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# Tridecadal aerosol impact on meteorology in the arid and humid regions of India (1991-2022)

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**सार** – यह अध्ययन भारत के दो अलग-अलग क्षेत्रों में निकट-सतह और स्तंभाकार एरोसोल में त्रि-दशकीय (1991-2022) रुझानों की जांच करता है: शुष्क क्षेत्र (गुजरात, पंजाब, हरियाणा, राजस्थान और दिल्ली को शामिल करता है) और आर्द्र पूर्वोत्तर क्षेत्र (मेघालय, असम, नागालैंड, मणिपुर, मिजोरम और त्रिपुरा सहित) इन दो क्षेत्रों में इन एरोसोल और मौसम संबंधी मापदंडों के बीच संबंध को समझने के लिए। भारतीय मानसून डेटा असिमिलेशन एंड एनालिसिस (IMDAA) और मॉडर्न-एरा रेट्रोस्पेक्टिव एनालिसिस फॉर रिसर्च एंड ऐप्लीकेशंस, संस्करण 2 (MERRA2) सहित सैटेलाइट रीएनालिसिस डेटासेट को नियोजित करके, अध्ययन ब्लैक कार्बन, सल्फेट, धूल और समुद्री नमक जैसे विविध एरोसोल प्रकारों पर विचार करते हुए एरोसोल ऑप्टिकल डेप्थ (AOD) और एंगस्ट्रॉम एक्सपोनेंट (AE) में स्थानिक और लौकिक विविधताओं का आकलन करता है मासिक भिन्नताएं एरोसोल सांद्रता में विशिष्ट पैटर्न को उजागर करती हैं, जो प्राकृतिक स्रोतों और मानवजनित गतिविधियों दोनों से प्रभावित होती हैं। हवा की गति और दिशा की जांच इस बात पर जोर देते हुए की गई कि हवा के संचलन पैटर्न एरोसोल फैलाव को कैसे स्पष्ट करते हैं, जिससे मौसमी प्रभावों पर प्रकाश डाला जाता है। एरोसोल और मौसम संबंधी विसंगतियों के बीच सहसंबंध विश्लेषण से वर्षा के साथ नकारात्मक सहसंबंध और तापमान के साथ सकारात्मक सहसंबंध का पता चलता है, जो क्रमशः एरोसोल के अप्रत्यक्ष और प्रत्यक्ष प्रभावों को दर्शाता है। दो क्षेत्रों में AOD और वर्षा की दीर्घकालिक आवधिकता का आकलन करने के लिए निरंतर वेवलेट ट्रांसफ़ॉर्म (CWT) का उपयोग किया गया था, जो वर्षा की अलग-अलग प्रचुरता के अधीन हैं। यह अध्ययन पिछले तीन दशकों में इन पर्यावरणीय सेटिंग्स और स्थानीय जलवायु में प्रचलित एरोसोल की परस्पर क्रिया के बारे में एक संक्षिप्त जानकारी प्रदान करता है, जिसमें दोनों क्षेत्रों में उल्लेखनीय अंतर है।

**ABSTRACT.** This study investigates tri-decadal (1991-2022) trends in near-surface and columnar aerosols in two distinct regions of India: the arid region (encompassing Gujarat, Punjab, Haryana, Rajasthan, and Delhi) and the humid Northeast Region (including Meghalaya, Assam, Nagaland, Manipur, Mizoram and Tripura) to comprehend the relation between these aerosols and meteorological parameters in these two regions. By employing satellite reanalysis datasets, including the Indian Monsoon Data Assimilation and Analysis (IMDAA) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA2), the study assesses spatial and temporal variations in aerosol optical depth (AOD) and Ångström Exponent (AE), considering diverse aerosol types such as black carbon, sulfate, dust, and sea salt. Results reveal distinct AOD characteristics between arid and humid regions, with differing medians and variability. Monthly variations highlight distinctive patterns in aerosol concentrations, influenced by both natural sources and anthropogenic activities. Wind speed and direction was investigated with emphasis on how wind circulation patterns elucidate aerosol dispersion, highlighting seasonal influences. Correlation analyses between aerosols and meteorological anomalies reveal negative correlations with precipitation and positive correlations with temperature, indicating aerosol indirect and direct effects, respectively. Continuous Wavelet Transform (CWT) was utilized to assess long-term periodicities of AOD and precipitation over the two regions which are subjected to distinct abundance of rainfall. This study offers a brief insight into the interaction of prevailing aerosols in these environmental settings and the local climate over past three decades with notable distinctions over the two regions.

**Key words** – Aerosol, Climate, Arid, Humid, AOD.

## 1. Introduction

Aerosols, defined as tiny solid or liquid particles suspended in the atmosphere, have various natural and anthropogenic sources (Calvo *et al.*, 2013; Duarte & Duarte, 2020). They can affect the climate system by scattering and absorbing solar radiation, modifying cloud properties and precipitation, and altering the atmospheric circulation (Li *et al.*, 2022; Voiland, 2010). In India, characterized by diverse climatic and topographic features spanning arid and semi-arid regions in the northwest to humid regions in the northeast, aerosol loading and composition vary significantly due to disparate emission sources.

