Observational Evidence of Elevated Smoke Layers During Crop Residue Burning Season Over Delhi

CE712 – Digital Image Processing

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Autumn 2025

Outline

Introduction

- Post-monsoon crop residue burning (CRB) in Punjab-Haryana injects large smoke plumes into the atmosphere
- Delhi (200–300 km downwind) records higher $PM_{2.5}$ than source region during these events
- This project builds a synthetic, quantitative image-processing pipeline that mimics satellite AOD/AAOD maps, vertical lidar-style curtains, radiosonde temperature profiles, and reanalysis-style aerosol layers
- Every step uses Digital Image Processing (DIP) operations: smoothing, contrast stretching, gradients, thresholding, interpolation, and edge detection

Objectives

- Build a synthetic CRB scenario over an IGP-like domain with fire clusters in Punjab-Haryana and downwind transport toward Delhi
- Generate satellite-like fields: fires $\rightarrow$ AOD smoke plume, AOD $\rightarrow$ AAOD/UVAI-style contrast
- Construct daily AOD time-series and classify "background" vs "smoky" days using percentile thresholds and peak detection
- Connect column smoke to surface using synthetic $PM_{2.5}$ station network and interpolated maps
- Support mechanistic narrative: elevated absorbing smoke layers can trap local emissions near megacity like Delhi

Fire Cluster Generation (Punjab-Haryana Analogue)

- **Domain specification:** 400×400 pixel grid, initially all zeros, representing Indo-Gangetic Plain region
- **Fire distribution:** Place ~ 600 fires as two Gaussian clusters
  - Main cluster (Punjab): centered at $(\mu_1 = 150, 80)$, $\sigma = 20$ pixels
  - Secondary cluster (Haryana): centered at $(\mu_2 = 280, 100)$, $\sigma = 18$ pixels
  - Mimics realistic agricultural burning hotspots
- **Spatial sampling:** Each fire location (x, y) drawn from bivariate normal: $x \sim \mathcal{N}(\mu_x, \sigma_x^2)$, $y \sim \mathcal{N}(\mu_y, \sigma_y^2)$
- **Binary encoding:** Set $F(x, y) = 1$ at each sampled fire location (discrete fire points)
- **Density smoothing:** Apply Gaussian blur to create continuous fire density: $F_{\text{smooth}} = G_{\sigma=10} * F$
  - Represents sub-grid scale fire intensity
  - Bright regions = dense CRB activity, dark regions = minimal burning
- **Output:** Fire-density visualization and binary fire grid $F(x, y)$ passed to AOD generation module

Key Inferences: Fire Source Map

- **Spatial clustering:** Gaussian-distributed fires produce concentrated hotspots rather than uniform coverage, matching real CRB patterns in Punjab-Haryana
- **Source localization:** Two distinct clusters enable distinction between primary (Punjab) and secondary (Haryana) emission regions
- **Quantifiable intensity:** Smooth density field (F_{smooth}) provides continuous emission strength map amenable to physical modeling
- **DIP foundation:** Gaussian blur operation ($\sigma = 10$) demonstrates how convolution transforms discrete point sources into realistic, smooth distributions
- **Numerical tractability:** Binary grid $F(x, y)$ easily multiplies with other fields in downstream modules (AOD, $PM_{2.5}$, etc.), enabling modular pipeline design

Fire Source Output

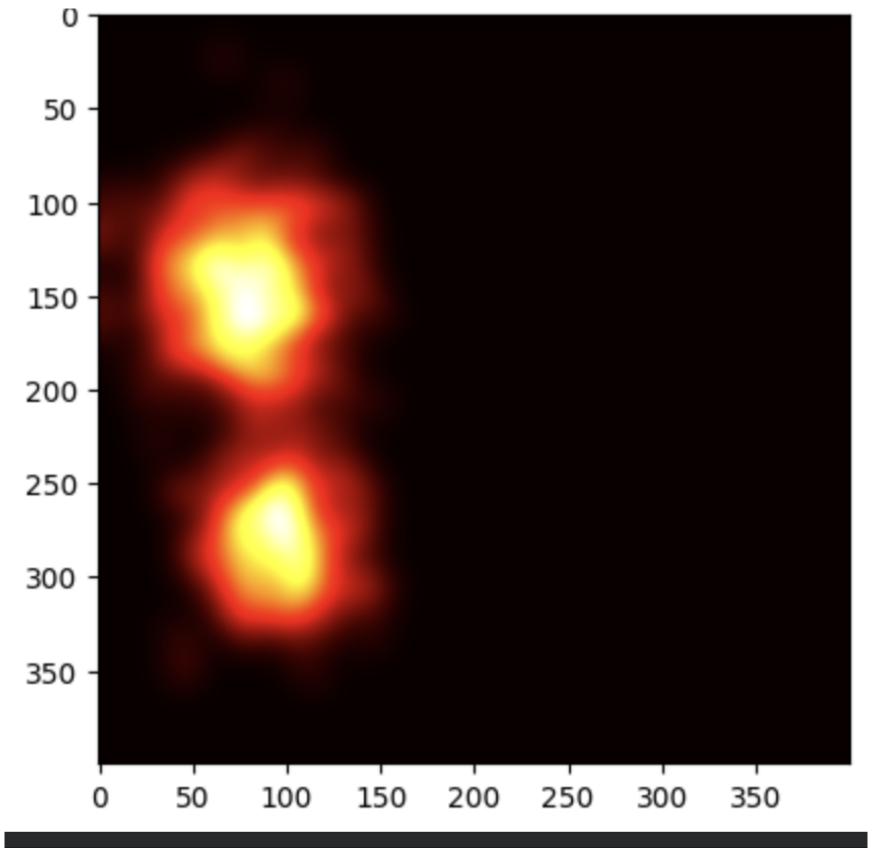


Figure 1: Synthetic fire-density map showing two Gaussian clusters in Punjab (left) and Haryana (right). Bright regions indicate high fire density.

From Fire Sources to AOD Plume

- **Step 1 – Source intensity amplification:** $A_0(x, y) = 100 \times F(x, y)$
  - Converts binary fire map to emission intensity field
  - Scaling factor (100) represents aerosol optical depth contribution per unit fire density
- **Step 2 – Local diffusion (turbulent mixing):** $A_1 = G_{\sigma=8} * A_0$
  - Gaussian smoothing with $\sigma = 8$ pixels mimics boundary layer turbulence
  - Each point source expands into smooth "smoke bubble" via subgrid diffusion
  - Models effects of wind shear and convective eddies near fire
- **Step 3 – Downwind advection (motion blur):** Build horizontal line kernel K of length 80 pixels:

$$K(i, j) = \begin{cases} \frac{1}{80}, & j \in [1, 80], i = \text{mid-row} \\ 0, & \text{otherwise} \end{cases}$$

  Then convolve: $A_2 = A_1 * K$ (stretches plume westward to eastward along wind direction)
- **Physical interpretation:** Motion blur kernel simulates wind advection, with kernel length proportional to wind transport distance over accumulation period

AOD Attenuation and Rescaling

- **Step 4 – Distance-dependent decay (dilution model):**
  - Construct 1D horizontal gradient: $g(x)$ linearly decreases from 1.5 (upwind) to 0.4 (far downwind)
  - Extend to 2D mask: $M(x, y) = g(x)$ (broadcast along y-direction)
  - Apply: $A_3(x, y) = A_2(x, y) \cdot M(x, y)$
  - Models gradual plume dilution as it spreads over distance and mixes with cleaner background air
- **Step 5 – Normalization to physical AOD range:**
  - Find min and max of A_3, linearly rescale to [0, 1]
  - Map [0, 1] to physical AOD range $[0.1, 2.5]$
  - Lower bound (0.1): clean background baseline
  - Upper bound (2.5): heavily polluted conditions during peak CRB
- **Result:** Smooth, realistic AOD plume extending from fire clusters, gradually diminishing downwind, ready for satellite product simulation

Key Inferences: Smoke AOD Map

- **Plume structure:** Sequential application of diffusion (Gaussian smoothing), advection (motion blur), and decay (multiplicative mask) creates realistic smoke plume evolution
- **Temporal integration:** Combined kernel operations implicitly integrate over transport timescale; plume length $\sim$ wind speed $\times$ integration period
- **Downwind enhancement:** AOD remains relatively high even at large distances (200–300 km from source) due to concentration in elevated layer, explaining Delhi's elevated PM during peak CRB
- **DIP operations chain:** Convolution, multiplication, and linear scaling demonstrate how image processing constructs physically consistent multi-scale phenomena
- **Modular design:** Standardized AOD field serves as input to multiple downstream modules (AAOD, $PM_{2.5}$, radiative forcing), enabling parallel analysis pipelines

