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Prediction of Decadal Trend in Black Carbon Over Indo-Gangetic Plain

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ABSTRACT:
The Indo-Gangetic Plain (IGP), one of the most densely populated and industrially active regions in South Asia, experiences substantial atmospheric loading of black carbon (BC), a critical short-lived climate pollutant influencing air quality, monsoon dynamics, and radiative forcing. This study aims to investigate the long-term temporal dynamics, seasonal variability, and statistical behaviour of BC concentrations over the IGP using MERRA-2 reanalysis data from 2001 to 2024. The uniqueness of this work lies in its comprehensive integration of linear and nonlinear trend analyses with temporal dependence diagnostics to enhance the robustness of interpretation. Methodologically, linear regression quantified long-term tendencies, LOESS smoothing captured nonlinear fluctuations, the Ljung–Box Q-test assessed serial dependence, and decadal and seasonal analyses delineated temporal and climatic patterns. Results indicate a gradual increase in BC levels from 2.37×10^{-6} kg/m² (2001–2010) to 2.55×10^{-6} kg/m² (2021– 2024), with pronounced seasonal peaks during winter (3.73×10^{-6} kg/m²) and post-monsoon (3.33×10^{-6} kg/m²) due to stable atmospheric conditions and biomass burning. The Ljung–Box test confirmed no significant serial autocorrelation, strengthening the reliability of detected trends. This study provides valuable insights for regional emission control and climate modelling. Future research may extend to spatial variability analysis and coupling, BC trends with satellite-derived radiative forcing and socio-economic drivers.

Keywords: *Black Carbon, Trend Analysis, LOESS, Seasonality, Indo-Gangetic Plain.*

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I. INTRODUCTION

Black carbon (BC) is a highly efficient light-absorbing aerosol that plays a critical role in the Earth's climate system by modifying the atmospheric radiation balance. Through the absorption of incoming solar radiation, BC contributes to atmospheric heating, particularly within the lower and middle troposphere, thereby influencing regional and global climate patterns. Although BC constitutes only a small fraction of the total aerosol mass, its radiative forcing efficiency is substantially higher than that of non-absorbing aerosols. Consequently, BC can partially offset the cooling effect induced by scattering aerosols such as sulphates, altering the net radiative impact of aerosol mixtures in the atmosphere (Ramanathan & Carmichael, 2008).

In addition to its climatic influence, BC is recognized as a major component of fine particulate matter ($PM_{2.5}$), which has been linked to adverse human health outcomes. Numerous epidemiological studies have reported associations between BC exposure and cardiopulmonary morbidity and mortality. However, uncertainties remain regarding the magnitude and long-term persistence of these health effects due to variability in exposure levels, chemical composition, and population sensitivity (Janssen et al., 2012). From a climate perspective, enhanced BC absorption is expected to warm the troposphere, leading to changes in atmospheric stability, cloud microphysical properties, and precipitation processes. Climate modeling studies suggest that BC-induced heating can suppress low-level clouds while modifying large-scale circulation patterns, with particularly pronounced impacts in tropical regions (Roeckner et al., 2006).

These effects are of special concern in South Asia, where regional climate is strongly governed by the summer monsoon system. The Indian subcontinent relies heavily on monsoon rainfall for agriculture, water resources, and food security. Perturbations in monsoon circulation and precipitation due to BC-related atmospheric heating may therefore have significant socio-economic consequences. Furthermore, BC deposition on snow and ice surfaces, especially in the Himalayan and Tibetan Plateau regions, reduces surface albedo and accelerates snowmelt, contributing to regional warming and altered hydrological cycles (Qian et al., 2014).

Recent studies have also indicated a possible link between increasing BC emissions and the intensification of tropical cyclones, particularly over the Arabian Sea. Enhanced atmospheric heating and changes in vertical temperature profiles associated with BC may create favorable conditions for cyclone development and intensification (Evan et al., 2011). Despite the recognized importance of BC, long-term observational records remain limited, especially over developing regions. Many studies based on ground-based and regional observations, including those conducted across Asia, have reported stable or even declining trends in BC concentrations over recent decades, likely reflecting emission control measures and changes in fuel usage patterns (Ahmed et al., 2014; Chen et al., 2016).