Various sources contribute to aerosol emissions, each playing a significant role in atmospheric composition. Biomass burning and forest fires are notable for releasing organic black carbon (soot) aerosols (Borgohain *et al.*, 2023; Prabhu *et al.*, 2020; Kondo *et al.*, 2011). Urbanization and industrial activities further contribute to aerosol pollution, adding to the atmospheric load of harmful particles (Sussman *et al.*, 2019; Lin *et al.*, 2018). Another significant source of aerosols is mineral dust, carried by winds and desert sandstorms and dispersed into the atmosphere (Schütz & Sebert, 1987; Knippertz & Stuut, 2014). Additionally, sea-salt aerosols are generated from sea spray, contributing to the natural aerosol load over the sea and adjoining landmasses (Grythe *et al.*, 2014; Schulz *et al.*, 2004). Moreover, these regions are influenced by distinct monsoonal systems that modulate the transport and deposition of aerosols (Yang *et al.*, 2021; Barman & Gorkhale, 2023).

In this study, we aim to analyze the tri-decadal (1991-2022) trends and climatic interactions of aerosols in two distinct regions of India: the arid region (encompassing Gujrat, Punjab, Haryana, Rajasthan and Delhi) and the humid Northeast Region (including Meghalaya, Assam, Nagaland, Manipur, Mizoram and Tripura).

In this study, we compare aerosol characteristics in two regions using two key parameters: aerosol optical depth (AOD), indicating light extinction and Ångström exponent (AE), reflecting wavelength dependence linked to aerosol particle size. By analyzing the spatial and temporal variations of AOD and AE from satellite and ground-based observations, we can infer the possible sources, types and sizes of aerosols in the two regions (Singh *et al.*, 2023). These aerosol components may have different effects on the radiative forcing, cloud formation, and precipitation processes in the regions (Haywood *et al.*, 2021; Douglas *et al.*, 2020). Through correlation analyses we investigate the interplay between aerosol composition

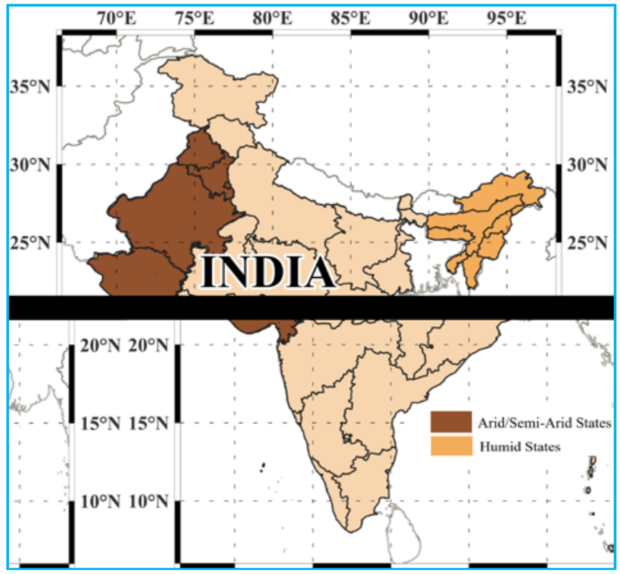



**Fig. 1.** Study Domain

and meteorological dynamics. This study examines diverse aerosol types-black carbon (BC) from incomplete combustion of fossil fuels and biomass, sulfate ($SO_4$) from sulfur dioxide oxidation in coal burning, dust from wind erosion, and sea salt from the evaporation of sea spray and wave breaking (Hu *et al.*, 2021; Liu *et al.*, 2021; Duniway *et al.*, 2019; Grythe *et al.*, 2014). Analyzing spatial and temporal variations in arid/semi-arid and humid regions of India, we assess their impact on regional climate and monsoon dynamics.

## 2. Methodology

This study employs a comprehensive methodology to analyze the long-term trends and interactions of aerosols and climate parameters in the arid/semi-arid regions and the humid regions of India (Fig. 1). The arid region of India considered for the study encompasses the northwestern states of Gujarat (GJR), Punjab (PJB), Haryana (HRY), Rajasthan (RAJ) and Delhi (DEL). The humid region includes the northeast India states of Meghalaya (MGL), Assam (ASM), Nagaland (NAG), Manipur (MNP), Mizoram (MIZ) and Tripura (TRP). A comparative study between the aerosol composition and their impact on the local climate of two contrasting regions can provide valuable insights into the complex interactions between aerosols and climate in different environmental settings.

This research employs high-resolution meteorological data (0.12° × 0.12°) sourced from the Indian Monsoon Data Assimilation and Analysis (IMDAA) system covering a time span of three decades

(1991-2022) (Rani *et al.*, 2021). The datasets, comprising quality-controlled information such as 2m Temperature, Total Precipitation and 10m Wind Speed, are obtained through the RDS Web Portal, offering insights into long-term climate variations. Additionally, satellite reanalysis datasets from MERRA2 (Randles *et al.*, 2017) (0.5° × 0.625° spatial resolution) for the same period are utilized to investigate the spatio-temporal distribution of AOD, AE and aerosols like dust, sea salt, BC and $SO_4$.

