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Spatio-Temporal Distribution of Aerosols Over Kerala: A Satellite-Based Assessment in Polluting Climate

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ABSTRACT

India has seen an increase in the extreme rainfall events (EREs) over the years, which is likely to continue due to global warming. The rising frequency of EREs is often linked to increasing atmospheric pollution, particularly atmospheric aerosols, which are one of the key components of the climate system. The recent increase in EREs over Kerala leading to extensive flooding and landslide has demonstrated the consequences of the combined impact of global warming and atmospheric pollution. Studies reveal that the recent EREs are particularly characterized by highly polluted (aerosol-rich) scenarios, supporting cloud invigoration with moisture convergence leading to EREs. In the current era of global warming, where the atmospheric water holding capacity is expected to increase, the prime question is whether there will be sufficient aerosols (as cloud condensation nuclei) to support precipitation? In this context, the present study is dedicated to understanding the spatial and temporal distribution of aerosols over the state of Kerala. Monthly average Aerosol Optical Depth (AOD, 550 nm) from Collection 6.1, level 3 AOD products (1° × 1°) derived from Terra's MODIS measurements for 21 years (2001 – 2021) is discussed in this study, while data from 2001 to 2019 is utilized for the analysis. Spatio-temporal analysis of the district-wise AOD data is carried out along with a trajectory analysis to ascertain probable aerosol sources. Time series analysis indicates a significant increasing trend in AOD over Kerala. A higher rate of increase in AOD is observed among the northern districts, with Kozhikode recording the fastest growth. AOD is particularly heavier during certain months, and the wind trajectory analysis performed reveals the direction of the wind which might have carried the possible sources like dust, sea salt, smoke, etc., during the observed monthly aerosol loading during highest and lowest concentrations. Further, the frequency analysis shows that the frequency of aerosol-pollution-episodes (AOD > 0.4) has increased alarmingly from 13.3 % (2001-2005) to 53.3% (2015-2019). Further, a classification of the districts based on mean AOD through 4 sub periods: 2001-2005, 2006-2010, 2011-2015, and 2016-2019 reveals that none of the districts were safe zones (AOD<0.3) after the 2001-2005 period. Eventually in recent years 2016-2019, Kozhikode district had turned highly vulnerable (AOD>0.5), while districts including Kasaragod, Kannur, Thrissur, Palakkad, Ernakulam, Kottayam, Alappuzha, and Pathanamthitta were vulnerable zones (0.4<AOD<0.5), and remaining districts continued as less vulnerable zones (0.3<AOD<0.4).

1. INTRODUCTION

Climate Change is likely to have an impact on all natural ecosystems and socioeconomic systems of India, as indicated in the National Communications Report of India to the United Nations Framework Convention on Climate Change (Indian Ministry of Environment and Forest, 2004). During the industrial era, emissions of greenhouse gases (GHGs), aerosols, and changes in land use and land cover affected the composition of the atmosphere and the planetary energy balance and are primarily responsible for climate change (IPCC 2018; Krishnan et al., 2020). Over the past few decades, India has seen an increase in extreme precipitation events, which are likely to continue due to the warming climate (Goswami et al., 2006; Pai et al., 2015, Roxy et al., 2017, Mukherjee et al., 2018;). The rising frequency of extreme precipitation events is often linked to increasing greenhouse gas emissions and aerosols (Cherian et al., 2013; Lau et al., 2016; Krishnan et al., 2016; Hazra et al., 2017). Aerosols are solid or liquid particles suspended in the atmosphere, and are one of the key components of the climate system and the hydrological cycle (Ramanathan et al., 2001). Atmospheric aerosol from both natural and anthropogenic activities has long been acknowledged as one of the important factors influencing regional and global climate change (Ramanathan et al., 2005; Wang et al., 2022). Analyzing the trends and patterns of these atmospheric particles is of utmost importance in the current polluting climate.

For monitoring aerosol, space-born sensors have become the primary tool (Xiaoli et al., 2020). The measurable quantity from space is the aerosol optical depth (AOD) which is derived from the solar radiation reflected to space. AOD is a valuable aerosol characteristic, which is a key parameter for various aerosol-related studies, such as aerosol radiative forcing, atmospheric corrections of the aerosol effect on remote sensing, etc. (Kaufman et al., 1997). Higher aerosol loading changes cloud properties in terms of size and microphysics, which results in more rainfall but delays the onset of rainfall. The aerosol-cloud microphysical feedback suggests that higher aerosol loading can enhance the strength of convective rainfall and increase the frequency and intensity of extreme rainfall during the Indian summer monsoon (Shukla et al., 2022). Extreme rainfall events may directly result from an increase in aerosol loading (Lau et al., 2006). Kerala State experienced severe extreme rainfall events and floods during August 2018 and August 2019 (KSCSTE report 2019). Jasmine et al., (2022) found that during the mid of August 2018, moisture built over the Kerala region was excessive enough to bury the semi-direct effect caused by aerosols, thus in contradiction aerosols amplified the cloud cover and led to intensified precipitation in Kerala along with combined effect of heavy dust loading near west coast of India.

Aerosols are a part of air pollution and have impacts on human health as well as climate. One of the serious concerns faced by India in the twenty-first century is air pollution (WHO), and around 1

million deaths were related to atmospheric aerosol pollution (vizhub.healthdata.org/gbd-compare/india; accessed on Dec 11, 2020). Kerala region is most affected by Vehicular Emission (VE) which is constantly increasing followed by Solid Fuel Burning (SFB) and Open Biomass Burning (OBB). VE contribution has been increasing at a slow rate from 35% (2005-2009) to 38% (2010-2014) to 39% (2015-2019). OBB contribution was from 11-15% with a major contribution in the 2010-2014 period. SFB had a contribution of 25% which hasn't shown any changes over years (Monami Dutta et al., 2022). The future projection in their study shows that southern India would become highly vulnerable in terms of aerosol pollution by 2023 if these sources continue to dominate. In the current era of global warming, where the atmospheric water holding capacity is expected to increase, the prime question is whether there will be sufficient aerosols (as cloud condensation nuclei) to support precipitation? In this context, the present study is dedicated to understand the spatial and temporal distribution of aerosols over the state of Kerala and to project the future AOD values. Spatiotemporal analysis of the district-wise AOD data is carried out along with a trajectory analysis to ascertain probable aerosol sources. Monthly average Aerosol Optical Depth (AOD, 550 nm) data from Collection 6.1, level 3 AOD products (1° × 1°) derived from Terra's MODIS measurements for 21 years (2001 – 2021) is used in this study. AOD Data from the period 2001 to 2019 is utilized for the AOD analysis while data during the Corona Virus (Covid-19) pandemic period (2020 to 2021) is discussed separately due to the variation from its long-term AOD trend. After announcing the triple lockdown in Kerala right after the nationwide lockdown of 21 days from March 25, 2020 all the educational institutes, offices, industries, shops, flight services, etc. remained closed which reduced the anthropogenic sources of aerosol emissions way less than in the previous years.

2. DATA AND METHODOLOGY

2.1. DATA USED

2.1.1. AOD DATA

As a decent tool to understand the spatiotemporal properties of aerosols and their effects from global to local scales, satellites are used (Misra et al. 2015). Aerosol optical depth (AOD) is a key parameter that reflects aerosol characteristics. The AOD is a measure of the solid and/or liquid particles suspended in the air including dust, sand, volcanic ash, smoke, and urban/industrial aerosols. The AOD measures the amount of light lost due to the presence of aerosols on a vertical path through the atmosphere. More formally the AOD is the extinction (scattering + absorption) vertical optical thickness of aerosols. In this study, Moderate Resolution Imaging Spectroradiometer (MODIS) data is used which is downloaded from Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC) which serves as a backup source for MODIS AOD data. The MODIS

is a space-borne sensor onboard the Terra satellite (launched in December 1999) and Aqua satellite (launched in May 2002). Both of these satellites scan the entire surface of the Earth, every 1 to 2 days and acquire data in 36 spectral bands or groups of a different wavelengths (Levy et al., 2007; Remer et al., 2005; Savtchenko et al., 2004). Two separate algorithms, i.e. Deep-Blue algorithm and Dark-Target algorithm (Mhawish et al., 2017), are utilized to retrieve the AOD (MODIS) data products. Here, AOD has been obtained from Level-3 MODIS monthly average global product 'MOD08_M3' (ESDT Long Name: MODIS/Terra Aerosol Cloud Water Vapor Ozone Monthly L3 Global 1 Deg CMG), at 550nm with a spatial resolution of 1 degree by 1 degree derived from Terra's MODIS measurements (Platnick et al. 2017). MOD08_M3 product files are available in Hierarchical Data Format (HDF). The AOD at 550 nm is utilized in this study as this product has better consistency (Lyapustin et al., 2018). The flowchart of the methodology utilized in this study is shown in Fig (1).

2.1.2. NCEP-NCAR REANALYSIS DATA

The National Centers for Atmospheric Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) have created different re-analysis projects with the objective of providing global gridded data for a long time period for different atmospheric parameters. The NCEP/NCAR Reanalysis I (Kalnay et al., 1996) is the constantly-updated globally gridded data set that covers the largest period, which extends from 1948 to the present. The data used here is the NCEP-NCAR Reanalysis 1 data provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov. The parameter considered here is NCEP Reanalysis wind data having a grid resolution of 2.5 degrees to carry out 2-day backward trajectory frequency analysis with the help of HYSPLIT model. The data are archived at the Air Resources Laboratory, and are freely available at Meteorology / ARL Data FTP / Archive (S112) (noaa.gov) which are already in HYSPLIT compatible format that can directly be used as the meteorological data to run the HYSPLIT model.

