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# Air Quality Interpretation of Four Geographically Distinct Hot Spot States of India-An Appraisal Using Aerosol Optical Depth and Particulate Matter

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**Abstract**: The application of Moderate Resolution Imaging Spectroradiometer-Aerosol Optical Depth (MODIS-AOD) for Air Quality (AQ) assessment has contributed significantly by making use of a spatiotemporal relationship between ground-level particulate matter and aerosol optical density at both city and state levels. Traditional ground-based site-specific particulate matter monitoring method has found a profound gap in their spatial coverage. Such challenging situations prevail over the progressive development of the combined usage of ground monitoring technique along with the MODIS-AOD product (with 10 km spatial resolution). This was achieved and derived by assembling the satellite sensor, Terra as a tool for the regional-based specific studies for monitoring airborne particles. Their analytical linear association was evaluated and explored their feasibility for monitoring either Respirable Suspended organic Matter (RSPM) or AQI in spatiotemporally distinct geographical sites situated in four States of India. Examined the interrelationship between RSPM-AOD against meteorological drivers through Principal Component Analysis (PCA) and Quantitative Risk Assessment (QRA) of the focussed four zones. Elevated Air Pollution was noticed in the urban and industrial cities of Pune, Kochi, and Chennai. They were flanked by various industrial clusters and the substantial personal handling of vehicles. A region-wise RSPM-AOD correlation was recorded for the categorized areas: WS1, WS2, SW, and ES. Each zone was subsequently judged and a noteworthy association was linked between the ground-monitored RSPM data and the retrieved AOD output. This means of records could represent the aerosol component; consequently, infer their sources of origin and in later days could come up with reasonable emission control channels. States of India Maharashtra, Karnataka, Kerala, and Tamil Nadu, are categorized as WS1, WS2, SW, and ES respectively.

**Keywords:** Air Quality, Aerosol, Pollution

## Introduction

Major cities are transformed into mega/metropolis due to the nationwide amalgamation of speedy industrialization and their widespread economic development. This altered the life pattern due to the thrown-out toxic aerosol particles into the atmospheric realm and caused deleterious effects on the Air Quality (AQ). These multifaceted hazardous air components: Smoke, haze, and particulate matter are exclusively derived through natural and anthropogenic activities, and chiefly constitute disease-causing organisms and trace gases. The subsequent manmade supplies are: Fossil fuel combustion refuses from incinerators, emanates of motor vehicles, open burning of household wastes, agricultural land reclamation processes, and construction activities, emissions from thermal power stations, and assorted industrial sectors. The natural means for generating toxic gases and their plumes carrying noxious chemical components are windblown specks of dust, the upshots of disasters like volcano eruptions, earthquakes, and forest fires.

World Health Organization (WHO) reports that one in eight global deaths accounts for the Air Pollution (AP) threat and features the drift to nearly ten million all over the world (WHO, 2014). This meticulous preference reduces the life expectancy and overshadows the clean image of the blue sky as disinfected throughout the bionetwork. The driven pollutants have created an adverse environmental state of affairs in the whole ecosystem because of their concentration limits register beyond the prescribed standard recommended levels of WHO (Zhang *et al*., 2015). These airborne particles detain the energy balance of the Earth, and change will arise in the atmospheric circulation prototype and hydrological cycle, distressing the ability of reproduction in biological organisms, and further enhancing various cardiovascular and allergenic diseases in the community (Manojkumar and Srimuruganandam, 2019; Joshua and Sujatha, 2019; Pöschl, 2005) interim targets are set globally by the Air Quality (AQ) Guidelines to sustain a healthy atmosphere; hence policies should be accordingly planned in a judicial approach through acquiring the AQ data, the yardstick for air pollution assessment to realize stainable cleaner energy. Countries are facing the problem of upholding the absolute permissible AQ guidelines in their livelihood and consequently experience AP-related health problems frequently. In several developing countries, an understandable depiction covering AP monitoring is lagging, not following the prescribed threshold limits amended by the public authorities. This current situation increases rigorous health impacts on humans in most of the major cities especially in India, the second most populous country in the world.

Customarily, urban AQ has been monitored, assessed, and interpreted through a network ground-based scheme, fixing identified specific stations in each region of importance. The derived acquired data were estimated and the variations in AQ in the designated discrete face were forecasted. Furthermore, limited accessibility exists for the Spatio-temporal coverage of AP network monitoring windows for assessing AQ. In this status, the AQ monitoring restricts time-space dynamics and therefore initiated for the development of a new advancement in Atmospheric Remote Sensing (ARS) and in Chemical Transport (CT) Models (Kumar *et al*., 2008). In such occurrences, the capabilities of Earth Observing Satellites (EOS) and the concurrently developed technological tools pave the way to share and add synoptic and geospatial repossessed imagery in conjunction with ground-based urban air shed quality network data for their validation (Engel-Cox *et al*., 2004a-b). This entrée is an indirect and fruitful way for AP status approximation and the AQ management program in society.

By the compilation of ARS data, an empirical relationship between satellite-based Aerosol Optical Depth (AOD) and Ambient Particulate Matter (APM) could be instigated for AQ monitoring and their assessment. AOD is a worldwide accepted proxy indicator and extends toward covering spatiotemporally observing techniques for the systematic understanding and monitoring of atmospheric quality profiles on a global scale (Wei *et al*., 2020). Hence, the present attempt is the first of its nature to express, analyze and establish the empirical interrelationship between the aerial-temporal distribution profile of ground-based Respirable Suspended Particulate Matter, $PM_{2.5}$ (RSPM) and the MODIS-related AOD products for the designated study period (Nov'16 to Dec'17). The spotted zones are in 11 distinguished identified sites, positioned in four geographically and demographically varying States: Maharashtra, Karnataka, Kerala, and Tamil Nadu of India. This was accomplished using "MODIS" 500 m resolution calibrated radiance data and these aerosols retrieved description profiles differed in their variability of terrain. Hence, error may commence depending on the surface reflectance of an urban area than that of an agriculture-based vegetative area or a hazy industrial-plumed vicinity.

## Materials and Methods

A brief outline explaining the ground monitoring and satellite monitoring of AQ data is measured using a High volume Sampler (HVS APM-415-Envirotech) for ground monitoring. The RSPM (PM) and trace gases are accurately rated using the instrument.

Air Quality Index (AQI) is a system for reporting the ranking category of ambient AP status and is a valuable communication tool for the associated health risk emerging to the public and is calculated as:

$$Q = (C/Cs) \times 100$$

Q = Quality rating
C = The observed concentration of pollutant
Cs = Standard concentration limit recommended for the pollutant

AQI is calculated as the recorded concentration of the $RSPM/NO_2/SO_2$ is divided by the respective standard value of AQ ($RSPM/NO_2/SO_2$) for (sensitive area) × 100 gives the AQI of each recorded day for RSPM and the Trace gases ($NO_2$ and $SO_2$) separately.

Hence, AQI is calculated as, AQI = (Conc: of $RSPM/NO_2/SO_2$/Std Conc: Of $RSPM/NO_2/SO_2$) ×100.

### *MODIS*

Moderate Resolution Imaging Spectroradiometer (MODIS) for global analysis of land, ocean, and atmospheric properties and their interactions. This thirty-six-band width values the visible and infrared radiation (0.4-14.5 μm with resolutions of 250, 500 m, and 1 km at the nadir) for obtaining products varying from land vegetation and ocean fluorescence to cloud and aerosol properties, fire occurrence, snow cover on land, and sea ice, etc., (King and Greenstone, 1999).

### *Data Interpretation*

Identified 11 distinct sites in four geographically divergent cities in India. A description of sampling sites (Table 1) and Map (Fig. 1) is given.