The spatial variations of AOD are investigated using box plots across different states. Monthly assessments include aerosol parameters like AOD, AE and the prevalence of aerosol types (dust, sea salt, black carbon, sulfates). Wind speed and direction are spatially visualized over the two regions over the different seasons to get an overview of the aerosol dispersion patterns. The research extends to a Pearson correlation analysis of the anomalies of these variables to identify potential connections between prevalent aerosols, temperature, and precipitation in both regions. This approach aims to provide a view of the prevalence of different aerosol types and their possible influence on the climate in the specified regions.

The Continuous Wavelet Transform (CWT) is employed to visually examine aerosol AOD and precipitation across different geographical regions (Katsavrias *et al.*, 2022; Gallegati, 2018; Torrence & Compo, 1998). The Morlet Wavelet was used with consistent parameters for each region, generating CWT power spectra that allow for cross-state comparisons. Utilizing global wavelet spectra (Katsavrias *et al.*, 2022) along with a global significance line facilitates the identification of significant AOD frequency variations, contributing to the understanding of regional influences and long-term trends in aerosol behavior. In mathematical terms, the CWT of a function $f(t)$with respect to a wavelet $\varphi(t)$ is defined as :

$$CWT_x(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} f(t)\varphi^*\left(\frac{t-b}{a}\right)dt$$

where$a$ and $b$ are the scale and translation parameters, respectively, and $\varphi^*$ denotes the complex conjugate of $\varphi$ (Hurley 2018), which is crucial due to the complex nature of the wavelet.

## 3. Results and discussions

### 3.1. *Land use and land cover*

Land Use/Land Cover (LULC) data were acquired from the Bhuvangeo portal of the Indian Space Research Organisation (ISRO), accessible *via* URL https://bhuvan.nrsc.gov.in, covering the periods 2005-06, 2011-12, and 2015-16.For each time period, multi-temporal satellite imagery from the Resourcesat-1 LISS III sensor were used to capture seasonal variations in land cover. State-wise statistics across study regions were compiled to determine the total area covered by each LULC type in both regions. Fig. 2 illustrates the LULC distribution that shows forest areas predominating in humid regions and agricultural lands in arid/semi arid regions.

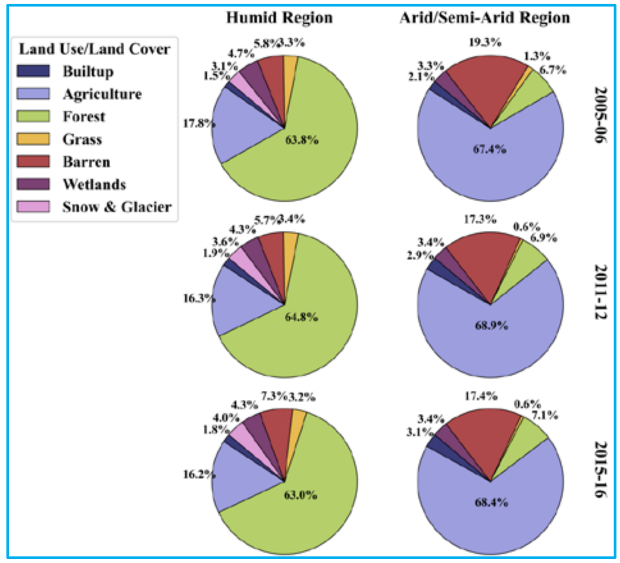



**Fig. 2.** LULC over the two contrasting regions

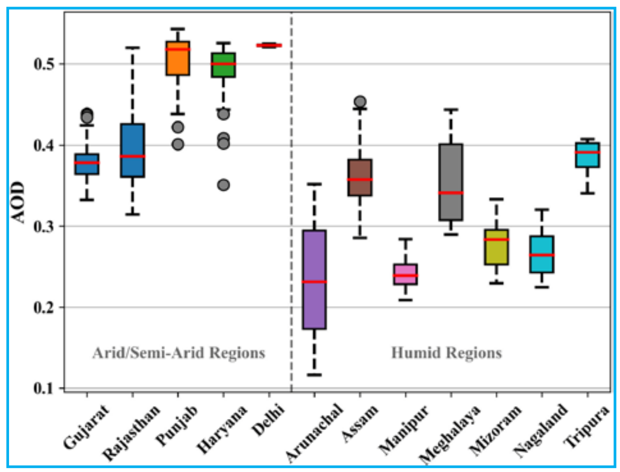



**Fig. 3.** State-wise spatial distribution of three decadal mean AOD values over the two regions

The extensive agricultural lands in arid/semi-arid regions contribute significantly to increases in BC and $SO_2$ emissions, primarily due to crop residue burning during October-November (Kumar *et al.*, 2021). Barren

