Long-term variations of aerosol concentrations and their interaction with the regional climate patterns over the NER of India

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Introduction

Overview:

❖This study investigates the long-term variation in aerosol optical depth and aerosol concentrations over the North-East Region (NER) of India for the past two decades.

❖The variations were analyzed considering the region's complex topography and land use/land cover changes. Air-mass source attribution using HYSPLIT back-trajectory cluster analysis was also utilized to infer the possible types of aerosols transported to the region.

❖The change in precipitation patterns over the same region and study period using rainfall indices defined by the India Meteorological Department, has also been studied to determine if they exhibit similar patterns, which may suggest aerosols influence on cloud microphysical properties and consequently, rainfall patterns.

Data Acquisition:

❖Aerosol optical depth (550nm) data were obtained from MODIS instrument aboard the Terra satellite. PM2.5 components from MERRA-2 were used to derive overall PM2.5 concentrations. Aerosol subtype profiles were obtained from the products of the CALIOP instrument aboard CALIPSO satellite. Air mass back trajectories were analyzed using data from the NOAA HYSPLIT model and GDAS data as meteorological input. IMD gridded rainfall data (0.25°) were sourced from IMD Pune (www.imdpune.gov.in). LULC changes were obtained from the Bhuvan portal (NRSC, www.nrsc.gov.in).

Dataset	Parameter	Spatial Resolution	Temporal Resolution
MODIS *MOD08_M3*	AOD (550 nm)	1°×1°	Monthly
MERRA2 *M2T1NXAER*	Dust(2.5µm), OC, BC, Sea salt(2.5µm), SO_4^{-2}	0.625°×0.5°	Hourly
CALIPSO *CAL_LID_L2*	Aerosol Types	5km×5km	~16 days
IMD Gridded Rainfall	Rainfall (mm/day)	0.25°×0.25°	Daily

Table 1. Details of the datasets used in the study.