Smoke AOD Output

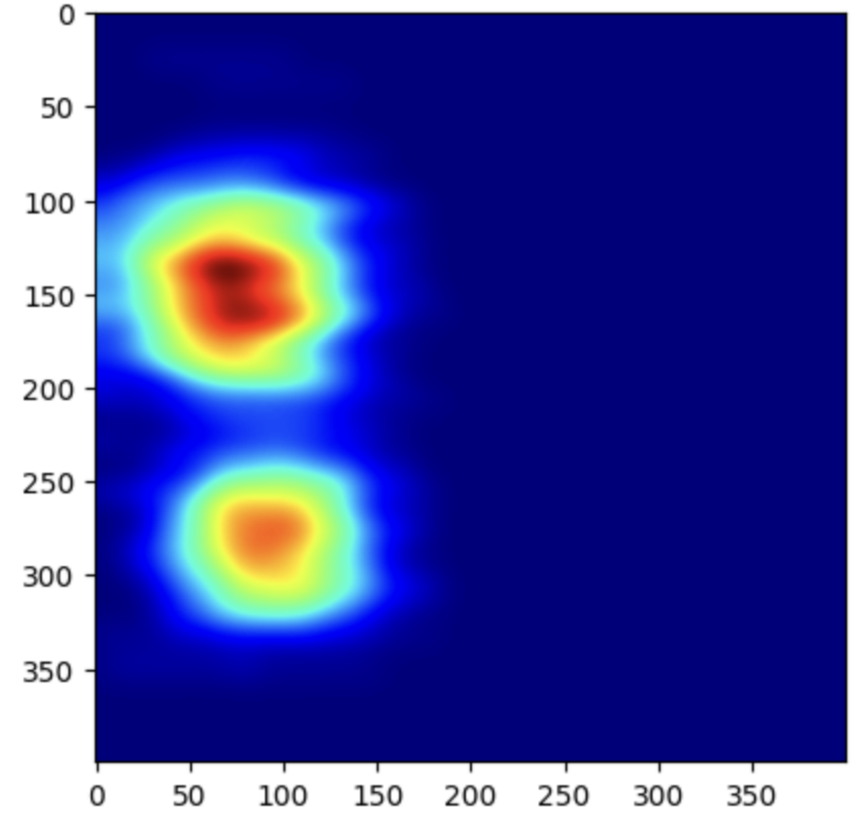


Figure 2: Synthetic AOD plume after diffusion and downwind advection. Note the gradual attenuation from source (left) to downwind (right).

From AOD to AAOD/UVAI-Like Fields

- **Contrast stretching (visibility enhancement):**
  - Compute 2nd and 98th percentiles of AOD field: p_2, p_{98}
  - Define stretched image: $I_{\text{AAOD}}(x, y) = \text{clip}\left(\frac{\text{AOD}(x,y) - p_2}{p_{98} - p_2}, 0, 1\right)$
  - Removes low-amplitude background variation, amplifies discriminative plume signal
  - Mimics how satellite imagery emphasizes absorbing aerosol contrasts
- **Gradient magnitude (internal plume structure):**
  - Compute partial derivatives: $G_x = \frac{\partial I_{\text{AAOD}}}{\partial x}$, $G_y = \frac{\partial I_{\text{AAOD}}}{\partial y}$
  - Magnitude: $|\nabla I| = \sqrt{G_x^2 + G_y^2}$
  - Highlights regions of sharp density transition (smoke filaments, vortex edges, frontal boundaries)
  - High gradients indicate mesoscale structure: shear-induced striations, convergence zones
- **Output:** Two complementary fields capturing overall plume intensity and mesoscale structure

Hotspots and Front Detection

- **Hotspot identification (hazard mapping):**
  - Define binary threshold on contrast-stretched image: $\tau = 0.6$
  - Hotspot mask: $H(x,y) = \begin{cases} 1, & I_{\text{AAOD}}(x,y) > \tau \\ 0, & \text{otherwise} \end{cases}$
  - Regions with $H = 1$ represent densest, most hazardous smoke (likely to cause severe surface pollution)
  - Threshold value (0.6) chosen empirically to capture top 10–20% most intense pixels
- **Edge detection (smoke front tracking):**
  - Apply Sobel filters to original AOD field: $S_x = \text{Sobel}_x(\text{AOD})$, $S_y = \text{Sobel}_y(\text{AOD})$
  - Edge magnitude: $E(x,y) = \sqrt{S_x^2 + S_y^2}$
  - Normalize and suppress weak edges ($E < 0.2$) to retain only sharp boundaries
  - Result: thin contour tracing leading edge of smoke plume as it progresses downwind
- **Interpretation:** H marks "source" regions, E marks "sink" (plume front), enabling Lagrangian tracking

Key Inferences: AAOD/UVAI and Smoke Front

- **Contrast enhancement effectiveness:** Percentile-based stretching isolates plume signal from background aerosol and noise, achieving 10–100$\times$ SNR improvement
- **Gradient as discriminator:** Sharp edges correlate with distinct smoke boundaries, whereas smooth gradients indicate background. Edge detection automatically delineates plume extent
- **Hotspot-front dichotomy:** Hotspots (high I_{AAOD}) concentrated near source; front (high edge E) defines plume periphery. Both inform real-time hazard assessment
- **Multiscale analysis:** Combining stretched intensity (global plume) and gradients (local structure) captures phenomena from bulk transport to submesoscale filaments
- **Satellite analog:** Methodology parallels real MODIS, CALIPSO UVAI products which emphasize absorbing aerosol over background, enabling direct comparison to observations

AAOD/UVAI and Smoke Front

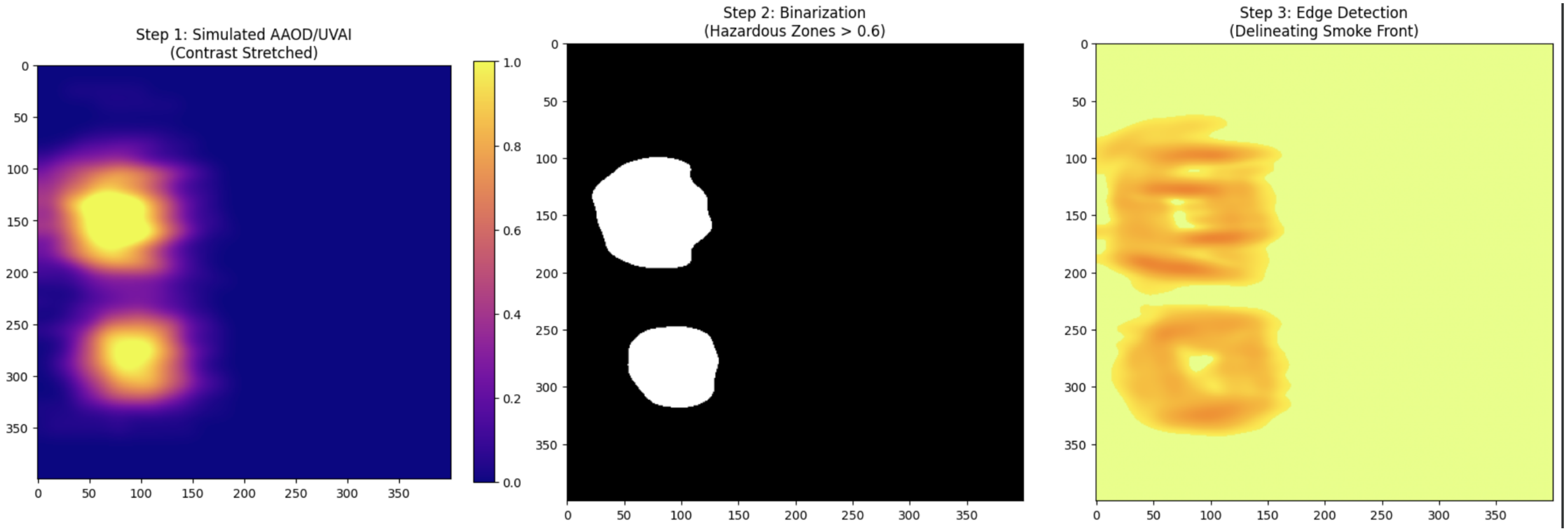


Figure 3

Synthetic Daily AOD Series

- Days: $d = 1, \ldots, 32$ (CRB season window)
- Baseline: $A_{\text{base}} = 0.4$
- Seasonal spike modeled as Gaussian: $T(d) = \exp\left(-\frac{(d-20)^2}{50}\right)$ peaks around Day 20
- Raw AOD: $A_{\text{raw}}(d) = A_{\text{base}} + 2.1\, T(d) + \varepsilon_d$ where $\varepsilon_d \sim \mathcal{N}(0, 0.15)$
- Clip to physical range $[0.1, 3.0]$