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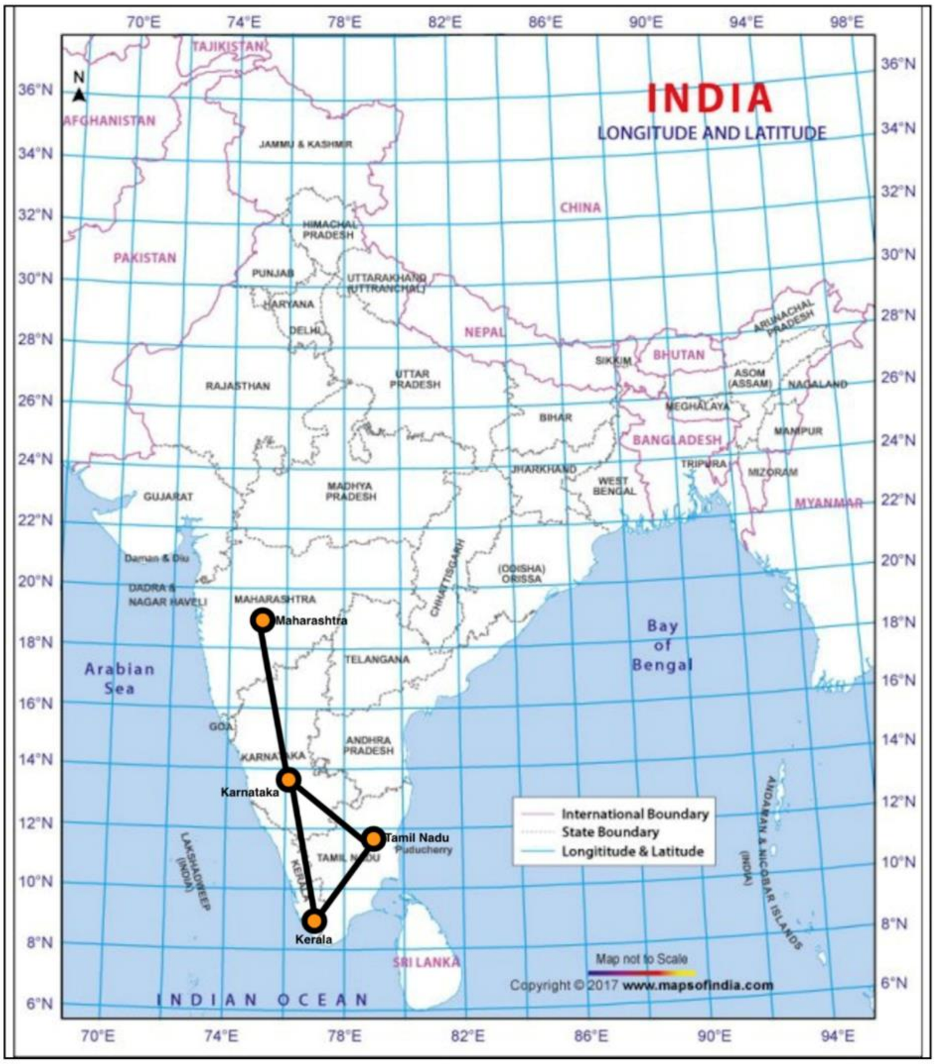


**Fig. 1:** Study map

To accomplish the theme, the study period was fixed from November 2016 to December 2017 covering 14 months representing diverse seasons with varying meteorological drivers. The processed data on the mass concentration of Particulate Matter or RSPM ($PM_{2.5}$) recorded from the national air quality assessment data center, India and the acquired AOD retrieved values from Modis Terra data sets are placed together. Later, the correlation analysis has been performed and interpreted according to the geography of the site description (Table 1) incorporating the concentration profile of RSPM against AOT. Scrutinized the inferred results for the relationship between the meteorological parameters on RSPM/AOT data. The common meteorological variables encountered are Surface Temperature (ST); Rainfall Density (RD); Relative Humidity (RH); and Wind Velocity or Speed (WV or WS). These parameters were retrieved from the NASA Null School Data Center and also from the established Govt. Meteorological data centre. The recorded observations are inspected against the varying zones, WS1, WS2, SW, and ES (Tables 2-5) with respect to RSPM/ AOT.

## *Geographical Description of 11 Sites and Seasonal Attributes*

The focussed 11 sites are classified geographically as WS1, WS2, SW, and ES. Brief descriptions of the states along with the selected specific sites are:

### *Maharashtra, Western Side (WS1)*

Maharashtra, is the wealthiest state in India, with a total population of nearly 123.74 lakhs. It has a tropical monsoon climate and the usual annual rainfall rate is recorded as between 400 to 600 mm. Three distinct seasons noticed are summer, Monsoon, and winter; March, April, and May are the hottest months. Temperature varies between 22 to 39°C during the summer season. Monsoon starts in the month of June and predominates in the month of July. August and September also get substantial amounts of rain. The rainfalls in Maharashtra vary from region to region. Ratnagiri received heavy rains whereas Pune showed less rainfall. In WS1, three sites were chosen to interpret the AQ assessment data they are Nagpur, Pune and Ratnagiri.

**Table 1:** Descriptions of sampling sites

| States | Sites | Latitude and longitude |
|---|---|---|
| Maharashtra: Western Side, WS1 | Nagpur | 21.1458°N, 79.0882°E |
| | Pune | 18.5204°N, 73.8567°E |
| | Ratnagiri | 17.2478°N, 73.3709°E |
| Karnataka: Western Side, WS2 | Shimoga | 13.9299°N, 75.5681°E |
| | Mysuru | 15.3173°N, 75.7139°E |
| Kerala: South West, SW | Kannur | 11.8745°N, 75.3704°E |
| | Kochi | 9.9312°N, 76.2673°E |
| | Kuttanad | 9.3528°N, 76.4042°E |
| Tamil Nadu: Eastern Side, ES | Chennai | 13.0827°N, 80.2707°E |
| | Coimbatore | 11.0168°N, 76.9558°E |
| | Tuticorin | 8.7642°N, 78.1348°E |

**Table 2:** RSPM V/s AoT, WS1

| Month | Nagpur RSPM (μg/m$^3$) | Nagpur AoT | Pune RSPM (μg/m$^3$) | Pune AoT | Ratnagiri RSPM (μg/m$^3$) | Ratnagiri AoT |
|---|---|---|---|---|---|---|
| Nov'16 | 44 | 0.457 | 226 | 0.106 | 58 | 0.205 |
| Dec | 161 | 0.857 | 114 | 1.113 | 75 | 0.609 |
| Jan'17 | 181 | 0.986 | 186 | 1.205 | 73 | 0.609 |
| Feb | 181 | 0.986 | 271 | 1.301 | 69 | 0.315 |
| March | 145 | 1.069 | 186 | 0.185 | 85 | 0.442 |
| April | 67 | 0.500 | 189 | 1.291 | 81 | 0.301 |
| May | 110 | 1.057 | 191 | 1.058 | 73 | 0.405 |
| June | 61 | 0.469 | 378 | 1.449 | 71 | 0.406 |
| July | 67 | 0.465 | 115 | 0.835 | 55 | 0.417 |
| Aug | 67 | 0.469 | 54 | 0.335 | 51 | 0.323 |
| Sept | 59 | 0.453 | 47 | 0.260 | 57 | 0.224 |
| Oct | 172 | 1.021 | 378 | 1.295 | 70 | 0.386 |
| Nov | 132 | 0.508 | 165 | 0.567 | 66 | 0.563 |
| Dec | 158 | 0.862 | 189 | 0.449 | 76 | 0.362 |

**Table 3:** RSPM V/s AOT, WS2

| Month | Shimoga RSPM (μg/m$^3$) | Shimoga AoT | Mysuru RSPM (μg/m$^3$) | Mysuru AoT |
|---|---|---|---|---|
| Nov'16 | 68 | 0.154 | 40 | 0.177 |
| Dec | 61 | 0.248 | 41 | 0.244 |
| Jan'17 | 59 | 0.299 | 26 | 0.320 |
| Feb | 52 | 0.350 | 32 | 0.295 |
| March | 46 | 0.240 | 27 | 0.280 |
| April | 45 | 0.180 | 23 | 0.484 |
| May | 46 | 0.035 | 21 | 0.335 |
| June | 44 | 0.185 | 22 | 0.260 |
| July | 37 | 0.339 | 24 | 0.332 |
| Aug | 34 | 0.358 | 21 | 0.252 |
| Sept | 41 | 0.295 | 22 | 0.130 |
| Oct | 43 | 0.343 | 23 | 0.476 |
| Nov | 54 | 0.638 | 27 | 0.732 |
| Dec | 60 | 0.945 | 30 | 0.551 |