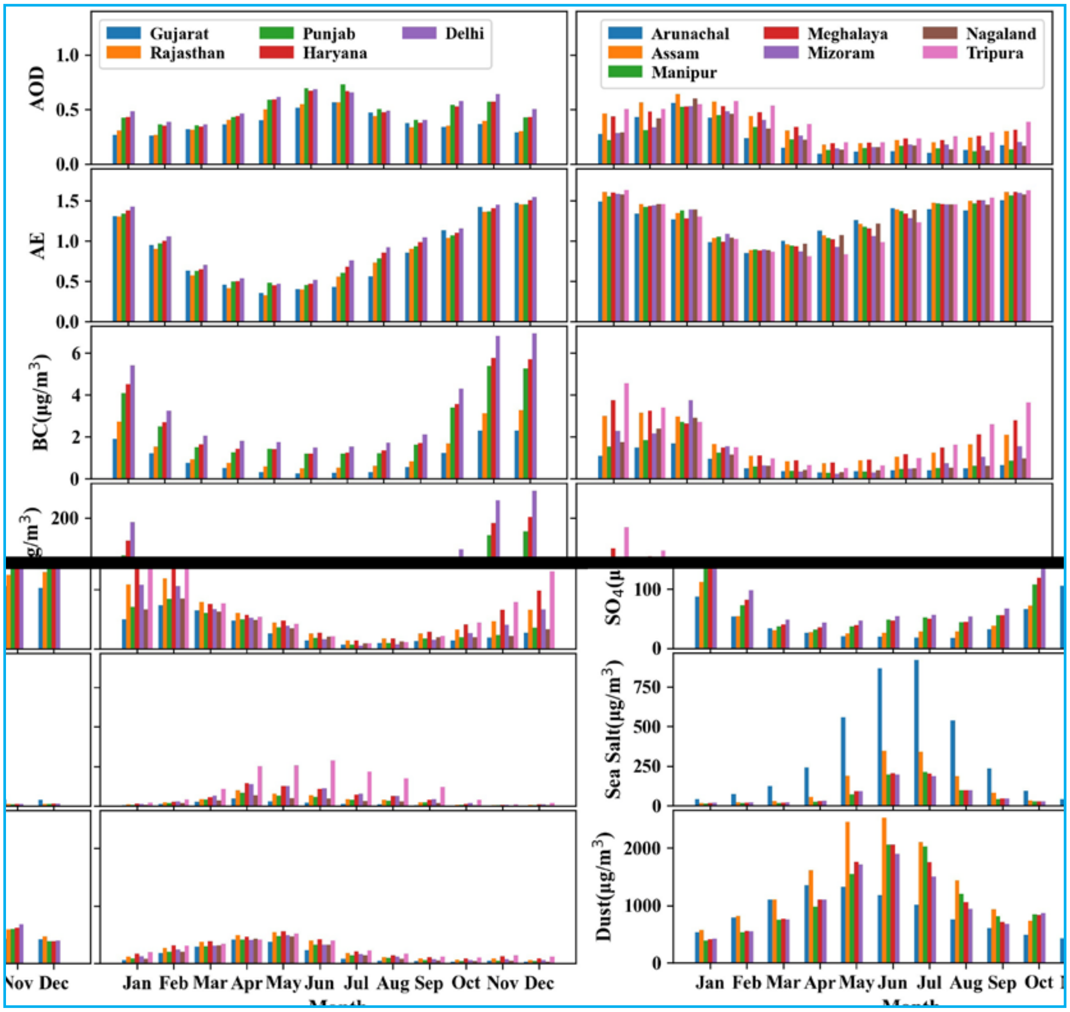
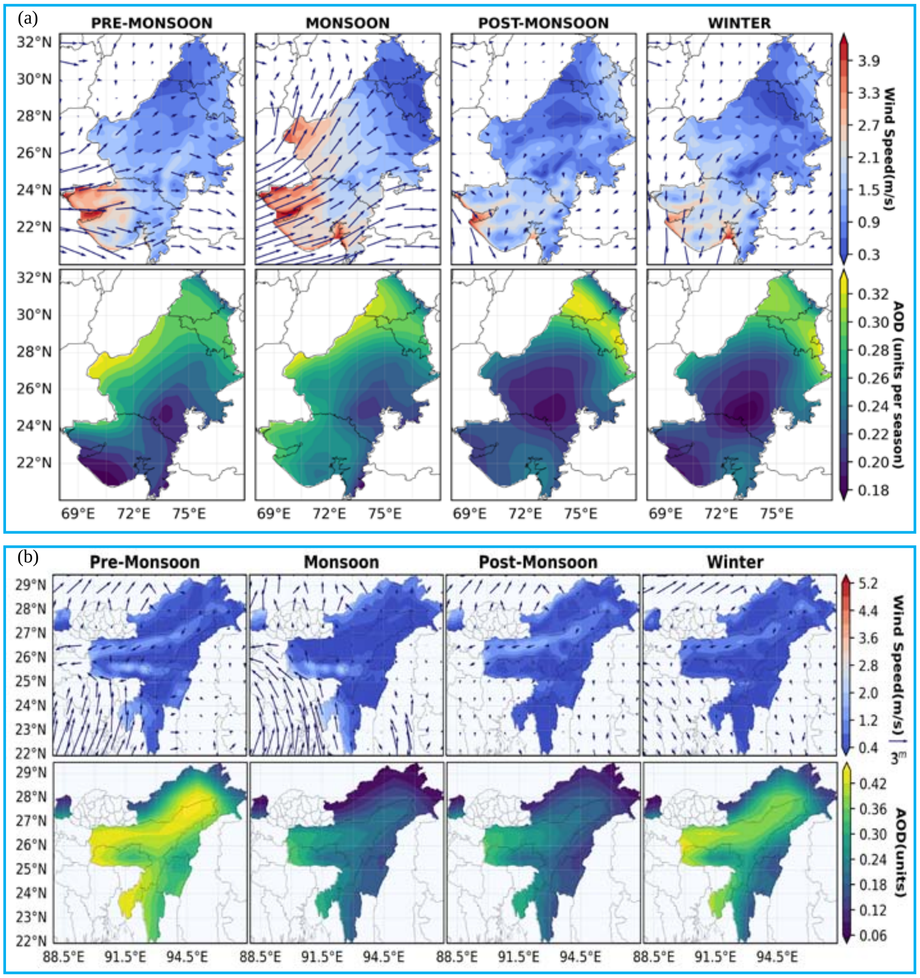