2.2. MANN-KENDALL TEST

Trend analysis of AOD has been investigated using the Mann-Kendall (MK) test. Mann (1945) initially used this test, and Kendall (1975) subsequently derived the test statistics distribution. Its benefit is that it is distribution-free and does not accept any unique structure for the distribution capacity of the information and has been suggested generally by the World Meteorological Organization (WMO) for public application. Subsequently, different researchers discovered the MK test to be a fantastic instrument for pattern identification in comparative applications. For the time series X1, ..Xn, the MK test uses the following statistic.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(Xj + Xi)$$

Where n is the number of observations, x_j is the $_j$th observation, and sgn () is the sign function which can be computed as:

$$sgn(x_j - x_i) = \begin{cases} 1\ if\ (x_j - x_i) > 0 \\ 0\ if\ (x_j - x_i) = 0 \\ -1\ if\ (x_j - x_i) < 0 \end{cases}$$

Under the assumption that the data are independent and identically distributed, the mean and variance of the S statistic in Equation (2) are given by Kendall (1975) as

E(S) = 0

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i\text{-}1)(2t_i + 5)}{18}$$

Where, m is the number of groups of tied ranks, each with t_i tied observations. The original MK statistic, designated by Z, was computed as

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}\ S > 0 \\ 0\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}\ S < 0 \end{cases}$$

If - $Z_{1\text{-}a/2} \leq Z \leq Z_{1\text{-}a/2}$, then the null hypothesis of no trend was accepted at the significance level of α. Otherwise, the null hypothesis was rejected, and the alternative hypothesis was accepted at the significance level of α

2.3. SEN'S SLOPE ESTIMATOR

Sen (1968) derived a method for estimating the Kendall Tau. This method has its application in the estimation of the slope of a linear trend, which arises from a linear equation as

$$\mathrm{f(t) = Qt + B}$$

Here, f(t) is a function of time representing the time series, t is the time, B is constant, and Q is the slope. Q can be contracted by the equation

$$Q_i = \frac{x_j - x_k}{j - k}$$

Here at time j and k, j > k and i = 1, 2 …, N, the values of the data pairs are represented by x_j and x_k. We can determine the median of the N values of Q_i by Rahman and Dawood (2017).

$$Q = \begin{cases} Q_{[\frac{N+1}{2}]} & ; if N is\ odd \\ \frac{1}{2} Q_{[\frac{N}{2}]} + Q_{[\frac{N+2}{2}]} & ; if\ N is\ even \end{cases}$$

When the value of Qi is positive, one can discern that there is an increasing trend, and similarly, a decreasing trend shows that the value of Qi is negative. A zero value indicates no trend (Salmi et al., 2002; Rahman et al., 2017).

2.4. SEASONALITY TEST

In the present study, the Seasonality Index (SI), which is proposed by Walsh & Lawler (1981) was applied to identify AOD regimes. In order to find out whether a seasonal variation is present or not for the long-term data of MODIS-derived AOD, SI is used, which is the function of mean monthly and annual AOD is computed using the formula,

$$SI = \frac{1}{12 * \bar{\tau}} \sum_{i=1}^{12} |\tau_i - \bar{\tau}|$$

Where $\bar{\tau}$ is the mean annual AOD and$\tau_i$is mean AOD of the month i.

In the present study, SI was estimated using MODIS for 19 years (2001-2019) of AOD data. Here in the study $\bar{\tau}$&τ_i are mean annual AOD & mean monthly AOD data averaged over 19. According to NASA Earth Observation 2021, an AOD of 0.1 indicates a clear sky with maximum visibility, and an AOD value of 1 indicates hazy conditions, so our mean monthly AOD was adjusted (the base value of 0.1 is subtracted from mean monthly AOD values). The classification of the AOD regime based on SI values is shown in the table follows.

Table 1: Classification of AOD regimes based on SI values (Walsh & Lawler, 1981)

AOD regime	Seasonality Index (SI)
Very equable	≤0.19
Equable with a definite pollution episode	0.20-0.39
Rather seasonal with short clear condition	0.40-0.59
Seasonal	0.60-0.79
Markedly seasonal with a long clear condition	0.80-0.99
Most aerosols in 3 months or less	1.00-1.19
Extreme, almost all aerosols in 1-2 months	≥1.20

2.5. TRAJECTORY FREQUENCY ANALYSIS

The HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is one of the popularly used models which is useful to calculate trajectories of air parcels, dispersion, transport, transformation, and deposition of pollutants using previously gridded meteorological data. It consists of a modular library structure with main programs for each primary application: trajectories and air concentrations (Draxler et al., 2014). Here the trajectory frequency analysis was done in the HYSPLIT model using the NCEP reanalysis data. The aerosol loading over the State is particularly heavier during certain months. Hence, the model is used to analyse the highest AOD recorded month and lowest AOD recorded month of Kozhikode and Thiruvananthapuram at altitudes of 100 meters and 1500 meters. Two- day trajectory analysis is done to estimate the trajectory frequency over the two districts and the direction of air mass that mainly causes aerosol loading over the region.

2.6. AUTOREGRESSIVE INTEGRATED MOVING AVERAGE (ARIMA)

The ARIMA method is an iterative and exploratory process intended to best fit long-term observations by using three steps—identification, estimation, and diagnostic checking—to build an adequate model for a time series. The Seasonal-ARIMA (SARIMA) model extends the ARIMA model by taking seasonality into account. Such models are expressed as $(p, d, q) \times (P, D, Q)_m$. where (p, d, q) are as for an ARIMA model, while $(P, D, Q)_m$ express the seasonal autoregressive, integration and moving average components where the seasonality period is m. Here SARIMA model is used. The model aims to simulate the AOD variation and predict future trends over the study area. The AOD data until 2019 is considered due to COVID-19 lockdowns during 2020 and 2021 which caused an overall variation in the trend of AOD.

3. RESULTS AND DISCUSSION

3.1. SPATIAL DISTRIBUTION OF AOD

From the spatial distribution, we can understand the long-term mean aerosol loading over each district during the 19 years period. The district-wise long-term mean of AOD during the study period (2001-2019) over Kerala is illustrated in Fig (2). It shows that among the districts Kannur, and Kozhikode districts had greater AOD in the range of 0.40 to 0.44, followed by Kasaragod, Alappuzha, and Kottayam, which ranges between 0.38 and 0.4. Districts including Thrissur, Ernakulam, and Pathanamthitta had AOD ranging from 0.36 to 0.38. The remaining districts including Wayanad, Malappuram, Palakkad, Idukki, Kollam, and Thiruvananthapuram had AOD in the range between 0.34 and 0.36.

Thereby understanding the spatial distribution of AOD, it is noticed that all districts had a considerable long-term mean AOD greater than 0.34. Thus it is evident that a considerable amount of aerosol loading has been occurring throughout Kerala from 2001 till 2019.

3.2. MONTHLY AEROSOL DISTRIBUTION

The monthly distribution of mean AOD over Kerala from 2001 to 2019 is shown in Fig (3). AOD data till 2019 is only considered as during 2020 and 2021, the aerosol loading had drastically changed due to the pandemic lockdown all over the state. Considering those years could show deviation from the normal trend of aerosols. From the monthly distribution analysis, the state is seen affected by aerosol loading throughout the year with a minimum monthly AOD value of 0.3 with a higher AOD during the pre-monsoon season (March-May) followed by summer monsoon season (June-September) while the least aerosol loading during the winter season. From the monthly data, statistical properties like mean, median, standard deviation, highest and lowest of the monthly, seasonal, and annual AOD is shown in Table (2).

Table 2: Mean, Median, Standard Deviation, Highest and Lowest of monthly, seasonal, and annual for the period 2001-2019

Month	Mean	Median	SD	Highest	Lowest
Jan	0.300674	0.291646	0.075439	0.537817	0.230028
Feb	0.302471	0.305738	0.066078	0.471208	0.18518
Mar	0.368138	0.376695	0.069229	0.519441	0.242671
Apr	0.443638	0.424589	0.086762	0.628653	0.303817
May	0.445477	0.45452	0.089759	0.58627	0.268801
Jun	0.386548	0.379807	0.087804	0.509894	0.211507
Jul	0.453325	0.456074	0.077483	0.590296	0.311091
Aug	0.404208	0.385726	0.055123	0.519761	0.316657
Sep	0.30196	0.306599	0.045369	0.390109	0.21779
Oct	0.372877	0.355784	0.076508	0.525517	0.252337
Nov	0.358298	0.323711	0.098337	0.596403	0.253658
Dec	0.28413	0.267025	0.082888	0.51308	0.178742
Season					
Winter	0.301573	0.301573	0.001271	0.302471	0.300674
Pre-monsoon	0.419084	0.443638	0.04413	0.445477	0.368138
Monsoon	0.38651	0.395378	0.063051	0.453325	0.30196
Post-monsoon	0.338435	0.358298	0.047591	0.372877	0.28413
Annual	0.368479	0.376338	0.045086	0.457108	0.300458

SI is used to find out whether the long-term MODIS-derived data used in the study has a seasonal variation or not. The calculated value of SI based on the long-term period (2001-2019) is 0.13 which

belongs to the "very equable" AOD regime based on Table (1). A very equable AOD regime indicates that every month has a considerable amount of aerosol loading throughout the year.

3.3. CLASSIFICATION OF KERALA DISTRICTS IN TERMS OF AEROSOL POLLUTION VULNERABILITY

Classification of Kerala districts in terms of aerosol pollution based vulnerability has been done based on the study by Monami et al., (2022) which aimed at understanding the aerosol pollution over Indian states. The classification of the states in terms of aerosol pollution vulnerability was done using the long-term mean value percentile of AOD. Based on these percentiles, they defined four different zones to indicate the level of vulnerability: green or safe zone (AOD value of less than 25th percentile; < 0.3), blue or less vulnerable zone (AOD value between 25th and 50th percentile; 0.3–0.4), orange or vulnerable zone (AOD value between 50th and 75th percentile; 0.4–0.5) and red or highly vulnerable zone (AOD value greater than 75th percentile; > 0.5). These zones are shown in Table (3).