Over the Indian subcontinent, BC is a ubiquitous component of the aerosol system and has been detected not only near the surface but also at higher altitudes, extending up to approximately 13 km in the free troposphere (Babu, Chaubey, et al., 2011). This vertical extent underscores the potential for long-range transport and large-scale climatic impacts of BC aerosols. Against this background, the primary objective of the present study is to investigate the spatio-temporal characteristics of BC over the Indo-Gangetic Basin (IGB) using a combination of ground-based observations and satellite-derived datasets. Decadal trend analysis and regression techniques are employed to assess long-term BC climatology over the IGB for the period 2001–2024. The details of the data sources, methodology, results, discussions, and key conclusions are presented in the following sections.

II. MATERIAL & METHODS

MERRA-2 stands for Modern-Era Retrospective Analysis for Research and Applications, version 2, is a reanalysis dataset that includes black carbon (BC) and other PM2.5 components. MERRA-2 model used to reconstruct spatiotemporal distributions of PM2.5 concentrations, BC, organic carbon, dust, sea salt, and sulphate (Li et al., 2024). MERRA-2 provides the spatial distribution of atmospheric BC concentration since 1980, with a spatial resolution of 0.5° × 0.625° and a temporal resolution of 1 h, 3 h and month. All products can be downloaded through the NASA Earth Science Data Website (https://earthdata.nasa.gov/).

III. RESULTS & DISCUSSION

Black carbon (BC) is a crucial component of atmospheric aerosols and plays a significant role in influencing the Earth's radiation balance, regional climate variability and public health. Due to its strong light-absorbing nature, BC contributes directly to atmospheric warming and indirectly affects cloud formation and precipitation processes. In the present study black carbon column mass density data obtained from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis model have been utilized to examine the spatial distribution and temporal variability of BC over the Indo-Gangetic Basin (IGB) (Li et al., 2024).

Figure 1a illustrates the spatial distribution of BC column mass density (kg m^{-2}) over the IGB for the period 2001–2024. The color gradient in the map highlights significant spatial heterogeneity in BC loading with darker red regions indicating higher concentrations and lighter yellow to orange shades representing comparatively lower levels. The BC column mass density reflects the vertically integrated amount of black carbon present in the atmosphere and serves as an important indicator of regional air pollution intensity and radiative forcing. Elevated BC levels over the IGB are primarily associated with dense population, rapid urbanization, industrial activities, vehicular emissions, and widespread biomass and biofuel burning (Rana et al., 2019).

The highest BC concentrations are observed in the central and eastern parts of the IGB, particularly within the latitudinal band of 25°–28° N and longitudinal range of 80°–88° E. In this region, the maximum BC column mass density reaches approximately 50.6×10^{-7} kg m^{-2}. This area encompasses major urban and industrial centers, intensive agricultural practices, and frequent biomass burning, all of which contribute substantially to BC emissions. Similar spatial patterns and elevated BC loading over the IGB have been reported in earlier studies, emphasizing the basin as one of the global hotspots of black carbon pollution (Rana et al., 2019).

To investigate the long-term variability and trend of BC over the IGB, monthly mean BC column mass density data from MERRA-2 for the period 2001–2024 have been analyzed, as shown in the bottom panel of **Figure** 1b. The time-series analysis reveals noticeable interannual variability along with a marginal increasing trend over the study period. The fitted linear regression line ($y = 9 \times 10^{-11}x - 1 \times 10^{-6}$) indicates a very slight upward tendency in BC column density, suggesting a gradual increase in BC loading over the IGB. Although the trend is weak, even small increases in BC concentrations can have significant implications for regional climate forcing, atmospheric heating, glacier retreat in the Himalayan region, and deterioration of air quality (Mehrotra et al., 2024). A temporary decline in BC concentration is evident during the period 2003–2004, which may be attributed to reduced anthropogenic activities during localized economic slowdowns or regulatory interventions. However, the overall increasing tendency highlights the continued influence of human activities on BC emissions in the IGB. Persistent BC pollution poses serious risks to human health, particularly through its contribution to fine particulate matter ($PM_{2.5}$), and underscores the need for effective emission mitigation strategies in this densely populated region.