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**Table 4:** RSPM V/s AOT, SW

| | Kannur | | Kochi | | Kuttanad | |
|---|---|---|---|---|---|---|
| Month | RSPM (μg/m$^3$) | AOT | RSPM (μg/m$^3$) | AOT | RSPM | AOT |
| Nov'16 | 52 | 0.150 | 90 | 0.806 | 65 | 0.434 |
| Dec | 50 | 0.343 | 89 | 0.713 | 70 | 0.422 |
| Jan'17 | 49 | 0.350 | 102 | 1.005 | 63 | 0.264 |
| Feb | 82 | 0.594 | 159 | 1.201 | 65 | 0.348 |
| March | 74 | 0.504 | 87 | 0.685 | 63 | 0.487 |
| April | 79 | 0.559 | 61 | 0.291 | 63 | 0.436 |
| May | 94 | 0.516 | 65 | 0.343 | 42 | 0.259 |
| June | 73 | 0.106 | 44 | 0.350 | 44 | 0.377 |
| July | 65 | 0.213 | 53 | 0.594 | 47 | 0.185 |
| Aug | 93 | 0.805 | 44 | 0.504 | 58 | 0.150 |
| Sept | 80 | 0.801 | 46 | 0.559 | 62 | 0.343 |
| Oct | 73 | 0.785 | 89 | 0.819 | 67 | 0.350 |
| Nov | 85 | 0.891 | 39 | 0.272 | 69 | 0.594 |
| Dec | 57 | 0.441 | 113 | 1.134 | 68 | 0.504 |

**Table 5:** RSPM V/s AOT, ES

| | Chennai | | Coimbatore | | Tuticorin | |
|---|---|---|---|---|---|---|
| Month | RSPM (μg/m$^3$) | AOT | RSPM (μg/m$^3$) | AOT | RSPM (μg/m$^3$) | AOT |
| Nov'16 | 96 | 01.095 | 39 | 0.343 | 57 | 0.234 |
| Dec | 90 | 1.018 | 41 | 0.406 | 92 | 1.118 |
| Jan'17 | 96 | 1.038 | 39 | 0.417 | 58 | 0.637 |
| Feb | 104 | 1.134 | 60 | 0.323 | 96 | 1.014 |
| March | 150 | 1.295 | 45 | 0.224 | 89 | 0.876 |
| April | 160 | 1.339 | 54 | 0.386 | 60 | 0.265 |
| May | 97 | 1.095 | 62 | 0.563 | 84 | 0.645 |
| June | 89 | 0.931 | 40 | 0.362 | 83 | 0.635 |
| July | 98 | 0.927 | 28 | 0.587 | 47 | 0.367 |
| Aug | 202 | 1.434 | 31 | 0.234 | 65 | 0.455 |
| Sept | 85 | 0.859 | 38 | 0.342 | 82 | 0.745 |
| Oct | 93 | 0.831 | 74 | 0.576 | 90 | 0.953 |
| Nov | 61 | 0.555 | 47 | 0.356 | 95 | 0.942 |
| Dec | 112 | 0.921 | 56 | 0.326 | 102 | 1.053 |

Nagpur is the tiger capital of Maharashtra and belongs to one of the fastest-growing cities in the world. It is famous for oranges, and timber for keeping its superior quality all the time. Pune is the second largest bustling metropolis city of Maharashtra. This city is an educational epicentre with a growing industrial hinterland, with emerging information technological centers along with large automotive engineering companies. The third site, Ratnagiri, the port city is famed for the biggest growing and production of Alphonsa mangoes.

### *Karnataka, Western Side (WS2)*

This state observes three types of climate patterns and experiences four seasons a year. Owing to its different geographical patterns and physiographic conditions, Karnataka shows a change in climate resulting in arid to semi-arid conditions in the plateau region. It exhibits sub-humid to humid tropical conditions in the Western Ghats and in the coastal plains recorded humid tropical monsoon. The monsoon starts from June to September and humidity sours in the State. From July to September, the humidity stays high, reducing heat because of rainfall. The post-monsoon season starts from October to December and receives few spells of rain with less humidity. In the winter season (January to February), humidity diminishes considerably. For the research analysis, the identified two sites are Mysuru and Shimoga. Mysuru is the cultural capital and tourist destiny of this State. A popular mode of public transport conveyance using a bicycle-sharing system is functioning to reduce vehicular emissions, make it economical, and for encouraging local commuters. The location of the city has played a prime role in progressive development and industrialization. Shimoga receives plenty of rainfall, bounded by beautiful greeneries with plenty of crop cultivation. It is the bread-providing nature for Karnataka and is known for procuring quality graded areca nuts and other crop products. The abundant green landscapes with a large number of waterfalls offer this county a tourist destination.

### *Kerala, Southern Side (SW)*

This State features a wet maritime climate and in the summer monsoon season experiences heavy rain (June to August). During the summer months, the State experiences strong winds, storm surges, and cyclone-related torrential downpours; noticed cooler and calm weather in the winter. Southwest monsoon is the rainy season and the wind blows from the Arabian Sea to the mainland from the direction of South-West. As it crosses into India in the month of May, the monsoon season will commence between June to September, this will stimulate heavy rainfall and is known as the "Indian summer Monsoon". North-East monsoon is bound to generate weak rain with seasonal winds and flows due to the South-West monsoon retreats from the mainland of India. Hereunder three sites have been selected for the study and are Kannur, Kochi, and Kuttanad. Kannur is the largest city in the North Malabar region of Kerala and is a land of looms and lore. Kochi, popularly known as the "Queen of Arabian Sea" records momentous developmental progress in this commercial and industrial hub coastal city. It is a densely populated metropolitan zone in the State of Kerala and is extensively known for its cultural heritage. Kuttanad is an amazing picture town residing a variety of birds and located in the backwater region of Alappuzha, where the inland waterways flow above land level. It is popularly known as "the rice bowl" of the Kerala state due to the rich cultivation of paddy crops.

### *Tamil Nadu, Eastern Side (ES)*

The geography of the state is highly influential to the climate and moderate temperature witnessed during the day and possesses cool nights. Very little difference in temperature both in the summer and winter months was observed in the coastal regions. The climate of Tamil Nadu is warm and exhibits humid summer and the température élevâtes up to 40°C. However, the closeness to the sea is favourable in bringing moisture and sea breezes into the land to suit a cool night. The hottest months are April and May; the winter months are November to February, and July to October months represent the monsoon periods. The annual rainfall ranges from roughly 635 to 1905 mm. For the present study three sites, namely Chennai, Coimbatore, and Tuticorin were chosen. Chennai, the capital of Tamil Nadu, is an urban agglomerate and is situated both on the coast and in the thermal equator, displaying a tropical wet and dry climate. Coimbatore is located on the banks of river Noyyal. It is a rapidly emerging industrialized smart city and is famed for the export of wet grinders, poultry products, and jewellery. Tuticorin is an energy hub city and is the locale of the Gulf of Mannar, Tamil Nadu. It is the mounting port with a direct connection to other major ports of the world. It is known for being the oldest and leading fishing harbour apart from the power plants and other mini-scale industrial units.