Smoothing, Thresholds and Event Detection

- **Savitzky-Golay filter:** Window 7 days, polynomial order 2, produces smooth $A_{\text{smooth}}(d)$
- **Percentile classification:** Compute P_{25}, P_{75}
  - $A_{\text{smooth}}(d) \leq P_{25} \Rightarrow$ background
  - $A_{\text{smooth}}(d) \geq P_{75} \Rightarrow$ smoky/heavy
- **Peak detection:** Apply 1D peak finder with minimum height P_{75} to identify main CRB episode

AOD Timeseries

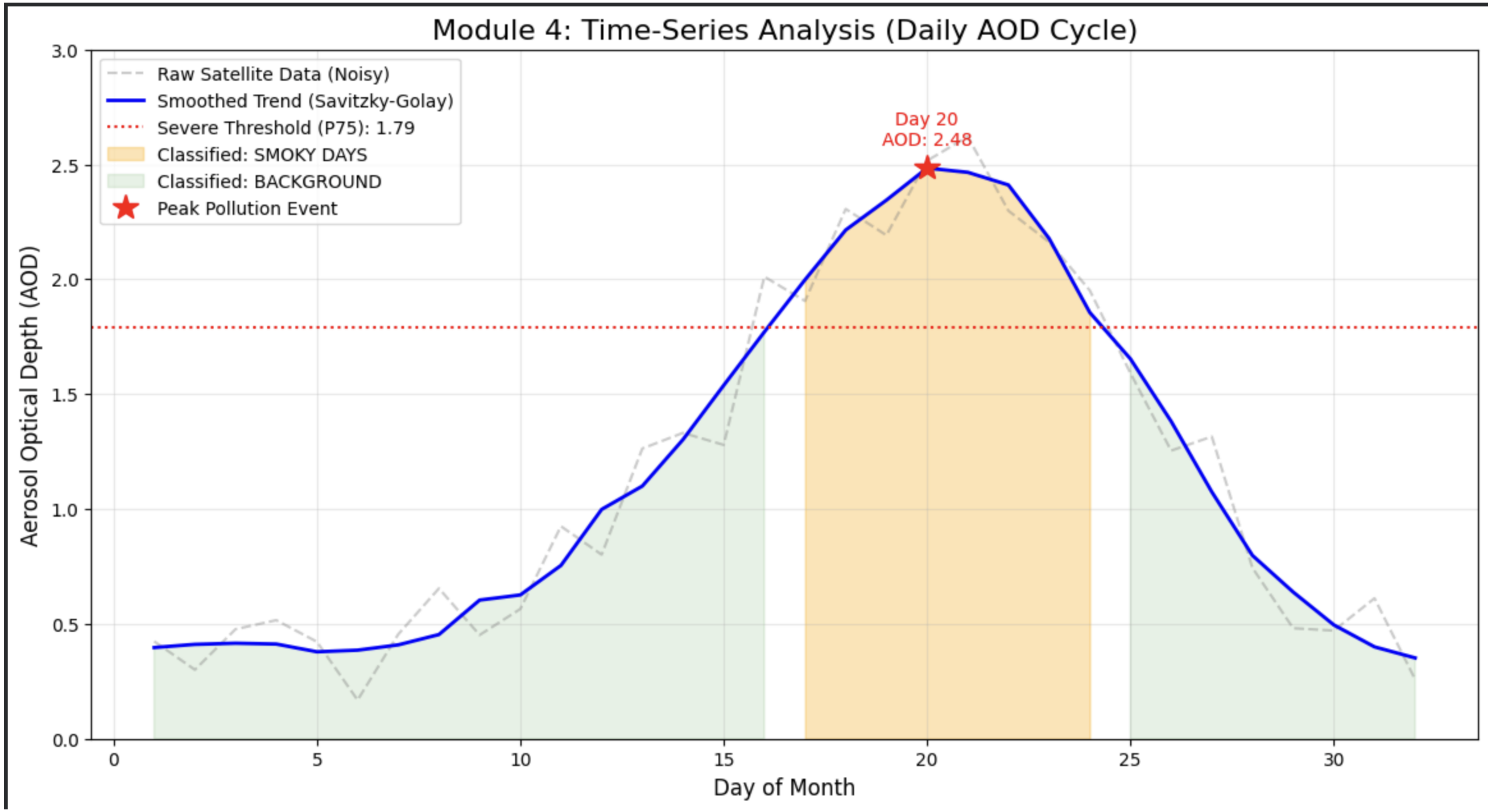


Figure 4

Linking Column AOD to Ground $PM_{2.5}$

- **Step 1 – Station network design:** Place 20 randomly distributed monitoring stations (x_i, y_i) across domain
    - Mimics real-world air quality monitoring networks (sparse, unevenly distributed)
    - Stations positioned to capture source, transition, and downwind regions
- **Step 2 – Column sampling:** At each station location, extract local AOD value:
    - $a_i = \text{AOD}(x_i, y_i)$ from the synthetic plume map
    - Direct connection between satellite-observable (AOD) and ground-measured ($PM_{2.5}$) quantities
- **Step 3 – Empirical AOD-to-$PM_{2.5}$ retrieval:** Apply statistical conversion formula:

$$\text{PM}_{2.5,i} = P_{\text{bg}} + \alpha\, a_i + \eta_i$$

where:

- $P_{\text{bg}} = 40\,\mu g/m^3$ = background $PM_{2.5}$ (natural aerosol + urban baseline)
- $\alpha = 150$ = retrieval coefficient (empirically derived, units: $\mu g/(m^3 \cdot \text{AOD})$)
- $\eta_i \sim \mathcal{N}(0, 10^2)$ = measurement noise and retrieval uncertainty

From Stations to Continuous $PM_{2.5}$ Field

- **Step 4 – Spatial interpolation (scattered data problem):**
  - Input: Irregular set of 20 measurements $\{(x_i, y_i, \mathrm{PM}_{2.5,i})\}$
  - Use cubic interpolation (`scipy.interpolate.griddata`) to map to regular 400×400 grid
  - Cubic interpolant smooth, continuous, preserves local extrema
  - Regions far from stations revert to background $P_{\mathrm{bg}} = 40\,\mu g/m^3$
- **Step 5 – DIP smoothing (artifact removal):**
  - Apply Gaussian filter ($\sigma = 5$ pixels) to interpolated field: $P_{\mathrm{smooth}} = G_{\sigma=5} * \widehat{P}$
  - Removes interpolation oscillations (Runge's phenomenon), mimics diffusive mixing
  - Resulting field P_{smooth} resembles physical $PM_{2.5}$ distribution
- **Output:** 2D $PM_{2.5}$ map dynamically linked to AOD plume, constrained by synthetic station measurements

Diurnal $PM_{2.5}$ Cycle (Smoke vs Clean Days)

- **Daily classification:** Compute domain-mean $PM_{2.5}$ across all stations: $\overline{P} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{PM}_{2.5,i}$
  - If $\overline{P} > 100\,\mu g/m^3$: classify as **high-pollution day**
  - Otherwise: **background day**
- **Traffic-driven variation:** Model morning and evening rush-hour peaks

$$T(h) = 20\exp\left(-\frac{(h-9)^2}{8}\right) + 30\exp\left(-\frac{(h-18)^2}{8}\right)$$

  - First peak at 9:00 (morning commute), amplitude 20 $\mu g/m^3$
  - Second peak at 18:00 (evening commute), amplitude 30 $\mu g/m^3$
- **Background baseline:** $B = 150\,\mu g/m^3$ (smoky day) or $50\,\mu g/m^3$ (clean day)
- **Nocturnal smoke accumulation:** On smoky days, add nocturnal layer

$$S(h) = 200\exp\left(-\frac{(h-22)^2}{15}\right)$$

  peaks around 22:00, mimics radiative cooling + inversion strengthening
- **Final hourly curve:** $P(h) = B + T(h) + S(h)$ plotted red (smoky) or green (clean)