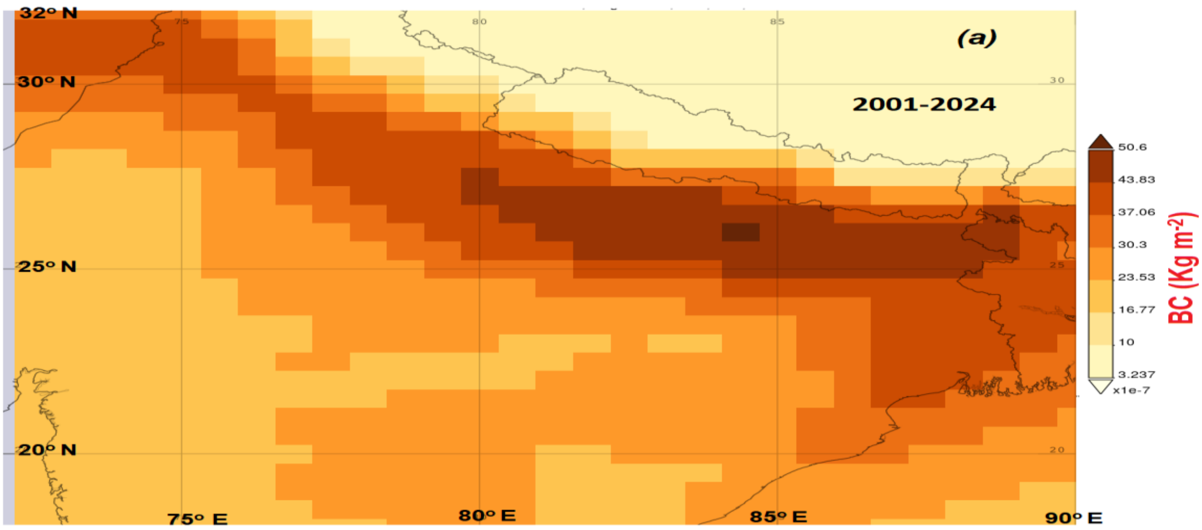

Figure 1a*:* Spatial distribution of black carbon column mass density (kgm^{-2}) during 2001-2024 over IGB from MERRA-2 reanalysis model.