The studies further incorporated the influencing driving factors for AQ interpretation and thereby adopt effective control strategies when similar situations come to pass. The present research analysis is directed to obtain accurate information that could reflect the ground-level concentration and temporal variation of aerosols in 11 hot spot regions along with the optical characteristics of ambient atmospheric pollutants having geographically and demographically distinct characters. Subsequently, assessed the AQ, Air Quality Index (AQI), the yardstick an understandable quality index that is piecewise data, linearly related to the mass concentrations of the PM monitored based on ground-level network schemes at different designated sites of 4 States. However, in this situation, all these analyzed 11 sites are considered as "residential areas", thus RSPM mass concentration and the AQI calculated become equal to the same. Generally, the conversion factor for estimating AQI is 100 for a residential area, therefore the RSPM = AQI was accounted as the same value in all the identified 11 sites. Compilation data were achieved on the major air pollution assessing pollutant, RSPM, and were compared with the extracted respective retrieved satellite AOD values. The data with RSPM less than 70 were classified as 'Low 'pollution level. The table showing the monthly average RSPM and AOT of WS1, WS2, SW, and ES given (Tables 2-5) and Fig. 2a showing the regional-wise AQ assessment-RSPM vs AOT was conducted by Pearson coefficient analysis (Fig. 2a) shows WS1-RSPM Vs AOT for Nagpur, Pune, and Ratnagiri; Fig. 2b shows WS2-RSPM and AOT for Mysuru and Shimoga; (Table 4 and Fig. 2c) shows RSPM and AOT for Kannur, Kochi, and Kuttanad; (Table 5) shows RSPM and AOT for Chennai, Coimbatore, and Tuticorin). The evaluated results are appended as.

### *Maharashtra, WS1*

The present study critically examined and evaluated the values of the three sites: Nagpur, Pune, and Ratnagiri situated in the state, of Maharashtra (Table 2).

The monthly average RSPM concentration and AOT at Nagpur range from 44 and 0.457 µg/m$^3$ to 181 and 0.986 µg/m$^3$. The lower concentration was recorded in the month of November'16 and the maximum concentration was recorded in the month of Jan'17 and Feb'17. In the case of Pune, the RSPM concentration and the AOT value are: Low concentration is 47 and the AOT is 0.26 µg/m$^3$. The maximum RSPM and AOT noted were 378 and 1.44 µg/m$^3$. The low concentration was noted during Sept'17 and the maximum concentration on June'17 and Oct'17. The site Ratnagiri recorded the low RSPM and AOT as 51 and 0.323 µg/m$^3$; the maximum value as 85 µg/m$^3$ and 0.442. The respective low and maximum concentration months were on Aug'17 and Mar'17.

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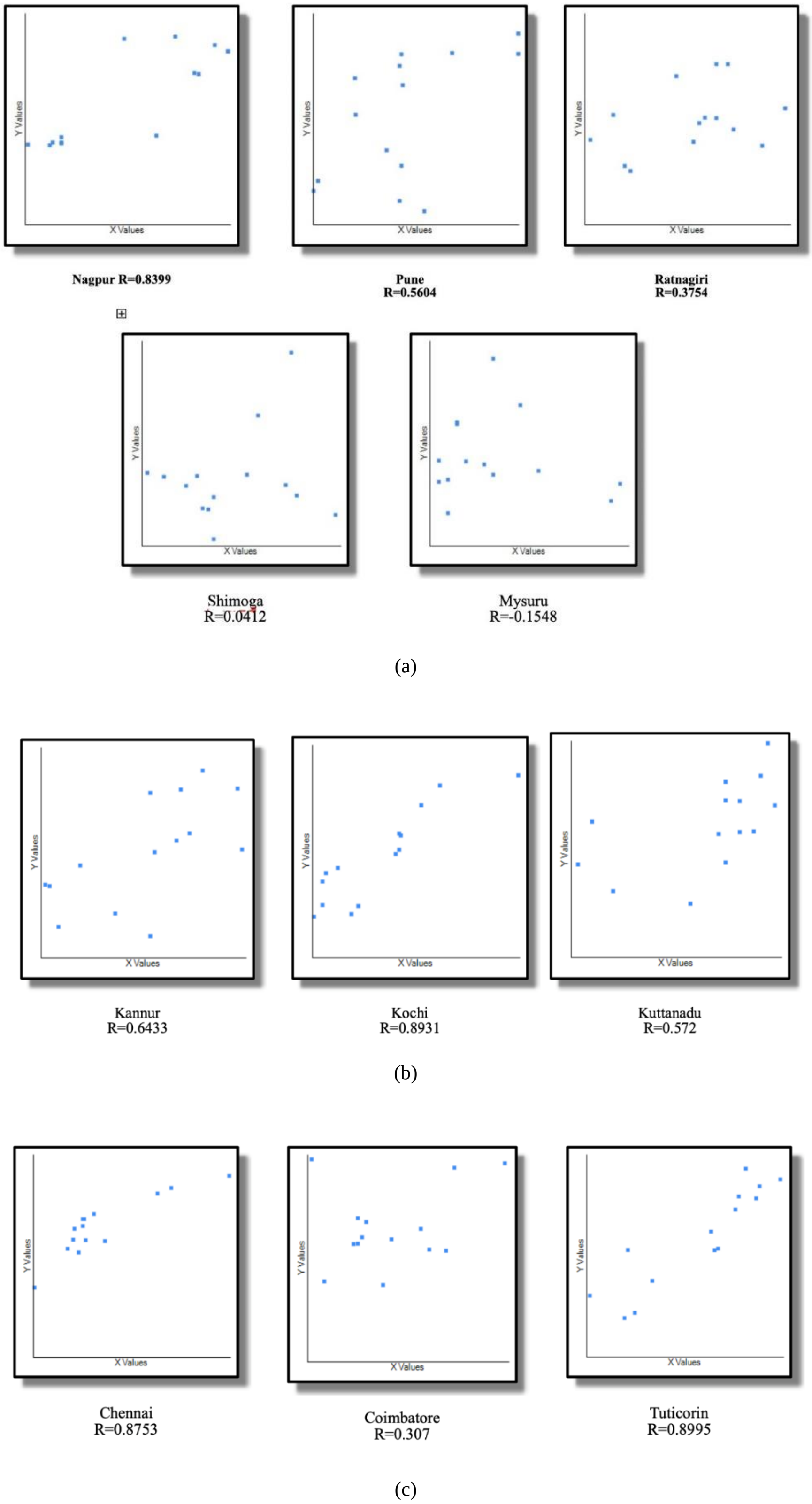


**Fig. 2:** (a) Pearson coefficient analysis of RSPM V/s AOT, WS1; (b) P.C A of RSPM V/s AOT, WS2; (c) Pearson coefficient analysis of RSPM V/s AOT, ES

### *Karnataka, WS2*

The WS2 sites constitute Mysuru and Shimoga (Table 3) at Shimoga, the RSPM and AOT values were noted as Low (41 and 0.295 μg/m$^3$) and Maximum (68 and 0.154 μg/m$^3$) in the month of Sept'17 and Nov'16 respectively. Whereas at Mysuru, the observed trends were: Low (21 and 0.335 μg/m$^3$), observed in the month of both May and August, and Maximum (41 and 0.244 μg/m$^3$) recorded in the month of and Dec'16.

### *Kerala, SW*

Kerala lies in the South West region, the selected sites are Kannur, Kochi, and Kuttanad. The estimated records on AQ assessment are given (Table 4). Kannur: The low (49 and 0.35 μg/m$^3$) and Maximum (94 and 0.516 μg/m$^3$) in the month of Jan '17 and May'17 respectively. While at the site, Kochi, the noted trends were: Low (44 and 0.35 μg/m$^3$) in the months, of June'17 and Aug'17; the maximum (159 and 1.201 μg/m$^3$) in the month Feb'17. At the SW, site Kuttanad, the Low and Maximum recorded values were: Low (42 and 0.259 μg/m$^3$ in the month, May'17 and Maximum (70 and 0.422 μg/m$^3$) and (69 and 0.594 μg/m$^3$) in the months, Dec'16 and Nov'17.

### *Tamil Nadu, ES*

The chosen sites in this Eastern side region were Chennai, Coimbatore, and Tuticorin (Table 5).

## Results

The above tables are thoroughly examined to witness the significant results of the major cities. Chennai: Low (61 and 0.555 μg/m$^3$ on Nov'17); Maximum (202 and 1.434 μg/m$^3$ on Aug'17); Coimbatore: Low (31 and 0.234 μg/m$^3$ on Aug'17); Maximum (62 and 0.563 μg/m$^3$ on May'17) and Tuticorin: Low (47 and 0.367 μg/m$^3$ on July'17); Maximum (102 and 1.053 μg/m$^3$ on Dec'17).

