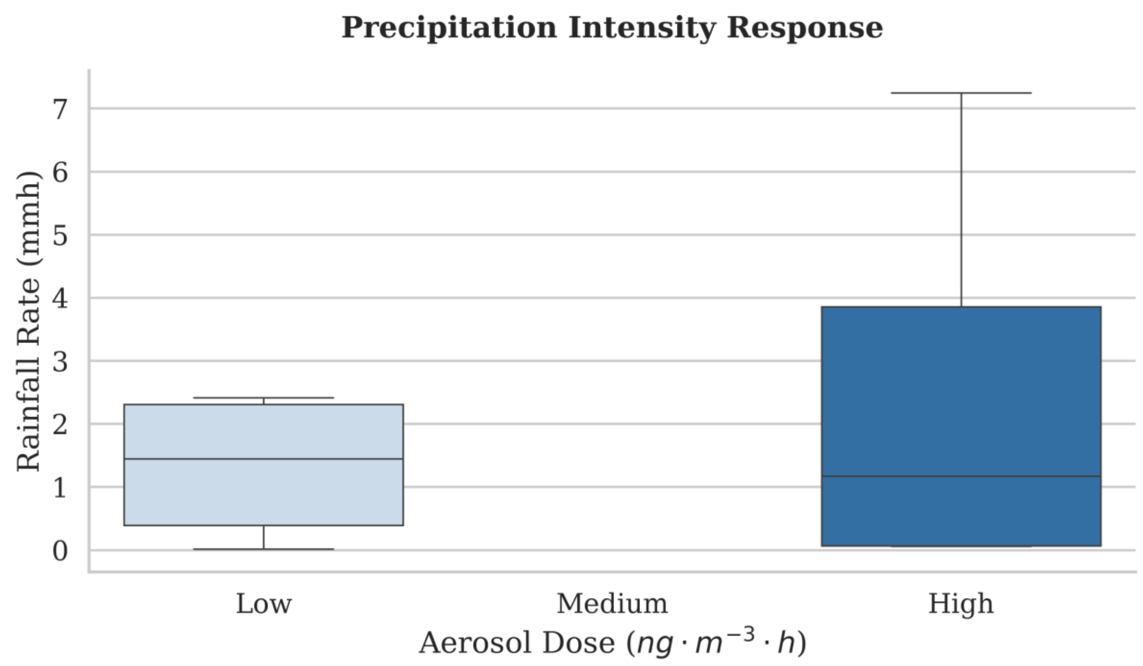
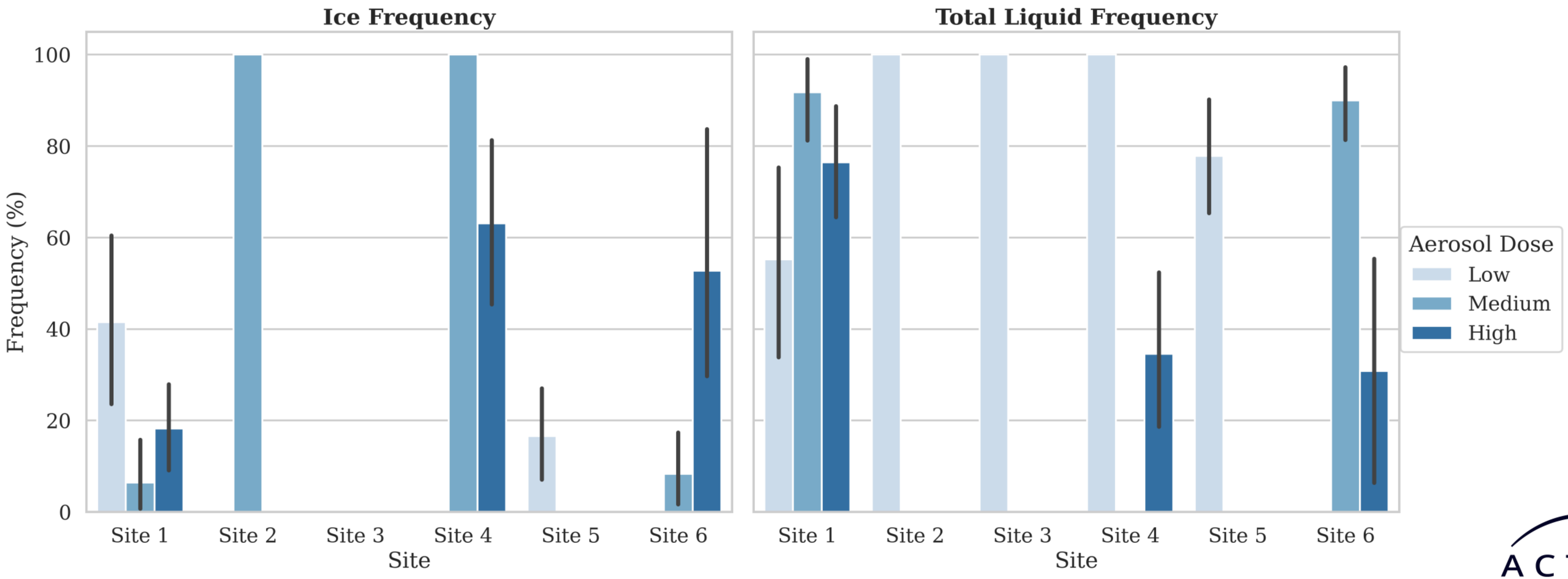
Results

