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A study of the long-term trend of CO_2 emission over the Indian region during 1970-2021

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Abstract

Carbon dioxide (CO_2) refers to a highly potent greenhouse gas (GHG) that is mainly a result of the burning of fossil fuels and subsequently contributes to global warming and climate change. The concern and addressal of such GHG emissions assume high importance in order to counter the effects on the environmental stability. This study analyzes the statistical trends of CO_2 emissions based on 52 years of Emissions Database for Global Atmospheric Research (EDGAR) data (1970-2021) in the context of a rapidly urbanizing environment in India. This study reveals that countries such as China, the United States of America, Russia, and India are the top greenhouse gas emitters. A linear trend analysis shows that Indian CO_2 emissions are augmenting at a faster rate compared to the global average. Fossil fuels are found to be the dominating sources of Indian CO_2 emissions, which are mainly concentrated in the Indo-Gangetic Plain and Northern India. Industrial production of electricity, heat, manufacturing industries, construction, road transport, residential sectors, manufacturing, and forest fires are identified as top-blue contributing sectors of fossil fuels. Biogenic CO_2 emissions are mainly contributed by residential sectors, manufacturing, and forest fires. This study highlights the need for focused strategies to counter climate change.

Keywords: CO_2 emissions, Climate change, Emission trends, Mitigation strategies, India, Fossil fuel emissions, Biogenic emissions, EDGAR, Sectoral

1. INTRODUCTION

Carbon dioxide (CO_2) is a major greenhouse gas contributing significantly to global warming and climate change. Most of the anthropogenic greenhouse gas emissions (GHG) originate from land use changes, industrialization, burning of fossil fuels or emissions of CO_2. Due to industrialization and economic growth, there has been a surge in GHG emissions worldwide in the early 21st century, thus intensifying the natural greenhouse effect and endangering human health along with the ecosystem (Ripple et al. 2014; UNEP report, 2020). Hence, this requires a more effective climate action to meet the targets set by the international community (Dubash et al., 2018; Rogelj et al., 2018; Ritchie and Roser, 2020; Friedlingstein et al., 2022). Although the COVID-19 pandemic caused an interim drop in emissions (Le Quéré et al., 2021; GCP report, 2021), world emissions increased again, approaching pandemic levels and exceeding 54Gt CO_2 equivalent in 2022 (EDGAR Report, 2023).

The rapidly increasing energy consumption in India has contributed to significant CO_2 emissions, mostly from the transportation, iron and steel, and power generation sectors (Sharma et al., 2006; Garg et al., 2017). According to Li et al. (2017) and Chen et al. (2019), India's CO_2 emissions increased by more than twenty percent between 2006 and 2010. Agriculture practices continue to be a contributing factor in CO_2 emissions, even with the significant decoupling between GDP development and emission rise (Raihan and Tuspekova, 2022). Throughout much of the previous century, Western industrialized nations predominantly drove the demand for hydrocarbons. There has been a paradigm shift, with China, India, and Japan at the forefront of driving hydrocarbon demand in the Asian region (Ahmed et al., 2023). India's dependence on coal has contributed to a steep increase in power consumption, surpassing economic growth and having a strong impact on the environment (Gilfillan and Marland, 2021). As one of the major carbon emitters, India has to balance its energy needs with environmental issues, taking into consideration future estimates and emission trends (IEA report, 2021).

In consideration of long-term climate goals, it is assumed by Crippa et al. (2022) that specific mitigation measures play a pivotal role. These assumptions are supported by bottom-up data datasets from the Emissions Database for Global Atmospheric Research (EDGAR) on mitigation measures. Global action illustrates the vision for global climate action, like the EU's targeted reduction goal of CO_2. In a bid to offer specific mitigation measures for proper environmental management, estimates on the level of CO2 emissions by India have been

considered on long-term trends including their spatial seasonal distribution, and sectoral contributions.

2. DATA SOURCE AND METHODOLOGY

EDGAR is a major global dataset, which is an objective and key tool monitoring systematically and scientifically emissions of atmospheric pollutants and anthropogenic greenhouse gases. Its uniqueness is derived from making autonomous estimates, which go beyond the requirements of officially reported data of European Member States or UNFCCC Parties. EDGAR exercises these estimates using international statistics along with consistent application of the IPCC method. Its coverage scope is higher than national aggregated emissions, as it presents grid maps at a global geographical resolution of 0.1 x 0.1 degrees, which is accessible on the EDGAR website portal (https://edgar.jrc.ec.europa.eu/). In-depth comprehension of emissions is facilitated by this resolution system, which varies from yearly compilation (1970-2021) to more intricate resolution levels on a monthly or hourly basis.

This study carries out a detailed assessment of the global and India's CO_2 emission comparisons and the bio and fossil fuel sectorial based contribution following the IPCC guidelines and classification (Table1) for the year 2006 and the most recent country-specific emission factors (Lohan et al., 2024). This new version provides the upgrade dataset, EDGARv7.0, that is a joint effort by the Joint Research Centre (JRC) and the International Energy Agency (IEA), aiming to provide harmonized estimates for CO_2 emissions resulting from the combustion of fossil fuels. Greenhouse gas emissions assessment with respect to sectors and countries is comprehensively taken care of within this version. Graphical representation of the trend is enabled with the level of detail for the EDGAR data that provides homogeneous estimates for the global emission sector. Various methods such as mean, root mean square error, and standard deviation have been used (Kumar et al., 2021, 2024; Verma et al., 2023). Moreover, the temporal and spatial trend analysis rate of change with respect to the space and time taken and the latitudinal and longitudinal mean have been calculated by Kumar et al., (2022, 2025). To calculate the concentrations of CO_2, statistical measures (Hyndman and Athanasopoulos, 2018; Kumar et al, 2021, 2023, 2024 Verma et al, 2023) have been used. These measures include Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Pearson Correlation Coefficient (R); offer diverse information regarding the accuracy, bias, efficiency. In addition, spatiotemporal variability of CO_2 emissions over India was analyzed using Empirical Orthogonal Function (EOF) decomposition (Lopez et al. 2022) for the period.

The analysis identifies two dominant modes of emission variability. Principal Component Analysis (PCA) was also used to identify dominant modes of CO_2 variability, and environmental drivers were included. The covariance matrix, eigenvalues, eigenvectors, explained variance, and principal component scores were calculated to improve understanding of the key variables that control regional climate trends and CO_2 emissions. Overall, there will be a brief discussion in the next results and discussion section below.

3. RESULTS AND DISCUSSION

This study aims to investigate CO_2 emissions in India, filling data gaps and informing specific mitigation actions towards long-term environmental management. This caused a dramatic increase in global warming during the industrial era, stressing the need to decrease CO_2 emissions quickly and equally to prevent near-term warming as well as mitigate air pollution (Le Quéré et al., 2021; Crippa et al., 2022). Previous studies (Gerber et al., 2013a, b; IEA report, 2021) reveal that the global GHG emissions are comprised of 72% CO_2 from fossil fuel combustion, 21% methane (CH_4), 5% nitrous oxide (N_2O), and 3% from F-gases. Per capita GHG emissions are thereby increasing annually with China, the USA, the European Union, Russia, India, Brazil and the United Kingdom (UK) as the prime emitters of CO_2 gas (Crippa et al., 2022).