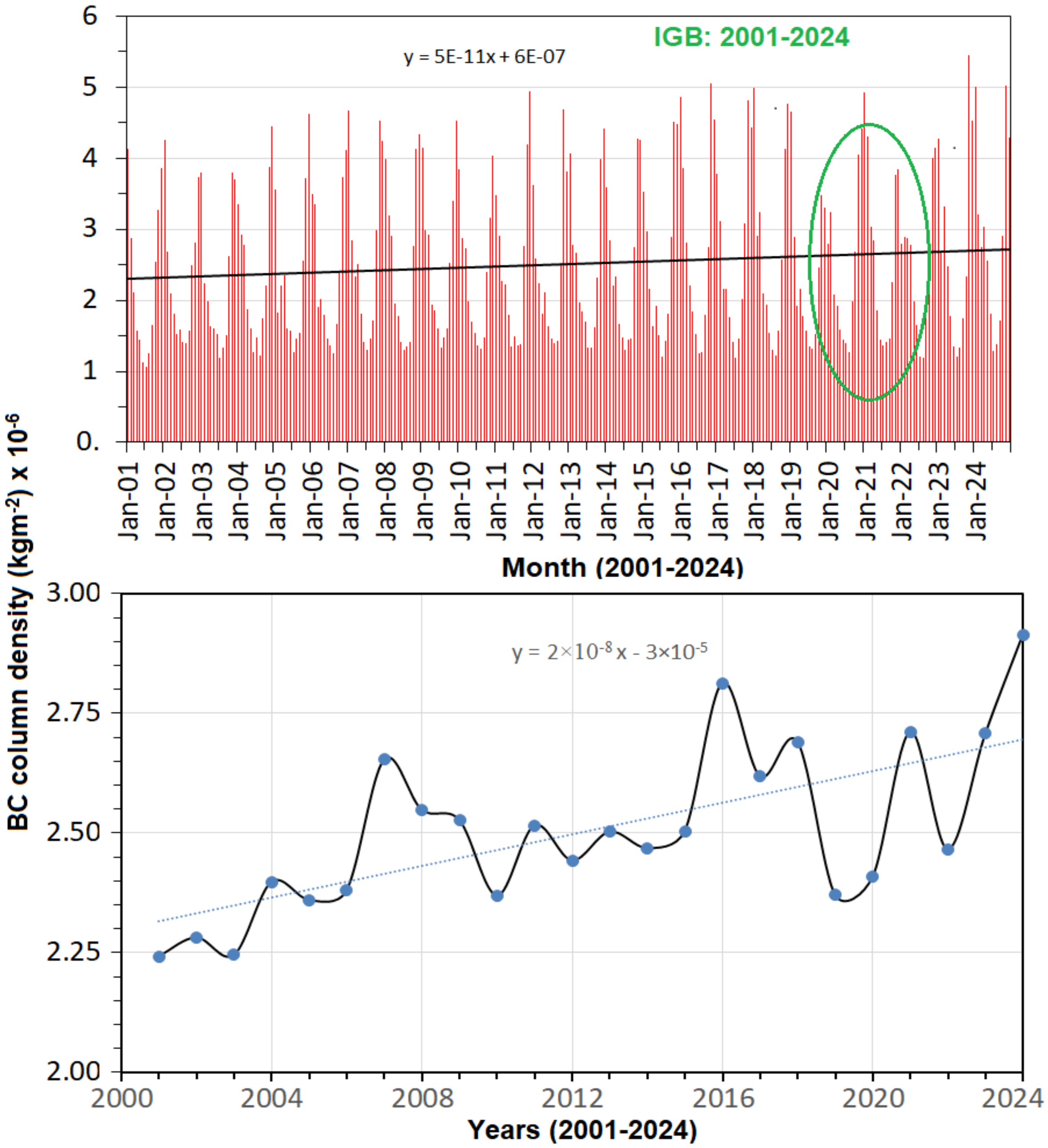

Figure 1b: Monthly and annual mean variation of black carbon column mass density (kgm-2) during 2001-2024 over IGB from MERRA-2 reanalysis model. Analysis indicates double decade BC mean (2.51±0.175) ×10-6 kg m-2 and increasing trend at the rate of 2×10-8 kg m-2 year-1.

Here figure 2 shows how annual mean black carbon (BC) concentrations have changed from 2001 to 2024, using observed data (black line with markers) and a LOESS-smoothed trendline (red line). Here LOESS stands for Locally estimated scatterplot smoothing, is a nonparametric method for smoothing a series of data in which no assumptions are made about the underlying structure of the data. It uses local regression to fit a smooth curve through a scatterplot of data.

Result indicates overall upward trend over 24 years from ~2.24×10^{-6} in 2001 to ~2.90×10^{-6} in 2024. Indicates a general increase in black carbon burden, especially towards the last decade. During 2001-2007, BC rises steadily from 2.24×10^{-6} to 2.65×10^{-6} which is probably due to increasing emissions (urbanization, transport, biomass burning, etc.).

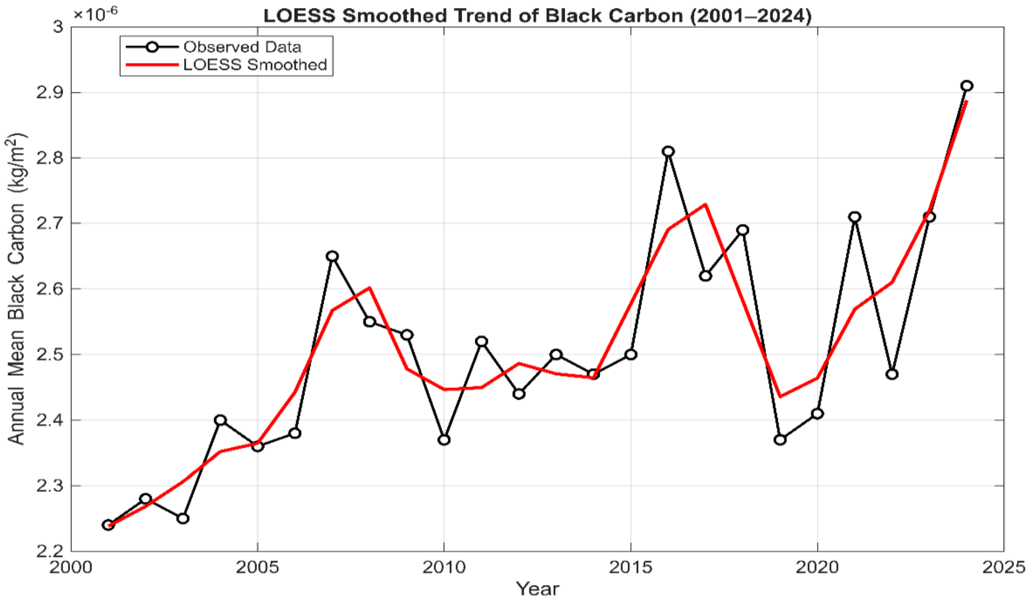

Figure 2: Annual mean black carbon (BC) concentrations have changed from 2001 to 2024, using observed data (black line with markers) and a LOESS-smoothed trendline (red line).