**Fig. 4.** Tri-decadal averaged monthly variation of different aerosol types and parameters

**TABLE 1**

**Box plot analysis results**

| Labels | Arid/Semi-Arid States | | | | | Humid States | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gujarat | Rajasthan | Punjab | Haryana | Delhi | Arunachal | Assam | Manipur | Meghalaya | Mizoram | Nagaland | Tripura |
| Min | 0.35 | 0.32 | 0.46 | 0.46 | 0.52 | 0.11 | 0.31 | 0.21 | 0.26 | 0.23 | 0.22 | 0.35 |
| Q1 | 0.36 | 0.36 | 0.48 | 0.48 | 0.52 | 0.17 | 0.33 | 0.22 | 0.3 | 0.25 | 0.24 | 0.37 |
| Median | 0.37 | 0.39 | 0.5 | 0.49 | 0.52 | 0.23 | 0.36 | 0.24 | 0.35 | 0.27 | 0.26 | 0.38 |
| Q2 | 0.38 | 0.42 | 0.52 | 0.51 | 0.52 | 0.29 | 0.38 | 0.25 | 0.4 | 0.29 | 0.28 | 0.4 |
| Max | 0.4 | 0.45 | 0.54 | 0.52 | 0.52 | 0.35 | 0.4 | 0.26 | 0.44 | 0.31 | 0.3 | 0.41 |
| IQR | 0.02 | 0.06 | 0.04 | 0.03 | 0.001 | 0.12 | 0.04 | 0.02 | 0.09 | 0.04 | 0.04 | 0.02 |
| Upper Outliers | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Lower Outliers | 0 | 0 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |




**Figs. 5(a&b).** (a) Seasonality of wind circulation and AOD averaged over the study period (2001-2022) over the arid and semi-arid region (b) Seasonality of wind circulation and AOD averaged over the study period over the humid region

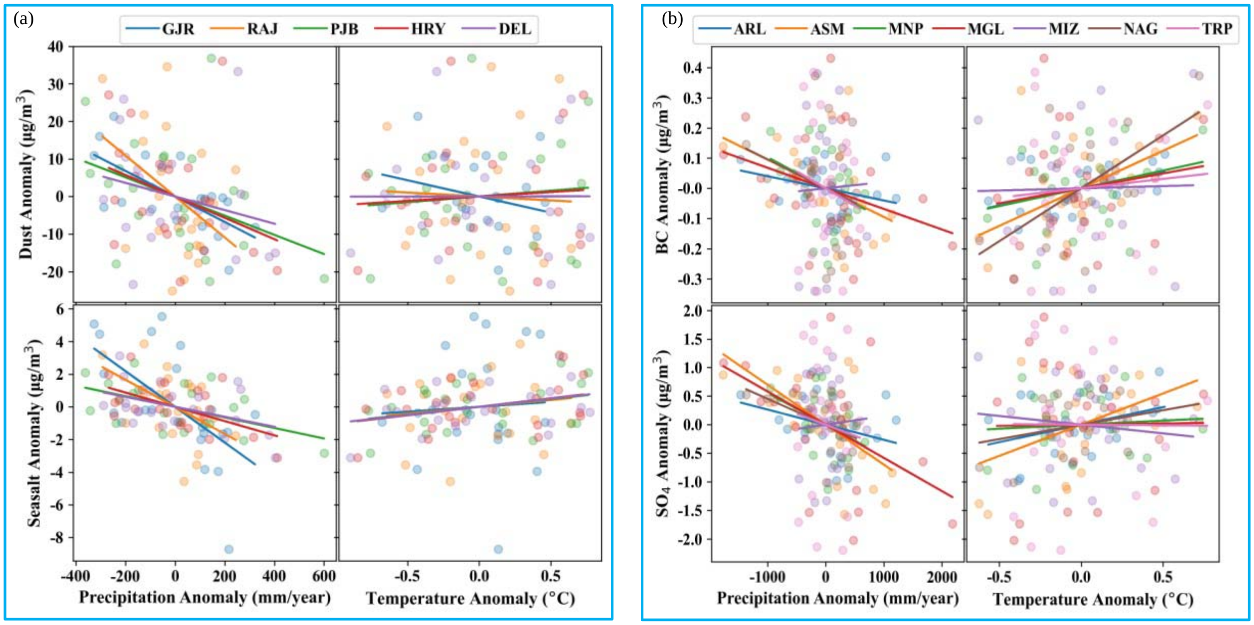
lands in these areas also contribute to dust aerosols, aggravated by severe dust storms driven by monsoon winds affecting air quality in northwestern India (Budakoti *et al.*, 2023). In the northeast regions, large forest and agricultural areas facilitate biomass burning activities, leading to the production of organic carbon (Borgohain *et al.*, 2023). Increase in built-up areas in both regions also contributes to anthropogenic activities and associated aerosol emissions (Rahman & Haque, 2022).