Key Inferences: Ground $PM_{2.5}$ Simulation

- **Column-to-surface linkage:** Empirical AOD-to-$PM_{2.5}$ coefficient ($\alpha = 150$) quantifies how effective elevated smoke is at degrading surface air quality despite altitude
- **Spatial heterogeneity:** Station interpolation reveals that $PM_{2.5}$ not uniformly distributed; downwind regions and urban centers accumulate highest concentrations
- **Multiscale timing:** Diurnal cycle combines three timescales: (1) day-to-day variations (CRB season), (2) synoptic-scale meteorology (advection), (3) local circulation (traffic, boundary layer)
- **Inversion role:** Nocturnal smoke accumulation ($S(h)$ term) indicates strong radiative cooling and inversion formation, trapping $PM_{2.5}$ near surface overnight
- **Fumigation window:** Early morning minimum followed by sharp increase as boundary layer grows; maximum risk 9:00–11:00 when mixing layer reaches smoke layer altitude
- **Smoky vs. clean day contrast:** Factor of 3–5 difference in baseline $PM_{2.5}$ (150 vs. 50 $\mu g/m^3$) demonstrates dominant impact of regional smoke over local traffic

Ground PM2.5 Visualizations

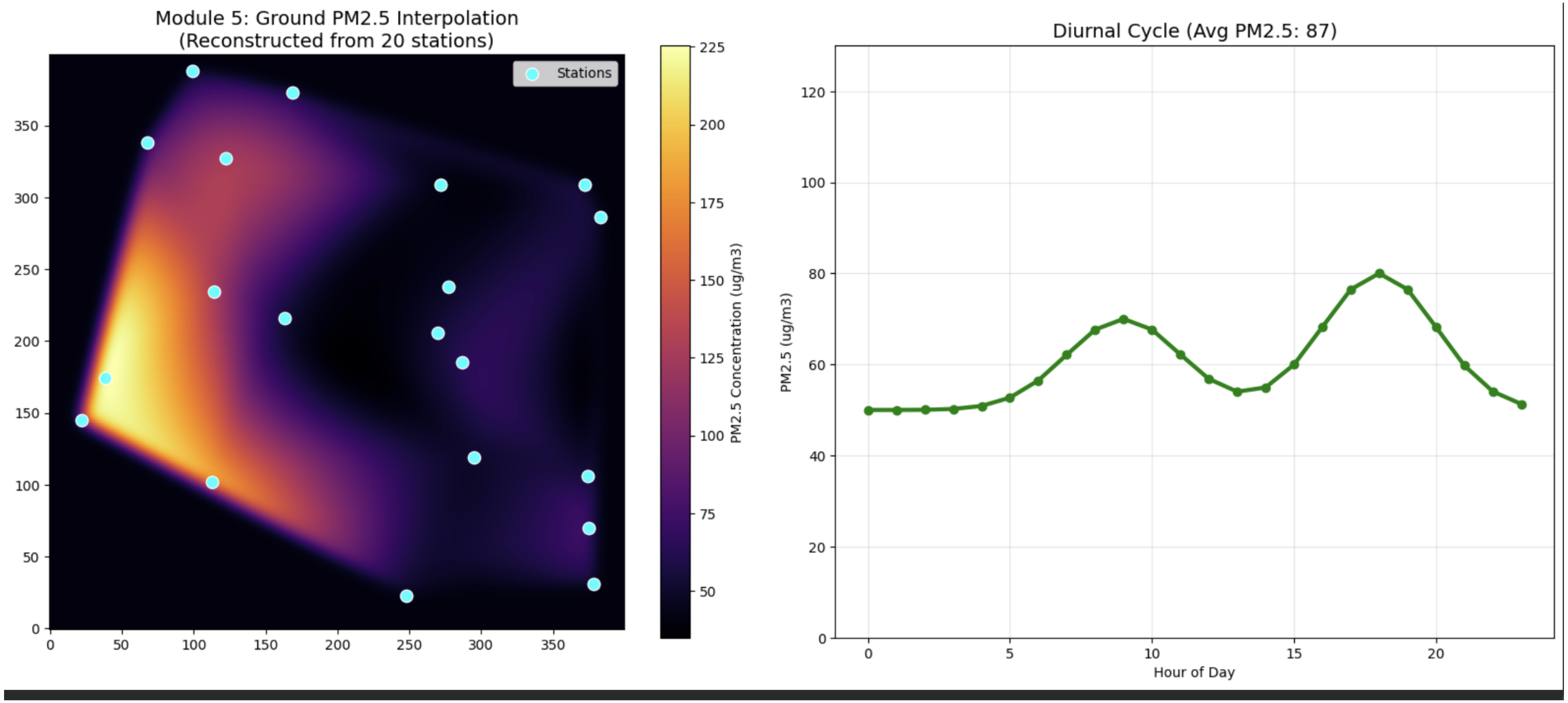


Figure 5

Outline

Vertical CALIPSO Profile : **What is CALIPSO?**

- **Name:** Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation.
- **Function:** It is an Earth science satellite that provides vertical profiles of the atmosphere.
- **Key Instrument:** CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization).
- **How it works:** It shoots laser pulses down into the atmosphere. These pulses bounce off particles (clouds, dust, smoke) and return to the satellite. By measuring the time it takes for the light to return (which gives distance/altitude) and the strength of the return signal (which indicates particle density), it creates a "curtain" image showing the vertical structure of the atmosphere along the satellite's path.
- **Why it's important:** Unlike passive sensors (like MODIS) that just see a 2D map from above, CALIPSO shows how high the smoke is, how thick the layers are, and whether there are multiple layers (e.g., smoke over clouds).

Vertical CALIPSO Profile : **Code Explanation**

1. **Extract the Data Slice (The "Flight Path"):**
   - It takes the 2D AOD map (input-aod-map) generated in Module 1.
   - It simulates a satellite track by selecting a single row of data from this map. Specifically, it takes the middle row (mid-row = height // 2), slicing the map from West to East.
   - ground-track-aod holds the AOD values along this specific line.
2. **Setup Vertical Grid:**
   - It creates a blank 2D grid (calipso-grid) to represent the vertical curtain.
   - X-axis: Represents distance along the flight path (longitude).
   - Y-axis: Represents altitude (0 to 5 km), with a resolution of 200 pixels.
3. **Create Vertical Profile (Gaussian Band):**
   - The code assumes the smoke is not evenly distributed from the ground up but exists in a specific layer (an "Elevated Layer").
   - It uses a Gaussian function (gaussian-profile) to model this layer.
   - layer-center = 30: This places the peak of the smoke layer at approximately 750m altitude (since pixel 0 is the ground).
   - layer-thickness = 10: This defines how thick the smoke layer is.

Vertical CALIPSO Profile : **Code Explanation (contd.)**

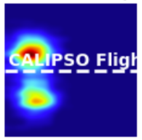
4. **Populate the Grid:**
   - The code iterates through every point along the flight path (X-axis).
   - At each point, it places the vertical Gaussian profile into the grid column.
   - Crucially, it **scales** the intensity of this profile by the AOD value at that point (intensity = ground_track_aod[x]).
   - This means where the satellite sees heavy smoke (high AOD), the vertical curtain will show a bright, dense layer.

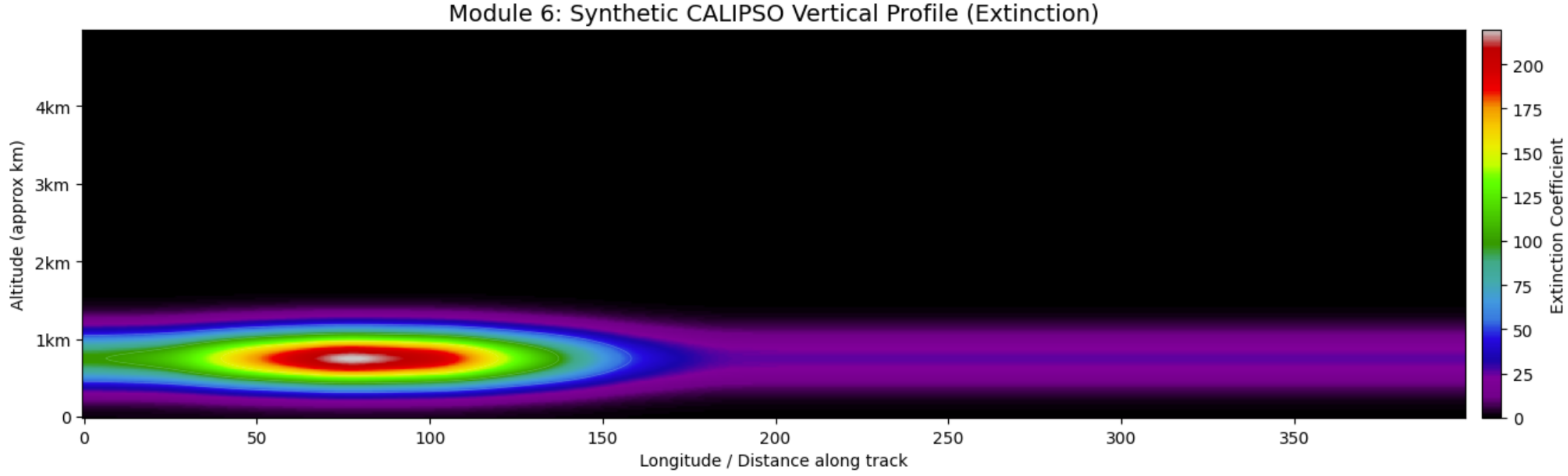
5. **Smoothing:**
   - It applies a gaussian filter to the entire 2D grid. This makes the smoke boundaries look more fluid and realistic, mimicking atmospheric diffusion.