Now come on to the figure 3 which shows the seasonal distribution of the BC level over IGB region during 2001-2024. The highest BC is noticed during the winter season which could be attributed to strong atmospheric inversion, increased biomass burning, low boundary layer height, calm wind.

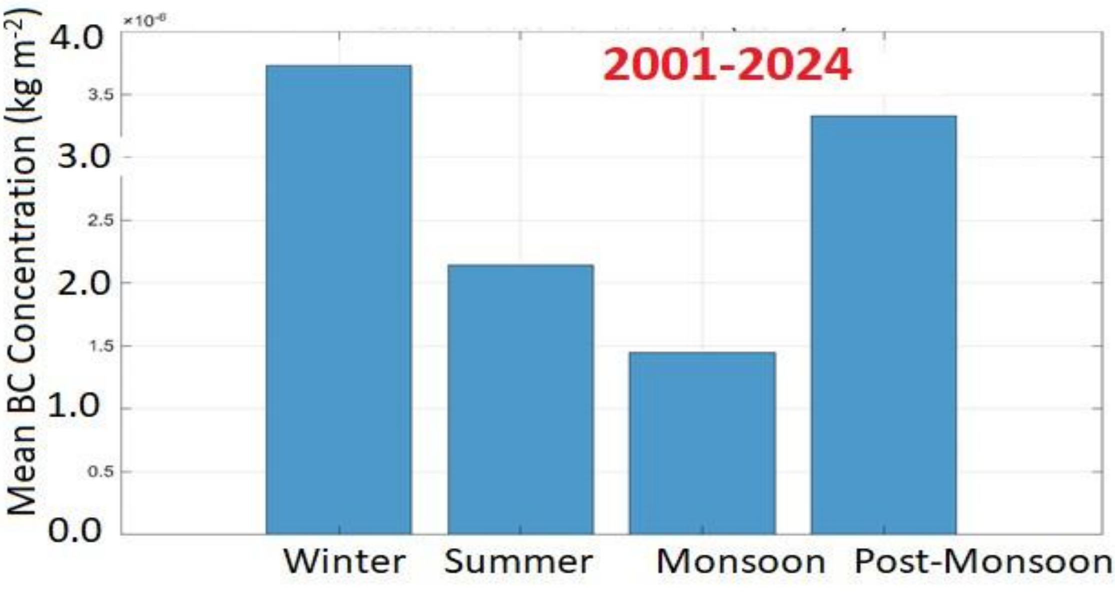

Figure 3: Seasonal distribution of BC concentration over IGB during 2001-2024. The Highest BC is noticed during the winter season.

IV. Summary & Conclusion

We analysed long-term trends in near-surface black carbon (BC) mass concentration over the Indo-Gangetic Basin (IGB) using multi-year data derived from the MERRA-2 reanalysis model. Contrary to expectations of a pronounced increase in BC loading driven by rapid urbanization, industrial growth, and intensified anthropogenic activities across the region, the surface-level BC concentrations do not exhibit a strong increasing trend over the past decade. This behavior is particularly noteworthy given the presence of a small but discernible increasing trend in aerosol optical depth (AOD) suggesting that changes in aerosol composition, vertical distribution or secondary aerosol formation may be influencing column-integrated aerosol loading without a corresponding rise in near-surface BC.

A comprehensive assessment of the long-term temporal evolution and seasonal variability of BC over the IGB was performed using MERRA-2 data. Both linear and non-linear trend analyses indicate a weak yet persistent increasing tendency in BC concentrations across the basin, although the magnitude of this increase remains modest. These results imply that emission controls, changes in fuel usage, or enhanced atmospheric dispersion processes may be partially offsetting the effects of growing emission sources at the surface.

Seasonal analysis reveals pronounced variability in BC concentrations with the highest levels consistently observed during the winter season. Elevated wintertime BC is primarily attributed to strong atmospheric inversion conditions that suppress vertical mixing, increased biomass and residential burning for heating purposes, reduced boundary layer height, and prevailing calm wind conditions. Together, these meteorological and emission-related factors favour the accumulation of BC near the surface, leading to enhanced concentrations over the IGB during winter months.

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