Study Region

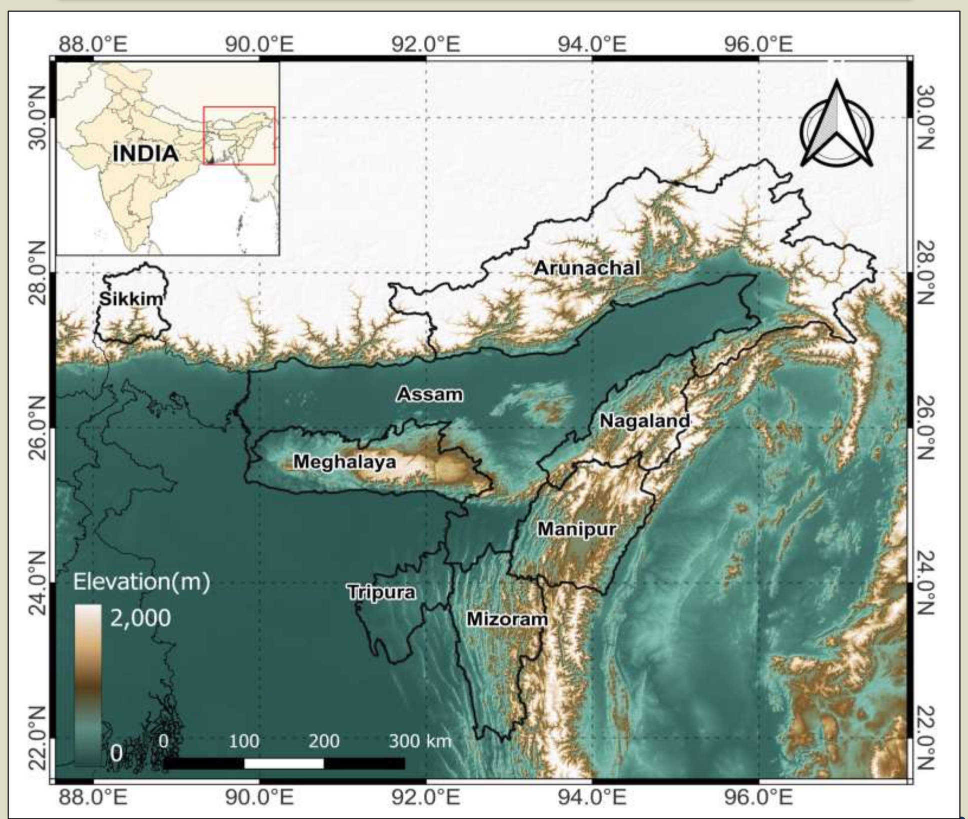

Fig 1. North-East Region (NER) of India (87.5–97.8°N, 21.5–30.8°E)

Aerosol optical depth over the NER

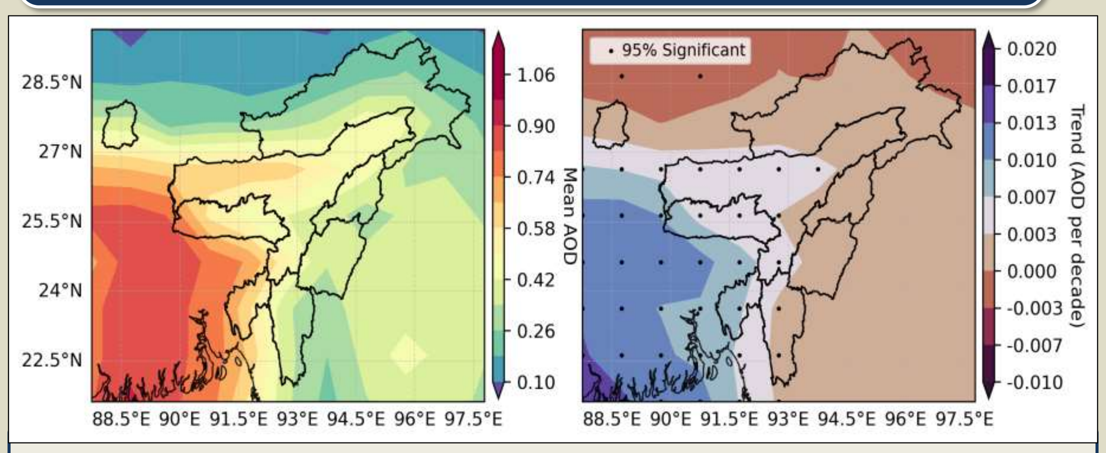

Fig 2. Mean MODIS AOD_{550} over the study region (left) shows highest aerosol loading over the IGP region with gradual decreases towards the east modulated by the regional topography. The increase in aerosol loading (right) obtained by the Mann-Kendall trends test also follow the same pattern with the increase being significant over the south-western part of NER.

