Spatial Statistical Modeling and Characterization of Aerosol Optical Thickness over Lahore using MODIS Data

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Motivation

Why this problem?

- **3 million** global annual deaths (WHO statistics)
- **20,000+** premature deaths among adults and almost **5,000,000 cases** of illness among children each year are recorded in Pakistan (World Bank report, 2014) [1]
- The average air pollution is up to **4 times higher** than the WHO limits recorded in Pakistan's big cities (Punjab's EPD)

What has already been done?

- Seasonal trends, backtracking to pollution sources and classification of aerosols (Lahore)[2]
- Correlation studies[3], ground-based data analysis[4-5] and impact of aerosols on climate[6]

What will be our contribution?

- To build a spatial statistical model for MODIS AOT around Lahore
- To characterize aerosol hot-spots around Lahore

What will we use?

- Satellite-based sensor's atmospheric data (Aerosol Optical Thickness)
- Geographical Information System (GIS)

Outline

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- **Background**
  - Atmospheric Pollution and its Effects
  - Quantification of Pollutants: Ground-based and Satellite-based Sensors
- **MODerate resolution Imaging Spectroradiometer (MODIS)**
  - Specifications
  - Data Processing Levels
  - Aerosol Product
- **Existing Work**
- **Problem Identification**
- **Study Site Description**
- **Preliminary Data Analyses**
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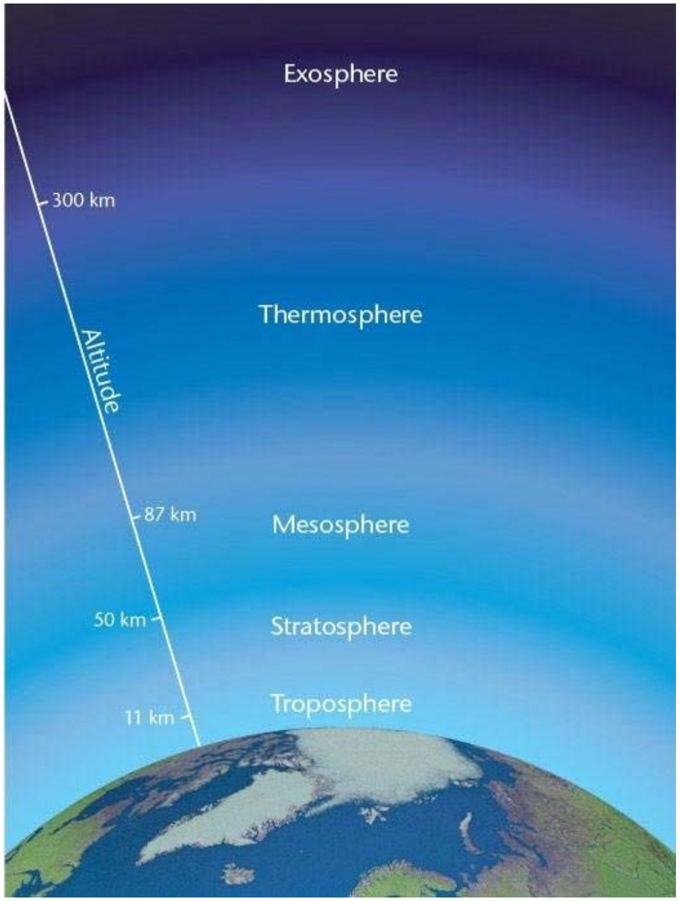
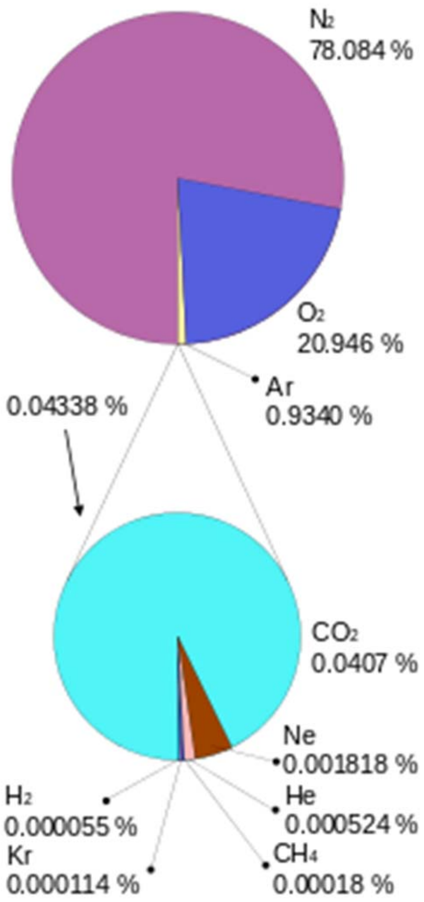
Background – Atmospheric Pollution and its Effects

Atmosphere



Composition of Air



https://www.metoffice.gov.uk/learning/making-a-forecast/first-steps/atmosphere/stratosphere
https://en.wikipedia.org/wiki/Atmosphere_of_Earth

Background – Atmospheric Pollution and its Effects

Two Major Sources of Pollution

Natural Sources	Anthropogenic Sources
Volcanic eruption	Industrial boilers
Wild fires	Vehicular fuel combustion
Sea Sprays	Burning of waste, coal and wood
Dust Storms	Commercial and residential heaters
Biological allergens	Chemically harmful sprays and paints

Background – Atmospheric Pollution and its Effects

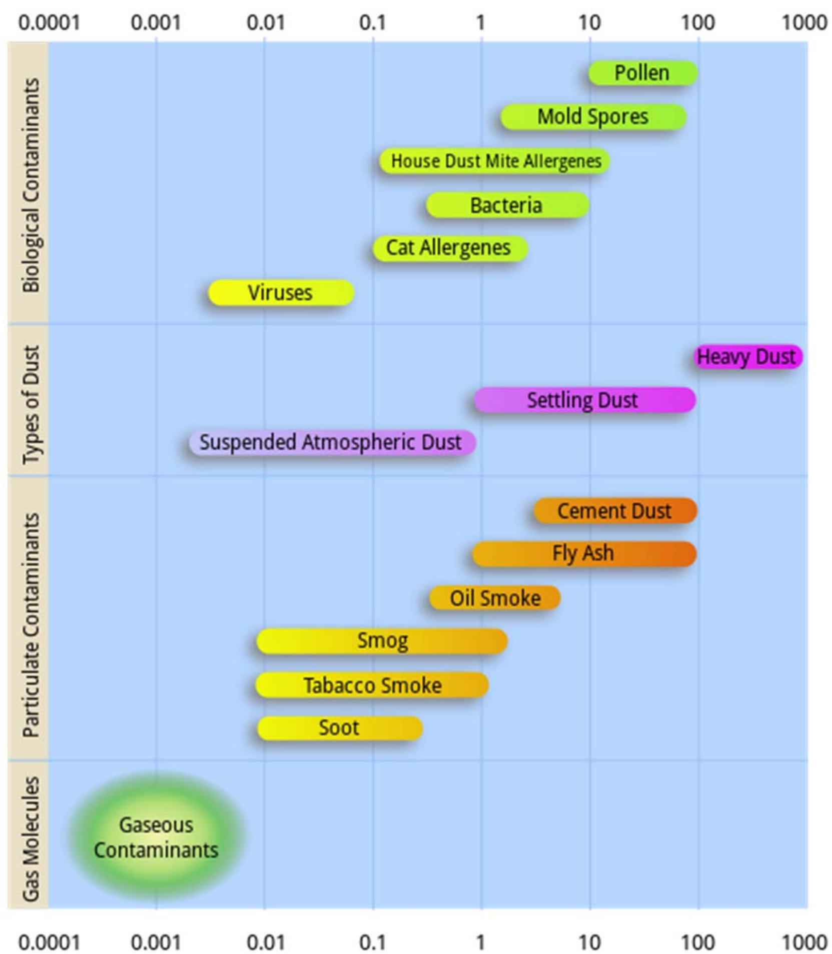
Common Pollutants	Effects
Sulphur dioxide (SO_2)	Lung damage, forms Acid rain (when combined with water)
Nitrogen oxides (NO_x)	Lung damage, forms Ozone
Particulate Matter (PM)	Lung damage, eye irritation, reduced visibility, crop damage
Carbon monoxide (CO)	Headache, heart damage by replacing O_2 in blood, reduced mental alertness
Hydrocarbons (VOCs)	Forms Ozone (NO_x + sunlight)
Ozone (VOC + NO_x)	Respiratory tract problems, forms smog

Background – Atmospheric Pollution and its Effects

Particulate Matter (PM) = Aerosols

Liquid droplets and small suspended particles present in the air

- **PM_{10} (size: 10 microns or less)**
  Penetrates into the lungs via mouth and nasal passage
- **$PM_{2.5}$ (size: 2.5 microns or less)**
  Penetrates deep into the bloodstreams



https://en.wikipedia.org/wiki/Particulates

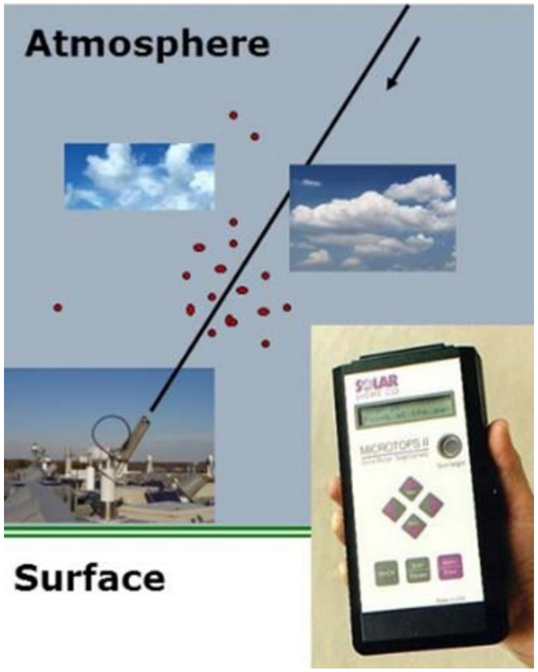
Background – Atmospheric Pollution and its Effects