Table 3: Vulnerability zones defined according to mean value percentiles

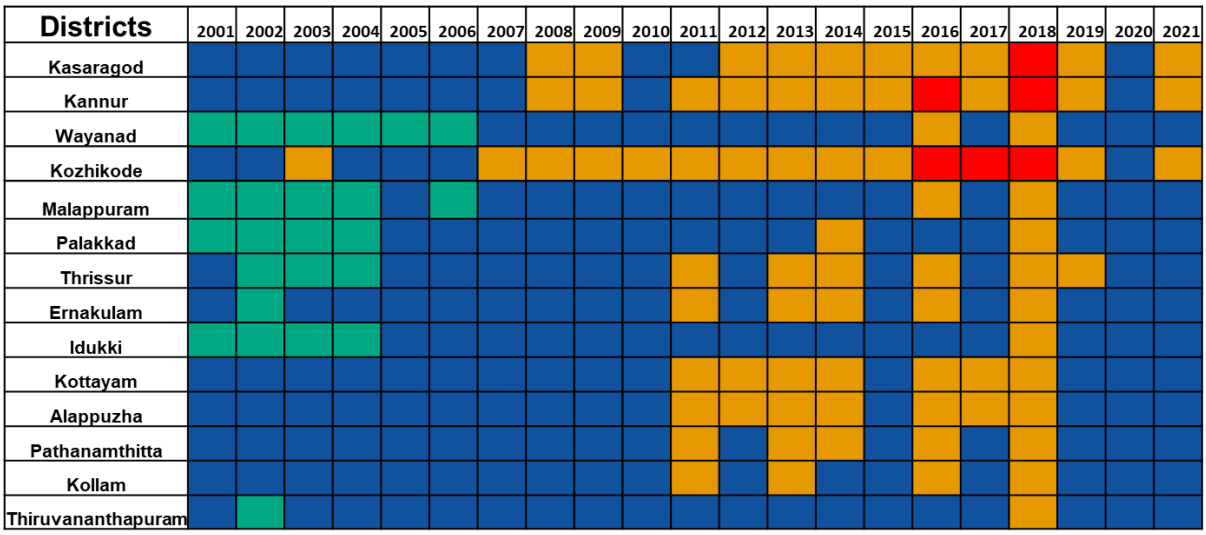
Colour	Safety Level	AOD
Green	SAFE	< 0.3
Blue	Less Vulnerable	0.3 - 0.4
Orange	Vulnerable	0.4 - 0.5
Red	Highly Vulnerable	>0.5

Annual maps based on vulnerability zones throughout the study period are shown in Fig (4). It is noted that during the initial study period, safe and less vulnerable zones prevailed but since 2007, no district is in the safe zone. The less vulnerable districts have been polluted into vulnerable zones. The vulnerability maps of 2020 and 2021 depict less vulnerability altogether because of pandemic lockdown restrictions all over the state. All the districts depict a dip in aerosol loading during this period.

It is evident that Kozhikode is the most aerosol-affected district in Kerala based on their annual mean AOD throughout the study period. In the case of vulnerability, Kozhikode was the first district in Kerala to turn into a vulnerable zone in 2003 and the polluted scenario has continued thereafter. From 2007 onwards, Kozhikode didn't fall short of the vulnerable zone until the district turned into a highly vulnerable zone from 2016 to 2018. Kozhikode even attained a less vulnerable level in 2020 but became vulnerable just the year after. Kozhikode is followed by Kannur and Kasaragod for its high aerosol concentrations. In 2008, both districts turned into vulnerable zones. In 2016, Kozhikode and

Kannur attained a highly vulnerable zone. In 2018 Kasaragod, Kannur, and Kozhikode together turned into a highly vulnerable zone along with all other districts that turned into vulnerable zones. Other districts that had worsened air conditions were Thrissur, Ernakulam, Kottayam, Alappuzha, and Kollam which started becoming vulnerable in 2011. Thiruvananthapuram, Idukki, Wayanad, Malappuram, and Palakkad are seen to be the districts with the least AOD value. 2018 was the most aerosol-affected year of Kerala. All the districts were in the vulnerable zone (AOD> 0.4) with Kasaragod, Kannur, and Kozhikode in the highly vulnerable zone (AOD>0.5). That was the year when the massive flood occurred in Kerala. The representation of districts according to their AOD vulnerability zones is shown in Table (4).

Table 4: A graphical representation of district-wise aerosol vulnerability during the period 2001-2021



We have further divided our study period into four sections: 2001-2005, 2006-2010, 2011-2015, and 2016-2019 to compare the mean aerosol loading over Kerala during the four periods. Fig (5) depicts district-wise AOD variation through the periods considered. Here vulnerability classification based on AOD during the pandemic lockdown period 2020-2021 Is also discussed.

3.3.1. 2001 - 2005

In this period, districts including Wayanad, Malappuram, Palakkad, and Idukki were safe zones (AOD <0.3). The remaining districts were less vulnerable zones (0.3< AOD <0.4).

3.3.2. 2006 - 2010

During this period, all the districts were found to be less vulnerable zones.

3.3.3. 2011 - 2015

Districts including Kasaragod, Kannur, Kozhikode, Thrissur, Ernakulam, Alappuzha, and Kottayam had turned into vulnerable zones (04< AOD <0.5). While the remaining districts continued as less vulnerable zones.

3.3.4. 2016 – 2019

Kasaragod had turned into a highly vulnerable zone (AOD > 0.5), and districts including Kasaragod, Kannur, Thrissur, Palakkad, Ernakulam, Kottayam, Alappuzha, and Pathanamthitta were vulnerable zones. While the remaining districts stayed as less vulnerable zones.

3.3.5. 2020 - 2021

Classification of the districts during 2020-2021 is discussed below indicating the variation in mean AOD due to the pandemic lockdown situation in Kerala. During 2020, the state government imposed a complete lockdown starting from March and nearly all services and factories were suspended. Strict actions were taken for violating norms of lockdown such as venturing out for no emergency, opening businesses, and also home quarantine violations. Gradually citizens showed solidarity with the lockdown rules, which led to reduction in anthropogenic pollution sources such as vehicular emissions, industrial emissions, etc. During 2020, all the districts had turned into less vulnerable zones (Fig 6.a) prior to the worsening conditions in previous years. During 2021, when the partial lockdown was imposed with necessary restrictions all districts remained as less vulnerable zones except Kasaragod, Kannur, and Kozhikode which turned into vulnerable zones (Fig 6.b).

3.4. FREQUENCY DISTRIBUTION

Frequency distribution analysis is done to compare the variation in AOD frequency for each district and the results are shown in Fig (7) for the past years 2001-2005 period and recent years 2015-2019. All the districts have seen an increase in the frequency of AOD above 0.4 from past years to recent years indicating their steady rise in vulnerability level. It is seen that Kozhikode followed by Kannur and Kasaragod peaks in vulnerability level. Malappuram district which never went above the 0.4 AOD range in 2001-2005 can be seen with a rise in the 2015-2019 period and districts including Wayanad, and Palakkad having less AOD value during past years have shown a rise in vulnerability range in recent years. District-wise AOD frequency distribution for all 14 districts of Kerala is discussed below.

3.4.1. KASARAGOD

In the case of Kasaragod, considering the variation in recent years, AOD in the range of 0.1-0.2 with a frequency distribution of 10.2%, diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 32.2% got reduced to 16.9%. AOD in the range of 0.3-0.4 with a frequency of 33.9% got reduced to 22%. While AOD > 0.4 has seen a rise in frequency from 23.7% to 61%.

3.4.2. KANNUR

In the case of Kannur, AOD in the range of 0.1-0.2 with a frequency distribution of 5.1% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 22% got reduced to 5%. AOD in the range of 0.3-0.4 with a frequency of 37.3% decreased to 25%, and AOD > 0.4 has seen a rise in frequency from 35.6% to 70%.

3.4.3. WAYANAD

In the case of Wayanad, AOD in the range of 0.1-0.2 with a frequency distribution of 10.2% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 50.8% got reduced to 25%. AOD in the range of 0.3-0.4 with a frequency of 37.3% decreased to 31.7% and AOD > 0.4 has seen a rise in frequency from 1.7% to 43.3%.

3.4.4. KOZHIKODE

In the case of Kozhikode, AOD in the range of 0.2-0.3 with a frequency of 16.9% got reduced to 5%. AOD in the range of 0.3-0.4 with a frequency of 35.6% increased to 18.3% and AOD > 0.4 has seen a rise in frequency from 47.5% to 76.7%.

3.4.5. MALAPPURAM

In the case of Malappuram, AOD in the range of 0.1-0.2 with a frequency distribution of 8.5% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 49.2% got reduced to 25%. AOD in the range of 0.3-0.4 with a frequency of 42.4% decreased to 31.7%. While AOD > 0.4 which was nil during 2001-2005 had seen a rise in frequency to 43.3% in recent years.

3.4.6. PALAKKAD

In the case of Palakkad, AOD in the range of 0.1-0.2 with a frequency distribution of 6.8%diminished to 1.7%. AOD in the range of 0.2-0.3 with a frequency of 45.8% got reduced to 21.7%. AOD in the range of 0.3-0.4 with a frequency of 45.8% got reduced to 26.7%. While AOD > 0.4 has seen a rise in frequency from 1.7% to 50%.