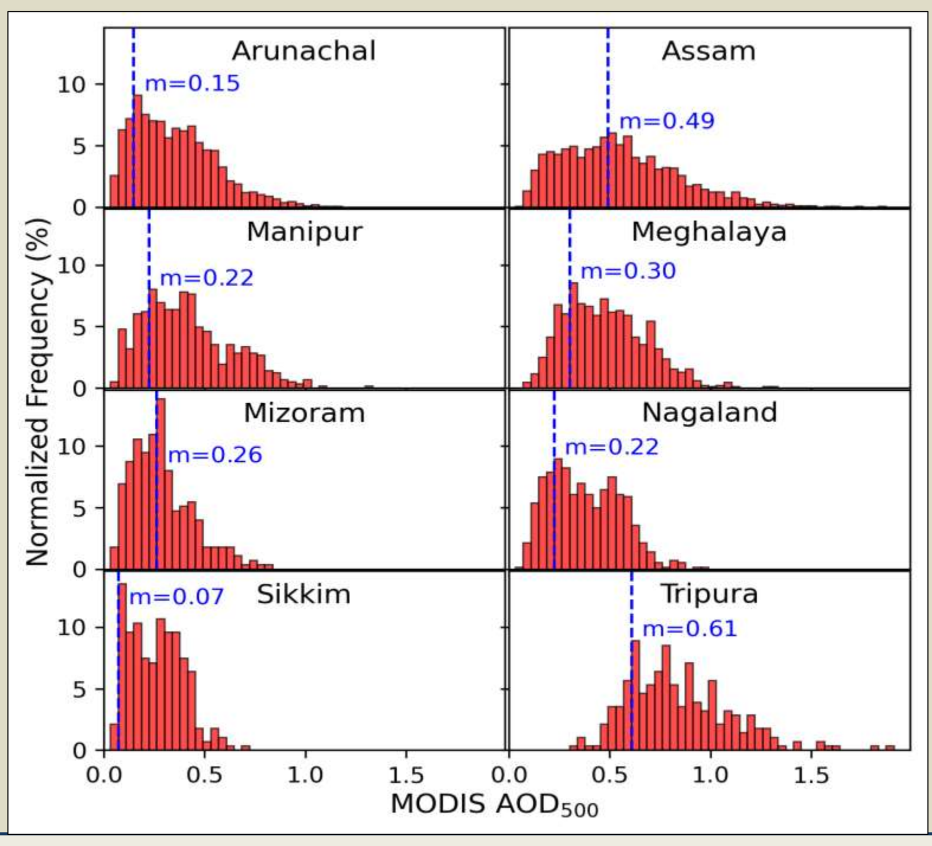

Fig 3. Frequency distribution shows states characterized as plain areas on the western NER like Tripura & Assam have higher modal (**m**) AOD_{550} values (≥0.49). The hilly and plateau states (Manipur, Meghalaya, Mizoram & Nagaland) show lower modal AOD_{550} (0.22–0.3) while the mountainous states of Sikkim and Arunachal have the least ($AOD_{550} \leq 0.15$).