Aerosol Optical Thickness (AOT):

- An important property of aerosols

AOT = Quantity of light removed from the beam

$$\tau(\lambda)_{Aerosol} = \tau(\lambda)_{TOT} - \tau(\lambda)_{water} - \tau(\lambda)_{Rayleigh} - \tau(\lambda)_{O3} - \tau(\lambda)_{NO2} - \tau(\lambda)_{CO2} - \tau(\lambda)_{CH4}$$



https://aeronet.gsfc.nasa.gov/new_web/Documents/Aerosol_Optical_Depth.pdf
https://deepblue.gsfc.nasa.gov/science

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Quantification of Pollutants – Ground-based

Measurement of Pollutant's Concentration

- Concentration measured in ppm, ppb and µg / m^3

Air Quality Index (AQI)

Air Quality Index (AQI) Values	Levels of Health Concern
0 to 50	Good
51 to 100	Moderate
101 to 150	Unhealthy for Sensitive Groups
151 to 200	Unhealthy
201 to 300	Very Unhealthy
301 to 500	Hazardous

Sensors Deployed in Lahore

- AERosol RObotic NETwork (AERONET)
  - Photometry: AOD, AE

  Jail Road

- Environmental Protection Department
  - Conc. of pollutants

  Gulberg, Jail Road, Ravi Road, Band Road

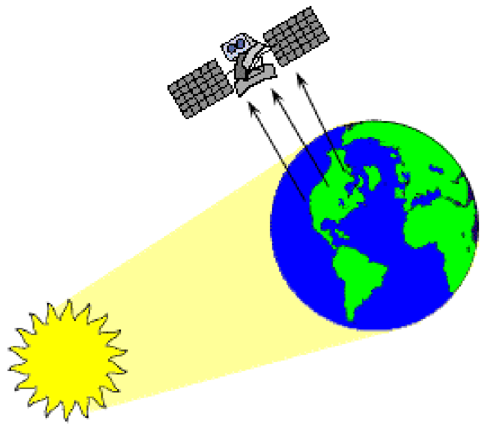
- Privately owned sensors (Airvisual)
  - Conc. of pollutants, AQI

  Abubakr Block, NETSOL- Ghazi Road Interchange, Lahore (Upper Mall), Bedian Road

Problem with ground-based data? - Sparsity!

https://en.wikipedia.org/wiki/Air_quality_index

Quantification of Pollutants – Satellite-based



Remote Sensing:

Measurement of radiance from a target

- Active Sensing
- Passive Sensing

Satellites that remotely sense atmospheric data:

- MODIS onboard NASA's Terra (1999) & Aqua (2002)
- ESA's Sentinel-2, NASA's Landsat8 and Aura

Why MODIS?

- Reasonable spatial and high temporal resolution (250m+, 1 day)[7]
- Validated high quality data products readily available
- MODIS AOT happens to be relatively accurate for Lahore[8]

https://owlcation.com/stem/-Introduction-and-Scope-of-Remote-Sensing

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MODIS – Specifications

MODerate resolution Imaging Spectroradiometer

- **Passive sensor** onboard Terra and Aqua satellites
- Hyperspectral **36 wavelength bands:** 0.4 µm to 14.4 µm
- **Spatial Resolution**: 250 m (bands 1–2), 500 m (bands 3–7), 1000 m (bands 8–36)
- **Temporal Resolution**: 1-2 days

Primary Use	Band	Bandwidth wavelength (nm)
Land/Cloud/Aerosols Boundaries	1	620 – 670
	2	841 – 876
Land/Cloud/Aerosols Properties	3	459 - 479
	4	545 – 565
	5	1230 - 1250
	6	1628 - 1652
	7	2105 - 2155
…	…	…

https://modis.gsfc.nasa.gov/about/specifications.php

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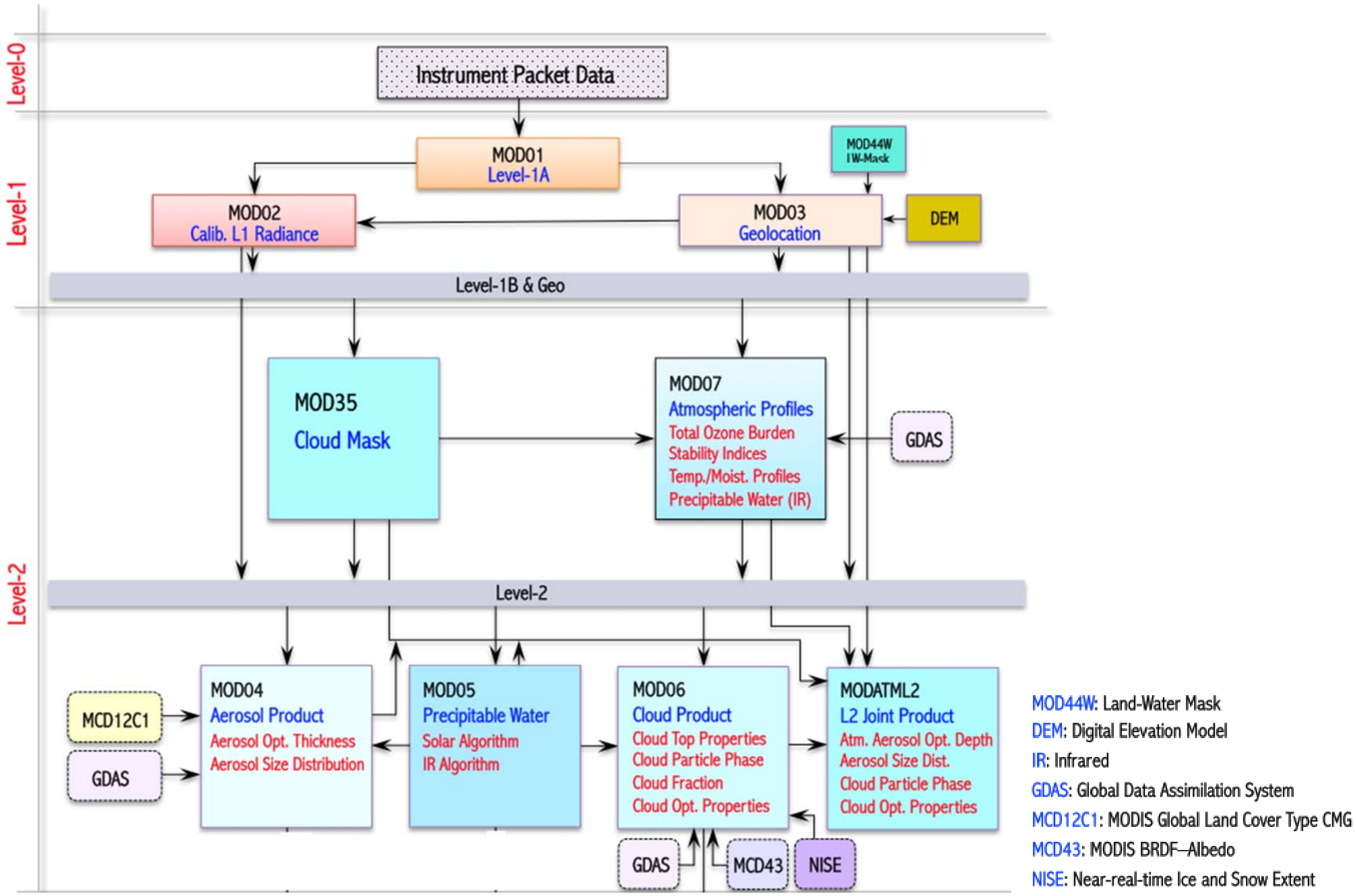
MODIS – Data Processing Levels

Level 1A- Photon counts

Level 1B- Calibrated data and Geolocation

Units of calibration: W/sr µm m²

Level 2- Data Products



https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/

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MODIS – Aerosol Product

From MODIS Level 1B (L1B) to Aerosol Product:

- Aerosol Optical Thickness (AOT)
- Aerosol Size Distribution (based on Angstrom Exponent)

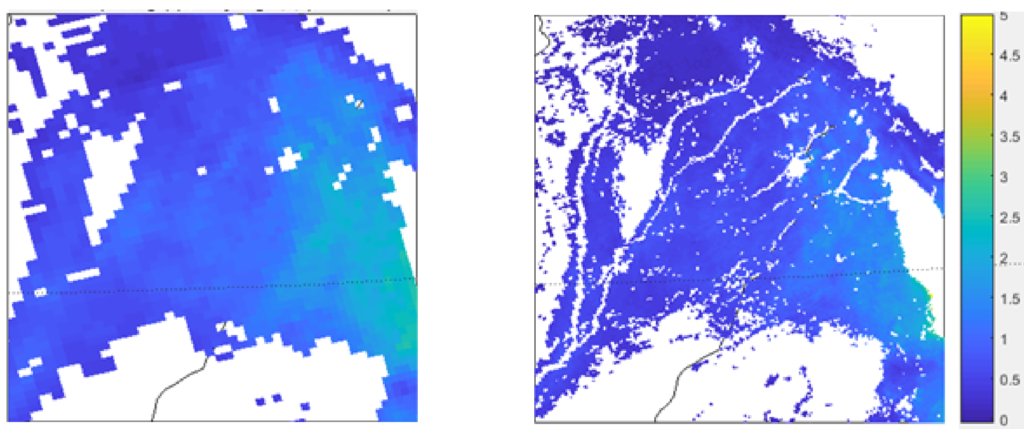
Algorithms for extracting AOT from MODIS-L1B data:

- **Dark Target for Land and Ocean**
  - 550 nm : dark targets appear dark, aerosols appear bright
- **Deep Blue for Land**
  - 412 nm : bright targets appear dark, aerosols appear bright
  - 470 nm : dark targets appear dark, aerosols appear bright

A study reveals: Dark Target is more suitable for Lahore as compared to Deep Blue[9]

MODIS – Aerosol Product

- Comparison of AOT at 10 km (DT and DB) and 3 km (DT only):



- **Limitations of MODIS AOT data**: Spatial data coverage holes (missing data)

  Reasons:
  - Cloud cover
  - AOT retrieval algorithm failure due to the surface type

https://deepblue.gsfc.nasa.gov/science

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Existing Work – Relevant Research Papers

Pakistan

- Seasonal Assessment and Classification of Aerosols Transported to Lahore using AERONET and MODIS Deep Blue Retrievals[2]
- A Study of Aerosol Properties over Lahore (Pakistan) by using AERONET Data[4]
- MODIS Aerosol Optical Depth Observations over Urban Areas in Pakistan: Quantity and Quality of the Data for Air Quality Monitoring[10]
- Spatio-temporal Distribution of Aerosol and Cloud Properties over Sindh using MODIS Satellite Data and a HYSPLIT Model[6]

China

- Filling the Missing Data Gaps of Daily MODIS AOD using Spatio-temporal Interpolation[10]
- A New Air Pollution Source Identification Method Based on Remotely Sensed Aerosol and Improved Glowworm Swarm Optimization[11]

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Problem Identification

Identified Problems:

- **Problem I:** Spatial data coverage holes in MODIS data i.e., missing data points
- **Problem II:** Non-existing spatial characterization of regional aerosol concentration in Pakistan

Proposed Solutions / Objectives of Thesis:

- **Objective I:** A spatial statistical model to fill data coverage holes over Lahore
- **Objective II:** Spatial characterization of regional aerosol concentration over Lahore

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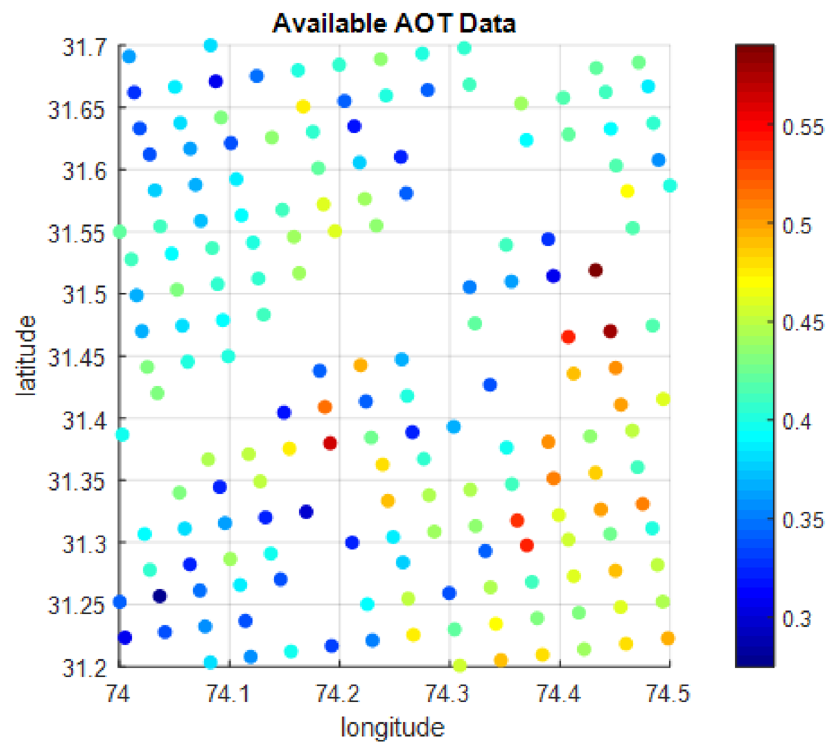
Study Site Description

Lahore and its Outskirts, $\mathcal{R}_{\mathcal{L}} \triangleq \{\mathbf{x} \mid 31.2 \leq x_1 \leq 31.7, 74 \leq x_2 \leq 74.5\}.$



https://www.google.com/maps/place/Lahore,+Punjab,+Pakistan

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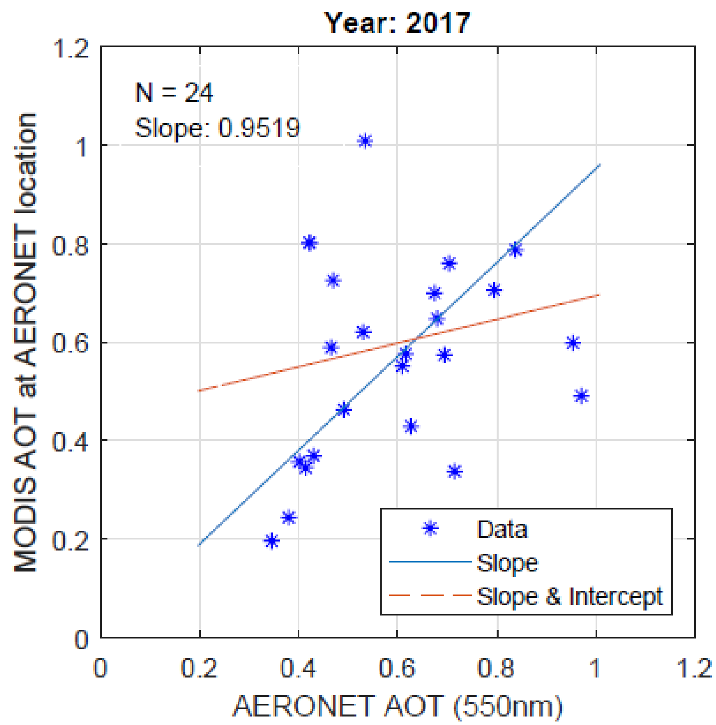
Preliminary Data Analyses

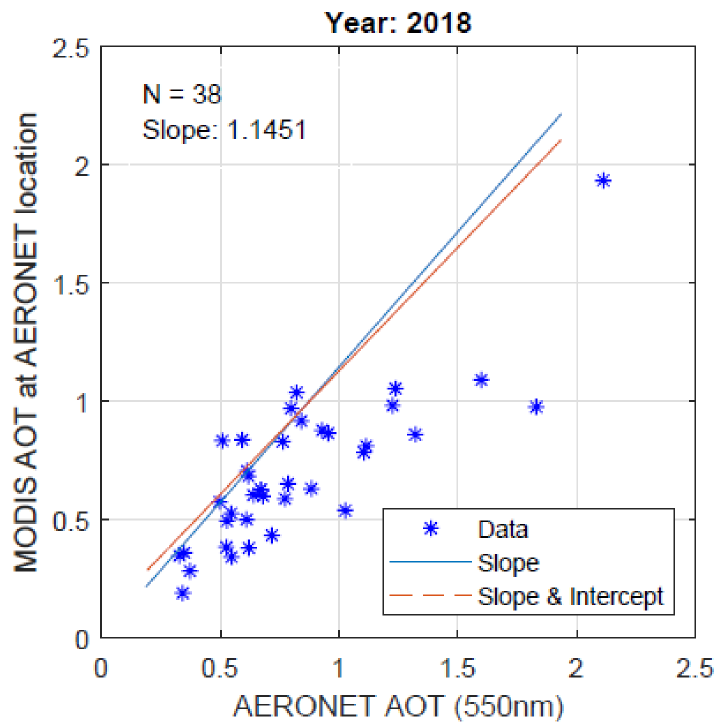
Analysis I: Correlation between AERONET (ground) and MODIS (satellite) AOT data

Objective: To validate MODIS data with ground data

Approach: Scatter plot of measurements taken at a same day and location

Results:





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Preliminary Data Analyses

Analysis II: Seasonal Variations in Aerosol Optical Thickness

Objective: To validate MODIS Data by comparing the analysis results with previous studies

Approach:

Averaging of AOT values in the whole region for each season

Division of Year into Four Seasons:

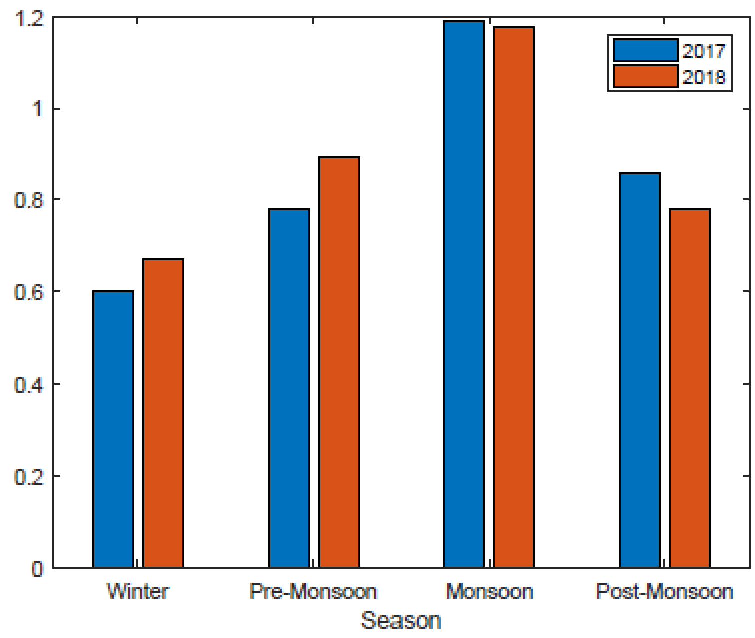
- Winter: December, January, February
- Pre-Monsoon: April, May, June
- Monsoon: July, August, September
- Post-Monsoon: October, November

Preliminary Data Analyses

Analysis II: Seasonal Variations in Aerosol Optical Thickness

Results:

Highest AOT observed for Monsoon season



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Spatial Statistical Modeling of Aerosol Optical Thickness

Objectives:

1) To fill the daily spatial data coverage holes in MODIS Data
2) To infer AOT value at any location in the region with a certain confidence level
3) To understand how AOT at one location relates to AOT at another location

Approach: Gaussian Processes Regression

Notation:

- Coordinates: $\mathrm{x_i}$
- Valid Data: Coordinates with AOT data available $\mathcal{D}^d = \{\mathrm{x_i}, y_i\}$ with $i = 1, 2, ..., N$
- Missing Data: Coordinates with missing AOT values $\mathcal{D}_t^d \triangleq \{\mathrm{x_i^*}\}$ with $i = 1, ..., M$

Spatial Statistical Modeling of Aerosol Optical Thickness

1- Model Assumptions:

- Each AOT data point $AOT(\mathrm{x_i})$ in a day's data is a univariate Gaussian RV
- Each observation y_i is the AOT value with an additive Gaussian sensor noise

2- Model for each observation in the data:

$$y_i = AOT(\mathrm{x_i}) + \epsilon, \qquad \text{with } i = 1, 2, ..., N$$

- Gaussian Process:

$$\mathbf{AOT} \sim \mathcal{GP}(0, \mathbf{K}).$$

- Additive Gaussian Noise:

$$\epsilon \sim \mathcal{N}(0, \sigma_n^2).$$

$$\mathbf{f} \sim \mathcal{GP}(0, \mathbf{K}),$$

$$\begin{bmatrix} f(\mathrm{x_i}) & f(\mathrm{x_j}) \end{bmatrix}^T \sim \mathcal{N}(0, \mathbf{K_{ij}}),$$

$$[\mathbf{K_{ij}}] = \begin{bmatrix} K_{ii} & K_{ij} \\ K_{ji} & K_{jj} \end{bmatrix}.$$

Spatial Statistical Modeling of Aerosol Optical Thickness

3- Learning of Model Parameters (Using likelihood maximization)

$$\log p(\mathbf{y}|\mathbf{x}, \boldsymbol{\theta}) = -\frac{1}{2}\mathbf{y}^T \mathbf{K}'^{-1}\mathbf{y} - \frac{1}{2}\log|\mathbf{K}'| - \frac{N}{2}\log 2\pi.$$

Optimum Kernel: ARD Exponential

Posterior distribution

$$\mathbf{Pr}\left(data \mid parameters\right)\mathbf{Pr}\left(parameters\right)$$

- **Squared Exponential Kernel:**

$$k(\mathbf{x}, \mathbf{x}') = \sigma_f^2 \exp\left(-\frac{1}{2}(\mathbf{x}-\mathbf{x}')^T \boldsymbol{\Sigma}^{-1}(\mathbf{x}-\mathbf{x}')\right),$$

- **ARD Exponential Kernel:** (1 signal standard deviation and 2 lengthscale parameters)

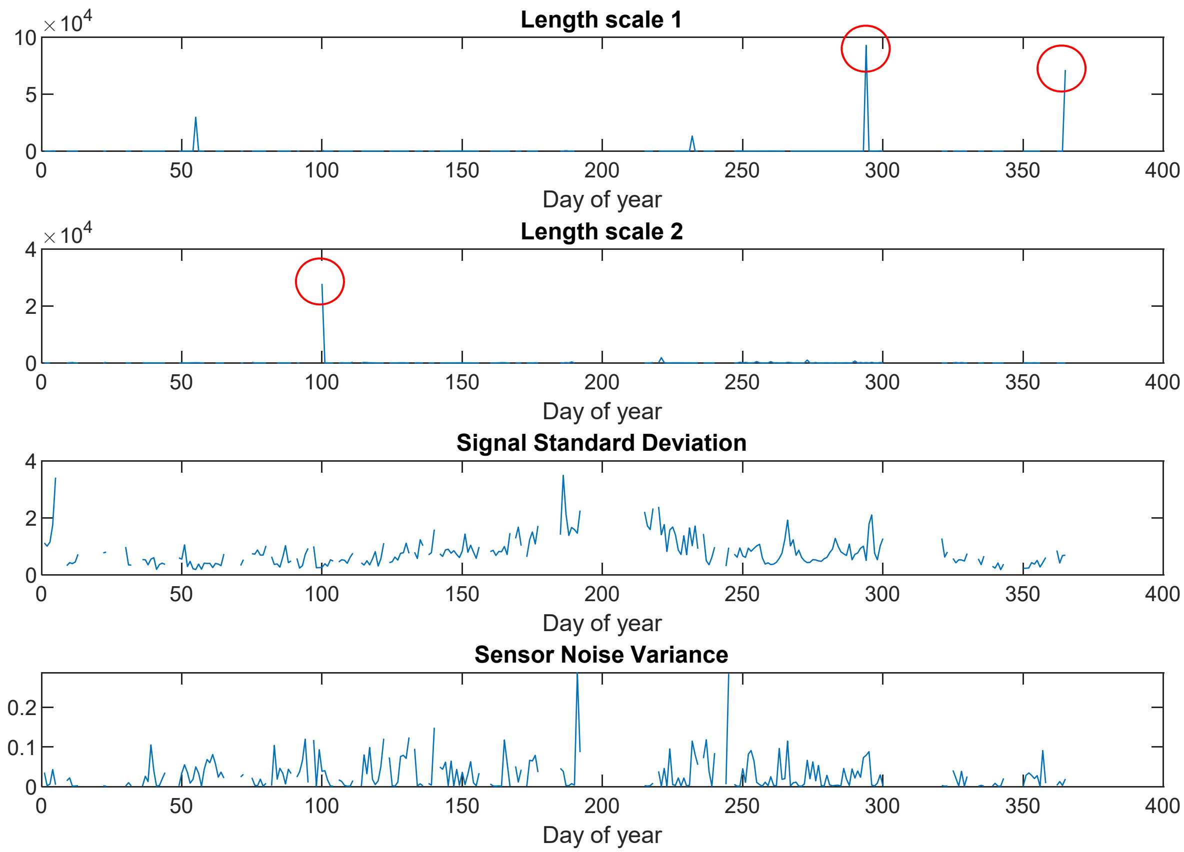
$$k(\mathbf{x}, \mathbf{x}') = \sigma_f^2 \exp\left(-\frac{1}{2}\sum_{j=1}^{D}\frac{1}{\sigma_j^2}(x_j - x_j')^2\right), \qquad \boldsymbol{\Sigma} = \mathrm{diag}(\sigma_1^{-2}\sigma_2^{-2}..., \sigma_D^{-2})$$

Spatial Statistical Modeling of Aerosol Optical Thickness

Results of Learned Parameters:

- d sets of **four parameters** were found for each valid d = 1, 2, …, 365.

Time-Series:



Spatial Statistical Modeling of Aerosol Optical Thickness

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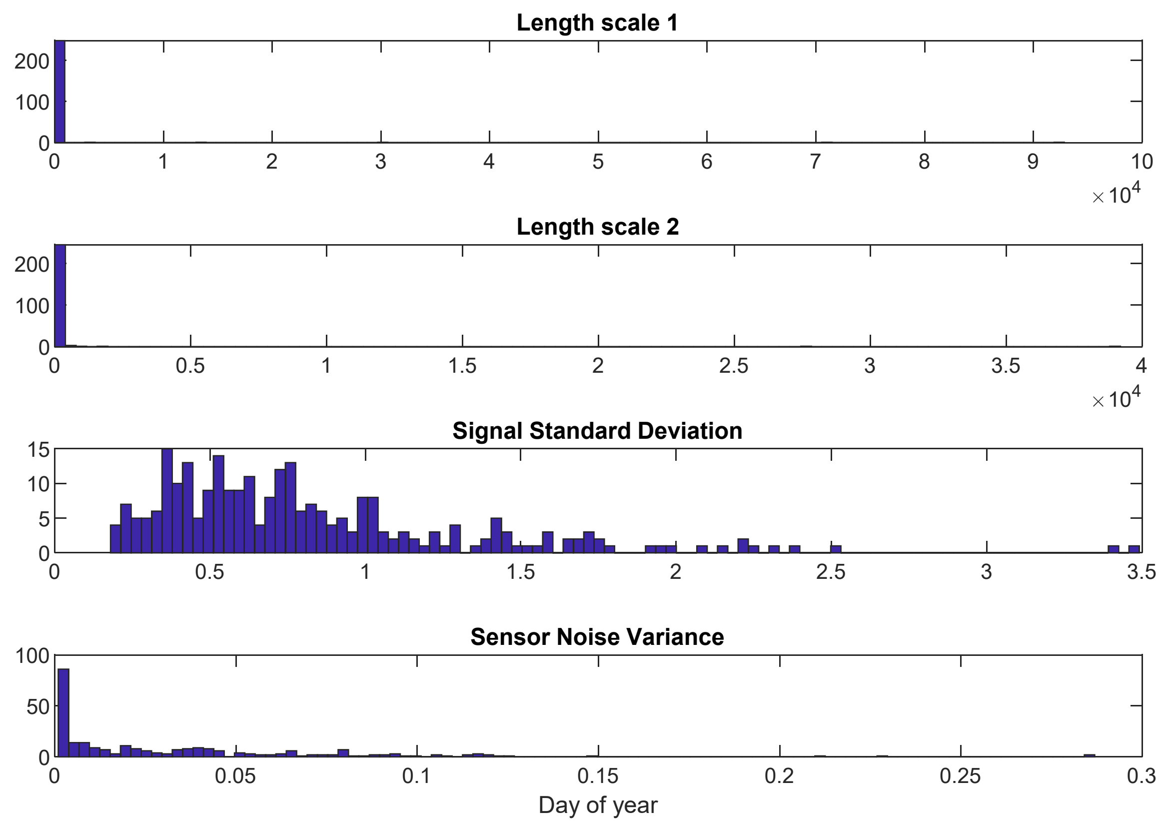
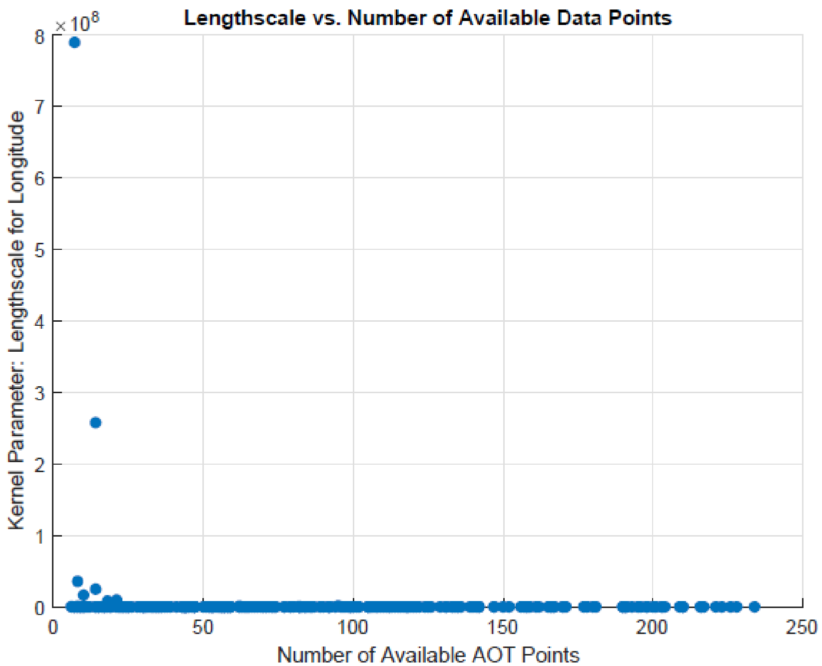
Histogram:

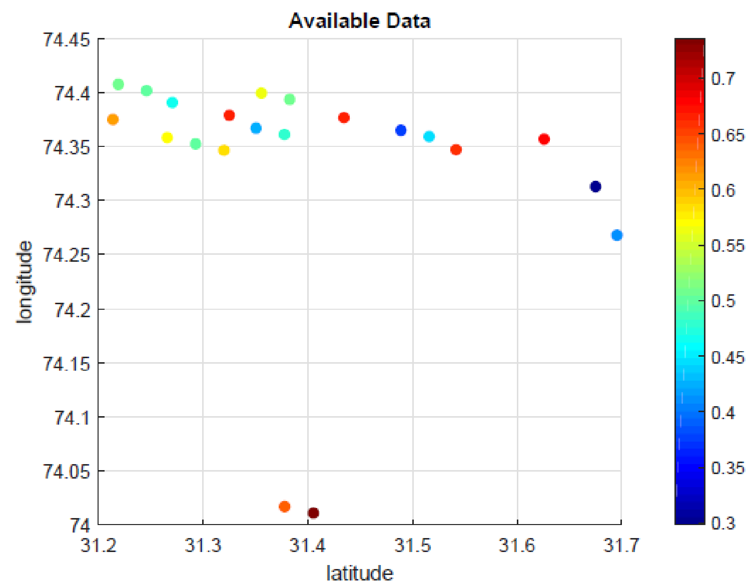


Spatial Statistical Modeling of Aerosol Optical Thickness

Problem: What's behind the large values of lengthscale parameter?

- Less number of available data points
- Data densely present at one region and missing on all the other regions





Spatial Statistical Modeling of Aerosol Optical Thickness

3- Inference using the Learned Statistical Model

- **Joint Distribution:**

$$\left[y(\mathbf{x}_1) \quad y(\mathbf{x}_2) \quad \ldots \quad y(\mathbf{x}_\mathrm{N}) \quad AOT(\mathbf{x}_1^*) \quad AOT(\mathbf{x}_2^*) \quad \ldots \quad AOT(\mathbf{x}_\mathrm{M}^*)\right]^T \sim \mathcal{N}(0, \mathcal{K}),$$

$$[\mathcal{K}] = \begin{bmatrix} \mathbf{K} + \sigma_n^2 \mathbf{I} & \mathbf{K}_* \\ \mathbf{K}_*^\mathbf{T} & \mathbf{K}_{**} \end{bmatrix}.$$

- **Predictive Posterior Distribution (Conditional):**

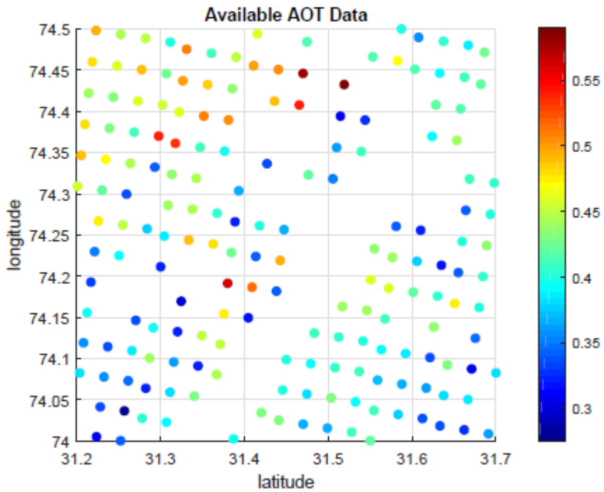
$$AOT(\mathbf{x}_1^*), \ldots, AOT(\mathbf{x}_\mathrm{M}^*) | y(\mathbf{x}_1), \ldots, y(\mathbf{x}_\mathrm{N}), \mathbf{x}_1, \ldots, \mathbf{x}_\mathrm{N}, \mathbf{x}_1^*, \ldots, \mathbf{x}_\mathrm{M}^* \sim \mathcal{N}(\boldsymbol{\mu}_c, \mathbf{K}_\mathbf{c}),$$

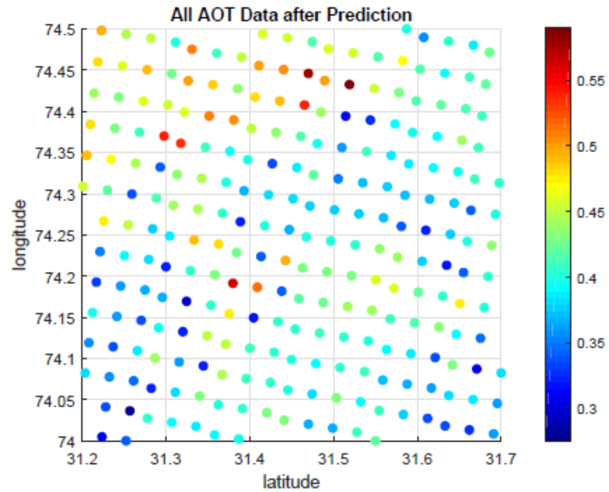
$$\boldsymbol{\mu}_c = \mathbf{K}_*^\mathbf{T} (\mathbf{K} + \sigma_n^2 \mathbf{I})^{-1} \mathbf{y}.$$

$$\mathbf{K}_\mathbf{c} = \mathbf{K}_{**} - \mathbf{K}_*^\mathbf{T} (\mathbf{K} + \sigma_n^2 \mathbf{I})^{-1} \mathbf{K}_*.$$

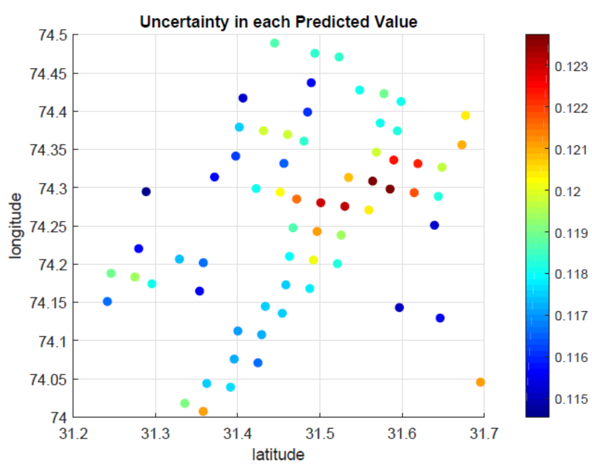
Spatial Statistical Modeling of Aerosol Optical Thickness