3.4.7. THRISSUR

In the case of Thrissur, AOD in the range of 0.1-0.2 with a frequency distribution of 3.4% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 44.1% got reduced to 16.7%. AOD in the range of 0.3-0.4 with a frequency of 45.8% got reduced to 30%. While AOD > 0.4 has seen a rise in frequency from 6.8% to 53.3%.

3.4.8. ERNAKULAM

In the case of Ernakulam, AOD in the range of 0.1-0.2 with a frequency distribution of 5% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 36.7% got reduced to 13.3%. AOD in the range of 0.3-0.4 with a frequency of 45% got reduced to 30%. While AOD > 0.4 has seen a rise in frequency from 13.3% to 56.7%.

3.4.9. IDUKKI

In the case of Idukki, AOD in the range of 0.1-0.2 with a frequency distribution of 10% diminished to nil percentage. AOD in the range of 0.2-0.3 with a frequency of 38.3% got reduced to 25%. AOD in the range of 0.3-0.4 with a frequency of 45% got reduced to 43.3%. While AOD > 0.4 has seen a rise in frequency from 6.7% to 31.7%.

3.4.10. KOTTAYAM

In the case of Kottayam, AOD in the range of 0.1-0.2 with a frequency distribution of 5.1% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 32.2% got reduced to 11.7%. AOD in the range of 0.3-0.4 with a frequency of 33.9% increased to 33.3%. While AOD > 0.4 has seen a rise in frequency from 28.8% to 55%.

3.4.11. ALAPPUZHA

In the case of Alappuzha, AOD in the range of 0.1-0.2 with a frequency distribution of 5.1% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 32.2% got reduced to 11.7%. AOD in the range of 0.3-0.4 with a frequency of 33.9% increased to 33.3%. While AOD > 0.4 has seen a rise in frequency from 28.8% to 55%.

3.4.12. PATHANAMTHITTA

In the case of Pathanamthitta, AOD in the range of 0.1-0.2 with a frequency distribution of 6.7% diminished to 1.7%. AOD in the range of 0.2-0.3 with a frequency of 30% got reduced to 15%. AOD in the range of 0.3-0.4 with a frequency of 45% remained as such in recent years too. While AOD > 0.4 has seen a rise in frequency from 18.3% to 38.3%.

3.4.13. KOLLAM

In the case of Kollam, AOD in the range of 0.1-0.2 with a frequency distribution of 5% diminished to a 1.7%nil percentage. AOD in the range of 0.2-0.3 with a frequency of 30% got reduced to 15%. AOD in the range of 0.3-0.4 with a frequency of 51.7% got reduced to 45%. While AOD > 0.4 has seen a rise in frequency from 13.3% to 38.3%.

3.4.14. THIRUVANANTHAPURAM

In the case of Thiruvananthapuram, AOD in the range of 0.1-0.2 with a frequency distribution of 5% diminished to 1.7%. AOD in the range of 0.2-0.3 with a frequency of 33.3% got reduced to 21.7%. AOD in the range of 0.3-0.4 with a frequency of 51.7% got reduced to 46.7%. While AOD > 0.4 has seen a rise in frequency from 10% to 30%.

Considering Kerala as a whole, AOD in the range of 0.1-0.2 with a frequency distribution of 5% diminished to a nil percentage. AOD in the range of 0.2-0.3 with a frequency of 31.7% got reduced to 13.3%. AOD in the range of 0.3-0.4 with a frequency of 50% got reduced to 33.3%. While AOD > 0.4 has seen a rise in frequency from 13.3% to 53.3%. Thus, the current scenario of Kerala and its districts are experiencing a steady increase in AOD.

3.5. TRENDS IN AOD

Spatial AOD averages were calculated for each month, which enables to study temporal changes over the region. Time series graphs are plotted for Kerala and each district using each monthly AOD during the time period of 2001-2019. Time series graphs are shown in Fig (8) for Kerala and every district. Time series analysis helps in understanding the temporal distribution of AOD over the region. Here, each district's long-term temporal distribution is closely observed, and to ensure the trend, trend analysis is done. The result of the trend analysis done using Mann-Kendall and Sen's slope estimator is shown in Table (5).

From the time series graphs, we can observe an increasing variation in all districts along with the trend line. According to the trend analysis, it is observed that all districts in Kerala are having an increasing trend with *99% significance except Trivandrum showing **95% significance. The slope per year is also given in the table above. Kannur had the highest slope of 0.00071 indicating the highest aerosol loading and the rest of the slopes per year for each district are Kasaragod (0.00067), Wayanad (0.000555), Kozhikode (0.000675), Malappuram (0.000582), Palakkad (0.00065), Thrissur (0.00069), Ernakulam (0.000636), Idukki (0.000448), Kottayam (0.000544), Alappuzha (0.000544), Pathanamthitta (0.000447), Kollam (0.000412) whereas the lowest slope is for Thiruvananthapuram

with 0.00034 indicating lowest aerosol loading. Considering Kerala, the state shows an increasing trend with a significance of 99% and a slope of 0.000577.

Table 5: Mann-Kendall and Sen's Slope Result

Sl. no.	District	Trend	Slope/Year
1	Kasaragod	Increasing*	0.00067
2	Kannur	Increasing*	0.00071
3	Wayanad	Increasing*	0.000555
4	Kozhikode	Increasing*	0.000675
5	Malappuram	Increasing*	0.000582
6	Palakkad	Increasing*	0.00065
7	Thrissur	Increasing*	0.00069
8	Ernakulam	Increasing*	0.000636
9	Idukki	Increasing*	0.000448
10	Kottayam	Increasing*	0.000544
11	Alappuzha	Increasing*	0.000544
12	Pathanamthitta	Increasing*	0.000447
13	Kollam	Increasing*	0.000412
14	Thiruvananthapuram	Increasing**	0.00034
	Kerala	**Increasing***	**0.000577**

3.6. SARIMA FORECAST

The time series of AOD was fitted using a SARIMA model to forecast future aerosol loading over the State. The AOD data from 2001 to 2015 was used to fit the SARIMA model and AOD values for the next four years were predicted. The predicted time-series with 95% confidence is shown in Fig. 9. The results indicate that the model estimates an increasing trend in AOD. The model also captured most of the peaks during 2016 to 2019. As the model showed a fairly good ability in estimating the time-series, the model was fitted for the period of 2001 – 2019, and AOD values for the next 4 years were predicted. An increase in AOD is expected in the future according to the SARIMA forecast which is consistent with the current trend in AOD. An increase in AOD in the future indicates an increase in vulnerability level.

3.7. TRAJECTORY FREQUENCY ANALYSIS

The aerosol loading over the state is relatively heavier during certain months, and the wind trajectory analysis reveals the possible sources of observed monthly aerosol variations. Thus, trajectory frequency analysis on the highest aerosol loading district (Kozhikode), and the lowest aerosol loading district (Thiruvananthapuram) are considered. Air parcel flow patterns from the HYSPLIT model are used to identify aerosols' origin. From the 2-day back–trajectory frequency plot by the HYSPLIT model, the air parcel flow patterns are illustrated for the months were the highest AOD and the lowest AOD is observed for both districts at 1500 m and 100 m altitude. It is noticed that AOD

concentration over Kozhikode is higher during the month of July, while the lowest AOD concentration during December. AOD concentration over Thiruvananthapuram is higher during the month of May and lowest during February. Kozhikode trajectory frequency at 1500m (Fig 10.a, b) and 100m (Fig 10. c, d) is shown for months July and December respectively, likewise for Thiruvananthapuram Fig 11(a, b) for the month of May and Fig 11(c, d) for the month February at both altitudes.

Analysing the trajectory frequency, in Kozhikode during the month of July when aerosol concentration is higher, the wind trajectories are found drawn from the west towards the district at 1500 and 100 meters. While during the month of December when the AOD concentration is at the lowest, air masses are drawn from the east at both altitudes to the district. From this, we can understand the direction from which the most probable sources are carried to Kozhikode during the months when aerosol loading is heavier as well as weaker. In Thiruvananthapuram, during the month of May when the AOD concentration is higher, the wind trajectories indicate that air masses are drawn from the west direction to the district whereas, during February when AOD concentration is at the lowest the air masses are seen drawn from the east at both altitudes. Thus it can be generally told that air masses from the west influence both districts when aerosol loading is heavier and air masses from the east influence the districts when the loading is weak.

The Trajectory frequency analysis for both Thiruvananthapuram and Kozhikode are similar to each other in the case of air masses influencing the aerosol loading at both altitudes. Thus, our output from the HYSPLIT model enables us to understand the two-day trajectory frequency and spot the direction of the probable sources of aerosols influencing the respective district. Further studies are required to find the exact source of the aerosol loading which is out of scope in this study.