3.1 Analysis of CO_2 Emissions by Major Country-Based Contribution

The present study provides a comprehensive analysis of 52-year trends and highlights the major contributions over various countries. **Figure 1,** portrays the notable contribution of different countries spanning from 1970 to 2021. **Figure 1a**, represents the mean contribution of CO_2 emissions in Asian countries while **Figure 1b**, shows the top-20 CO_2 emitting countries. Also, the spatial distribution illustrates the varying contributions and responsibilities of different nations to the overall global CO_2 emissions landscape, and variations in causative nations over the mentioned period. China and the USA together account for over 50% of the top five global emitters, which is nearly double the contribution of other major emitters like Russia, India, and Japan.

The current analysis demonstrated that the worldwide higher contributors (in million tons, or Mt) are China (~200 Mt), USA (~190 Mt), Russia (~80 Mt), India (~60 Mt), and Japan (~40 Mt). The European Union is not considered alone in our study. Moreover, in terms of

contributions within Asia, China accounts for less than 44% of emissions. Other significant contributors include India (15%), Japan (~10%), Indonesia (~5%), and Saudi Arabia (~4%) which contribute significantly due to deforestation and oil-based economies. Other major emitters include Pakistan (2.4%), Kazakhstan (2.1%), Thailand (1.2%), Turkey (1.2%), and the United Arab Emirates (1.2%). They are the major contributors to industrial development, fossil fuel reliance, and urbanization, and the remaining nations in Asia contribute a total of 7.7% under the others section. It highlights the dominant role of China and India in regional and global emissions and the urgent need for sustainable mitigation policies. The present study provides deeper insights into the Indian region to understand the major scenarios of contributions and increasing trends over the past few decades. It also includes the spatial and temporal trends, both annual and monthly and delves into sectoral source variations, comparing global trends with those specific to India over the mentioned period.

3.2 Spatiotemporal Analysis of CO_2 Emissions over India

Our study provided insights into the spatial and temporal variations in the contributing world vs. India over the specified study period (**Figures 2-4**). The rate of change in emissions per unit area was estimated by mean annual variations and long-term trends for both India and the global regions. In addition, the latitudinal and longitudinal distribution of emissions was assessed by investigating variations within latitude bands to identify major contributing regions. This detailed estimation illuminates growth, decline, and major emission-contributing sectors over time. **Figure 2**, demonstrates the spatial representation allowing for a nuanced examination of how CO_2 emission variability (in terms of flux, scale 10^9 $kg.m^{-2}s^{-1}$) has evolved on a world scale (Figure 2a) and the Indian region (Figure 2b).

The present study also **(Figure 3)** demonstrates the variation in per year CO_2 emissions over Indian region. Figure 3a illustrates the mean annual changing rate per year (kg/m^2s per year, scaled by 10^9) estimation over Indian region and Figure 3b represents the annual mean latitudinal variation of CO_2 emissions ($kg/m^2 \cdot s \cdot yr$, scaled by 10^8) over Indian region (considering 5-40 °N latitudinal range), drawing a comparative analysis between the hotspot regions over Indian domain. It also gives the spatial distribution of the mean annual rate of change of CO_2, showing hotspots of increasing emissions, with the most concentrated over the Indo-Gangetic Plain and Northern and eastern India, indicating faster urbanization and industrial processes there. In addition, the study shows the variability in annual zonal mean

CO_2 emissions plotted against latitude, revealing distinct latitudinal peaks between approximately 20°N and 27°N, which correspond to major emission belts across central and northern Indian urban-industrial corridors.

A comparative analysis illustrates the annual trends (both show increasing trends) of CO_2 emission (in Mt, **Figure 4**) drawing between the global (scale of 10^3, Figure 4a) and Indian (scale of 10^2, Figure 4b) regions. The results suggest an increase in the trend of both and a maximum at 2021 base GDP criteria for the mentioned period. It is also notified that in 2020 due to the COVID-19 scenario the world and India had the least emissions (both showing decreasing trends) as compared to other recent years (Le Quéré et al., 2021). The investigation also complements using EOF decomposition of gridded CO_2 emissions over India variability into two dominant modes that together explain the primary variance in emission dataset. Basically, EOF1 captures large-scale national emissions, while EOF2 represents emerging localized variability. In EOF1 (Fig. 10a, b), which explains the spatial pattern, there is a distinct north-south gradient, with negative values in peninsular and central India and positive values in the north. In time series, it shows changes from negative values in the 1970s, peaking in 2005 (~3×10^7), and then falling off sharply with increasing randomness from 2010 onwards, because of various policies and the pandemic, indicate that there is systematic regional variation in Indian CO_2 emissions due to regional patterns of industry and urbanization. EOF2 (Fig. 10c, d), explaining the second major localized pattern of CO_2 emissions, is characterized by a heterogeneous spatial distribution over central and eastern India. Initially, it remained stable up to 2010, followed by an abrupt but steep exponential growth from 2020, with the highest amplitude (~$4 - 5 \times 10^7$) over the entire period, as well as novel regional hotspots that have accelerated lately, necessitating differential regional responses tailored to these varied patterns in Indian emissions. These two modes suggest that CO_2 emissions released by the Indian subcontinent are following the pattern of industry and urbanization at the regional level (EOF1), while new hotspots with increasing intensity over the years are also present (EOF2). Thus, the need for regional treatment strategies differs according to the pattern of CO_2 emissions by India.

According to the EDGAR classification, CO_2 emissions are categorized into biogenic sources (e.g., biomass burning) and fossil fuel-based sectors (e.g., energy, transport, and industry), which helps in targeted mitigation analysis. These categorizations are also discussed

further in the results sections to highlight sectoral emission trends. In addition, results also suggest the monthly mean variation for the world and India for the same time period (**Figure 6**). Figures 6a and 6b give the monthly variability in the mean CO_2 emission of the world and India. Increased values are predominantly observed for January-March and November-December months for the globe (Figure 6a, scale of 10^4) and December-January months for Indian regions (Figure 6b, scale of 10^3) respectively. CO_2 emissions fluctuations on a monthly basis can provide significant details for informed decision-making for successful environmental management plans (Scarpelli et al. 2020). This study emphasizes CO_2 climate impact, especially in India's estimation of landfill emissions and the contribution of animals. The above analysis indicates emission trends, with the energy and agricultural sectors being the principal emitters. It also shows that the greatest anthropogenic source is agricultural use, contributing about one-quarter of emissions, and the energy sector, which includes emissions from coal, oil, natural gas, and biofuel (Jha et al, 2011; Kumari et al, 2014; Tongia and Gross, 2019).