From the recorded analytical results, the inferred results of WS1, WS2, SW and ES were: The lowest trend on RSPM, AOT and the respective months were: WS1: Nagpur was showed the lowest (44 and 0.457 μg/m$^3$, month as Nov'16) WS2: Mysuru recorded the lowest (21 and 0.337 μg/m$^3$, month May, Aug'17) SW: Kuttanad was noted as the lowest (42 and 0.35 μg/m$^3$ on May'17) and ES: Coimbatore was recorded as the Lowest (31 and 0.234 μg/m$^3$ on Aug'17). Among these, the lowest minimum recorded RSPM and AOT was at the site, Mysuru of the WS2 region (21 μg/m$^3$ 0.337 in the months' May'17 and Aug'17). The second position noted for the lowest concentration and AOT was at Coimbatore of ES, Low (31 and AOT as 0.234 μg/m$^3$ in Aug'17).

Similarly, the Maximum trend of RSPM, and AOT with the respective sites were: WS1: Pune recorded the maximum (378 and the respective AOT was 1.44 μg/m$^3$). These recorded months were June and Oct'17. WS2: Shimoga showed the maximum than that of Mysuru as (68 and 0.154 μg/m$^3$) in the months of Sept'17 and Nov'16. SW: The maximum showed at Kochi (159 and 1.201 μg/m$^3$) in the month Feb'17. ES: Chennai showed the maximum as (202 and 1.434 μg/m$^3$ on Aug'17); among these four regions the maximum concentration exhibited as Pune >Chennai>Kochi>Shimoga.

Pune: 378 μg/m$^3$ and the respective AOT was 1.44. These recorded months were June and Oct'17; Chennai: 202 and 1.434 μg/m$^3$ on Aug'17; 102 and 1.005 μg/m$^3$; 113 and 1.134 μg/m$^3$) in the months Jan'17 and Dec'17.

Kochi: Denoted the third position and the maximum concentration as 159 and 1.201 μg/m$^3$; in the month of Feb'17 and the fourth position comes for Shimoga: and Maximum (68 and 0.154 μg/m$^3$) in the month of Sept'17 and Nov'16 respectively. This research investigation correlated the profile of the acquired RSPM distribution concentration against the MODIS retrieved AOT. The study concentrated on selected '11 'hotspot sites of varying demographic and geographic character. The analysis was conducted during the period between Nov'16 to Dec'17 covering 14 months. As explained earlier, the designated 11 sites were categorized State wise as Maharashtra, Western Side, (WS) (Nagpur, Pune, and Ratnagiri); Karnataka, Western Side, (WS) (Mysore and Shimoga); Kerala, Southern Side, SS (Kannur, Kochi, and Kuttanad) and Tamil Nadu, Eastern Side, (ES) (Chennai, Coimbatore, and Tuticorin). In all 11 sites, the RSPM concentrations were considered in the aspects based on the recommended guidelines for residential areas. Up to 70 μg/m$^3$ is accounted for as 'Low' level pollution. The correlation graph and derived inferences are appended here.

Pearson Correlation analysis was performed with the acquired RSPM data against the extracted AOT values and retrieved the respective correlation coefficient (Fig. 2).

Figure (2a) pearson coefficient analysis of RSPM V/s AOT, WS1; (B) P.C A of RSPM V/s AOT, WS2; (C) Pearson coefficient analysis of RSPM V/s AOT, ES.

The Pearson correlation coefficient R for each geographical area is given as:

Maharashtra, WS1 Nagpur, R = 0.8399, in this analysis it is found that the RSPM has a very strong correlation with the AOT; Pune, R = 0.5604, has a moderate correlation with the factor, whereas Ratnagiri, (R = 0.3754) showed it has a weaker relationship, although technically a Positive Correlation, the relationship is weak.

Karnataka, WS2 Shimoga, R = 0.0412, a strong positive correlation; and Mysuru, R = -0.1548, here only Mysuru noted a negative correlation.

Kerala, SW Kannur, R = 0.6433, noted a moderate positive correlation Kochi, R = 0.8931, observed a very strong positive correlation; whereas Kuttanadu, R = 0.572, estimated a moderate positive correlation Tamilnadu, ES Chennai, R = 0.8753, exhibited a strong positive correlation Coimbatore, R = 0.307, has a weaker relationship, although technically a positive Correlation, the relationship is weak; and Tuticorin, R = 0.8995, showed a strong positive correlation.

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**Table 6:** Meteorological parameters of WS1

| Meteorological parameters of WS1-Maharashtra | RH (%) Nagpur Ratnagiri | Temp (°C) Pune Nagpur Pune Ratnagiri | Wind Velocity (km/hr) Nagpur Pune Ratnagiri | Rainfall (mm) Nagpur Pune Ratnagiri |
|---|---|---|---|---|
| Nov' 16 | 58,77,68.0000 | 28.1,29.9,29 | 4.6.,1.6,11 | 12,2,2 |
| Dec | 60,67,77.0000 | 29,27.9,30.000 | 5.9.,2.7,10 | 10,18 |
| Jan' 17 | 62,66.23,76 | 31,27.3,30.000 | 9.8.,2.8,7.4 | 19,2,5 |
| Feb | 63,68.1,750 | 32,29.5,29.000 | 10.6.,3.7,6.8 | 15.,13,47 |
| Mar | 68,63.56,72 | 33,31.2,31.000 | 7.9.,6.3,8.3 | 16,41,87 |
| Apr | 52,68.67,72 | 34,32.4,31.000 | 2.4.,7.1,9.5 | 50,122,92 |
| May | 58,69.34,73 | 32,33.1,30.000 | 3.5.,5.4,8.9 | 60.,211,270 |
| June | 61,62.45,74 | 31,30.3.,29.000 | 4.7,6.7,10 | 271,128,356 |
| July | 61,62.45,77 | 30,29.9,31.000 | 9.3,4.1,12 | 195,132,432 |
| Aug | 60,1.23,76 | 31,30.1,29.000 | 10.4.,1.5,12 | 163,82,543 |
| Sept | 59,62.24,78 | 31,30.1,31.000 | 7.5,1.490 | 300,26,347 |
| Oct | 59,65,76.0000 | 29.3,31.2,28 | 6.8,1.1,8.700 | 100,5,289 |
| Nov | 60,67,75.0000 | 29.2,30.2,28 | 7.8.,1.4,12.100 | 25,1,128 |
| Dec' 17 | 61,68,78.0000 | 28,28.8,27.000 | 6.7,2.7,9.200 | 18,3,167 |

**Table 7:** Meteorological parameters of WS2

| Meteorological parameters of Karnataka: Western side, WS2 | RH (%) shimoga mysore | Temp (°C) mysore | Wind velocity (km/hr), shimoga mysore | Rainfall (mm) shimoga mysore |
|---|---|---|---|---|
| Nov' 16 | 79,66 | 28.6,26.400 | 3.7,19 | 5,2 |
| Dec | 76,62 | 27.7,25.670 | 6.4,90 | 7,8 |
| Jan' 17 | 76,73 | 27.6,23.450 | 7.1,60 | 5,47 |
| Feb | 75,68 | 28.1,23.800 | 8.1,50 | 40,127 |
| Mar | 78,71 | 29.12,24.56 | 6.9,40 | 81,25 |
| Apr | 79,67 | 30.01,24.56 | 3.2,14 | 120,38 |
| May | 80,73 | 31.02,25.99 | 3.8,12 | 201,78 |
| June | 75,75 | 30.34,26.96 | 4.1,11 | 220,150 |
| July | 75,72 | 30.01,26.24 | 3.2,12 | 119,44 |
| Aug | 77,71 | 29.05,26.80 | 4.2,11 | 76,24 |
| Sept | 78,69 | 29.89,28.32 | 7.1,80 | 121,19 |
| Oct | 77,71 | 29.6,27.2,00 | 8.1,90 | 27,11 |
| Nov | 78,68 | 29.3,27.100 | 6.7,90 | 12,26 |
| Dec' 17 | 77,67 | 27.8,24.500 | 7.1,11 | 16,21 |