Filling the Gaps in MODIS AOT Data using Statistical Model:





Uncertainty in Each Predicted AOT value:

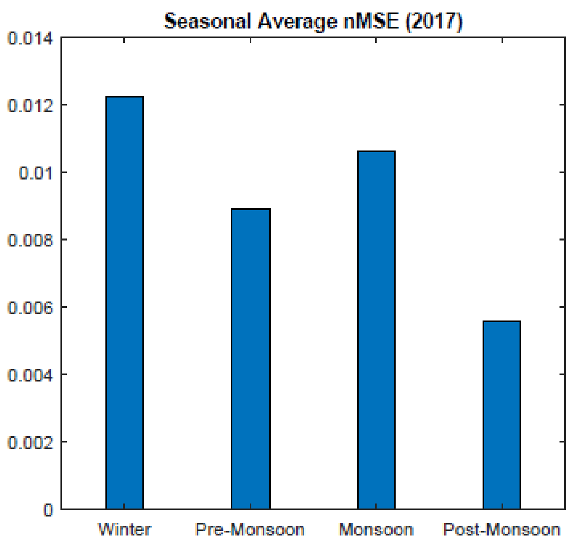


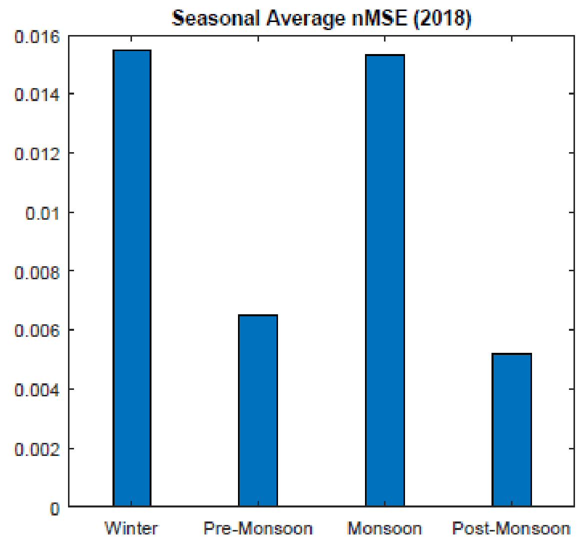
Spatial Statistical Modeling of Aerosol Optical Thickness

4- Model Evaluation using 10-folds Cross-Validation

- **Energy Normalized MSE** $$nMSE = \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i)^2}$$

- **Seasonal nMSE Values:**





- **Yearly nMSE Values:** 0.0093 and 0.0106 for 2017 and 2018, respectively

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Characterization of Aerosol Hot-spots over Lahore

Objectives:

1) To **identify** the potential aerosol hot-spot regions in and around Lahore
2) To **quantify** the aerosol content in the identified hot-spots

Approach:

Identification using Glowworm Swarm Optimization Algorithm followed by quantification based on AOT data

What is an aerosol hot-spot?

- Regions where the AOT values tend to stay higher than their surroundings persistently with time
- Could be potential sources of air pollution

Characterization of Aerosol Hot-spots over Lahore

1- Identification of Hot-spot Locations = locate local maxima

Glowworm Swarm Optimization (GSO) Algorithm (2005) [12]

- A Swarm Intelligence (SI) algorithm
- No gradient or global information of the function required
- Dynamic decision range
- A recent study in China for identifying pollution sources used GSO[11]

Working Principles:

1) Fitness broadcast – Luciferin value (like glow of a glowworm)
2) Adaptive neighborhood
3) Positive taxis – movement towards stimulus

Characterization of Aerosol Hot-spots over Lahore

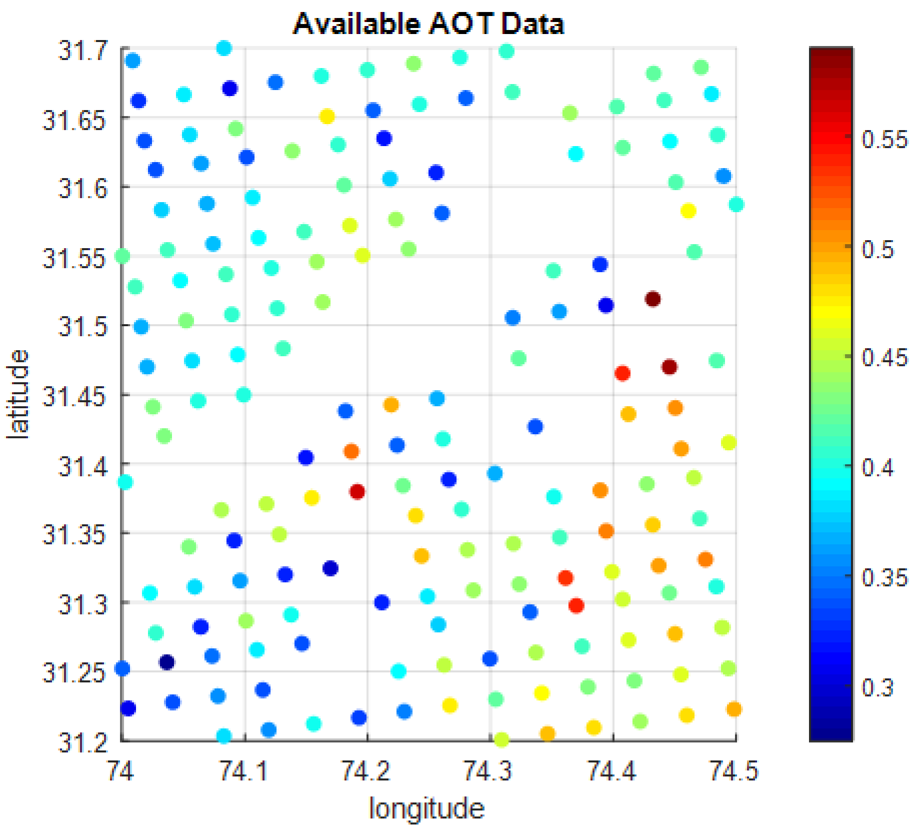
Assumptions:

- All AOT points in the data are glowworms
- All AOT points possess a Luciferin-level (glow)

Algorithm:

Step 1: Initialization

ρ	γ	β	n_t	s	l_0
0.2	0.6	0.08	5	0.03	2

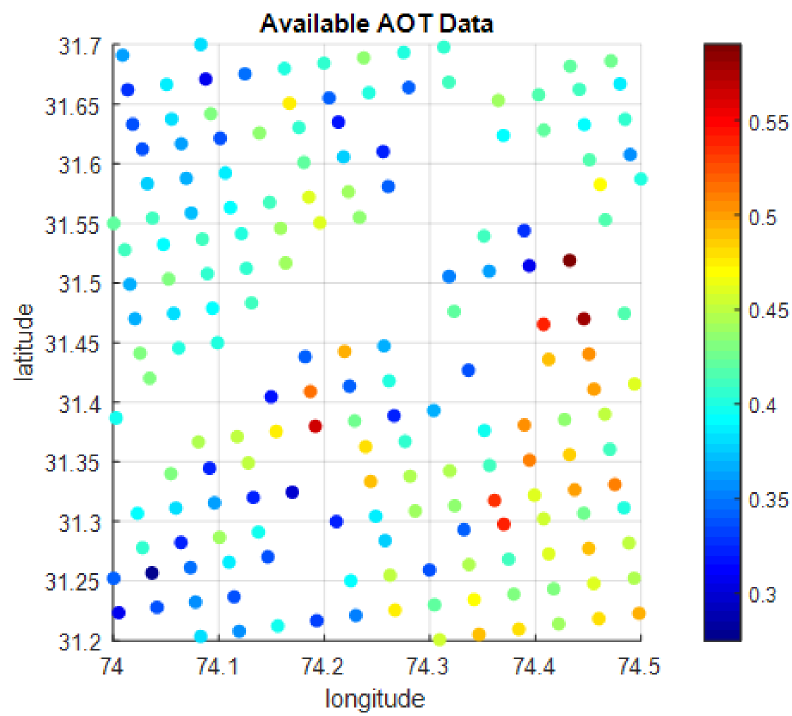


Characterization of Aerosol Hot-spots over Lahore

Step 2: Luciferin Update Equation

$$l_i(t+1) = (1-\rho)l_i(t) + \gamma y_i(t+1) \qquad \text{with } i = 1, 2, ..., N$$

- $l_i(t)$: Luciferin-level of ith-AOT data point at iteration t
- y_i : Value of i-th AOT data point



Parameters:

- Luciferin-decay constant $0 < \rho < 1$
- Luciferin-enhancement constant γ

Characterization of Aerosol Hot-spots over Lahore

Step 3: Movement Phase

$$x_i(t+1) = x_i(t) + s\frac{x_j(t) - x_i(t)}{\|x_j(t) - x_i(t)\|}. \qquad x_i(t) \in \mathbb{R}^m$$

with $i = 1, 2, ..., N$

Which neighbor to move towards?