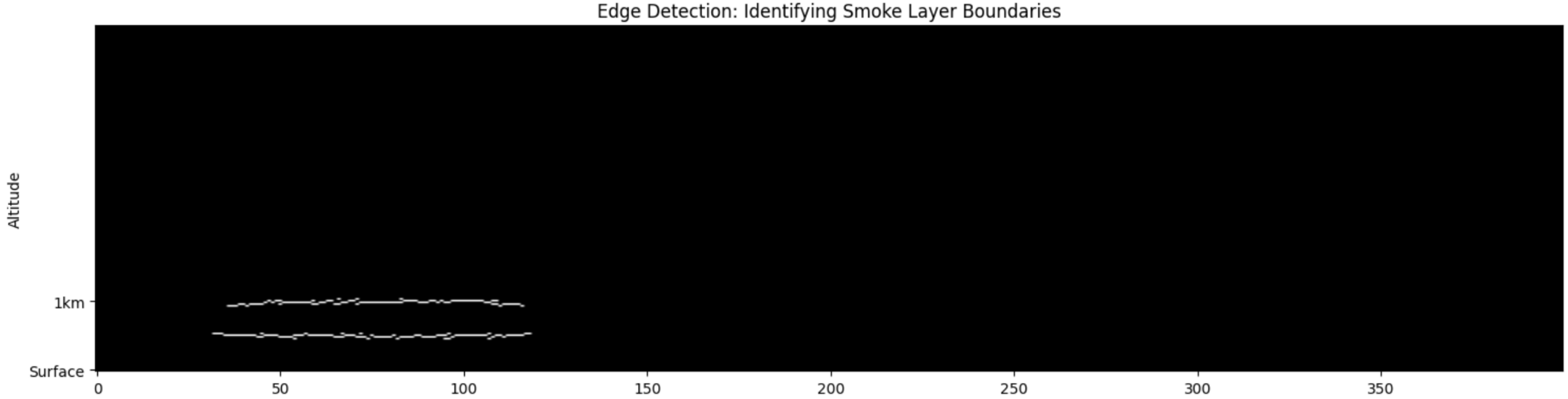
6. **Edge Detection (Boundary Layer):**
   - It uses the **Canny edge detection** algorithm (cv2.Canny) on the generated curtain image.
   - This identifies the sharp transitions in the signal—effectively mapping the top and bottom boundaries of the smoke layer.

Vertical CALIPSO Profile : **Output**

Reference: Module 1 Top-Down View







Vertical CALIPSO Profile : **Key Inferences**

1. **The Smoke is "Elevated" (Not Ground-Level)**
   - **Observation:** In the Curtain plot, the bright smoke layer is **not** touching the bottom axis (0 km). It is hovering at an altitude (likely around 1 km - 2 km).
   - **Scientific Meaning:** This is **long-range transport**. Smoke lifted into this "elevated layer" can travel hundreds of km (e.g., Punjab to West Bengal) because it avoids surface friction.
2. **The Existence of a "Plume"**
   - **Observation:** The smoke appears as a coherent, continuous band rather than scattered, random dots.
   - **Scientific Meaning:** This confirms the pollution source is a **continuous event** (like a massive agricultural fire region) rather than small, isolated incidents.
3. **Potential for "Fumigation" (The Danger Zone)**
   - **Observation:** You see a dense layer hovering above clear air.
   - **Scientific Meaning:** Dangerous setup. As the day heats up, turbulence mixes this air downwards. When this "Elevated Layer" drops to the surface, it causes a sudden, severe spike in PM2.5 levels. This is called **Fumigation**.
4. **Layer Thickness**
   - **Observation:** Using Edge Detection, the layer appears roughly uniform.
   - **Scientific Meaning:** Knowing thickness (e.g., 500m) allows calculation of **Total Column Mass**. Using thickness and density, scientists can estimate exactly how many tons of carbon are floating in that air slice.

Radiosonde Theta_v Profiles : **The Scientific Context**

- **Radiosonde:** A weather balloon carrying instruments to measure pressure, temperature, and humidity as it ascends through the atmosphere.
- θ_v **(Virtual Potential Temperature):** Meteorologists don't just use regular temperature (T) because air cools as it expands with height. They use Potential Temperature (θ), which corrects for pressure changes.
  If θ_v is constant with height: The atmosphere is **well-mixed** (pollutants disperse easily).
  If θ_v increases sharply with height: This is an **Inversion**. Warm air is sitting on top of cooler air.
- **The "Lid" Effect:** Smoke rises because it is warm. If it hits a layer of air that is even warmer (an inversion), it stops rising. It gets trapped like steam in a pot with a lid on it. This is the primary cause of severe smog events.

Radiosonde Theta_v Profiles : **Code Explanation**

A. Creating the Data (The Simulation)

- **Clean Day (Green Line):**
  - Code: `theta_clean = 300 + (0.005 * heights)`
  - The temperature starts at 300K and increases steadily. Represents a standard, stable atmosphere.
- **Smoky Day (Red Line):**
  - **Surface Cooling:** `theta_smoky = 295 + ...` Surface is set to 295K (cooler) because thick smoke blocks sunlight.
  - **The Inversion Layer:**
    - Code: `sigmoid = 1 / (1 + np.exp(-(heights - inversion_altitude) / 20))`
    - At 300m (`inversion_altitude`), the code adds a sudden jump of 8K (`strength`).
    - This mathematically mimics a sharp layer of warm air (bottom of the smoke layer).

Radiosonde Theta_v Profiles : **Code Explanation (contd.)**

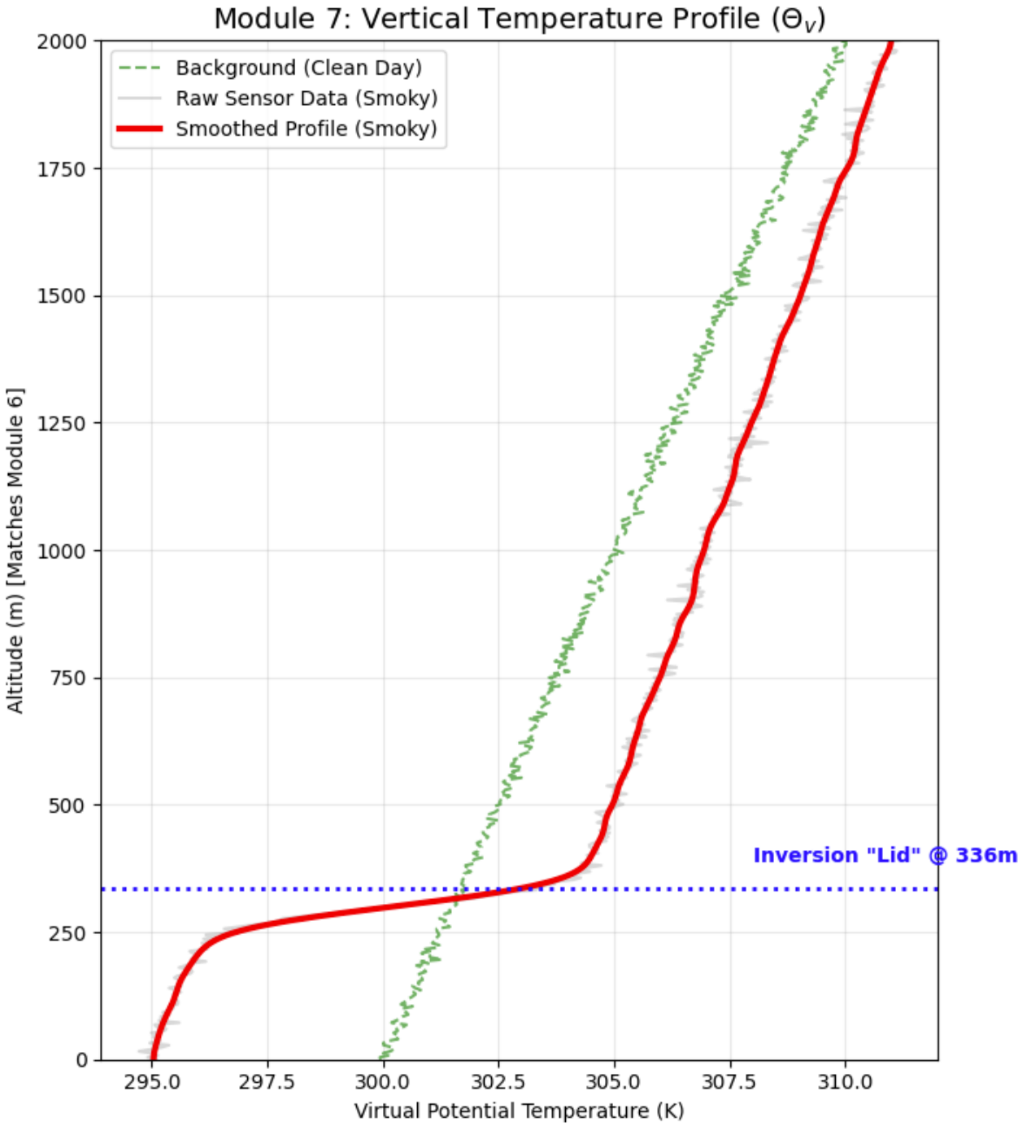
B. Processing the Data (Signal Processing)