4. CONCLUSION

The 19 years (2001-2019) long-term study reveals the status of aerosol loading over the districts of Kerala. The spatial analysis indicates that Kannur and Kozhikode districts have greater AOD (0.4-0.44), followed by Kasaragod, Alappuzha, and Kottayam (0.38-0.4). The districts including Pathanamthitta, Ernakulam, and Thrissur have a considerable amount of AOD (0.36-0.38) followed by districts in the range of 0.34-0.36 AOD value which included Thiruvananthapuram, Kollam, Idukki, Palakkad, Malappuram, and Idukki. Comparing the vulnerability variation during the past periods (2001-2005, 2006-2010, 2011-2015), and the recent period (2016-2019) it was observed that Kozhikode had become highly vulnerable (AOD>0.5). Districts including Kasaragod, Kannur, Thrissur, Palakkad, Ernakulam, Kottayam, Alappuzha, and Pathanamthitta were exposed to worsening air indicating vulnerable condition (AOD>0.4). Thiruvananthapuram, Kollam, Idukki, Wayanad, and Malappuram were in the less vulnerable (AOD>0.3) zone. The variation in recent decades also shows

that no district is safe from aerosol loading. Moreover, the frequency distribution analysis shows an alarming situation, where the frequency of aerosol-pollution-episodes (AOD > 0.4) in Kerala has increased from 13.3 % (2001-2005) to 53.3% (2016-2019). The trend analysis confirms that AOD over every district is expected to increase in the future. Considering the slope, Kannur had the highest slope of 0.00071 indicating the highest aerosol loading per year while Thiruvananthapuram with 0.00034 indicated the lowest aerosol loading per year. An increase in AOD is expected in the future according to the SARIMA forecast which is consistent with the current trend in AOD. The most aerosol-affected year of Kerala was 2018 when Kozhikode, Kannur, and, Kasaragod districts became highly vulnerable and, all other districts were vulnerable zones. The aerosol concentration in 2018 must have been a factor in that year's flood occurrence in Kerala. It was stated by Jasmine et al., (2022) that aerosols had an effect on the flood occurrence in Kerala in 2018. Air mass from the west is seen drawn during the months of July and May towards Kozhikode and Thiruvananthapuram respectively when there was heavy aerosol loading while air mass from the east is seen drawn during December and February towards Kozhikode and Thiruvananthapuram respectively when aerosol loading was weak.

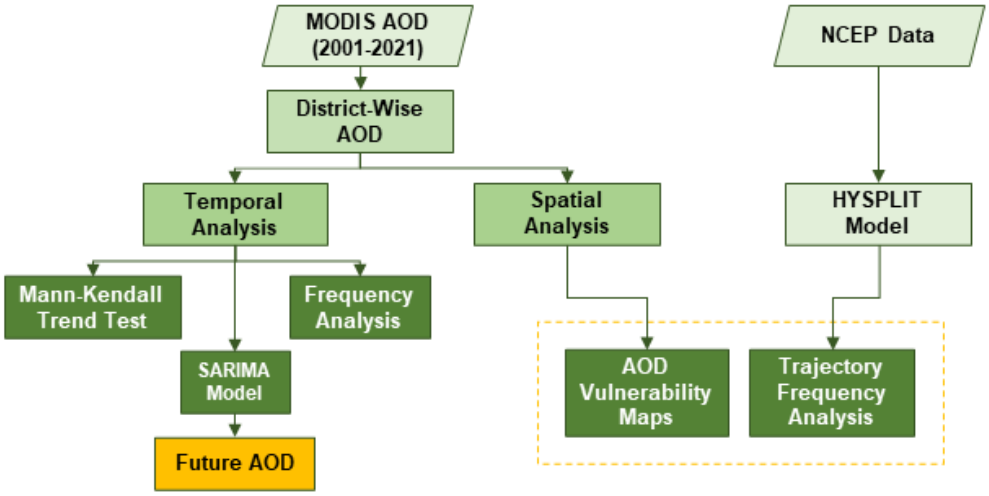


Figure 1: Flow chart of the methodology

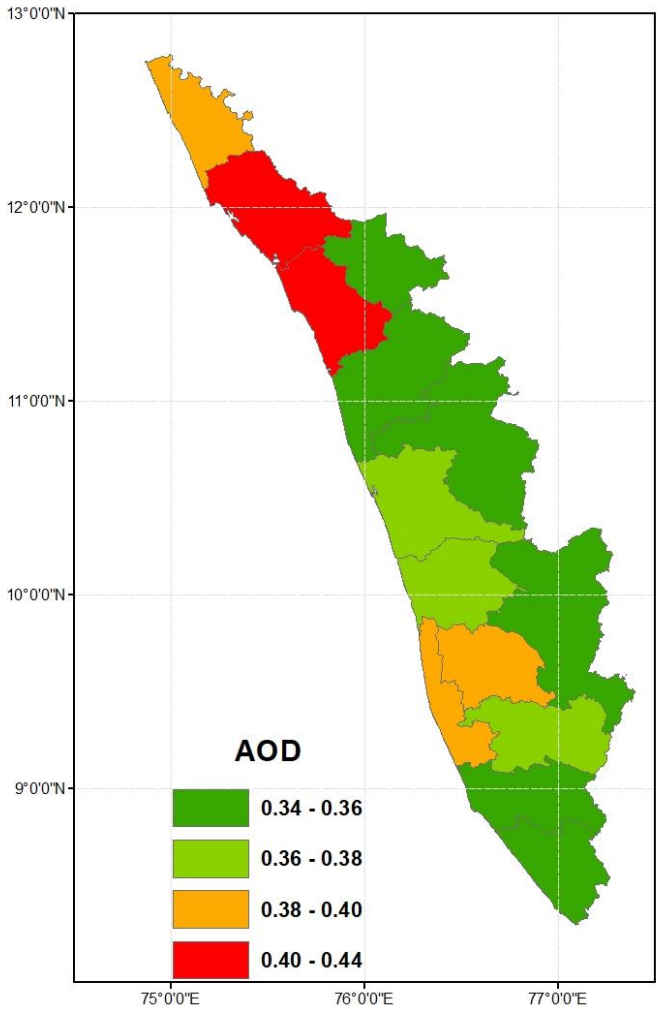


Figure 2: Spatial Distribution of mean AOD over Kerala during 2001-2019

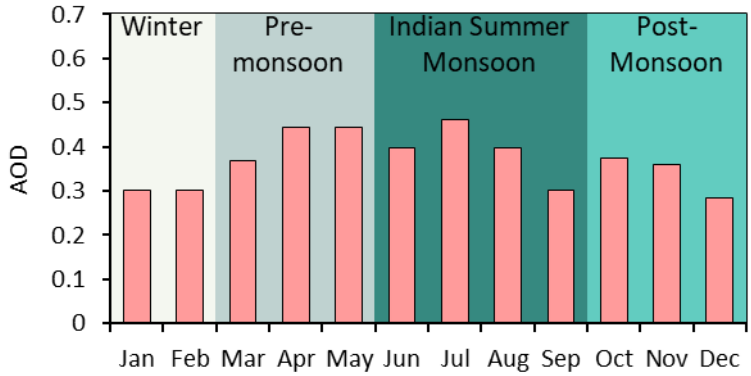


Figure 3: Monthly distribution of AOD over Kerala (2001-2019)

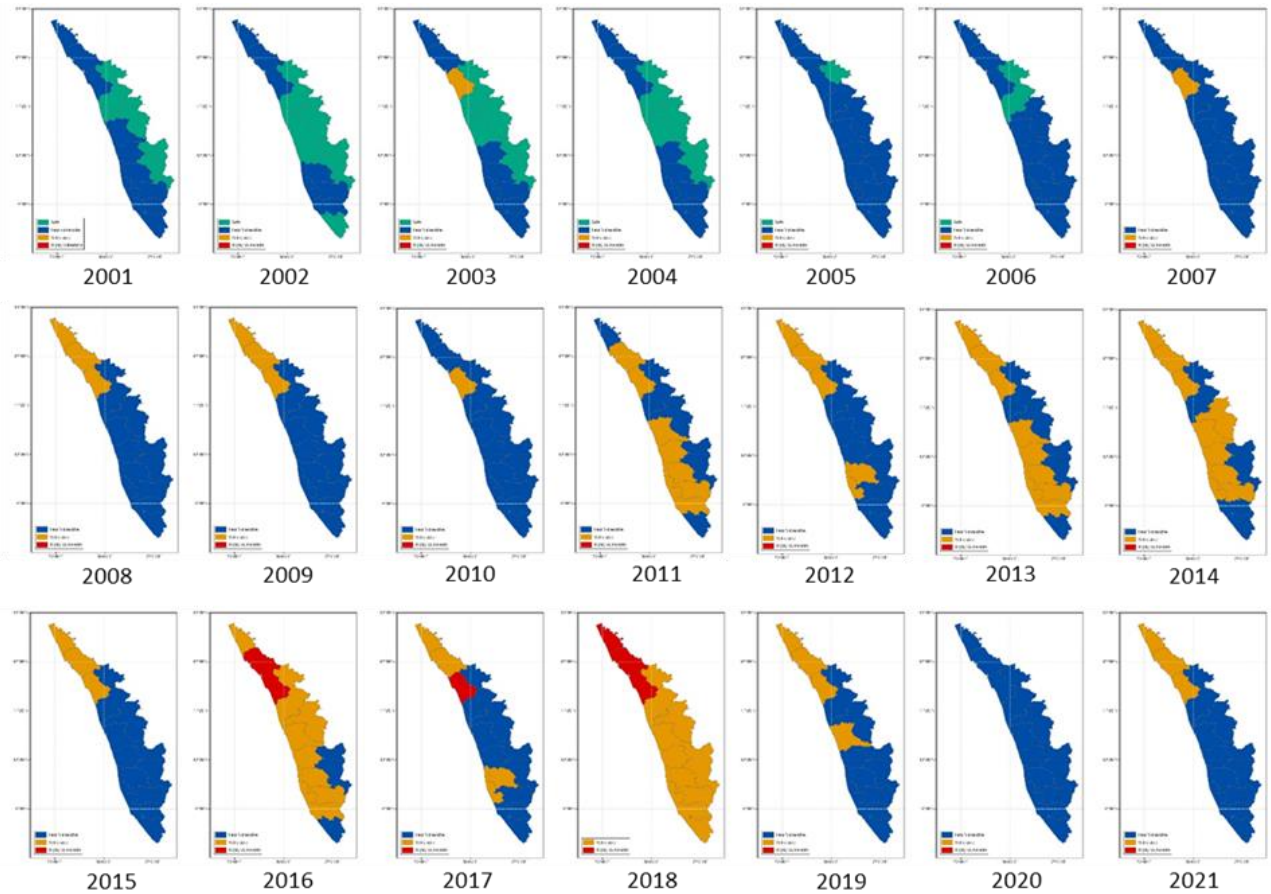


Figure 4: Classification of districts into zones in context to vulnerability level during the period 2001-2021