The seasonal CO_2 emissions data over India present a 19% winter peak (4.59 Mt CO_2) relative to its pre-monsoon minimum (3.86 Mt CO_2), with the highest statistical variability in winter (coefficient of variation: 5.9%; **Table 2**), indicating episodic emission events driven by agricultural residue burning and fluctuating heating demand within the season (**Figure S1**). These atmospheric dynamics reveal winter boundary layer inversion that traps CO_2 close to the surface due to stable meteorological conditions, contrasted with enhanced vertical mixing and precipitation-induced washout effects during the monsoon period that maintain relatively steady emissions at 3.92 MtCO_2. The least variability occurs post-monsoon (CV: 1.3%), which points toward a consistent pattern of emissions in the atmospheric transition period; similarly, the gradual increase from pre-monsoon to post-monsoon (3.86 → 3.95 MtCO_2) reflects a systematic buildup of the seasonal cycle to its peak in winter months. Thus, the increase in winter CO_2 correlates with the peak agricultural burning season following kharif crop harvest, biomass combustion for space heating in northern India, the increased demand for fossil fuel, and reduced atmospheric dispersion capacity manifested by shallow mixing heights and frequent temperature inversions that commonly mark the Indo-Gangetic Plain throughout the winter season. The winter spike correlates with peak agricultural burning season following kharif crop harvest, increased biomass combustion for space heating in northern India, and enhanced fossil fuel demand, compounded by reduced atmospheric dispersion capacity due to

shallow mixing heights and frequent temperature inversions that characterize the Indo-Gangetic Plain during winter months. This seasonal emission pattern demonstrates the critical interplay between anthropogenic sources (biomass burning, heating) and meteorological controls (boundary layer dynamics, precipitation patterns), with implications for both regional air quality management and carbon cycle modeling, as the winter emission maximum coincides with periods of poorest atmospheric ventilation capacity. The recent years have seen a tremendous increase in CO_2 emissions, with bio (Dornburg et al., 2007; Ingale et al., 2013; Smith et al., 2016; Joshi et al., 2017) and fossil fuel combustion (Jackson et al., 2018, 2019; Friedlingstein et al., 2022) consequently being the leading causes.

3.3 India's Analysis of Bio and Fossil Fuel Sectorial Contribution to CO_2 Emissions

The sectoral emissions of the bio and fossil sectors of the global mean CO_2 emissions of the world and India for the same period are shown in Figures 7-10. The data set outlines the linear trends of CO_2 emissions from fossil and bio-origins in Figure 7, with a general timeseries contrast between the global perspective (Figure 6a, scale of 10^2Mt and Figure 6c, scale of 10^3Mt) and within India (Figures 7b, scale of 10^1 and Figure 7d, scale of 10^2). **Figure 7** also suggests that both the bio (**Figure 7 a, b**) and fossil fuel (**Figure 7 c, d**) sectorial contribution to CO_2 emissions, the time series plot shows a continuous increase in the trend (Crippa et al., 2022). Emissions of both fossil and biogenic CO_2 have been rising gradually for both the global and Indian areas between 1970 and 2021. India's biofuel emissions rose faster than the global rate, and fossil emissions in India also slightly outpaced global growth, highlighting India's relatively sharper emission rise over the 52 years. However, in the year 2020, there was a sudden decrease due to the COVID-19 pandemic scenario, which resulted in reduced human activities and consequently lower emissions worldwide compared to other recent years (GCP report, 2021).

This report under the 2006 IPCC Guidelines, provides a comprehensive assessment of the CO_2 emissions in India, showing a remarkable alteration in their proportion of the nation's total greenhouse gas emissions. The EDGAR dataset separates the bio and fossil fuel emissions and also estimates them based on the sectoral contributions and main sources, providing a more nuanced picture of emission trends over the past 52 years for India as well as global regions. **Figure 8** delves into the details, presenting a bio source contributions (in Mt %) for both global and Indian regions, respectively, based on the 52-year mean from 1970 to 2021. Biomass

burning, ROS, MIC, and EHP emerge as leading sources in both cases but have more significant contributions within India,(Figure 8a, b). The dominance of the residential sector, which accounts for 41.2% globally and 43.9% in India, is significantly due to biomass combustion for cooking and heating, while the significant contribution to manufacturing, 38.5% globally and 26.3% in India, is indicative of biofuel use in the course of several industrial processes and productions of bio-based materials. The biomass burning sector accounts for another major source, especially in developing countries like India, at 10.5%, where open burning of agricultural residues and forest fires are also identified as direct sources of CO_2 emissions and secondary organic aerosol formation. The analysis of biogenic CO_2 emissions depicts a highly concentrated sectoral distribution dominated by residential and other sectors (ROS) and manufacturing industries and construction (MIC), which cumulatively hold about 80% of the global biogenic emissions on a logarithmic scale (**Figure S2**) ranging from 10^1 to 10^7 Mt annually. The logarithmic pattern describes that the transport sectors-road, rail, aviation, and water-borne-each account for less than 15% of the combined share of biogenic CO_2 attributable to transportation and stationary sources, highlighting the current limited penetration of biofuels in transport applications. The number of active sectors is smaller in India's emission profile compared to the global distribution, suggesting either a lower adoption of biofuels in a few industry sectors or different strategies in energy mix, with a very negligible contribution to electricity and heat production from biogenic origins at 1.4% against the major dominance of fossil fuels, while oil and natural gas sectors show the minimal presence of biogenic sources, pointing toward the minimal integration of biogas into existing petroleum infrastructure(Smith et al., 2016).

Moreover, the comparative analysis in **Figure 9** further elucidates this variability, distinctly highlighting the sectorial contribution of fossil fuel CO_2 emissions worldwide and over the Indian region. Figures 9a and 9b present a representation of the various sources of fossil contributions in Mt (%) for the 52-year mean (1970–2021) period for global and Indian contributions, respectively. In Figure 9a (Global), the dominant sources contributing to fossil fuel emissions are EHP, MIC, RTNR, and ROS, while Figure 8b illustrates these sources as leading contributors for India, although their rank varies in terms of magnitude. CO_2 emissions from fossil fuels show a dramatically different sectoral composition compared to biogenic sources, with EHP dominating by a wide margin in both the global (42.1%) and Indian (44.4%)

emission profiles, reflecting the heavy dependence on coal, natural gas, and oil for power generation across logarithmic scales (in **figure S3**) of 10^1 to 10^8 Mt annually. The manufacturing industries and construction sector is the second-largest emitter at 21.0% globally and 23.5% in India, mainly from industrial process heating, cement, and steel manufacture. Then comes RTNR, responsible for 18.0% of global and 12.8% of Indian total emissions through the direct combustion of gasoline and diesel fuels. The concentration pattern is far less extreme than in the case of biogenic emissions, with the top four sectors accounting for 96.1% of global fossil fuel-based emissions, reflecting greater sectoral diversity in the use of fossil fuels compared to biomass sources. From a global perspective, the pattern of India's emission inventory is very similar to the global profile but has a disproportionately large contribution from the electricity sector and lower transport-related emissions, indicating different stages of energy infrastructure development and urbanization; industrial processes are emissions from PR, CI, and MI, representing heavy industries that depend on fossil fuels not only for energy but also as chemical feedstocks in petrochemical conversions. This study highlights the importance of sectoral and spatial hotspots in India that have been identified from previous studies(Dornburg et al., 2007; Peters et al., 2020).