**Table 8:** Meteorological parameters of SW

| Meteorological parameters of Kerala: South West, SW | RH (%) Kannur Kochi Kuttanadu | Temp (°C) Kannur Kochi Kuttanadu | Wind velocity (km/hr) Kannur Kochi Kuttanadu | Rainfall (mm) Kannur Kochi Kuttanad |
|---|---|---|---|---|
| Nov' 16 | 78,77,79.000 | 29.5,28.8,28.60 | 6.97.8,6.60 | 1119,28 |
| Dec | 76,78,76.000 | 29.5,27.1,27.70 | 6.27.3,9.10 | 2033,39 |
| Jan' 17 | 72,76,76.000 | 29.4,27.2,27.60 | 6.67.5,10.3 | 27,49,56 |
| Feb | 78,75,75.000 | 30.8,29.6,28.10 | 5.76.5,8.30 | 121139,144 |
| Mar | 66,72,78.000 | 32.8,31.2,29.12 | 6.56.4,9.30 | 91124,336 |
| Apr | 60,73,79.000 | 33.4,32.2,30.01 | 6.77.6,9.70 | 92119,489 |
| May | 63,72.9,80 | 33.5,30.5,31.02 | 7.26.4,9.50 | 180303,423 |
| June | 74,73.9,75 | 31.2,30.4.,30.34 | 5.16.7,9.90 | 258375,321 |
| July | 78,76,75.000 | 29.9,28.7,30.01 | 6.97.8,9.30 | 220428,267 |
| Aug | 79,77,77.000 | 31.5,29.4,29.05 | 7.28.3,10.0 | 345408,298 |
| Sept | 73,76,78.000 | 31.5,29.8,29.89 | 7.38.2,8.30 | 80162,211 |
| Oct | 78,74,78.000 | 30.2,29.1,29.60 | 7.38.9,6.40 | 3748,123 |
| Nov | 74,78,77.000 | 29.6,28.9,29.30 | 6.47.9,7.10 | 1926,45 |
| Dec' 17 | 76,79,79.000 | 29.8,27.5,27.80 | 6.37.6,10.3 | 2227,78 |

**Table 9:** Meteorological parameters of ES

| Meteorological Parameters of Tamil Nadu: Eastern Side, ES | RH (%) Chennai Coimbatore Tuticorin | Temp (°C) Chennai Coimbatore Tuticorin | Wind velocity (km/hr) Chennai Coimbatore Tuticorin | Rainfall (mm) Chennai Coimbatore Tuticorin |
|---|---|---|---|---|
| Nov' 16 | 65,64,59 | 31.330,31.1 | 10.87,19.5 | 158,8 |
| Dec | 66,66,60 | 29.828.9,29.1 | 7.59,7.1 | 39,29 |
| Jan' 17 | 64.547.3, 62.43 | 3028,29.3 | 9.111,6.4 | 212,16 |
| Feb | 65,62.4,61.43 | 3129.6,30.7 | 11.66,4.6 | 1053,10 |
| Mar | 62.45,60.34,58.14 | 3332.4,31.4 | 11.24,9.2 | 12475,48 |
| Apr | 6055.1,57.34 | 35.133.5,32.08 | 11.79,8.6 | 3235,28 |
| May | 61.545,5.3,61.34 | 36.234.7,32.45 | 10.94,7.9 | 5641,4 |
| June | 64.346,6.9,61.79 | 32.331.2,31.34 | 9.88,8.8 | 11130,5 |
| July | 66.436,8.7,62.54 | 30.231.1,29.3 | 8.37,9.6 | 15444,3 |
| Aug | 65.716,6.89,70 | 31.330.2.,31.5 | 8.37,9.7 | 121151,14 |
| Sept | 64.14,68.3,71 | 30.230.6.,29.2 | 7.29,8.2 | 241121,136 |
| Oct | 65.662 | 32.431.2,30.1 | 7.512,7.2 | 32939,329 |
| Nov | 64.263,76 | 30.131.4,31.1 | 7.911,6.9 | 12312,238 |
| Dec' 17 | 7962,75 | 3129.8,32 | 8.59,7.2 | 13110,93 |

Generally, the attainment of RSPM is directly influenced by meteorological drivers like Relative Humidity (RH), Rainfall Intensity (RI), Temperature, Wind Speed, etc. Therefore, the meteorological parameters of the four distinct geographical areas are accounted for and given in (Tables 6-9). The meteorological conditions exhibited a trend in variations with varying R-values resulting from performing the Quadratic Regression Analysis (QRA). QRA was done by selecting one site from each geographical area WS1, WS2, SW, and ES. The criteria were based on the elevated concentration inferred in the study period.

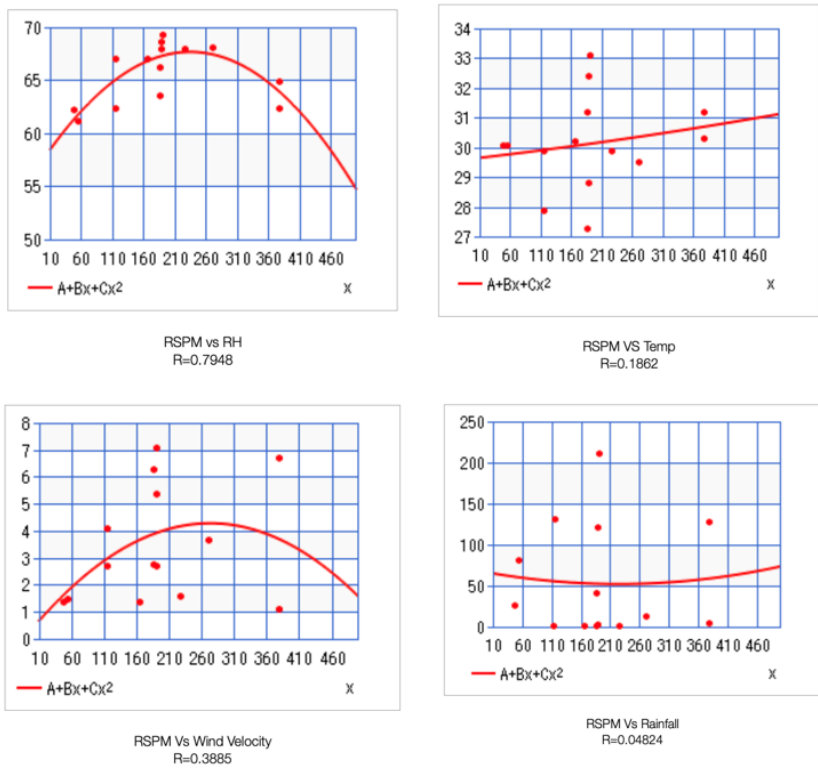
Each site geographically exhibited varying meteorological parameters; thereby the extracted AOT also fundamentally affected their change in the correlation pattern with the driving meteorological factors.