$$p_{ij}(t) = \frac{l_j(t) - l_i(t)}{\sum_{k \in N_i(t)} l_k(t) - l_i(t)}$$

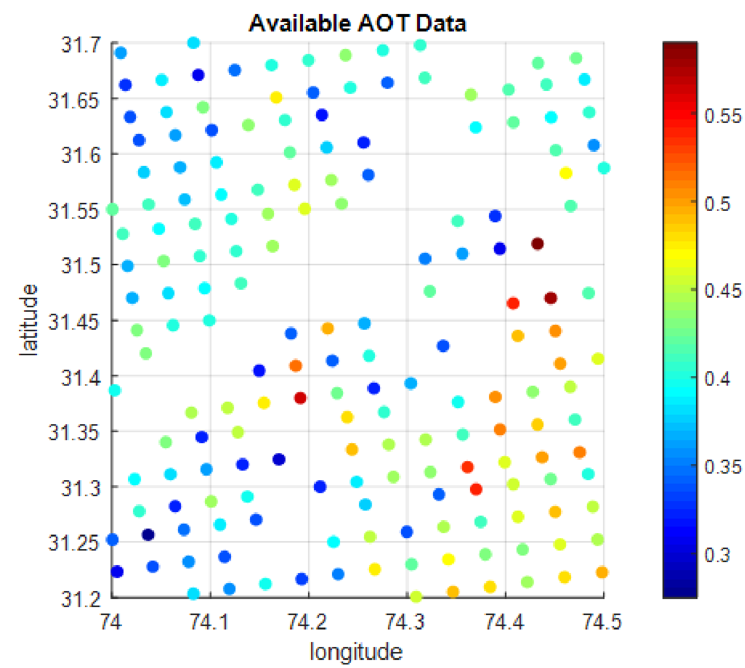
with.

j belongs to $N_i(t)$

$$N_i(t) = \{j : d_{ij}(t) < r_d^i; l_i(t) < lj(t)\}$$

↑

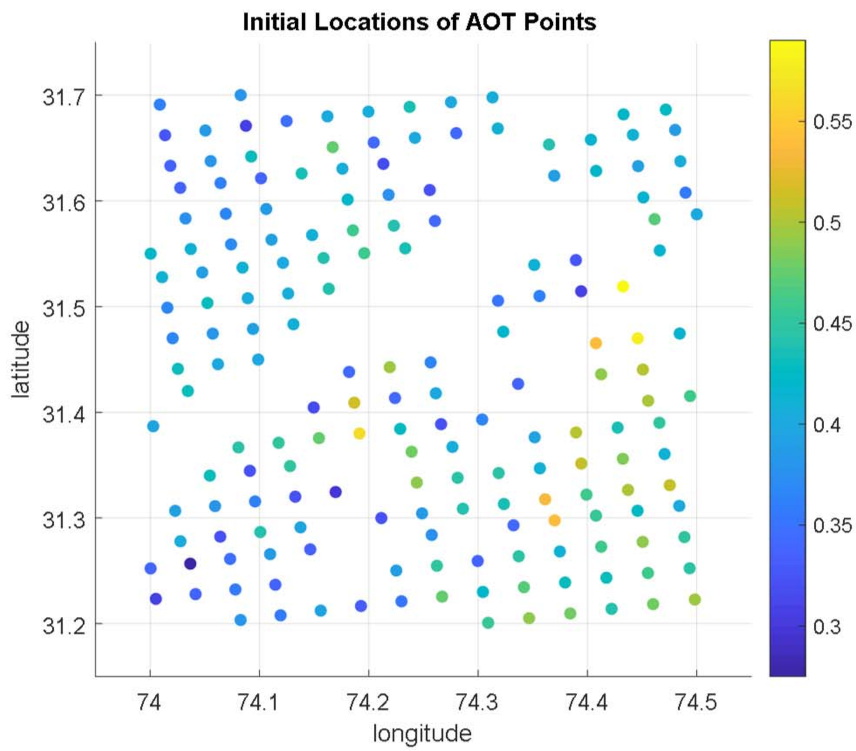
dynamic decision range

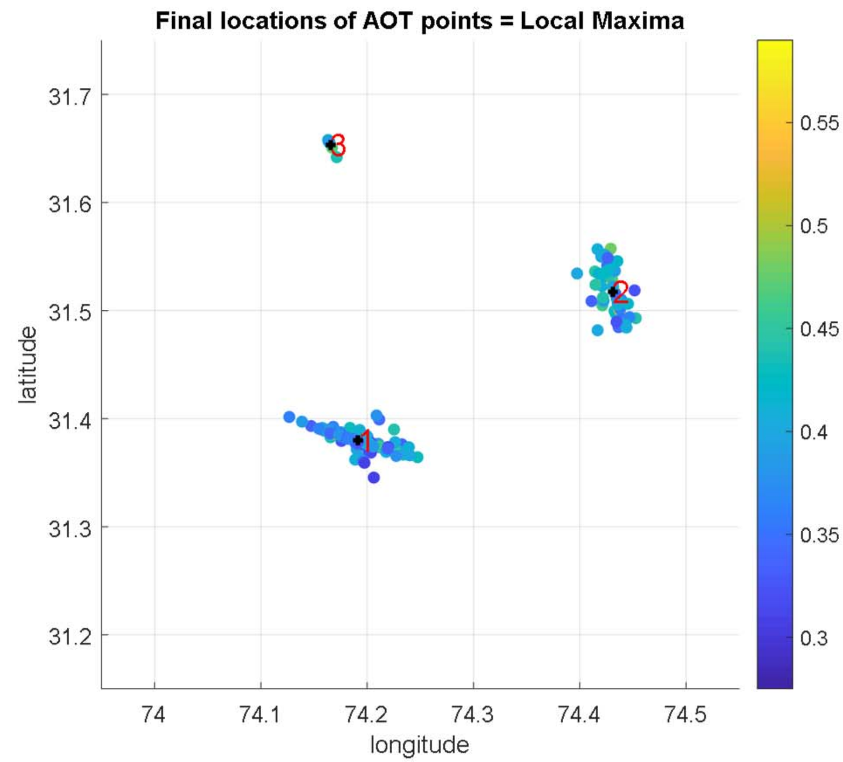


Characterization of Aerosol Hot-spots over Lahore

Step 4: Neighborhood Range Update

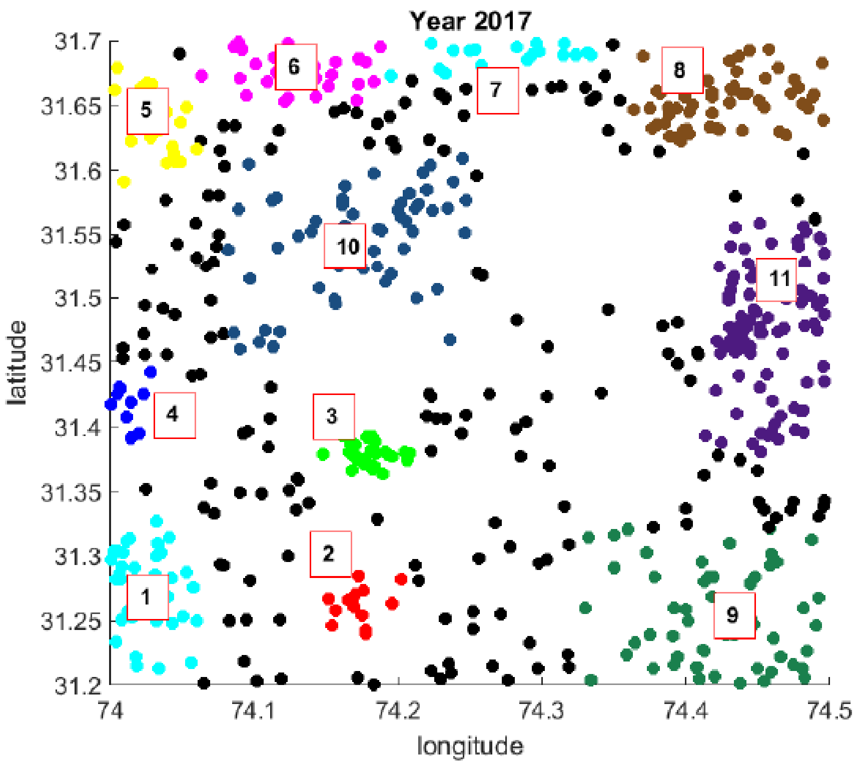
$$r_d^i(t+1) = \min_{r_s}\{r_s, \max(0, r_d^i(t) + \beta(n_t - N_i(t)). \quad \text{with } i = 1, 2, ..., N$$