Aerosol Composition over NEI

PM2.5 variations with AOD_{550}

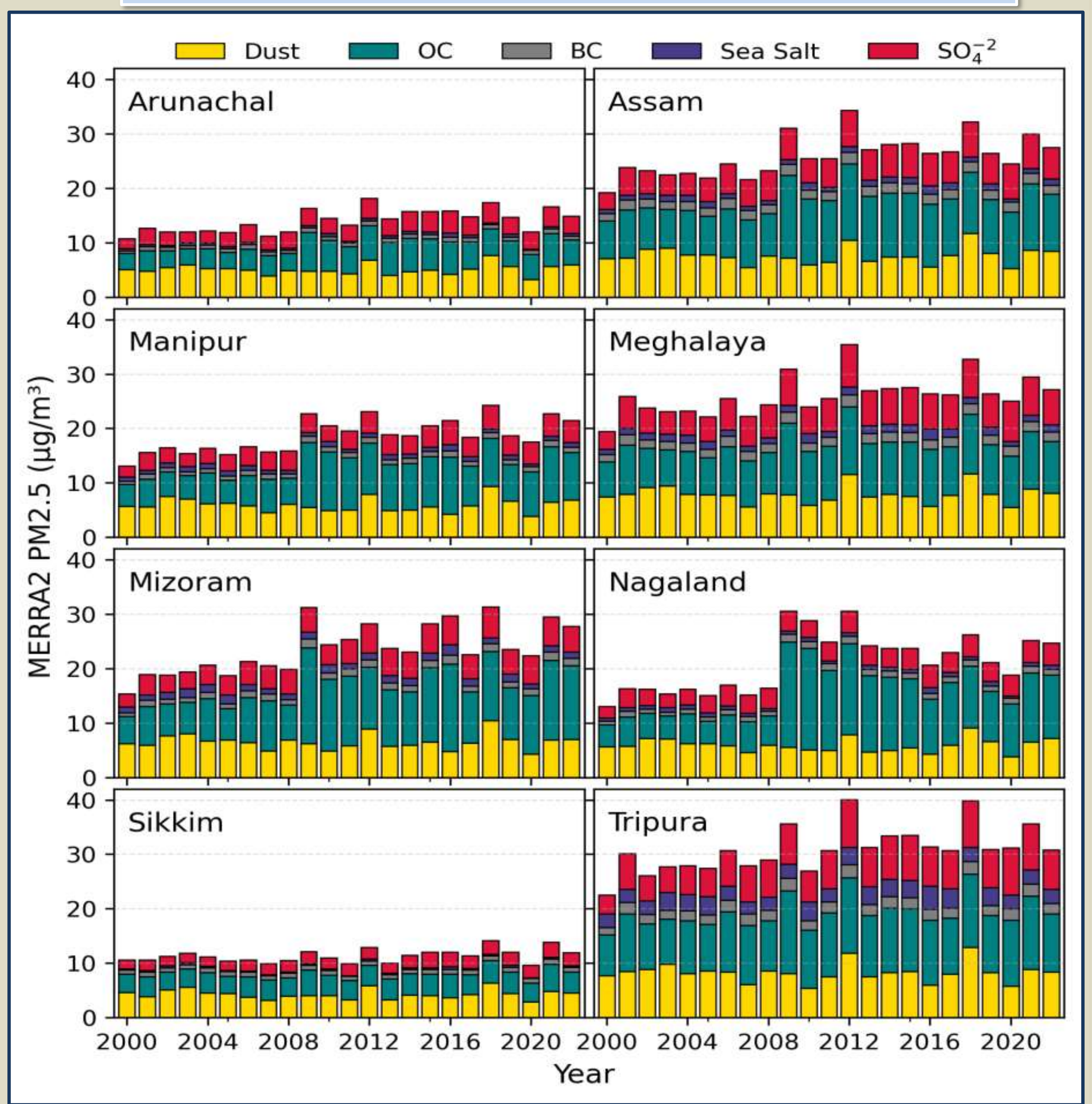

Fig 4. Annual monthly mean PM2.5 aerosols show an overall increase in all the states over the past 2 decades. Sulphate (SO_4^{-2}) aerosols show more prominence in the western states (Tripura, Assam, Meghalaya) while peak years (2009 & 2012) are associated with elevated organic carbon (OC) in majority of the states.

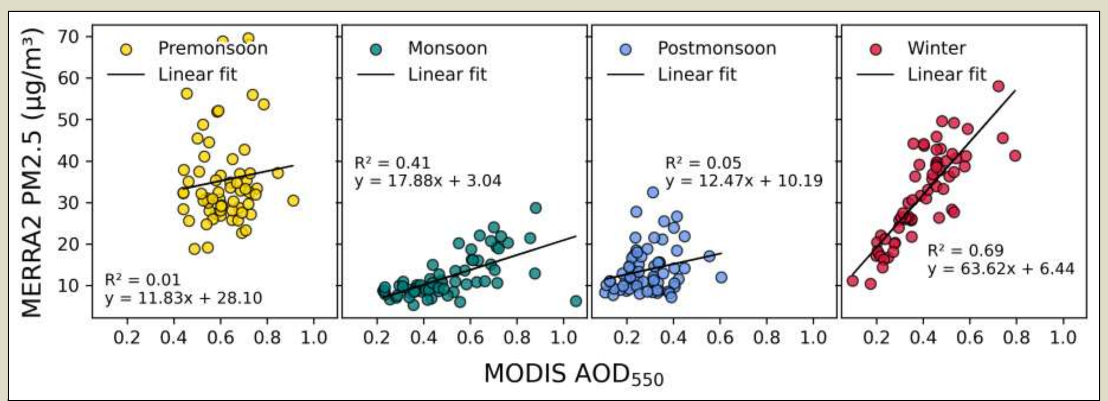

Fig 5. Seasonal comparison between PM2.5 and AOD_{550} taken over NESAC, a remote hilly location (25.67°N, 91.90°E) in Meghalaya, taken as an approximate centre of the NER, show winter PM2.5 having the highest correlation (R^2=0.69) with AOD_{550}. This suggest finer particles as major contributors to AOD during the winter. Pre monsoon and post monsoon show negligible correlation ($R^2 \leq 0.05$) likely due to more complex mixtures with coarser particles.