### 3.2. *State-wise spatial AOD distributions*

Box plot distribution of AOD spatially over the different states of the arid/semi-arid and humid regions (Fig. 3) visualize the skewness and the tendency of the data to elucidate how the data values are spread out and where they are centered. Table 1 shows AOD varying among Indian states, with humid states showing lower medians (0.24 to 0.38) and higher variability (IQR = 0.02 to 0.12), while arid/semi-arid states exhibit generally higher (0.37 to 0.52) and less variable values (IQR = 0.01 to 0.06). The humid northeast Indian states have lower but more varying degrees of AOD potentially a consequence abundant rainfall, complex terrains and comparatively lower anthropogenic activity (Biswas *et al.*, 2017; Dahutia *et al.*, 2018). Arid and semi-arid northwestern Indian states however show higher and less varying AOD levels mostly due to abundant desert dust, low rainfall, higher industrial activity and a relatively flat terrain.

### 3.3. *Average Monthly Variation*

A three-decade averaged monthly variations of key atmospheric parameters, namely AOD, AE, BC, $SO_4$, sea salt and dust reveal a distinct temporal pattern in the two contrasting regions of arid/semi-arid northwestern Indian states and humid northeast Indian states as seen in Fig. 4. In the arid states, AOD values exhibit a pronounced peak




**Figs.6(a&b).** (a) Pearson correlations between anomalous dust and sea salt aerosol concentration with precipitation and temperature in arid and semi-arid states and (b)Pearson correlations between anomalous BC and $SO_4$ concentration with precipitation and temperature in arid and semi-arid states

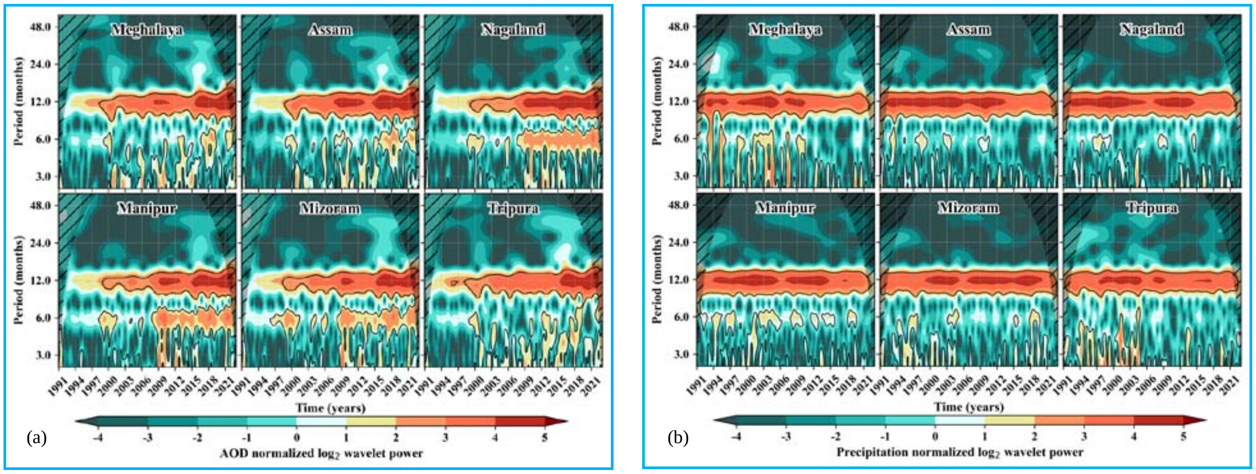
during the monsoon period, coinciding with elevated levels of dust and sea salt as seen in previous studies (Midhuna *et al.*, 2017). This underscores the significant influence of these aerosols on atmospheric optical properties during the monsoon season. In contrast, the humid states display a distinctive pattern in AOD values, aligning more closely with the temporal variations observed in BC and $SO_4$ concentrations indicating the dominance of these aerosols in the region (Arun *et al.*, 2021). Additionally, in arid states, the AOD peak during the monsoon aligns with elevated dust and sea salt levels, while agricultural crop residue burning contributes to heighten AOD in October-November, emphasizing diverse aerosol sources (Yang *et al.*, 2019; Kaskaoutis *et al.*, 2014). Notably, heightened AOD levels in the northeast coincide with the winter and pre-monsoon months, reflecting the prevalence of black carbon and sulfate aerosols during these periods (Chatterjee *et al.*, 2010; Guha *et al.*, 2015). The AE values provide further insights into aerosol characteristics. In the arid regions, lower AE values substantiate the prevalence of coarse aerosols, characteristic of dust and sea salt (Rani & Kumar, 2022). Conversely, the northeast region exhibits higher AE values, indicative of a dominance of smaller-sized aerosol particles.