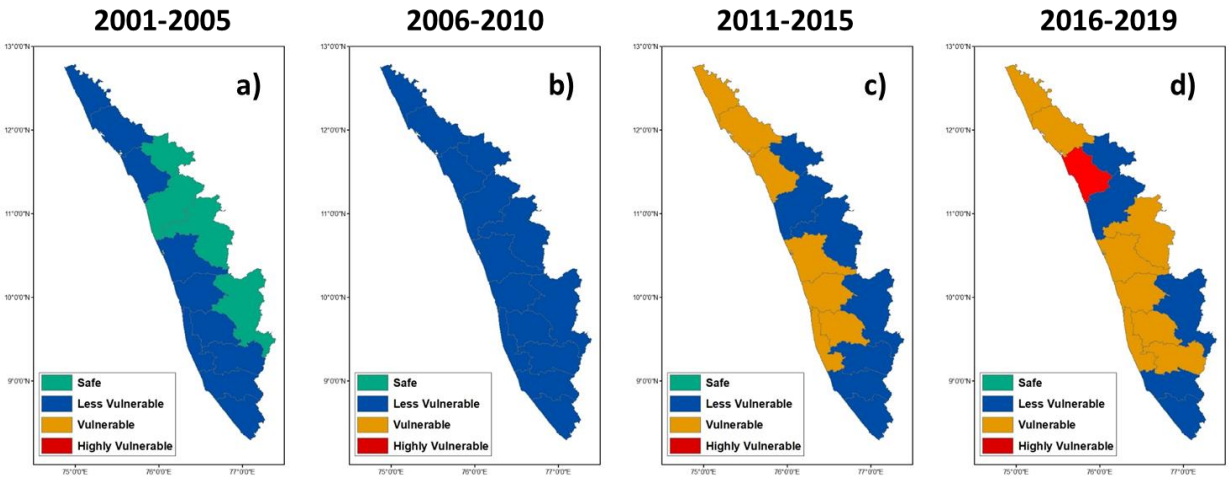


Figure 5: Variation in Vulnerability level during a) 2001-2005, b) 2006-2010, c) 2011-2015, and d) 2016-2019.

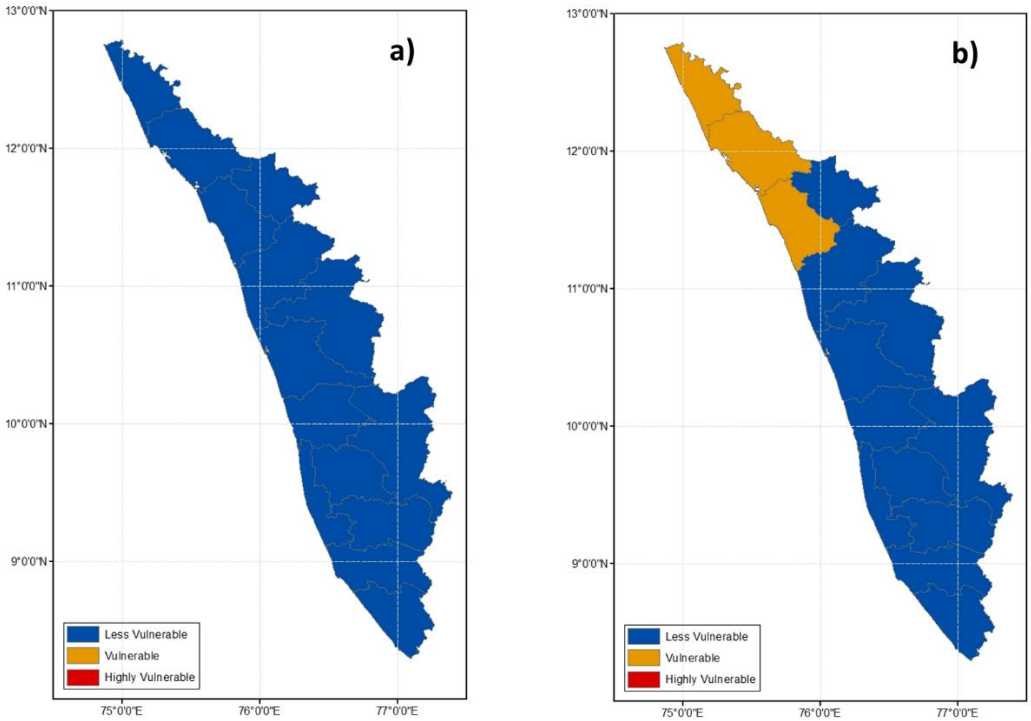


Figure 6: Vulnerability level of Kerala during the pandemic lockdown period a) 2020 and b) 2021

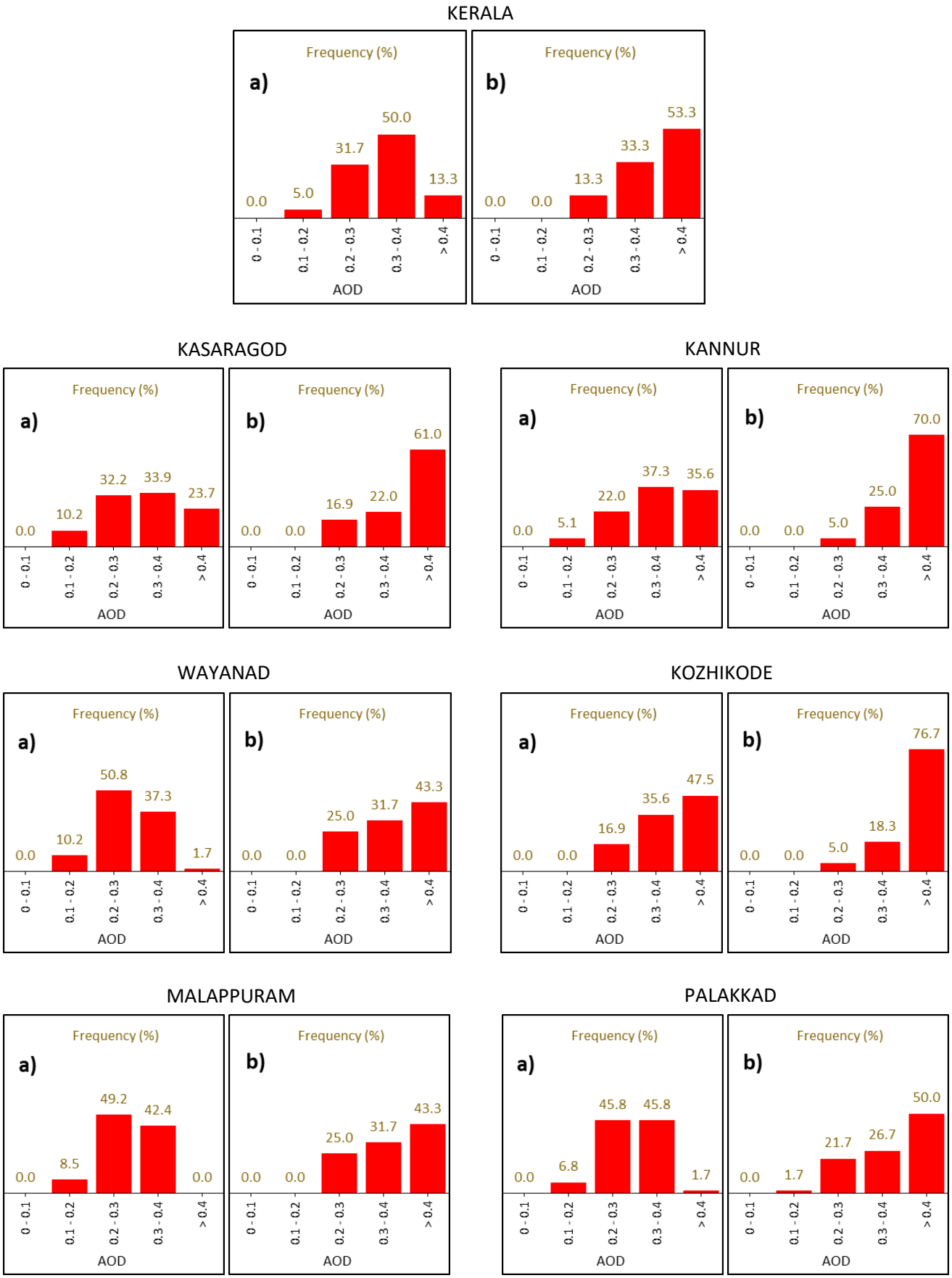


Figure 7: Variation in Frequency Distribution (%) of AOD during (a) 2001-2005, and (b) 2015-2019.