Based on the combined analysis of CO_2 emissions across sectors with multipliers applied in **Figure 10**. The data show marked heterogeneity in the emission pattern and fuel dependencies across different economic sectors. Fossil fuel emissions (red color) are dominant in the overall profile, contributing about 67.2% compared to only 32.8% by the biogenic fraction (green color), which means the fossil fuel dominance is 2:1. The highest-emitting sector includes EHP, MIC, and CY, with 540 Mt total, 640 Mt, and 280 Mt, respectively. Further breakdown of the highest-emitting sectors reveals a mixed profile for EHP-150 Mt for the biogenic sector and 390 Mt for the fossil fuel sector-whereas MIC shows almost equal contributions, with 320 Mt each. Third, many sectors have pure fuel-type dependencies, with some sectors such as RTNR, ONG, and BB being pure biogenic, representing carbon-neutral biomass combustion and natural processes. Other sectors like PR, CARTNR, RWBN, CY, and L are purely fossil fuel-dependent, reflecting heavy industrial processes, transport, and energy generation. Lastly, there is three orders of magnitude variation in the span in terms of emission intensity from quite low values in GPOU to more than 400 Mt in major emitters, indicating greatly differing carbon footprints and decarbonization potentials across economic sectors.

This heterogeneous distribution indicates that targeted mitigation efforts need to focus on high-emission sectors while considering the feasibility of fuel switching in mixed-dependency sectors versus efficiency improvements in the fossil-dependent sectors.

The results analysis, based on the EDGAR CO_2 emissions data of India's bio sector, show a striking concentration of the sector's emissions in two dominant sectors, together responsible for 680 Mt CO_2 per year. ROS is the number one contributor, at 370 Mt CO_2 (54.4%), while MIC follows with 275 Mt CO_2 (40.4%), creating a 94.8% emission footprint from only two sectors (Table2). This reflects the wide use of biomass burning in residential cooking and heating across rural India, where access to clean cooking fuels is still restricted, combined with significant industrial biomass use in the country's manufacturing processes-including cement, steel, and bricks. The scientific significance lies in this disproportionate concentration of emissions. Contrasting this, Energy for Heat Production provides only 25 Mt CO_2 (3.7%). In addition, Road Transport Non-Road and Oil & Natural Gas each contribute about 10 Mt CO_2-an overall contribution of 1.5%. Such overwhelming dominance of residential biomass combustion reflects incomplete combustion efficiency and very poor air-fuel mixing conditions typical of traditional cookstoves and open burning practices. Biomass Burning (BB) is estimated to be about 125 Mt CO_2 (18.4%). This likely reflects agricultural residue burning and forest fires, releasing stored carbon rapidly and contributing both to climate change and air quality degradation. Therefore, targeted interventions in residential energy access and waste management in agriculture might potentially reduce India's bioCO2 emissions by more than 70% through improved cookstove technologies, cleaner fuel transitions, and sustainable agricultural practices.

CONCLUSIONS

This present study offers a holistic perspective of CO2 emissions in India, within the broader effort of climate change mitigation through global cooperation. The conclusions are highlighted in the sections that follow.

(i) The study highlights the relevance of greenhouse gases and their emission on a monthly and yearly basis within the past years. It states that major emitters of greenhouse gases, such as China, the US, and India, must lower their emissions to counter global warming.

(ii) Emissions of CO_2 in India have been studied, where the main source of the emissions has been identified as fossil fuels, especially in high-emitting areas like the Indo-Gangetic Plains and Northern India. CO_2 has been established as a key player in rising global temperatures since the Industrial Revolution.

(iii) In the analysis, the variation in the mean value of the global as well as the regional level of CO_2 emissions monthly has been established.

(iv) The study provides insights into variations in emissions, differences in regions on a spatial level, contribution of various sectors, and major biofuel and fossil fuel emissions in India. It is observed that the biofuel and fossil fuel emissions in India are rising at a comparatively faster pace than the global emissions.

(v) The current study shows electricity and heat production (EHP), manufacturing industries and construction (MIC), and road transport are major sources of fossil carbon dioxide (CO_2) emission worldwide and in India, whereas the major contributors of biogenic CO_2 emission are ROS, MIC, BB at global and Indian levels, respectively. Similarly, in the Indian context, ROS, MIC, BB, are major sources of biogenic CO_2 emission.

(vi) Current studies underscore the relevance of continued observation and anticipatory action for CO_2 emission reduction. This is with particular significance to their profound climatic repercussions. The present work is useful for the formulation of specific strategies for the reduction of such emissions in the ever-changing Indian landscape. This is very crucial to environmental sustainability.

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Author Credit Statement

Subodh Kumar and Pratyush Mishra conducted all the analysis, designed the study, and were responsible for data acquisition, analysis, interpretation, and paper writing. Subodh Kumar significantly contributed to conceptualization, methodology, and manuscript writing. Subodh kumar improved the introduction, results and discussion of the manuscript, and strengthened the concept of presentation.

Data Availability

EDGAR is a gridded monthly and annual data sets which is available at the web portal (https://edgar.jrc.ec.europa.eu/)