### 3.4. *Wind circulation and aerosol dispersion*

Wind speed and wind direction were studied as factors in understanding particle dispersion across the four seasons including winter (Dec-Feb), pre-monsoon (Mar-May), monsoon (Jun-Sep) and post-monsoon (Oct-Nov) as seen in Figs. 5(a&b). Seasonal variations in AOD in arid and semi-arid regions of India for the past 3 decades show widespread prominence during monsoon when southwesterly winds carry moisture and dust from the Arabian Sea and the Thar Desert to the Indian subcontinent (Solanki & Pathak, 2023; Ramachandran & Cherian, 2008), increasing the AOD over most of the northwestern region, while post-monsoon AOD intensifies in Punjab, Haryana and Delhi as the result of crop residue burning the harvest season, which emits large amounts of smoke and particulate matter into the air (Kumar *et al.*, 2021). The humid regions of northeast India experience higher aerosol levels during the dry winter and pre-monsoon seasons than other seasons. This is due to a combination of factors, such as biomass burning, dust storms and anthropogenic emissions (Pathak *et al.*, 2016, Dahutia *et al.*, 2018) as well as the transport of pollutants from the Indo-Gangetic plains by variable northwest winds (Kaur *et al.*, 2023; Barman & Gorkhale, 2023), depending on the atmospheric circulation patterns.

### 3.5. *Correlation in Anomalies*

Pearson correlation between the prevalent aerosols and meteorological anomalies over the two regions Figs. 6(a&b) show similar relations with negative correlations between the aerosol and precipitation anomalies and positive correlation between the aerosol




**Figs.7(a&b).** CWT spectrum over the different states for (a)AOD and (b) Precipitation of the humid states of India over the tri-decadal period

**TABLE 2(a)**

**Pearson correlation results between aerosol and climate anomalies in arid and semi-arid states**

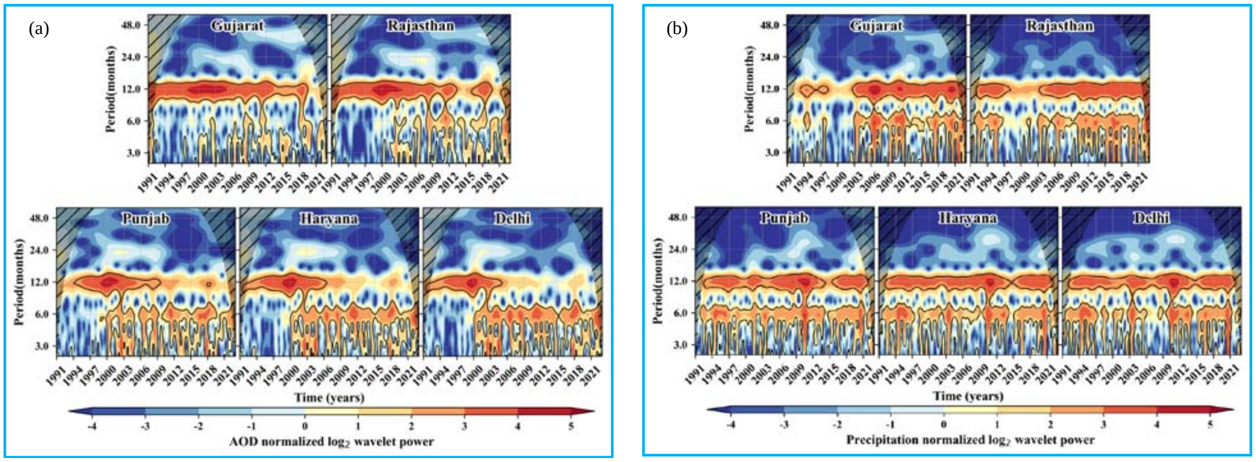
| | Precipitation | | Temperature | |
|---|---|---|---|---|
| | Dust | Sea salt | Dust | Sea salt |
| Gujarat | -0.654 | -0.611 | -0.258 | 0.052 |
| Rajasthan | -0.392 | -0.477 | -0.045 | 0.144 |
| Punjab | -0.397 | -0.523 | 0.098 | 0.318 |
| Haryana | -0.351 | -0.557 | 0.079 | 0.352 |
| Delhi | -0.267 | -0.452 | 0.002 | 0.352 |