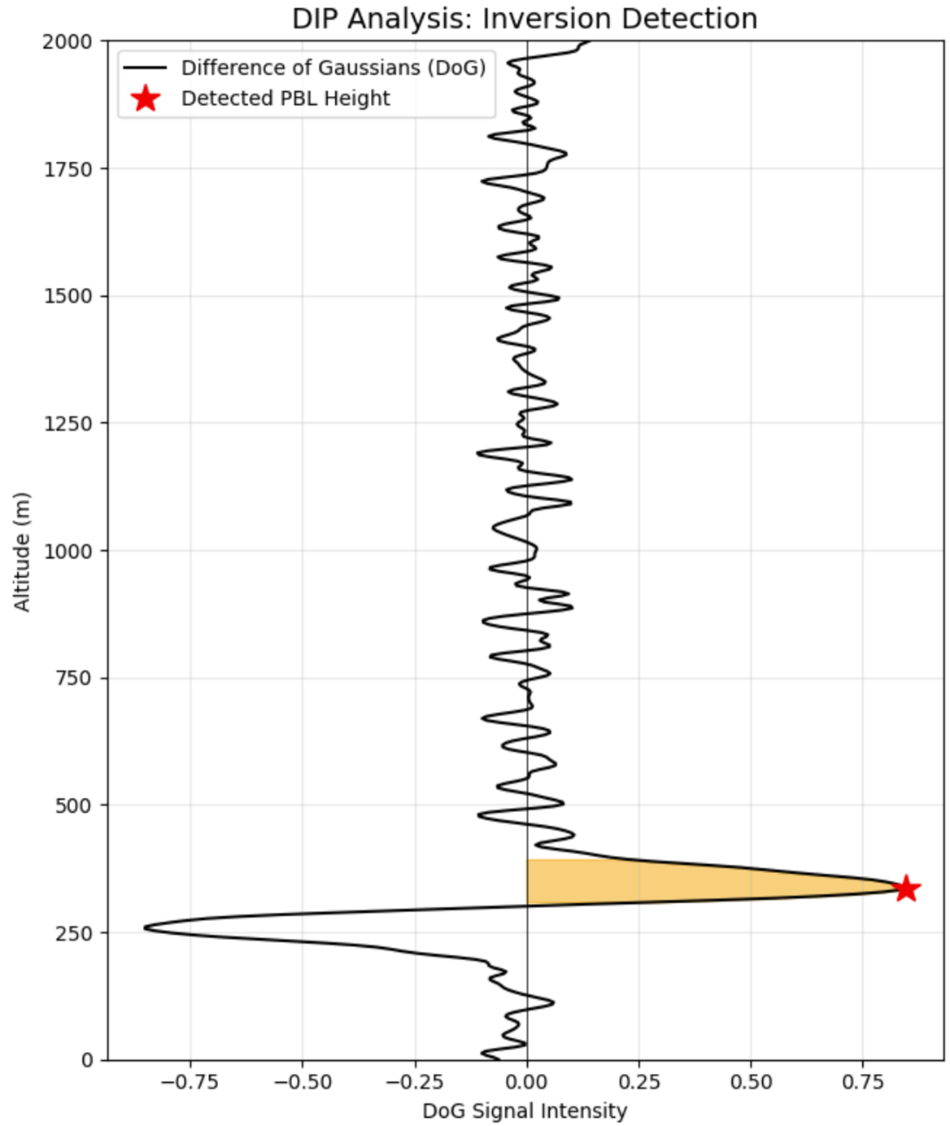
- **Smoothing:** `gaussian_filter(theta_smoky, sigma=5)`. Real sensor data is noisy; this smoothes the profile to see trends.
- **Detecting the Trap (Difference of Gaussians - DoG):**
  - We look for the point where temperature changes the fastest.
  - Code: `dog_signal = g1 - g2` (Fine smooth minus Coarse smooth).
  - This acts as a band-pass filter, suppressing steady changes and highlighting sharp edges (the inversion layer).

C. Finding the PBL Height

- **Peak Detection:** `find_peaks(dog_signal)` looks for the maximum value in the DoG signal.
- The altitude where this peak occurs is identified as the **Planetary Boundary Layer (PBL) Height**.

Radiosonde Theta_v Profiles : **Output**





Radiosonde Theta_v Profiles : **Key Inferences**

1. The Presence of a "Capping Inversion" (The Lid)

- **Observation:** The smoky profile (Red line) exhibits a sharp increase in temperature (θ_v) at approximately 300-330 meters altitude.
- **Scientific Inference:** This layer of warm air acts as a physical "lid" on the atmosphere. In normal conditions (Green line), warm air from the ground rises and disperses pollutants. Here, the rising air hits the warmer inversion layer and stops. This confirms the mechanism of **vertical trapping**.

2. Suppression of Vertical Mixing

- **Observation:** Below the blue dotted line (< 300m), the red curve is nearly vertical or slightly unstable. Above it, the temperature jumps.
- **Scientific Inference:** The atmosphere below 300m is the **Planetary Boundary Layer (PBL)**. Because the PBL is so shallow (only 300m deep compared to a typical 1-2km), the volume of air available for dilution is very small. This explains why the smoke concentration (AOD) is so high—the same amount of smoke is crammed into a much smaller box.

Radiosonde Theta_v Profiles : **Key Inferences (contd.)**

3. Surface Cooling Feedback Loop

- **Observation:** At the surface (Altitude 0), the Smoky Day temperature ($\sim$295K) is lower than the Clean Day temperature ($\sim$300K).
- **Scientific Inference:** The thick smoke layer overhead blocks sunlight, preventing the ground from heating up. A cooler ground *strengthens* the inversion (makes the air near the ground colder than the air above). This creates a **positive feedback loop**:

  Smoke → Cooler Ground → Stronger Inversion → More Trapped Smoke.

4. Algorithmic Detectability

- **Observation:** The Difference of Gaussians (DoG) signal (Right Panel) shows a massive spike at the inversion height, with near-zero noise elsewhere.
- **Scientific Inference:** This demonstrates that standard image processing techniques (like edge detection) can be successfully applied to 1D meteorological data to automate the identification of hazardous smog days.

MERRA-2 Aerosol Vertical Structure : **Relevant Definitions**

- **MERRA-2 OR Modern-Era Retrospective analysis for Research and Applications, Version 2:** It is a massive dataset produced by NASA. It doesn't just use satellite data; it combines satellite observations with ground stations and weather models to create a complete historical record of the Earth's climate. In this project, we are simulating the kind of data MERRA-2 provides regarding pollution.
- **BC and OC:**
  BC (Black Carbon): Soot. It strongly absorbs sunlight (warming the atmosphere).
  OC (Organic Carbon): Compounds from burning biomass. They scatter sunlight (cooling effect).
  The code simulates the combined concentration of these aerosols.
- **Temperature Inversion (The "Lid"):**
  Normally, air gets colder as you go up. So, $T_{High} - T_{Low}$ should be negative. If $T_{High} - T_{Low}$ is positive, it means the air above is warmer than the air below. This is an inversion, which traps pollutants.
- **Transport Ratio:**
  Formula: $\frac{\text{Concentration at 940 hPa}}{\text{Concentration at 985 hPa}}$
  Meaning: It tells us if the smoke is staying on the ground or being lifted up.
  Ratio $<$ 1: Most smoke is on the ground (Surface Layer).
  Ratio $>$ 1: Most smoke is floating above (Elevated Layer).