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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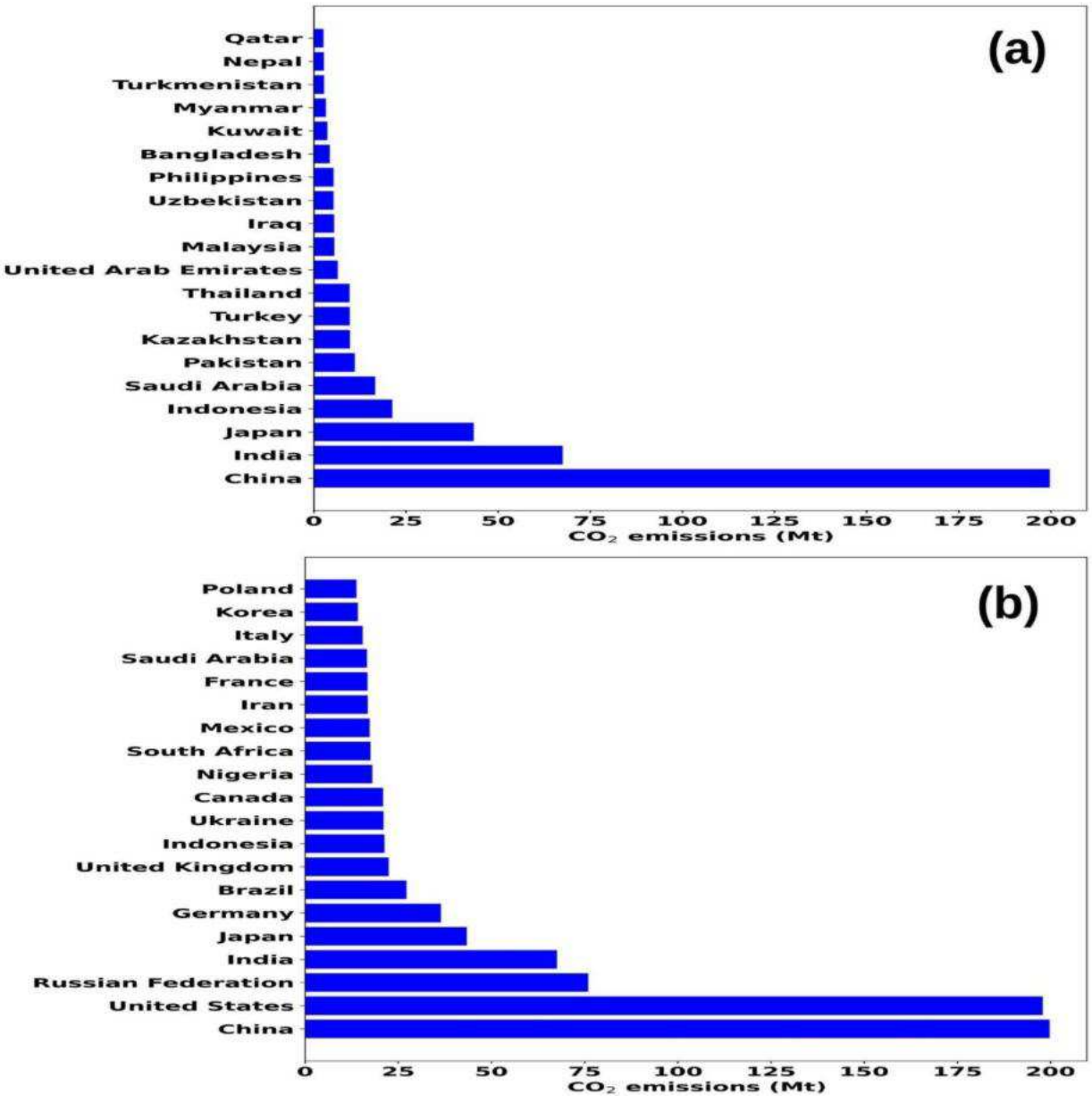
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583

584 **Figures list**

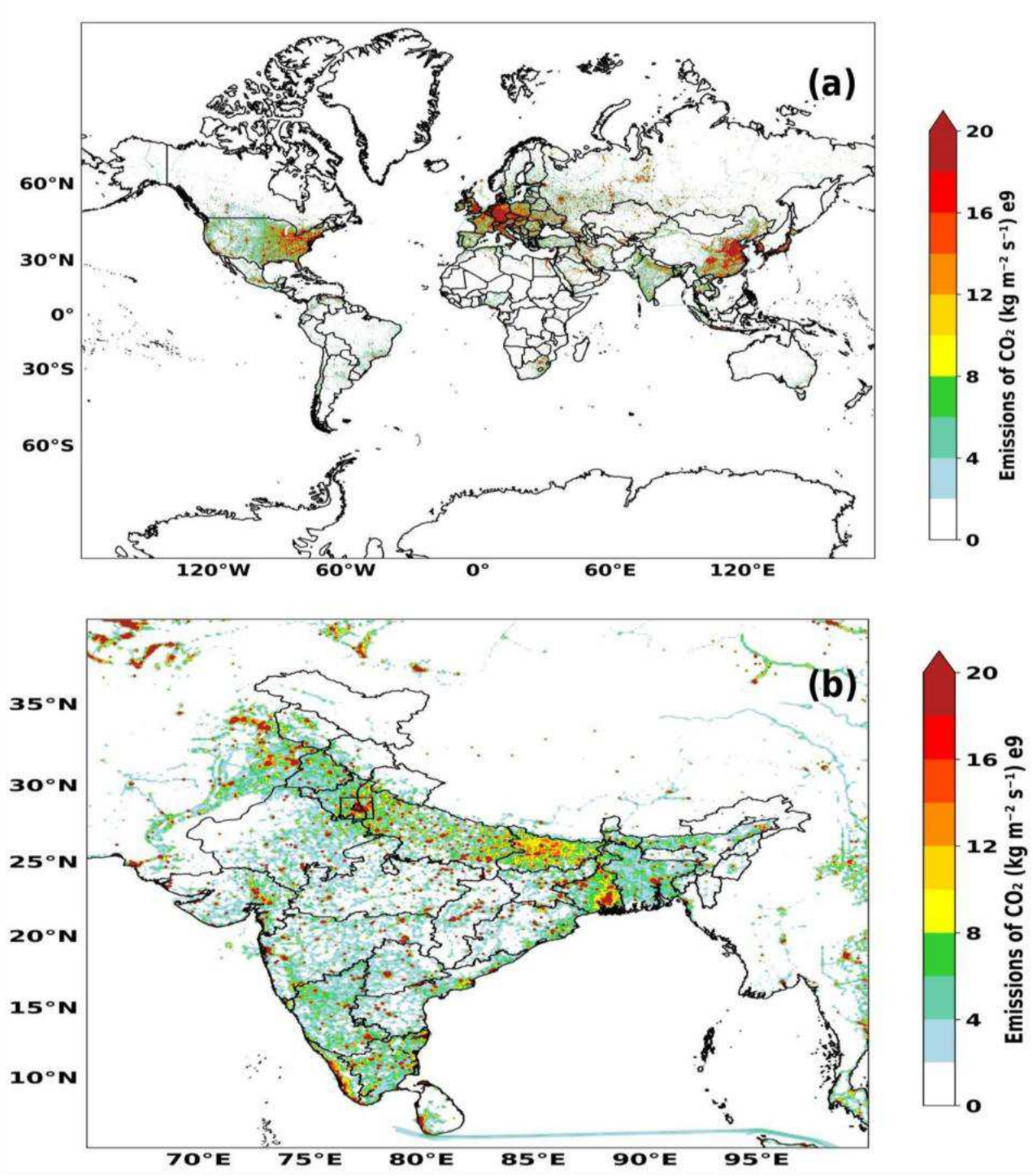


585

586 **Figure 1.** Major contributions to the 52-year mean CO_2 emissions (in Mega tonnes, Mt): Top

587 20 countries in (a) Asia and (b) the world.

588



589

590 **Figure 2.** Spatial variation of mean CO_2 emissions (kg/m²·s, scaled by 10^9 (or -e9)) over (a)
591 the world and (b) India, for the mentioned period 1970–2021.