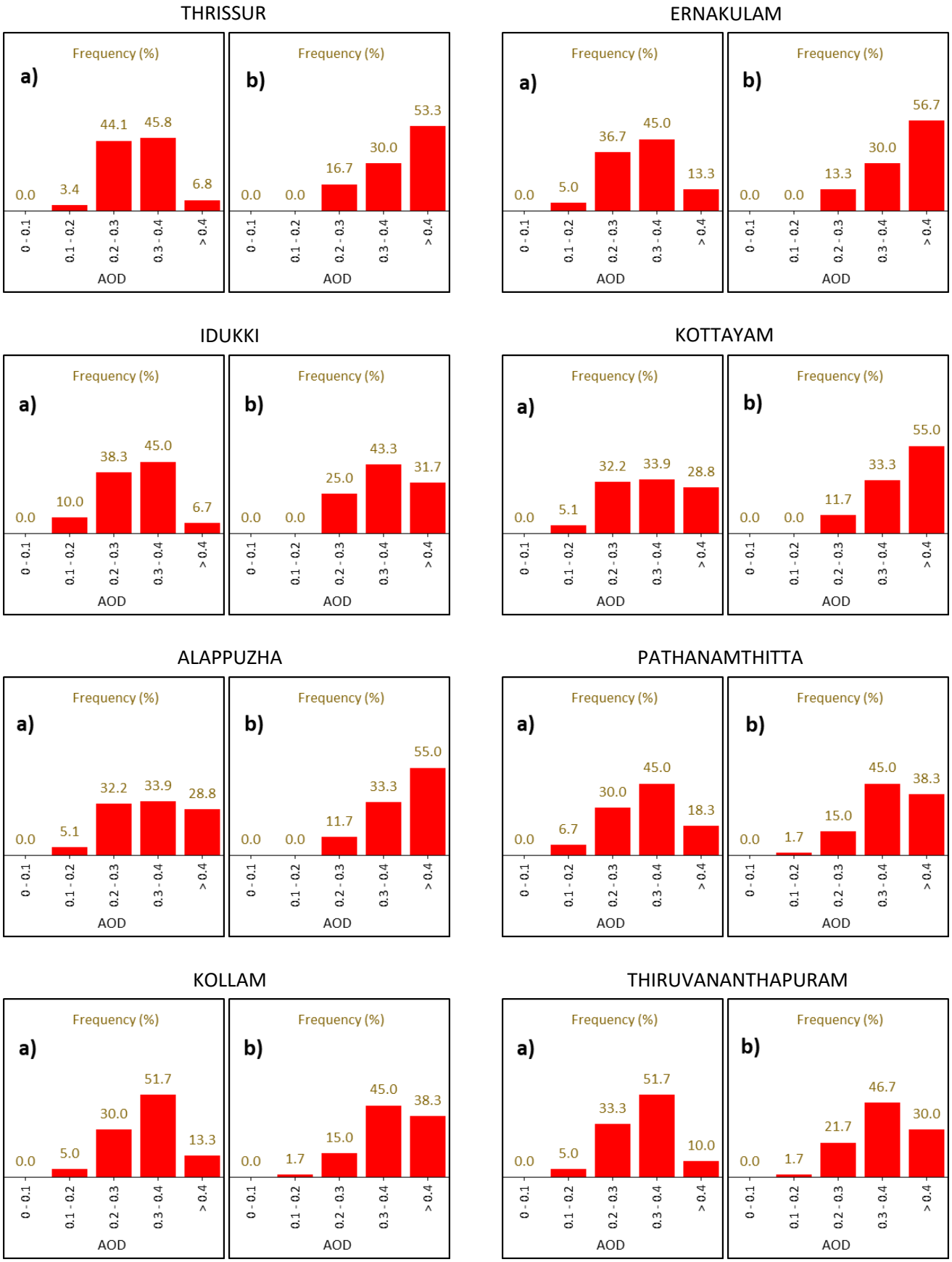


Figure 7 (Continued): Variation in Frequency Distribution (%) of AOD during (a) 2001-2005, and (b) 2015-2019.

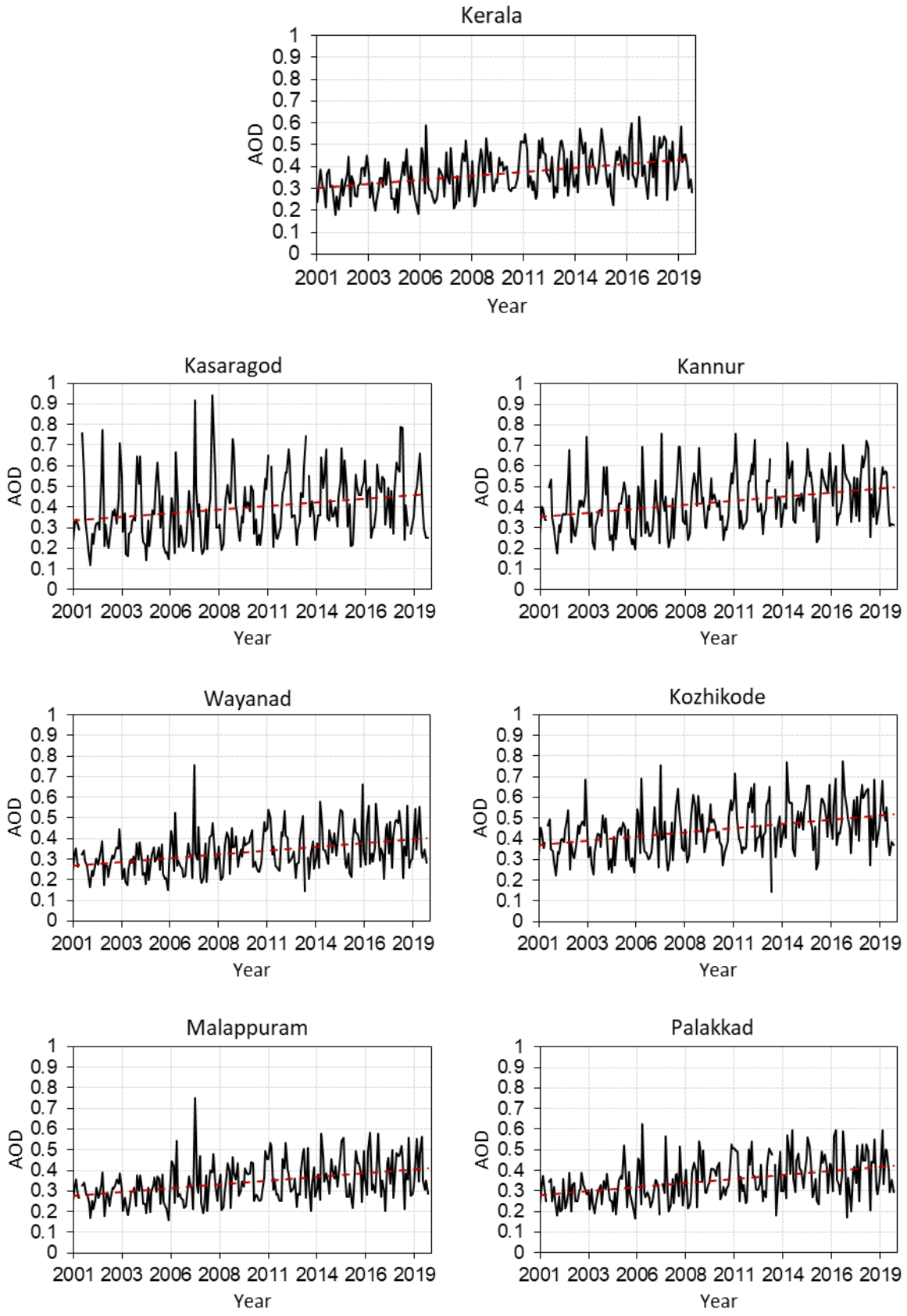


Figure 8: Time Series of AOD over Kerala districts.

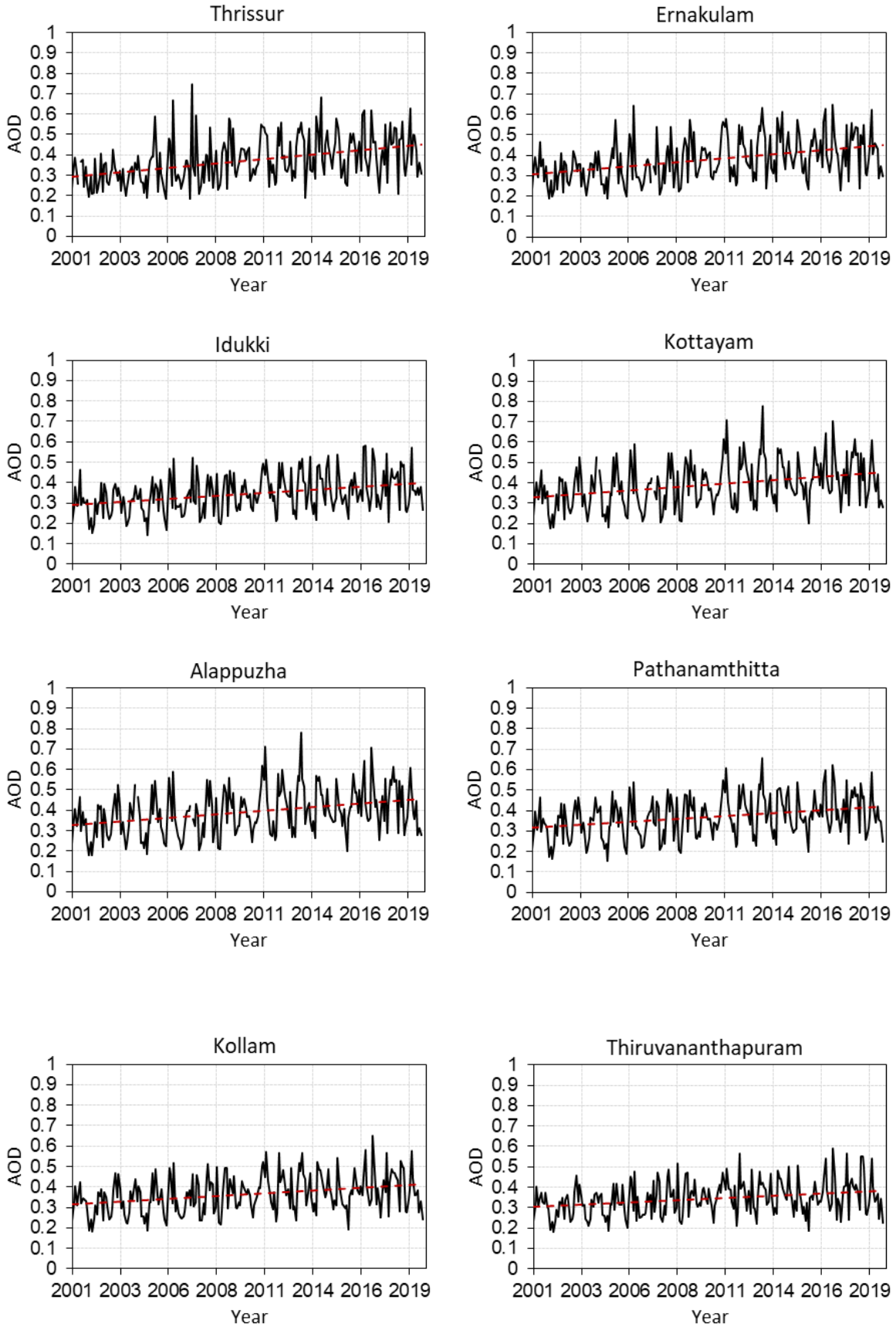


Figure 8(Continued): Time Series of AOD over Kerala districts.