- **Medium dose** had virtually no rainfall recorded
- **Low dose** shows modest baseline rainfall (median ~1.5 mm/h), representing relatively unperturbed cloud behavior
- **High dose** produces the widest rainfall distribution, with the upper whisker reaching ~7.2 mm/h
- The pattern reflects a **regime shift**: at high loading, precipitation eventually forms via the ice phase rather than warm-rain coalescence



Results

- Sites 2 and 4 show **100% ice frequency** under Medium dose, likely reflecting **locally higher cloud altitudes or colder conditions**
- Site 4 shows the **sharpest aerosol signal**: liquid frequency collapses from ~100% (Low) to ~35% (High)
- Sites 2 and 3 are dominated by **warm liquid clouds** under Low/Medium dose, with minimal ice
- The **dose-response signal** in previous slides is reproduced across multiple independent sites, ruling out single-site artifacts
- Large error bars at several sites reflect *limited samples* per dose-category combination



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Conclusions

- **Wildfire smoke** consistently modified cloud microphysics across all stations, with higher aerosol loading reducing droplet size and increasing droplet concentration
- A **non-linear dose-response** emerged: **medium loading** suppressed precipitation most efficiently, while **high loading** ultimately triggered intense rainfall by shifting precipitation from warm-rain to ice-phase pathways
- **High aerosol dose** drove a **sharp increase** in cloud glaciation (~42% ice), suggesting wildfire smoke at sufficient concentrations acts as both CCN and ice-nucleating particles
- The **wave structure** of the event provided a rare natural experiment, demonstrating that long-range transported wildfire smoke is a quantifiable and active modifier of cloud development and precipitation on regional scales

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Future plans

- Move toward a layer-specific, multi-proxy aerosol dose normalized by local clean-air baselines.
- Integrate ground-level in-situ measurements to validate remote sensing microphysics.
- Explore the use of satellite data to complement ground-based measurements and better track plume movement across the continent.

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Thank you

This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022- 2027 with the support of MCID, project no. PN23 05/ 3.01.2023 and was financed by Smart Growth, Digitization and Financial Instruments Program (PoCIDIF) 2021-2027, Action 1.3 Integration of the national RDI ecosystem in the European and international Research Space, project "Supporting the operation of facilities in Romania within the ACTRIS ERIC research infrastructure", SMIS code 309113.

The main author received financial support (Young Researcher and Innovator Conference grant) from the COST (European Cooperation in Science and Technology) under the Action CA24135 EARLICOST (European Atmospheric Research LIdar COoperation on Science and Technology).

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