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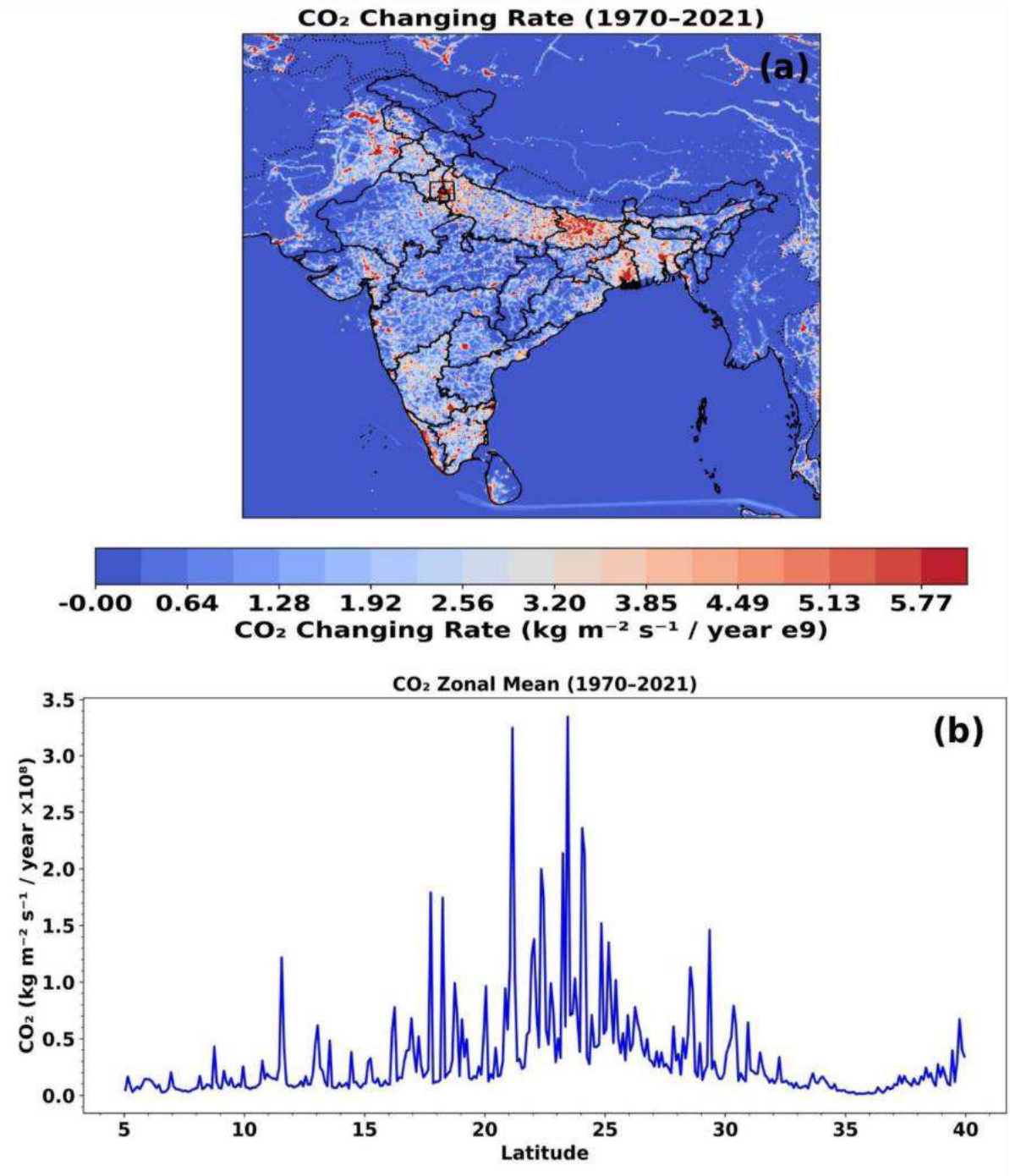
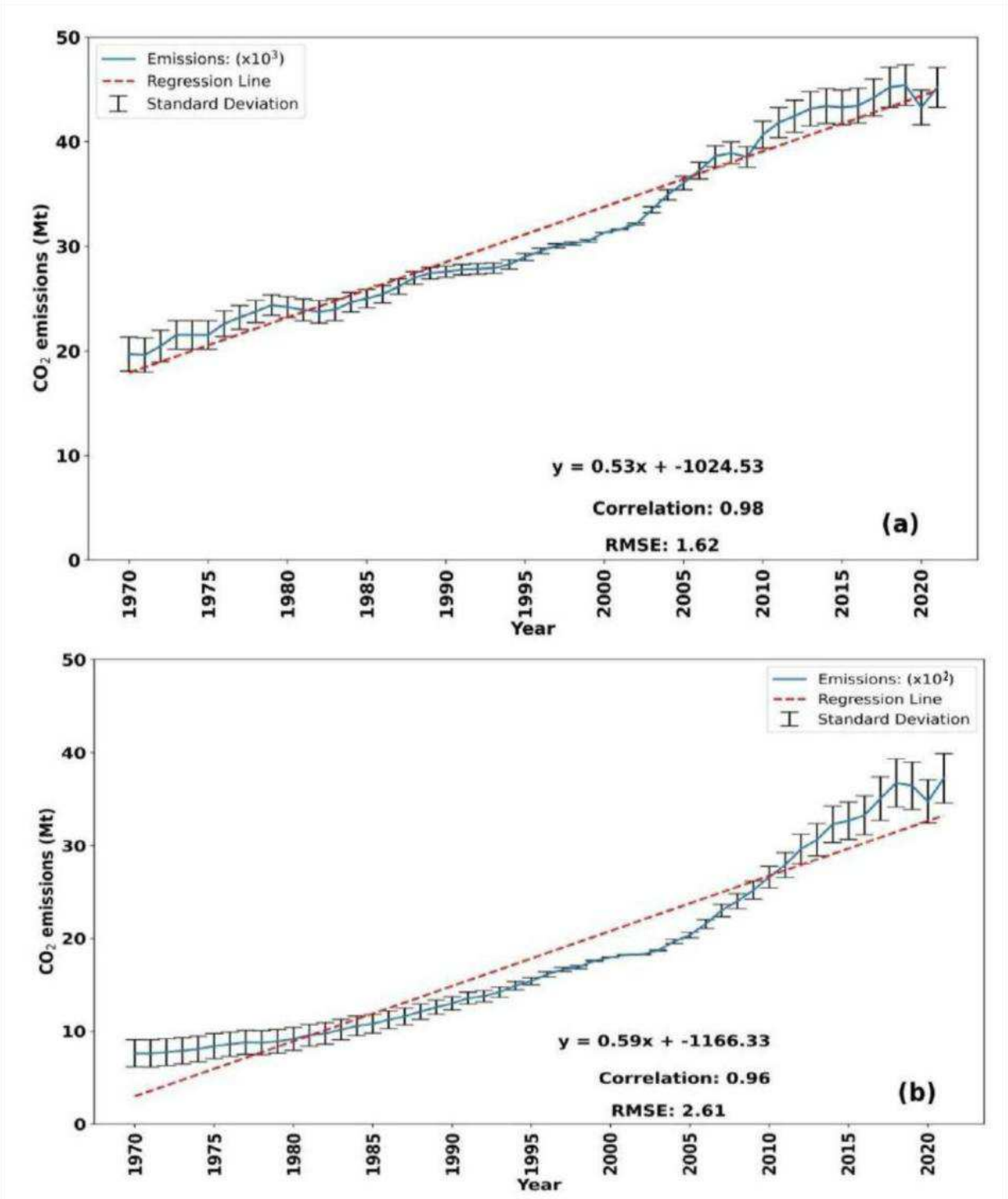