## Discussion

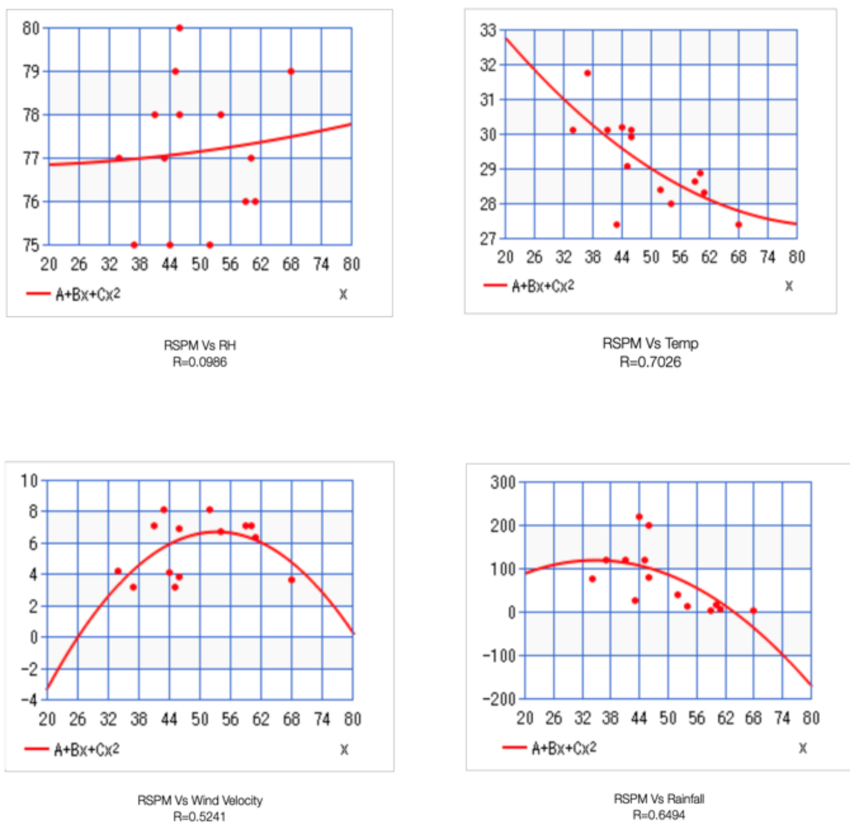
Previous reports have well-established mixed positive and negative results on the AOD-PM relationship. The correlation coefficient on a monthly average basis is more crucial and essential than that of yearly average analysis in AQ assessment. Similarly, earlier studies related to MODIS-AOT data were compared with the respective recorded ground-based PM data. They were out-sourced from the network AQ monitoring data bank of each represented site and analyzed the trend pattern for AQ assessment (Li and Yin, 2017; D'Angelo *et al*., 2016; Di *et al*., 2016)

A significant correlation between MODIS-derived AOT and ground-monitored particulate matter concentration was recorded earlier (D'Angelo *et al*., 2016; Liu *et al*., 2012; 2004; 2003; 2001; Paciorek *et al*., 2008; Hoff and Christopher, 2009) and estimated the near-surface $PM_{2.5}$ concentration by means of acquiring geostationary satellite AOT data at higher temporal resolutions. The inferences suggested that AQ could be tracked over a wide spatial Domain to monitor aerosol particles and their sources, and transport pathways. Detailed investigations were conducted by Hoff and Christopher, (Thomas *et al*., 2019) based on the correlation of AOT (as a columnar aerosol loading quantity) and $PM_{2.5}$ as surface measured concentration. Meteorological information such as Relative Humidity (RH), Surface Temperature (TS), Wind Speed (WS), Wind Direction (WD), changes in sunlight due to clouds, rainfall intensity, atmospheric pressure, sea surface pressure, temperature, and dust extinction, etc., which are playing a vital influencing role on the AQ profile interpretation. Thomas *et al*., (2019) made a conclusion that most of the air parcels are in the well-mixed boundary layer and utilized for the relationship between $PM_{2.5}$ and AOD.

Hazy days are generally recognized as high aerosol loading in the atmospheric realm, especially during the winter periods, and showing less visibility. Such anomalous behaviour in the increment of air pollutants is associated due to the intense use of biomass fuel for burning in various purposes. Mostly this trend is eminent in the Indian Subcontinent in the months of November to December (Li *et al*., 2017). In winter time hazardous air pollution scenarios over the densely populated regions of China and India had received the utmost scientific attention (Zhang *et al*., 2015; Kumar *et al*., 2008; Zhao *et al*., 2018). The trend in aerosol strength over the Arabian Sea that of the Bay of Bengal is higher due to the downwind location to Central India during the winter season. This season is characterized by a shallower boundary layer with lower wind speed and low precipitation leading to the accumulation of aerosols near the surface. Winter can reduce radiation by nearly 70% to the surface, thereby decreasing crop yield. Aerosols could also act as cloud condensation nuclei and affect to the formation of clouds. Regional-wise coincidence and relationship exist between the hotspot regions of intense aerosol loading with the urbanised industrial regions of high population density. Cases of biomass burning also contribute to the elevation of ubiquitous air parcels in the ambient atmosphere.


A+Bx+Cx2
x
RSPM vs RH
R=0.7948
RSPM VS Temp
R=0.1862
RSPM Vs Wind Velocity
R=0.3885
RSPM Vs Rainfall
R=0.04824

(a)


A+Bx+Cx2
x
RSPM Vs RH
R=0.0986
RSPM Vs Temp
R=0.7026
RSPM Vs Wind Velocity
R=0.5241
RSPM Vs Rainfall
R=0.6494

(b)

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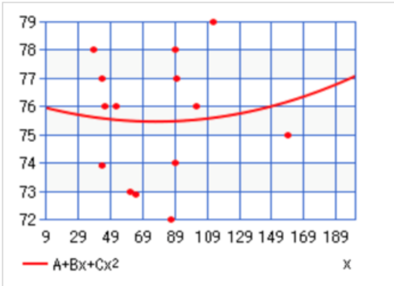
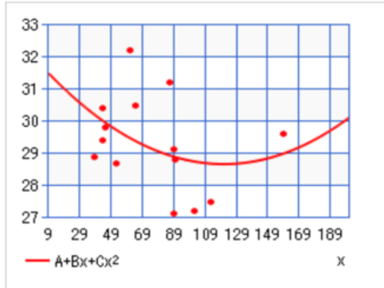
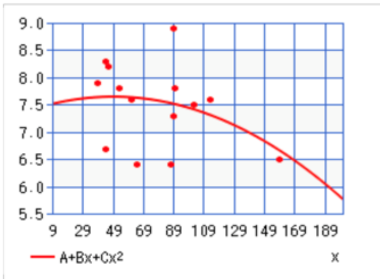


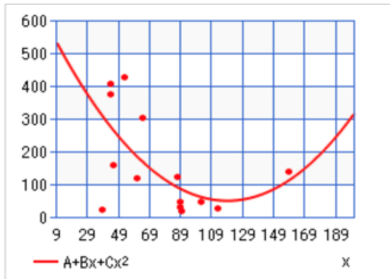

RSPM Vs RH
R=0.0828




RSPM Vs Temp
R=0.3682

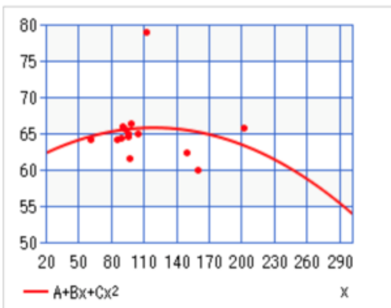



RSPM Vs Wind Velocity
R=0.3431

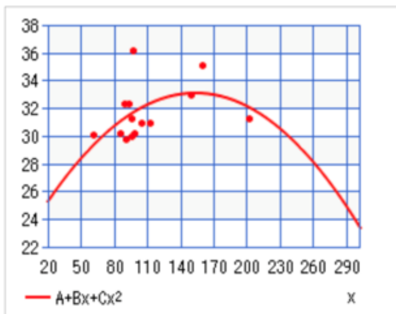



RSPM Vs Rainfall
R=0.6008

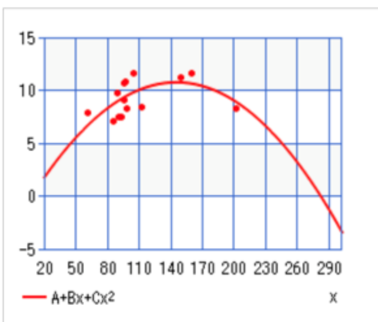
(c)



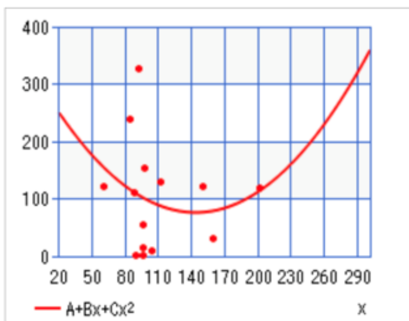

RSPM Vs RH
R=0.1472




RSPM Vs Temp
R=0.4661




RSPM Vs Wind Velocity
R=0.5925




RSPM Vs Rainfall
R=0.1970

(d)