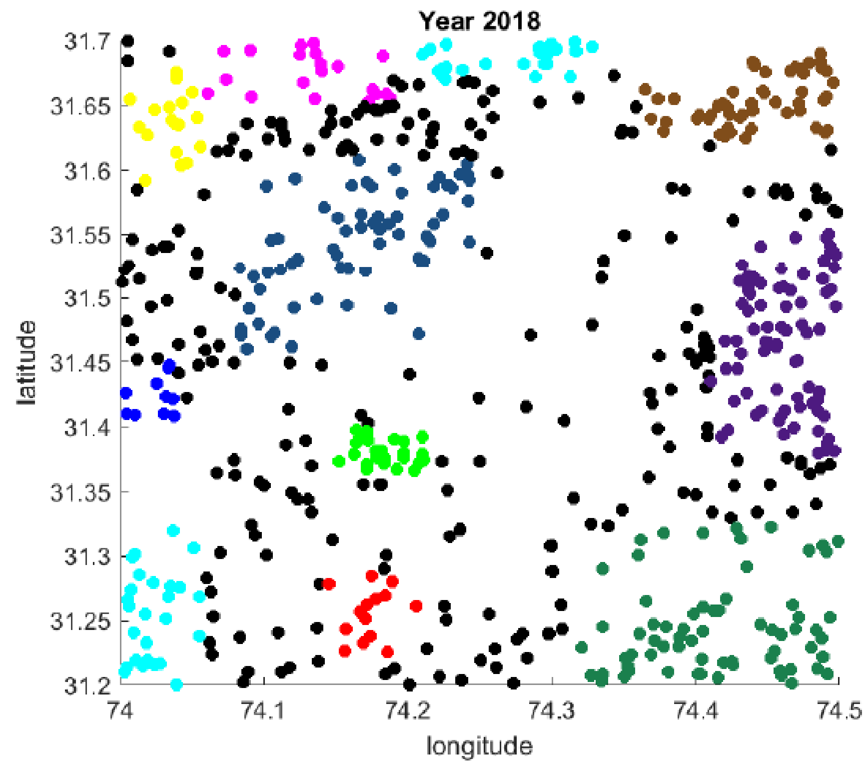




Characterization of Aerosol Hot-spots over Lahore

Overlaid Local Maxima for Each Day of the Two Years





Characterization of Aerosol Hot-spots over Lahore

Identified Hotspot Regions:

1: Fields and industries near Manga Mandi

2: Sundar Industrial Estate and Raiwind

3: Industrial Area near Valencia and Bahria Town

4: Industries near Mandi Faizabad and Mirzapur

5: Shekhupura-Sharaqpur Road

6: Industrial area of Lahore-Sheikhupura Road

7: Kala Shah Kaaku

8: Field area

9: Industrial area near Attu Asal and Mustafabad and surrounding field area

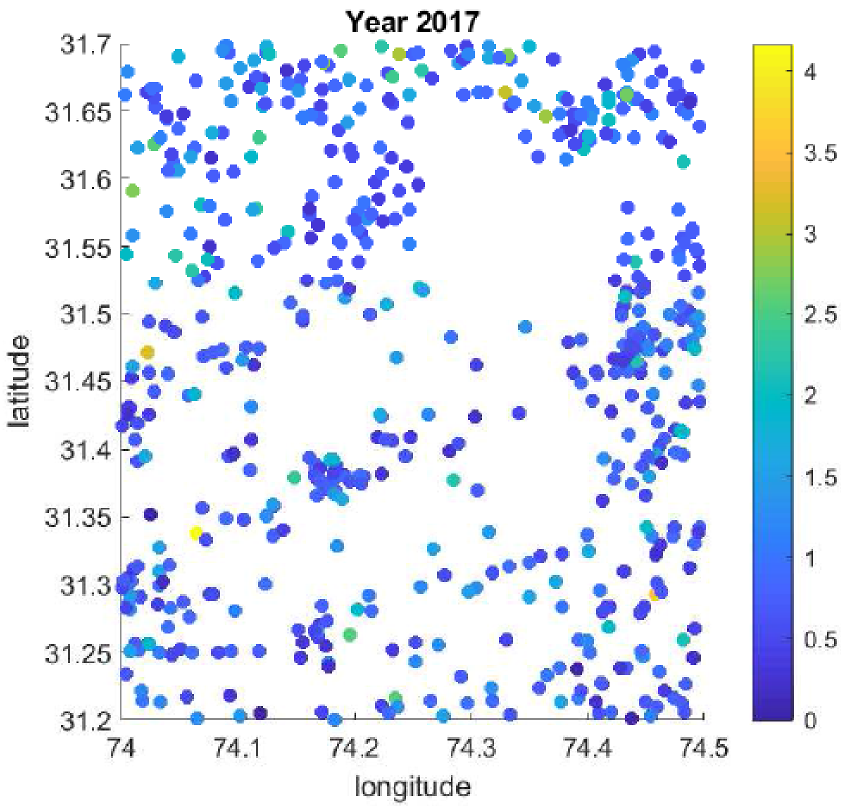
10: Lahore-Jaranwala Road (Burj Attari to Sharaqpur)

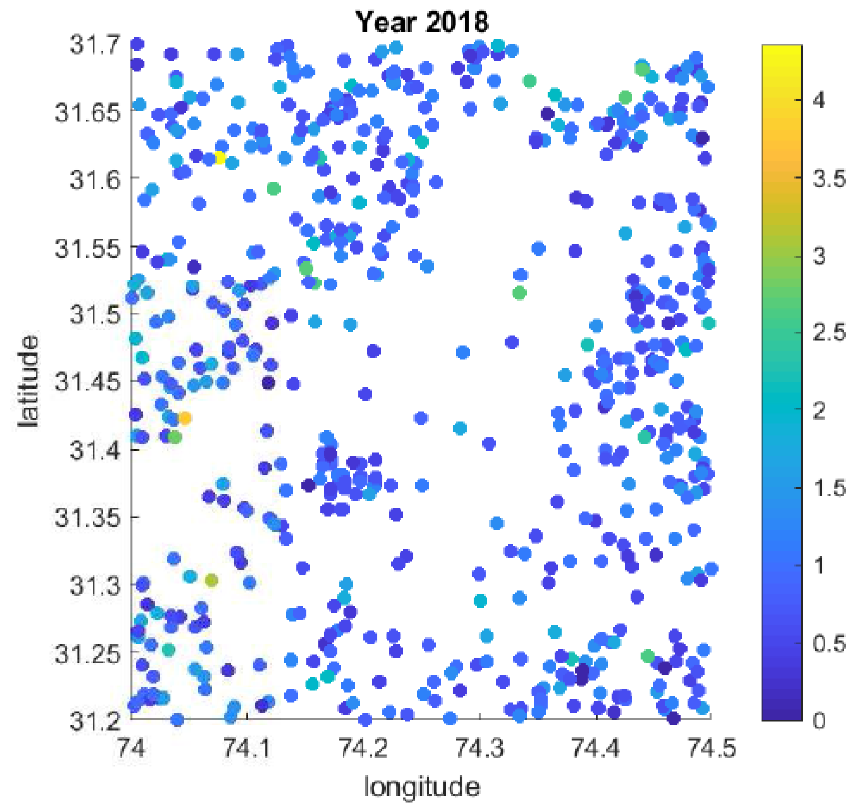
11: Field area

Characterization of Aerosol Hot-spots over Lahore

2 – Quantification of Aerosol Content of Each Hot-Spot

Based on a radial quantification metric around each local maxima

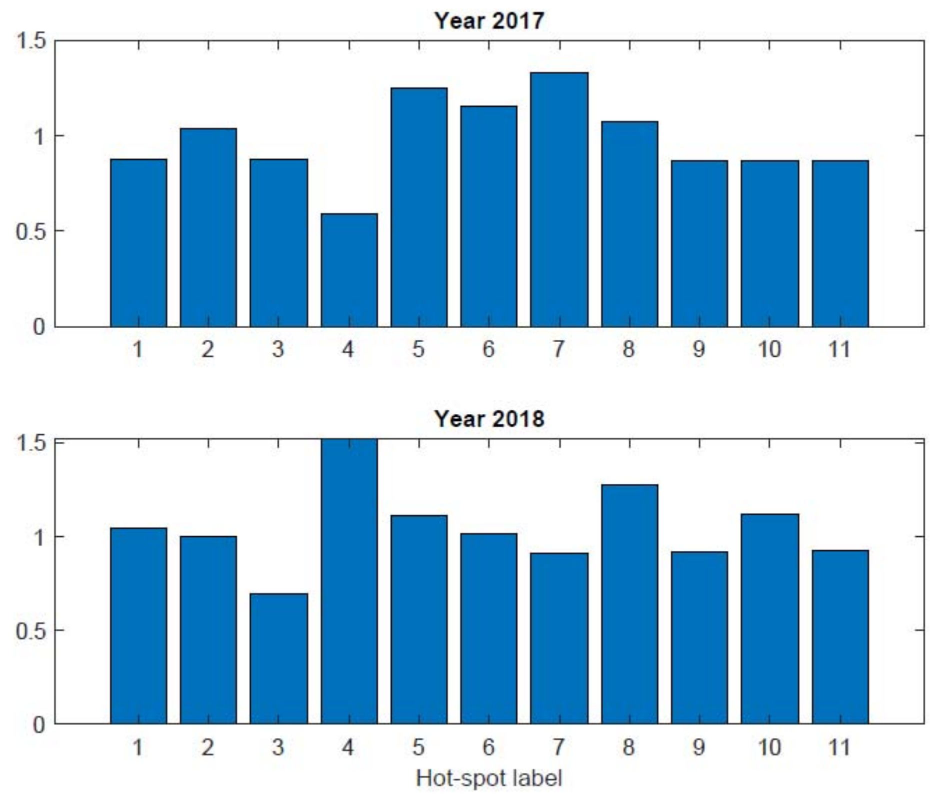




Characterization of Aerosol Hot-spots over Lahore

2 – Quantification of Aerosol Content of Each Hot-Spot

Averaging of each hot-spot's aerosol content



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Conclusions and Future Directions

Conclusions:

- Proposal of a spatial statistical model based on Gaussian Processes with ARD Exponential kernel to fill missing data in MODIS
- Prediction of AOT value at any location within the region of study with a certain confidence level
- Identification of aerosol hot-spots over Lahore
- Quantification of aerosol content in identified hot-spots

Future Directions:

- Proposal of a spatio-temporal statistical model based on Gaussian Processes
- Deployment of air-quality sensors in the identified hot-spot locations to evaluate the performance of quantification method to improve the proposed characterization

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Questions?

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