Figure 3. Annual variation of CO_2 emission rate per year over the Indian region: (a) Spatial rate of change estimated (units: kg/m²·s·yr, scaled by 10^9 or e9), and (b) Latitudinal distribution of the zonal mean annual CO_2 emission rate (units: kg/m²·s·yr, scaled by 10^8).



597

598 **Figure 4.** Comparison of annual temporal trends in CO_2 emissions (in Mt) for (a) the world
599 (scaled by 10^3, considering all countries) and (b) the Indian region (scaled by 10^2).

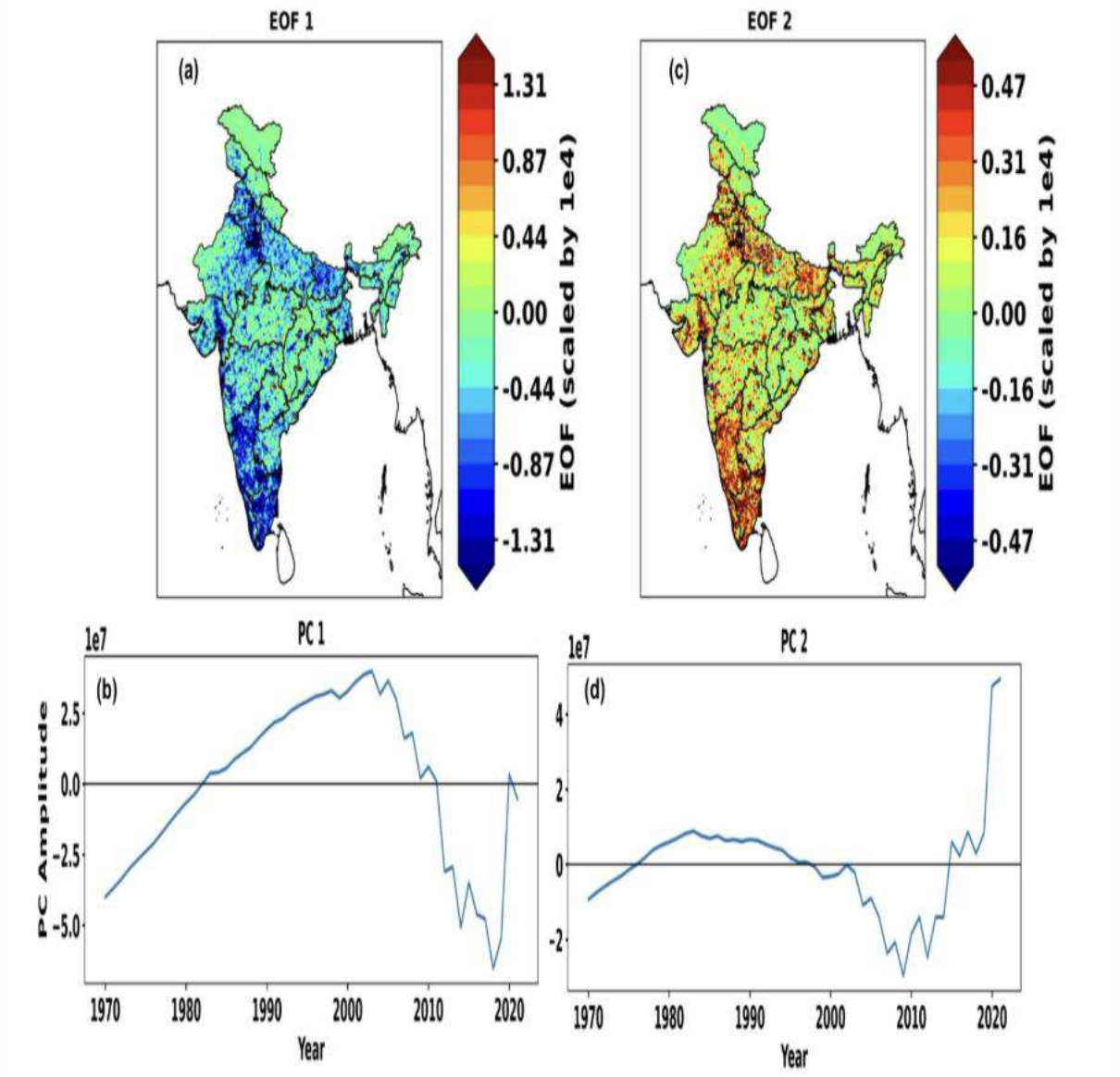
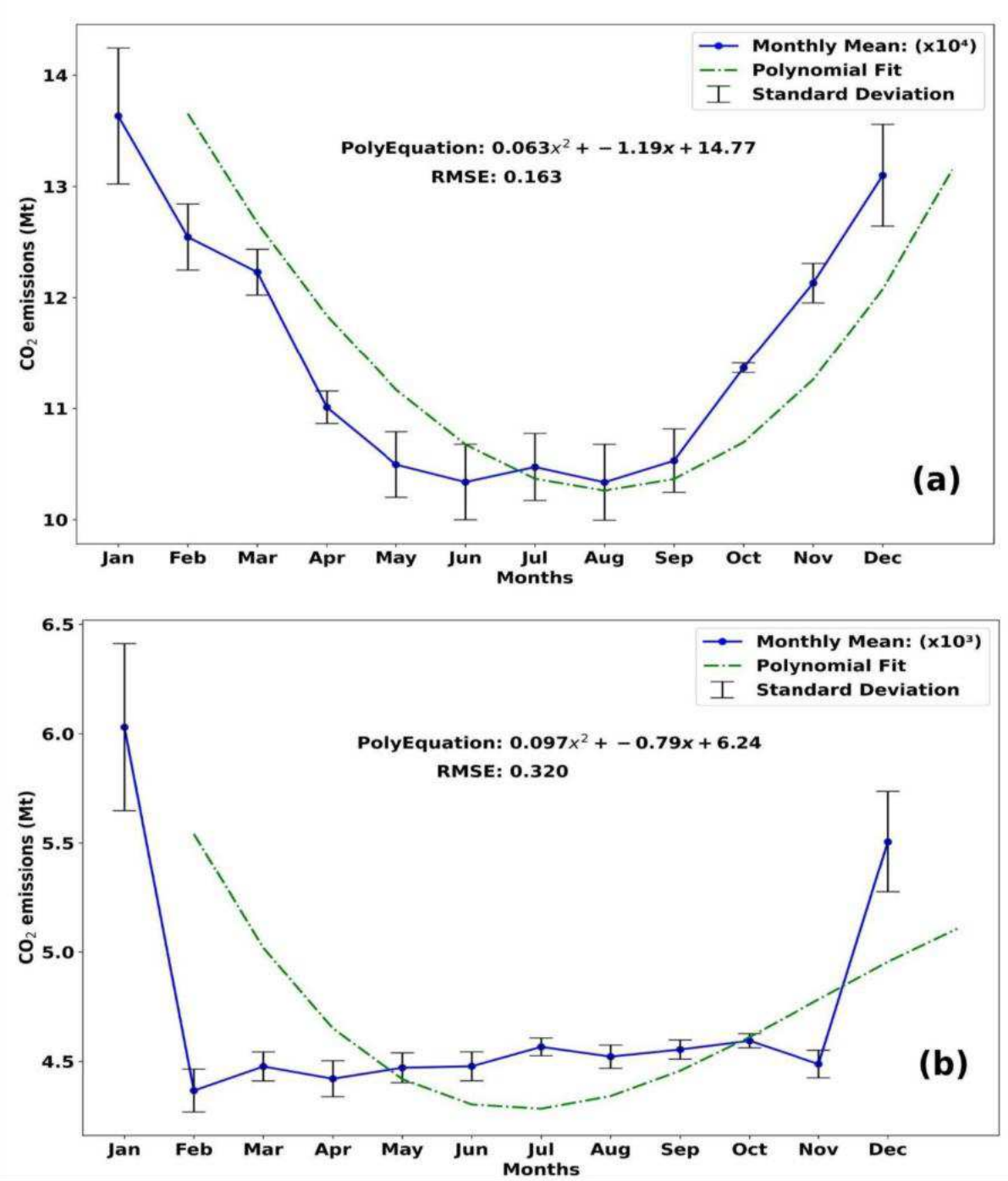