**Fig. 3:** (A) Quadratic regression analysis of WS1, Pune-RSPM vs supporting parameters; (B) Quadratic regression analysis of WS2, Shimoga RSPM vs supporting parameters; (C) Quadratic regression analysis of SW, Kochi-RSPM vs supporting parameters; (D) Quadratic Regression Analysis of ES, Chennai-RSPM vs supporting parameters

Several earlier researchers (Engel-Cox *et al*., 2004a-b; Zhang *et al*., 2013; Chu *et al*., 2002; Wang and Christopher, 2003) effectively studied AP globally, regionally, and locally by applying AOD in their research area and conducted the analysis either qualitatively or quantitatively. The investigation concluded that the retrieved satellite remote-sensing information and ground-level air pollutant concentrations exhibited considerable correlations. Similarly, Wang and Christopher, (Retalis *et al*., 2010) compared the satellite-retrieved AOD data with ground-level observations on multiple stations and recorded a significant positive correlation. The inferences drawn from the earlier study (Wei *et al*., 2020; Zhang *et al*., 2013; Conen *et al*., 2017) explained that the air parcels have resided in the mixing layer for measuring AOD suitably which could be valid and applied as a better way of approach for AQ assessment. Equally, the outcome of the analyzed results of QRA (Fig. 3) as given below played a prominent role in the screened data on meteorological parameters and RSPM to interpret the regional-based transport of aerosols in the atmospheric niche.

Quadratic Regression Analysis (QRA) guidelines for interpreting correlation coefficient r:

$0.7 < |r| \leqq 1$ strong correlation

$0.4 < |r| < 0.7$ moderate correlation

$0.2 < |r| < 0.4$ weak correlation

$0 \leqq |r| < 0.2$ no correlation

### *WS1 Pune*

RSPM Vs RH The correlation coefficient is R = 0.7948, so the RSPM has a strong correlation with the RH.

RSPM Vs temperature R = 0.1862, RSPM has no correlation with the temperature. RSPM Vs wind velocity R = 0.3885, RSPM has a weak correlation with wind velocity. RSPM Vs Rainfall R = 0.04824, RSPM has no correlation with Rainfall. WS2 Shimoga.

RSPM Vs RH correlation coefficient, R = 0.0986, so the RSPM has no correlation with the RH.

RSPM Vs temperature R = 0.7026, RSPM has strong correlation with the temperature. RSPM Vs wind velocity R = 0.5241, RSPM has a moderate correlation with Wind velocity. RSPM Vs Rainfall R = 0.6494, RSPM has a moderate correlation with Rainfall. SW Kochi.

RSPM Vs RH Correlation coefficient, R = 0.0828, So the RSPM has no correlation with the RH. RSPM Vs temperature R = 0.3682, RSPM has weak correlation with the temperature. RSPM Vs wind velocity R = 0.3431, RSPM has a weak correlation with wind velocity. RSPM Vs Rainfall R = 0.6008, RSPM has a moderate correlation with Rainfall. ES Chennai.

### *RSPM Vs RH*

Correlation coefficient, R = 0.1472, so the RSPM has no correlation with the RH. RSPM Vs temperature R = 0.4661, RSPM has moderate correlation with the Temperature. RSPM Vs wind velocity R = 0.5925, RSPM has a moderate correlation with wind velocity. RSPM Vs Rainfall R = 0.1970, RSPM has a no correlation with Rainfall.

In the past, similar to the present investigation, the temporal variability of surface-measured PM concentrations and their relationship with meteorological variables and aerosol AOD, by means of source apportionment studies, were prepared for four urban cities (Liu *et al*., 2012; Zhao *et al*., 2018; Lee *et al*., 2008; King and Greenstone, 1999). The study revealed that AQ of these sites is in a deteriorating situation though various stringent measures are undergoing in the respective regions of Pune, Shimoga, Kochi and Chennai. In addition, the natural meteorological forcers are also contributing to an immense coverage and should be encountered in detail when it is necessitated. Since local meteorological parameters could persuade profoundly to enhance or withdraw the aerosol loading, hence individually their effects were examined thoroughly and separately for each distinct season. Furthermore, the interrelation with AOD values was also correlated concurrently.

AOD/RSPM Vs RD/RH/ST/WS have found a noteworthy association (Pune-RSPM Vs RH correlation coefficient R = 0.7948; Shimoga-RSPM Vs Temp R = 0.7026, RSPM Vs wind velocity R = 0.5241, RSPM Vs Rainfall R = 0.6494; Kochi-RSPM Vs Rainfall R = 0.6008; Chennai-RSPM Vs wind velocity R = 0.5925).

AOT remote sensing is highly influenced by ambient RH that is when the RH is relatively high; the water-soluble particles would deliquesce and expand to influence the change in AOT values (Li *et al*., 2017). While the RH can distort the weight of PM by inflating the size of the aerosol particle, in these circumstances, the atmospheric pressure is linked to the mobility of this air-driven matter. As reported earlier, low pressure results in high mobility for the suspended fine particulate matter (Kumar *et al*., 2008). In this present inference, the RSPM ($PM_{2.5}$) is more detectable or sensible to RH as revealed in the Pune site.

## Conclusion

In the contemporary attempt, similarities and variations were erudite in the spatial distribution of AOD and RSPM in certain months. The results are concluded according to the maximum RSPM concentration derived for the 14 months in all the WS1, WS2, SW, and ES regions under consideration. The estimates of AOD could span over this period of time and also the geographic scale of these two datasets is varying; PM data could interpolate using point-wise, whereas AOD data only extract at the area of 10 km pixels. In addition, sources of RSPM origin also contribute to elevating the levels of both PM mass concentration and AOD value. These results were well perceived in the case of Pune, Kochi, and Chennai where these areas are flanked by various industrial clusters. Industrial manufacturing sources and their derived product transportation utility elevate the pollutant levels and simultaneously the extracted AOD values. The unabated usage of vehicles for personal needs elevates the concentration levels of ambient atmospheric particulates and generated a deteriorating situation.

This means of records could initiate to represent the pollutant component and subsequently infer the sources of particulate pollutants and in later days could come up with reasonable emission control measures. The investigation extracted the ground-level data along with the retrieved satellite AOT observation only in limited sites owing to the hindrance to making macro-level analysis on the emanating sources and variation in the trend pattern of pollutants. The emerged inferences could bring reasonable strategic measures to cope with the regional AP trend in each geographically varying spotted station. As illustrated in previous sections, a number of reports were available throughout the world by utilizing this type of monitoring strategy. The results of this study would benefit the validation of satellite-derived outputs and ground-based monitored measurements over these studied areas to make a representation of the upcoming research work. Future research can be performed for the progress of satellite AOD products to improve the Spatio-temporal resolution of aerosol-associated properties. The trials of AOD satellite remote sensing also imply a great deal of chance for effective AP control, air navigation, public health assessment, and forecasting meteorology. In this platform, a vast amount of satellite products provides information about air and earth conditions around the globe, thus the researchers in this field of study could well utilize such opportunities.

### *Declaration of Competing Interest*

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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## Ethics

This material is the authors' own original work, which has not been previously published elsewhere.

### *Environmental Significant Statement*

Noteworthy contributions to air quality assessment have brought the Spatio-temporal relationship between the ground level monitored particulate matter and the satellite sensor retrieved aerosol optical thickness in urban cities globally. The present attempt evaluated the feasibility of measuring the air quality index/PM against AOD in four geographically distinct states with specific zone sites in India. Examined interrelationship of RSPM-AOD/meteorological drivers through PCA and QRA of the focussed areas. Elevated air pollution was noticed in Pune, Kochi, and Chennai. They were flanked by various industrial clusters and the unabated usage of vehicles for personal wants. This means of records could represent the aerosol component, subsequently infer source origin and in later days come up with reasonable emission control measures.

## Author's Contributions

**Jacob Joshua:** Participated in all experiments, coordinated the data analysis and contributed to the written of the manuscript.

**Aishwarya Sathyachandran:** Coordinated the data analysis, contributed to the written of the manuscript, and coordinated the mouse work.

**Chenicherry House Sujatha:** Designed the research plan, organized the study, and to the written of the manuscript.

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