PM2.5 Components	Pre-monsoon	Monsoon	Post-monsoon	Winter
Sea Salt	0.13 (0.328)	0.51 (**0.000**)	0.57 (**0.000**)	0.46 (**0.000**)
OC	-0.09 (0.493)	0.03 (0.811)	-0.01 (0.943)	0.66 (**0.000**)
BC	-0.13 (0.328)	0.22 (0.088)	0.08 (0.528)	0.68 (**0.000**)
SO_4^{-2}	0.21 (0.093)	0.60 (**0.000**)	0.13 (0.316)	0.85 (**0.000**)
Dust	0.37 (**0.003**)	0.63 (**0.000**)	0.43 (**0.000**)	0.53 (**0.000**)

Table 2. A correlation assessment between the PM2.5 components and AOD_{550} over the same location shows all winter PM2.5 components having significant correlation ($p \leq 0.05$) with sulphate aerosols showing the strongest correlation (R^2=0.85). Fine-mode dust shows a moderate correlation in the pre-monsoon season, while in the monsoon and post-monsoon seasons, fine-mode dust and sea salt exhibit significant correlations, with sulphates contributing during the monsoon.

Aerosol Subtypes Vertical Profile

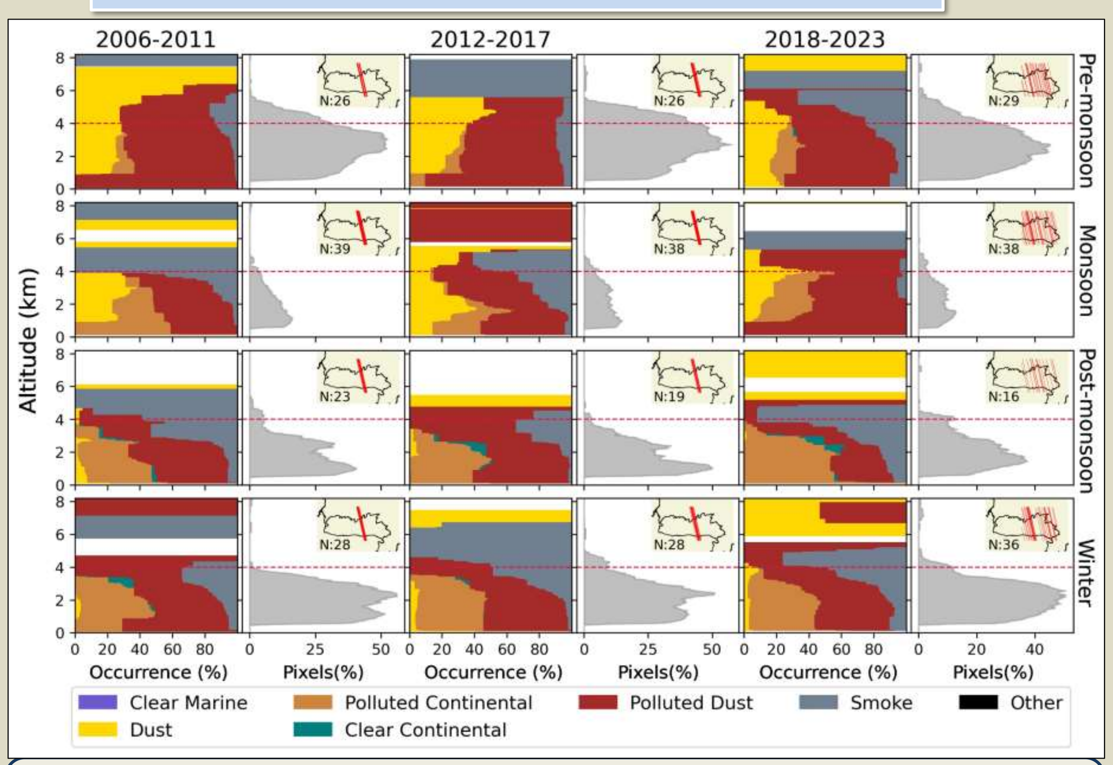

Fig 6. Vertical profiles of aerosol subtypes obtained from CALIOP satellite products from 2006-2023 within an 80km radius from the observation site (25.67° N, 91.90° E) reveal distinct seasonal variability. The percentage of aerosol pixel counts relative to the total pixels is highest during winter and the pre-monsoon seasons, while the lowest values are observed during the monsoon season. This reduction during the monsoon can be attributed to the wet scavenging effect associated with precipitation processes. Above 4 km (red dashed line), the pre-monsoon season shows the highest pixel counts, indicating elevated aerosols, primarily dust and smoke, due to long-range transport and/or stronger convection during this season. Dust aerosols also contribute more below 4 km during the pre-monsoon and monsoon seasons as compared to the other seasons.