**TABLE 2(b)**

**Pearson correlation results between aerosol and climate anomalies in humid states**

| | Precipitation | | Temperature | |
|---|---|---|---|---|
| | BC | $SO_4$ | BC | $SO_4$ |
| Arunachal | -0.333 | -0.319 | 0.463 | 0.366 |
| Assam | -0.435 | -0.611 | 0.518 | 0.433 |
| Manipur | -0.323 | -0.416 | 0.274 | 0.079 |
| Meghalaya | -0.340 | -0.500 | 0.171 | 0.012 |
| Mizoram | 0.027 | 0.052 | 0.022 | -0.125 |
| Nagaland | -0.253 | -0.476 | 0.573 | 0.330 |
| Tripura | -0.167 | -0.098 | 0.091 | -0.006 |

and temperature anomalies. The negative correlation of aerosol concentration anomalies (Table 2) may be attributed to aerosol indirect effects as aerosol particles act as cloud condensation nuclei (CCN), affecting cloud microphysics and precipitation processes (Tao *et al.*, 2012; Haywood & Boucher, 2000). The positive correlations with temperature suggest aerosol direct effects whereby aerosols absorb and scatter solar radiation, influencing the radiative balance of the atmosphere and surface (Guleria & Kumar, 2018; Haywood & Boucher, 2000). The extent of these correlations however is notably different when comparing the two regions. Dust and sea salt aerosol anomalies exhibit more pronounced negative correlation levels (-0.267 to -0.654 and -0.452 to -0.611, respectively) with precipitation in dry regions. Aerosol-rich regions like northwestern India may produce polluted clouds that evaporate water before precipitation due to reduced surface heating from the aerosol haze layer (Rosenfeld *et al.*, 2008). In contrast, in humid states, the negative correlations between precipitation and BC anomalies are moderate with ranges from -0.167 to -0.435, while precipitation and $SO_4$ show notable correlations ranging from -0.098 to -0.611, particularly across the northeast states. Regarding temperature, no notable correlation is observed with dust or aerosols, and sea salt shows no to slight correlations. In the humid regions, most states exhibit no notable correlations, except for Arunachal, Assam and Nagaland (0.366, 0.433, and 0.330) where significant correlations between $SO_4$ and temperature are observed. Similar trends are noticed in temperature-BC correlations, with Assam and Nagaland (0.518 and 0.573) displaying the highest correlations. The most notable positive correlation of temperature is observed with black carbon as unlike the other aerosols which may reflect sunlight, the darker black carbon aerosols absorbs solar radiation, contributing to global warming by enhancing the effects of greenhouse gases (Ramanathan & Carmichael, 2008).




**Figs. 8(a&b).** CWT spectrum over the different states for (a) AOD and (b) Precipitation of the dry states of India over the tri-decadal period

## 4. Periodicities of AOD and precipitation

Continuous Wavelet Transform analyzes aerosol optical depth and precipitation across states, using Morlet Wavelet to compare power spectra for regional trends and patterns. The COI to account for the edge effects is indicated by the hatched and shaded region while significant oscillations are lie within thick black closed contour lines.

Figs. 7(a&b) normalized 12-month spectral power periodicity of AOD show dominant trends annual periodicities with traces of significant semi-annual (~6 months) as well as intra-seasonal periodicities (~3 months) for both AOD and precipitation (Payra *et al.* 2021). Although sparse observations of quasi-biennial aerosol oscillation (QBO) arising from stratospheric zonal wind circulation exist as reported by Beegum *et al.* (2009), they do not reveal significant patterns.

Figs. 8(a&b) depict the noteworthy and prevailing normalized 12-month spectral power periodicity of AOD during the initial two decades, primarily attributed to the annual monsoon circulation. In contrast, precipitation exhibits greater dominance in the latter two decades. The states of Punjab, Haryana, and Delhi exhibit a more pronounced presence of semi-annual periodicity (~6 months) as well as intra-seasonal periodicities (~3 months) in both AOD and precipitation, as documented by Panicker and Shaima (2021) and Beegum *et al.* (2009). As in the humid regions, traces of quasi-biennial aerosol oscillation (QBO) from stratospheric circulation of zonal winds are observed but show no significant patterns.

## 5. Conclusion

In conclusion, this study provides a comprehensive analysis of the long-term variation and interaction of aerosols and meteorology in the arid/semi-arid and humid regions of India over the period 2001-2022. The contrasting climatic and topographic characteristics of these regions lead to distinct aerosol compositions and dynamics, which in turn influence the regional climate and monsoon patterns. Arid/Semi-Arid regions have higher AOD due to dust and monsoon, while humid regions show lower AOD with biomass burning. Seasonal peaks occur during monsoon in arid regions and dry seasons in the humid region. Wind circulation patterns are examined to understand aerosol dispersion, emphasizing the seasonal influence on AOD levels. The correlation analysis between prevalent aerosols and meteorological anomalies showed negative correlations between aerosols and precipitation, indicating aerosol indirect effects, and positive correlations with temperature, suggesting aerosol direct effects Arid/Semi-Arid regions have higher AOD due to dust and monsoon, while humid regions show lower AOD with biomass burning. Seasonal peaks occur during monsoon in arid regions and dry seasons in the humid region. These correlations, however, exhibit notable differences between the states of the two regions. In general, this research provides a perspective on the complex relationship between aerosols and meteorological conditions in the two different environmental settings within India.

This study utilizes extensive data over a long period, comparing conditions over contrasting arid and humid regions in India using high-resolution reanalysis datasets.

Notable differences in aerosol distributions and characteristics were observed between the two regions. This study however, utilizes a broad characterization method over two large scaled regions over India. Future research could benefit from incorporating high-accuracy in-situ datasets and conducting more detailed investigations into the complex interactions between aerosols and climate, building upon the findings of this study.

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