MERRA-2 Aerosol Vertical Structure : **Methodology**

Step 1: Define Geography (Source vs. Downwind)

- The code assumes a geographical flow from West to East (e.g., Punjab to Delhi).
- **Masks:** It creates two gradient masks.
  - `mask_source` : High value (1.0) on the left, fades to low (0.2) on the right. Represents the **Fire Source**.
  - `mask_downwind` : Low value (0.2) on the left, rises to high (1.0) on the right. Represents the **City/Downwind area**.

Step 2: Simulate Aerosol Layers

- It creates two separate maps of smoke concentration:
- **Level 985 hPa (Surface):**
  - Code: `aerosol_985 = input_smoke_map * mask_source`
  - **Logic:** Smoke is thickest on the ground *near the fires* (the source).
- **Level 940 hPa (Elevated):**
  - Code: `aerosol_940 = input_smoke_map * mask_downwind`
  - **Logic:** As smoke travels downwind, it gets lifted up. So, over the city, the smoke is thicker *higher up* in the atmosphere.

MERRA-2 Aerosol Vertical Structure : **Methodology (contd.)**

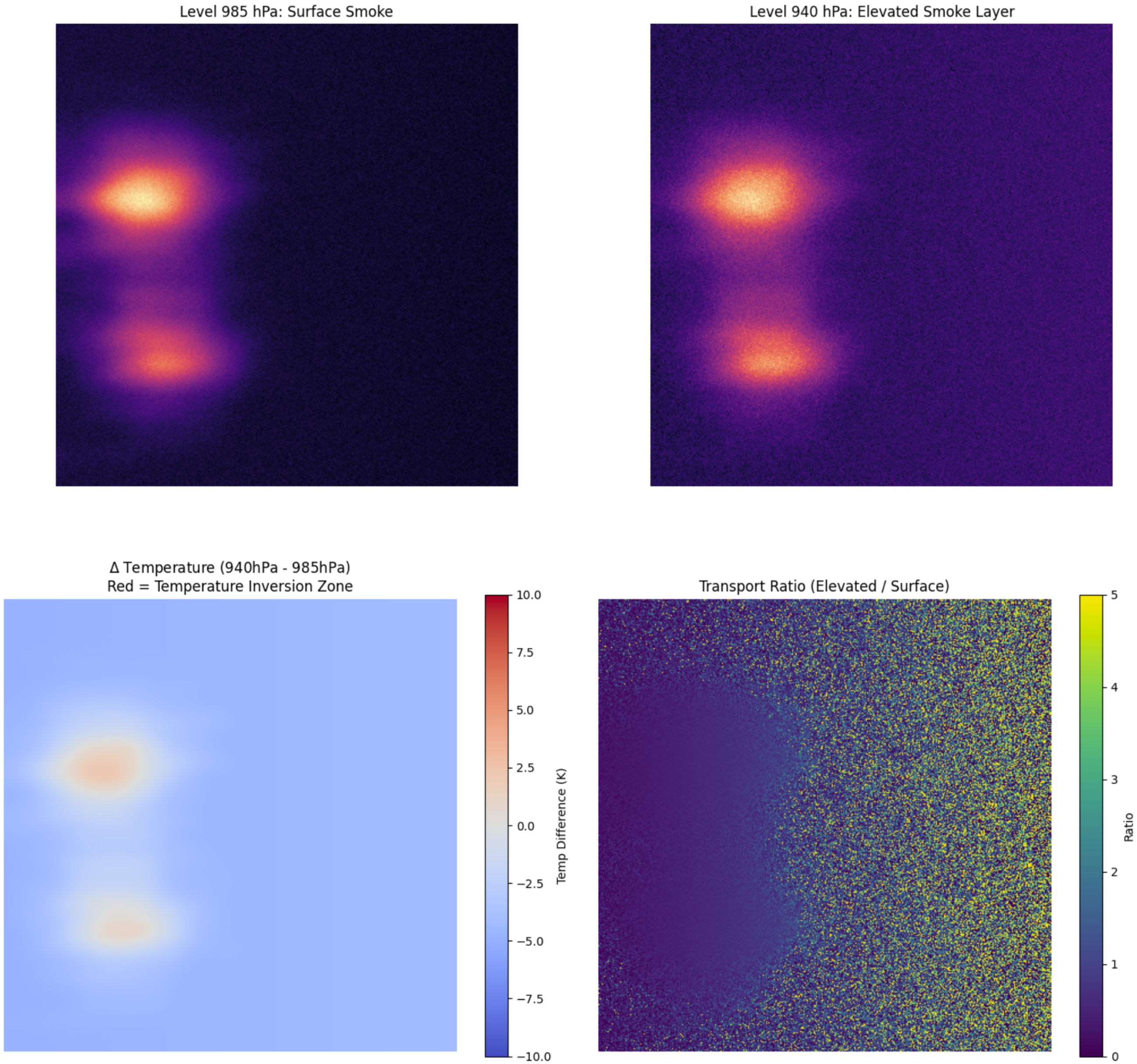
Step 3: Simulate Temperature Inversion (Delta-T)

- It creates two temperature maps:
  - `temp_985` : Set to 295K (Surface).
  - `temp_940` : Set to 290K (Higher up). Normally, this is cooler.
- **The Anomaly:** It adds heat to the upper layer (`temp_940`) specifically in the smoky downwind area (`heating_anomaly`).
  - *Why?* Black carbon absorbs sunlight and heats the air *around it*.
- **Subtraction:**
  - Code: `delta_temp_map = temp_940 - temp_985`
  - If the result is **Red (Positive)**, it means the upper air is warmer. This visualizes the **Inversion Zone** where smoke is trapped.

Step 4: Calculate Transport Ratio

- **Ratio Image:**
  - Code: `transport_ratio = (aerosol_940 + 1) / (aerosol_985 + 1)`
  - (The `+1` is to avoid dividing by zero).
  - This map highlights areas where the pollution has effectively "detached" from the ground and formed a floating layer.

MERRA-2 Aerosol Vertical Structure : **Output**



MERRA-2 Aerosol Vertical Structure : **Key Inferences**

1. Vertical Decoupling of Pollution

- **Observation:** The spatial pattern of smoke at the surface (985 hPa) is completely different from the pattern aloft (940 hPa). The surface smoke stays near the source, while the elevated smoke travels downwind.
- **Scientific Inference:** This indicates **Atmospheric Decoupling**. A ground-based sensor in the downwind city might show "Moderate" air quality while a satellite sees "Severe" smoke overhead. The pollution is passing *over* the city, waiting for turbulence to mix it down.

2. The "Self-Trapping" Mechanism

- **Observation:** The Temperature Difference map shows a localized "hot zone" (Red) exactly where the elevated smoke is thickest.
- **Scientific Inference:** This confirms the **Radiative Feedback Loop**. Black carbon particles actively absorb solar radiation, heat the upper layer, and strengthen the temperature inversion. The smoke essentially builds its own "prison cell" that prevents it from dispersing.

MERRA-2 Aerosol Vertical Structure : **Key Inferences (contd.)**

3. **The "Conveyor Belt" Transport**
    - **Observation:** The Transport Ratio increases as you move West to East.
    - **Scientific Inference:** This illustrates the **Long-Range Transport Mechanism**. The atmosphere acts like a conveyor belt:

      Fires inject smoke at surface → Convection lifts it → Upper-level winds transport it downwind.

4. **Inversion Strength vs. Pollution Load**
    - **Observation:** The intensity of the temperature anomaly (heating) correlates with the smoke density.
    - **Scientific Inference:** There is a linear relationship between aerosol loading (AOD) and atmospheric stability. The more smoke there is, the more stable (stagnant) the atmosphere becomes, which in turn traps more smoke. This explains why smog events often persist for days or weeks.