Environmental variations over NER

Seasonal transport

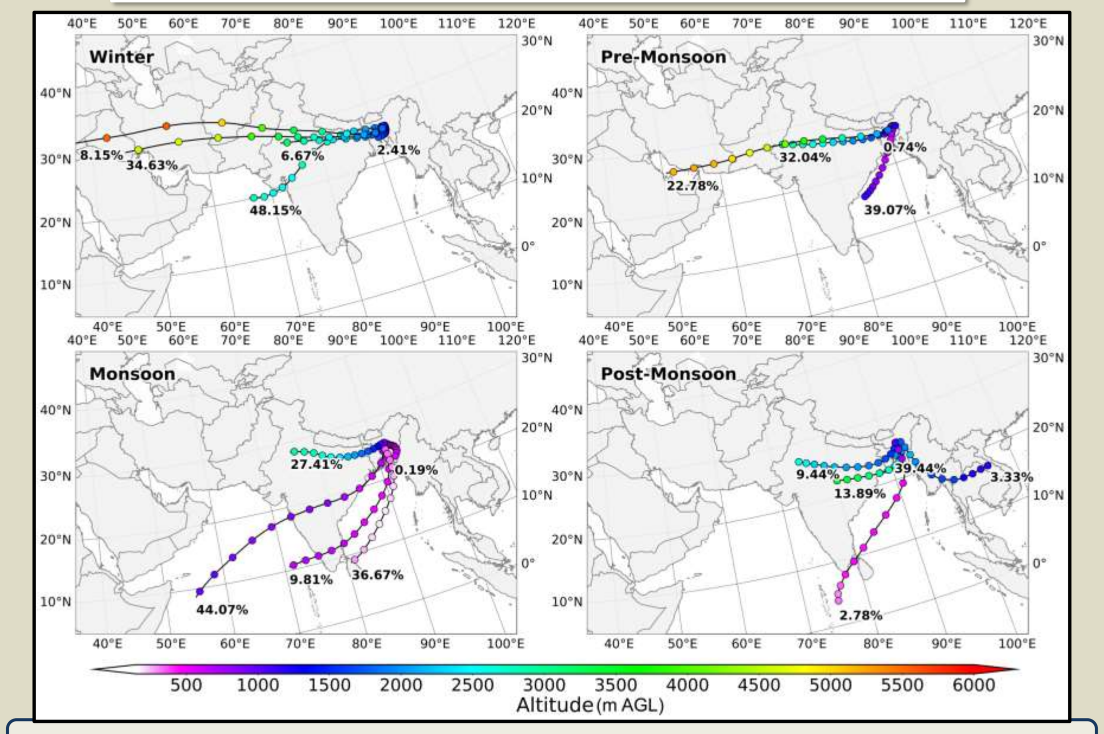

Fig 7. The seasonal 5-day HYSPLIT back-trajectory cluster analysis for the study site (25.67° N, 91.90° E) in 2023 suggests that air masses primarily originate from the northwestern Indian region and pass through the IGP during the pre-monsoon and winter seasons. The post-monsoon period has shorter transport distances, while the monsoon is influenced by air masses from the Arabian Sea and Bay of Bengal.

Changes in LULC

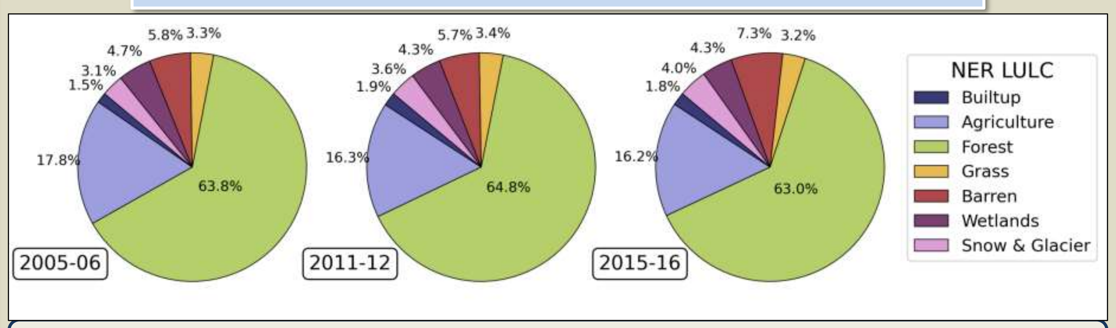

Fig 8. Changes in LULC proportions across the NER indicate a general increase in built-up areas and barren land. This shift leads to a rise in anthropogenic emissions, primarily due to vehicular emissions and biomass burning, as well as intensified dust emissions from the barren land. While the decline in agricultural land might lead to a reduction in aerosols produced from crop burning, the decrease in forest cover which act as aerosol sinks, diminishes the dry deposition processes.