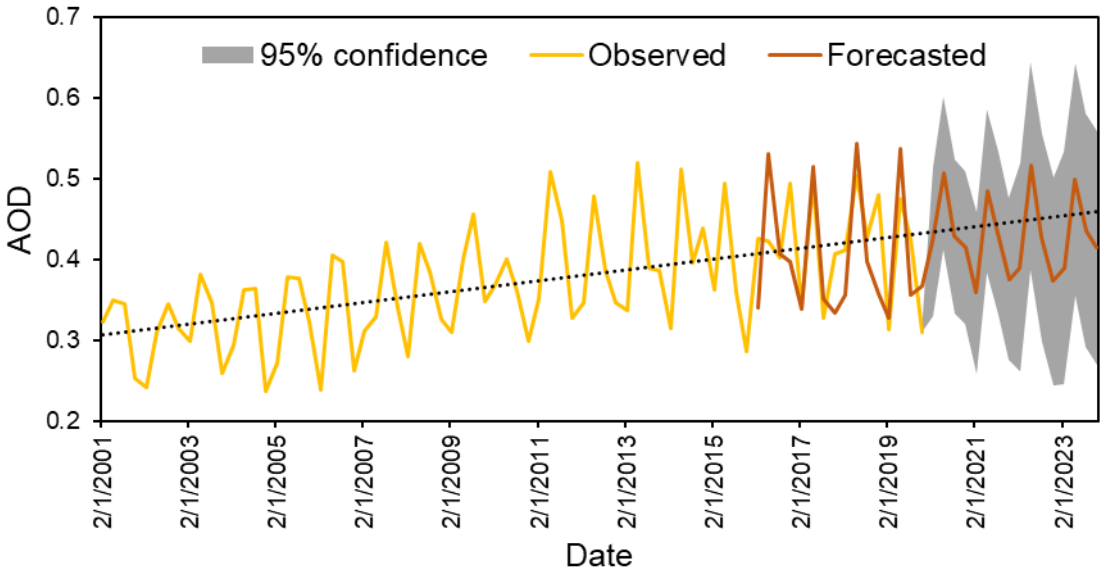


Figure 9: SARIMA forecast until 2023

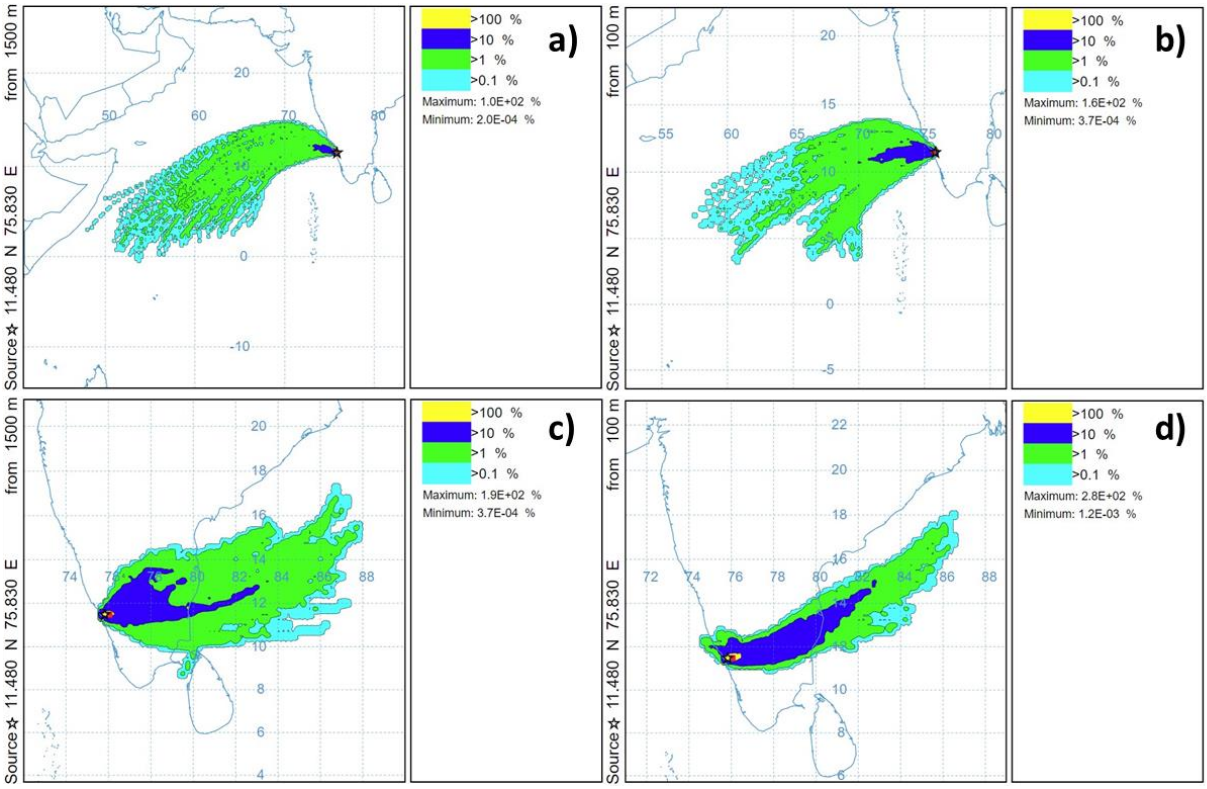


Figure 10: Trajectory Frequency of Kozhikode at 1500m and 100m altitude during July (a, b) and December (c, d)

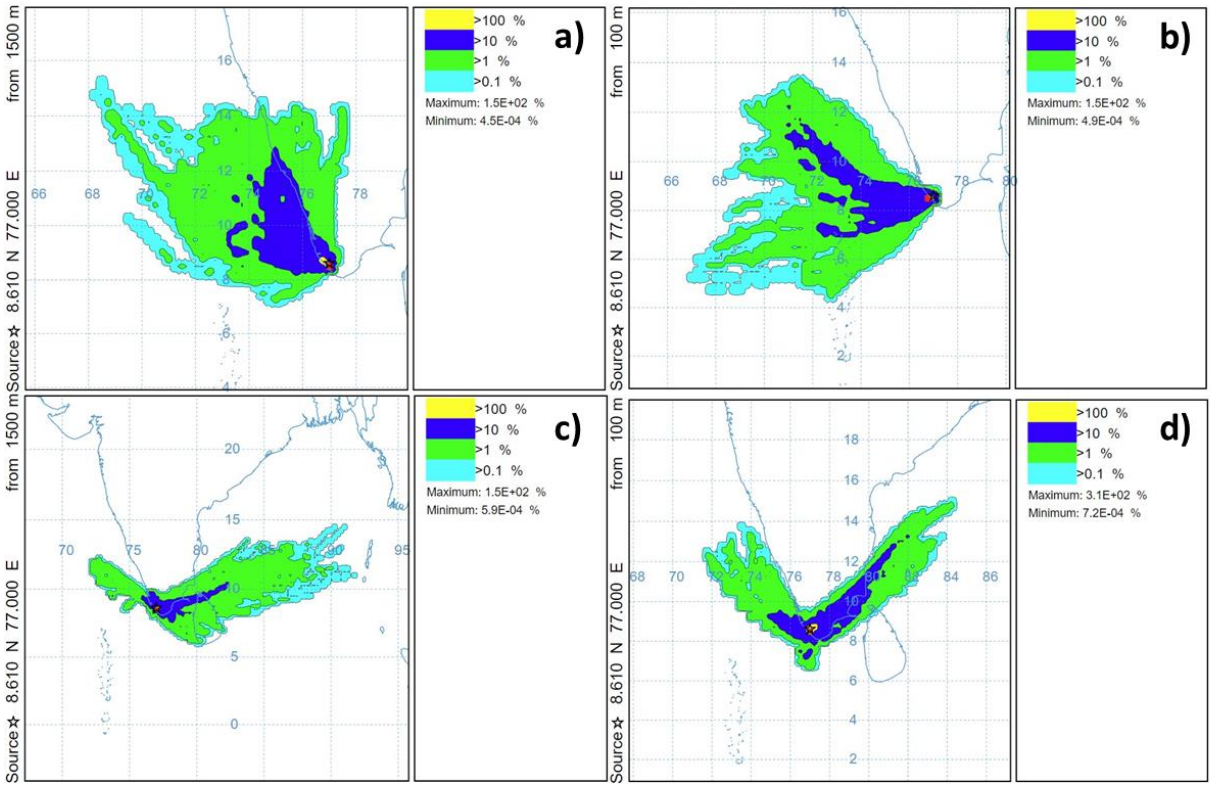


Figure 11: Trajectory Frequency of Thiruvananthapuram at 1500m and 100m altitude during May (a, b), and February (c, d)

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