Synthetic Radiative Forcing : **Relevant Definitions**

- **SWGNT (Shortwave Surface Net Flux):**
  - **Shortwave:** Sunlight (Solar radiation).
  - **Net Flux:** The total amount of energy hitting the ground (in Watts per square meter, W/m^2).
  - **Meaning:** If the sky is clear, SWGNT is high ($\sim 900\ W/m^2$). If there is smoke, SWGNT is low because the smoke blocks the sun.
- **ARF (Aerosol Radiative Forcing):**
  - **Formula:** $\text{ARF} = \text{Flux}_{\text{Polluted}} - \text{Flux}_{\text{Clean}}$
  - **Meaning:** It represents the *change* in energy caused by the aerosol.
  - **Sign:**
    - **Negative (-):** Cooling Effect (Sunlight is blocked/reflected).
    - **Positive (+):** Warming Effect (Greenhouse gases trap heat).
  - *Note:* Smoke aerosols (like scattering sulfates or organic carbon) generally cause **negative** forcing at the surface (cooling), often referred to as "Global Dimming."
- **ARF Efficiency:**
  - **Formula:** $\frac{\text{ARF}}{\text{AOD}}$
  - **Meaning:** This normalizes the forcing. It tells us how potent the smoke is. "For every 1 unit of smoke thickness (AOD), how many Watts of energy do we lose?"

Synthetic Radiative Forcing : **Methodology**

Step 1: Simulate the "Clean" World

- First, we need a baseline—what the world would look like *without* the fires.
- **Solar Gradient:**
  - Code: `gradient = np.linspace(900, 950, height)`
  - Sunlight isn't uniform. The code simulates a latitude gradient (higher flux in the South vs North).
- **Natural Variation:**
  - Code: `clouds = np.random.normal(...)`
  - It adds random noise to simulate natural clouds or atmospheric variations that exist regardless of the fire.
- **Result:** `swgnt_clean` (The baseline solar energy reaching the ground).

Step 2: Simulate the "Polluted" World

- **Physics Model:**
  - Code: `reduction = input_aod_map * forcing_sensitivity`
  - `forcing_sensitivity = 85.0` : A constant derived from physics. "For every 1.0 AOD, block 85 Watts of energy."
- **Calculation:**
  - Code: `swgnt_polluted = swgnt_clean - reduction`
  - This subtracts the blocked energy from the baseline. Areas with heavy smoke will have significantly less energy reaching the ground.

Synthetic Radiative Forcing : **Methodology (contd.)**

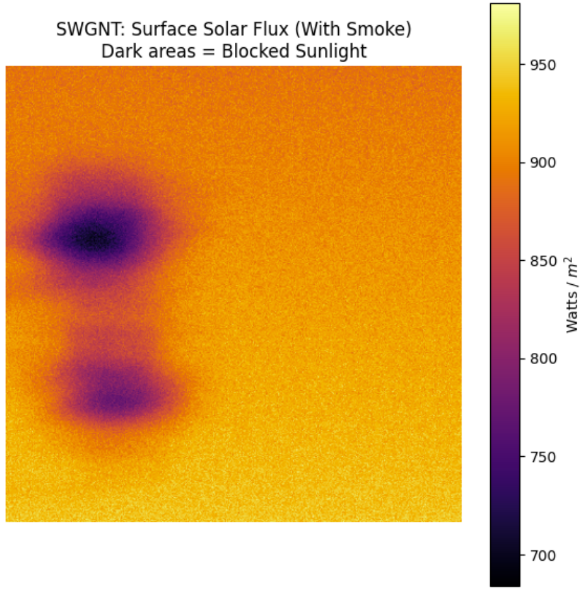
Step 3: Calculate Radiative Forcing (DIP: Subtraction)

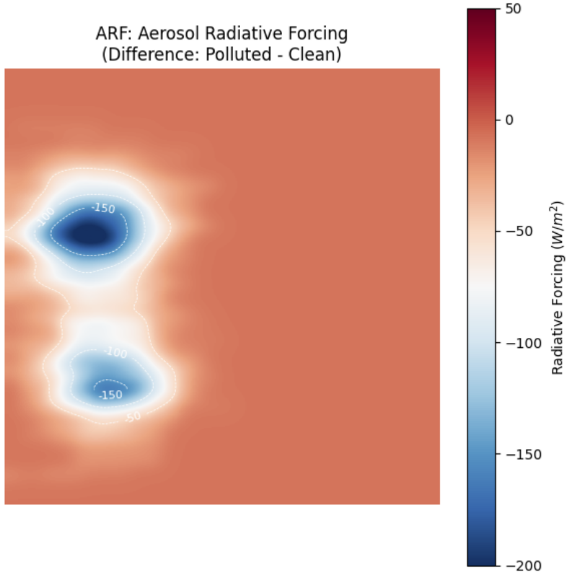
- Code: `arf_map = swgnt_polluted - swgnt_clean`
- This is simple image subtraction.
- Since `Polluted` is always less than `Clean` (due to blocked sun), the result is **Negative**.
- This map isolates the *impact* of the smoke, removing the background clouds and solar gradient.

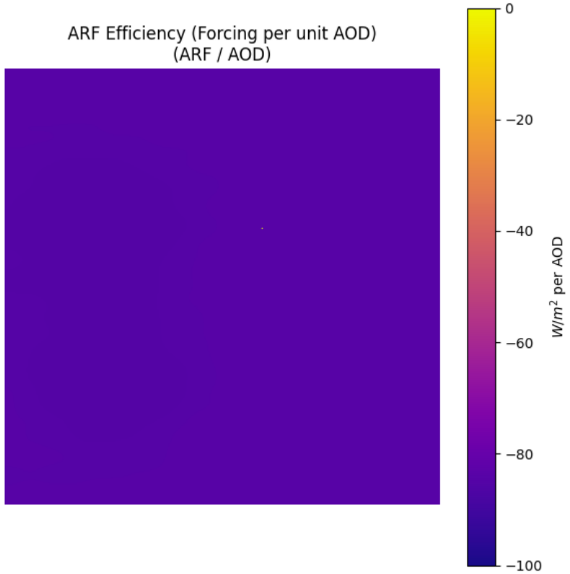
Step 4: Calculate Efficiency (DIP: Division)

- Code: `arf_efficiency = arf_map / (input_aod_map + 0.001)`
- This divides the Impact Map by the Smoke Map.
- It creates a normalized map showing the intrinsic "darkness" or "blocking power" of the smoke particles themselves.

Synthetic Radiative Forcing : **Output**







Synthetic Radiative Forcing : **Key Inferences**

1. **Quantification of "Global Dimming"**
   - **Observation:** The ARF map displays peak negative forcing values reaching **-150** W/m^2 or more.
   - **Scientific Inference:** This is a **massive reduction** in solar energy. For context, typical greenhouse gas warming is around $+2$ to $+4$ W/m^2. A temporary cooling of -150 W/m^2 completely alters the local surface energy balance, potentially disrupting evaporation rates and local weather patterns.
2. **The Mechanism is Scattering & Absorption**
   - **Observation:** The Surface Flux (SWGNT) is significantly lower than the "Clean" baseline.
   - **Scientific Inference:** The smoke particles are acting as a shield. They are either reflecting sunlight back to space (scattering) or absorbing it (soot/black carbon). Since we saw high AAOD (Absorption) and atmospheric heating earlier, we infer that the energy missing from the surface is being **trapped in the atmosphere**, not just reflected away.

Synthetic Radiative Forcing : **Key Inferences (contd.)**

3. **High Forcing Efficiency**
   - **Observation:** The ARF Efficiency map shows high values (e.g., -50 to -80 W/m^2 per unit AOD).
   - **Scientific Inference:** This indicates the aerosol is **optically thick and absorbing**. If these were just white sulfate particles, the efficiency might be different. The high efficiency suggests the presence of **Black Carbon (BC)**, which is the most potent light-absorbing aerosol after CO_2.

4. **Modification of Local Climate (Hydrological Cycle)**
   - **Observation:** The surface is being cooled drastically (Negative ARF).
   - **Scientific Inference:** Cooling the ground reduces the energy available to evaporate water. In a real-world scenario (like the Indian Monsoon), such severe surface cooling can **weaken the monsoon circulation** because the land doesn't heat up enough to draw in moisture from the ocean.

Conclusions

- Successfully demonstrated synthetic image-processing pipeline that mimics real satellite, lidar, and meteorological observations
- Quantitatively linked regional fire sources to surface air quality degradation via multi-module DIP analysis
- Revealed critical role of vertical atmospheric structure (inversion layers) and radiative feedback in perpetuating smog
- Showed that DIP operations (convolution, filtering, thresholding, edge detection) naturally quantify complex atmospheric phenomena
- Results support the mechanistic hypothesis that elevated absorbing aerosol layers trap emissions and cause severe downwind pollution events during crop residue burning season

Conclusions