Precipitation patterns over the NER

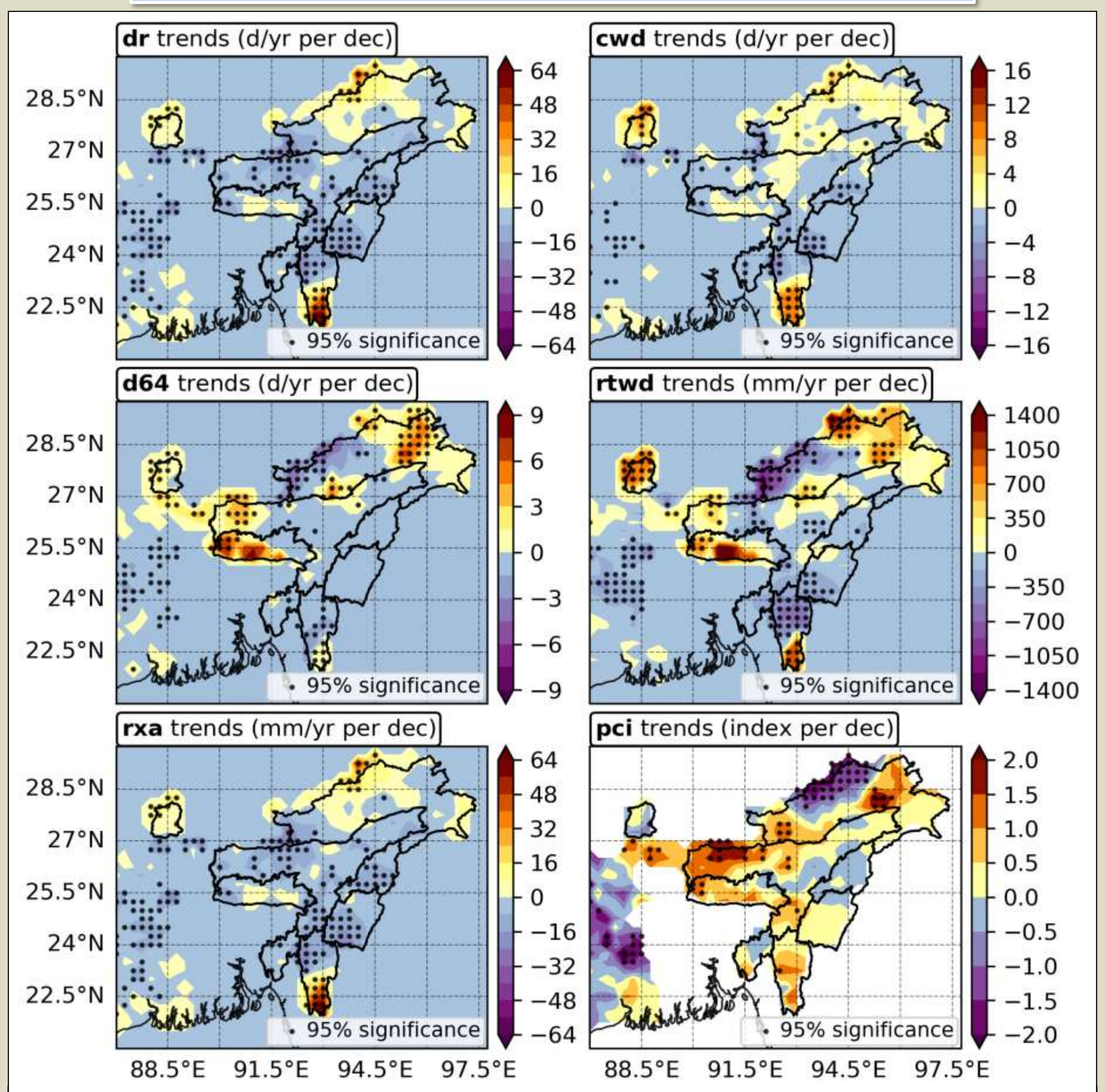

Fig 9. Changes in rainfall patterns over the 2001-2023 period in the NER are observed from the variations in IMD rainfall indices—rainy days (**dr**), consecutive wet days (**cwd**), heavy precipitation days (**d64**), total precipitation in wet days (**rtwd**), maximum daily rainfall (**rxa**) and precipitation concentration index (**pci**). Trends in total precipitation over the study region (rtwd) is modulated by trends in heavy rainfall (d64) in most parts except for western Mizoram and the increasing precipitation amounts (rtwd) are associated with prominent increases in rainfall occurrences and persistence (dr & cwd). The increasing trends of pci over most parts of the region highlight a shift towards more intense rainfall in fewer, more concentrated events. This change could elevate the risk of flooding while also contributing to prolonged dry spells, creating a more volatile and unpredictable climate.

Conclusion

❖The topography of the NER significantly influences aerosol loading, with higher concentrations in the plains and lower levels in hilly and mountainous regions.

❖Fine-mode aerosols exhibit a strong correlation with aerosol optical depth during the winter season, with anthropogenic aerosols (such as BC, OC, and SO_4^{2-}) demonstrating the most pronounced correlation.

❖The increase in built-up areas observed within the region, coupled with a decrease in forest cover, which acts as a sink for dry deposition, may have contributed to the increase in anthropogenic aerosol loading.

❖Intense, short-duration precipitation events have been increasing over the past two decades over most parts of the region. Such events can happen with the increase in fine-mode aerosols which strongly affect cloud microphysics which suppresses light rainfall but can lead to delayed, intense downpours.

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