Figure 5. EOF decomposition analysis of CO_2 emissions over India for 1970–2021. (a) Spatial pattern of EOF1 and (b) its corresponding principal component (PC1) analysis. (c) Spatial pattern of EOF2 and (d) its corresponding principal component (PC2) analysis. EOF loadings are scaled by 10^4. PCs represent the temporal evolution of the respective modes.

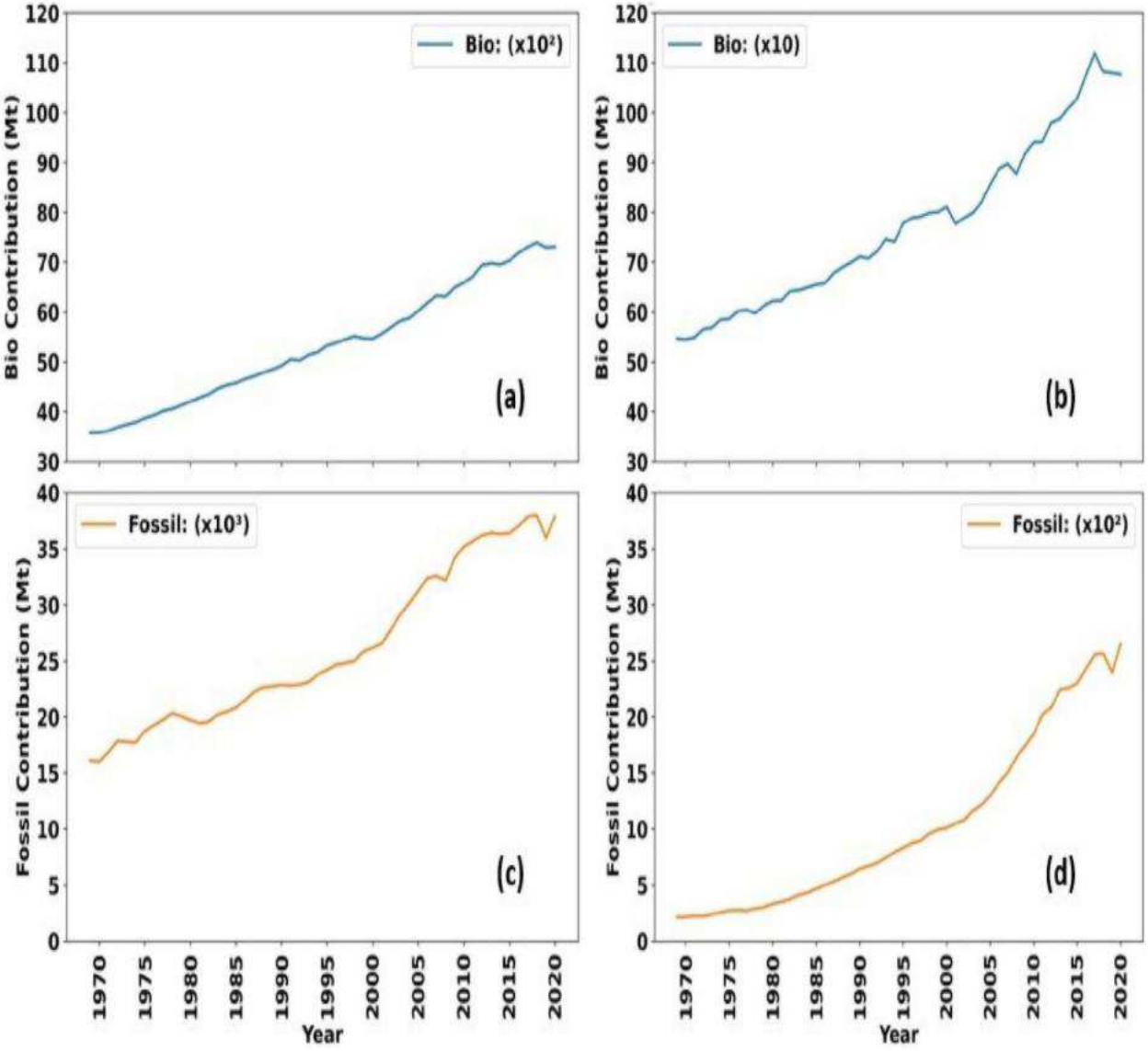


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607 **Figure 6.** Comparison of monthly variation in CO_2 emissions (in Mt) for (**a**) World (scaled
608 by 10^4) and (**b**) the Indian region (scaled by 10^3).

609



610

611 **Figure 7.** Comparison of annual mean temporal trends in overall biogenic (biofuel) and fossil
612 fuel CO_2 emission contributions (in Mt) for: (a, c) the Global region (scaled by 10^2 and 10^3,
613 respectively), (b, d) Indian region (scaled by 10^1 and 10^2, respectively).

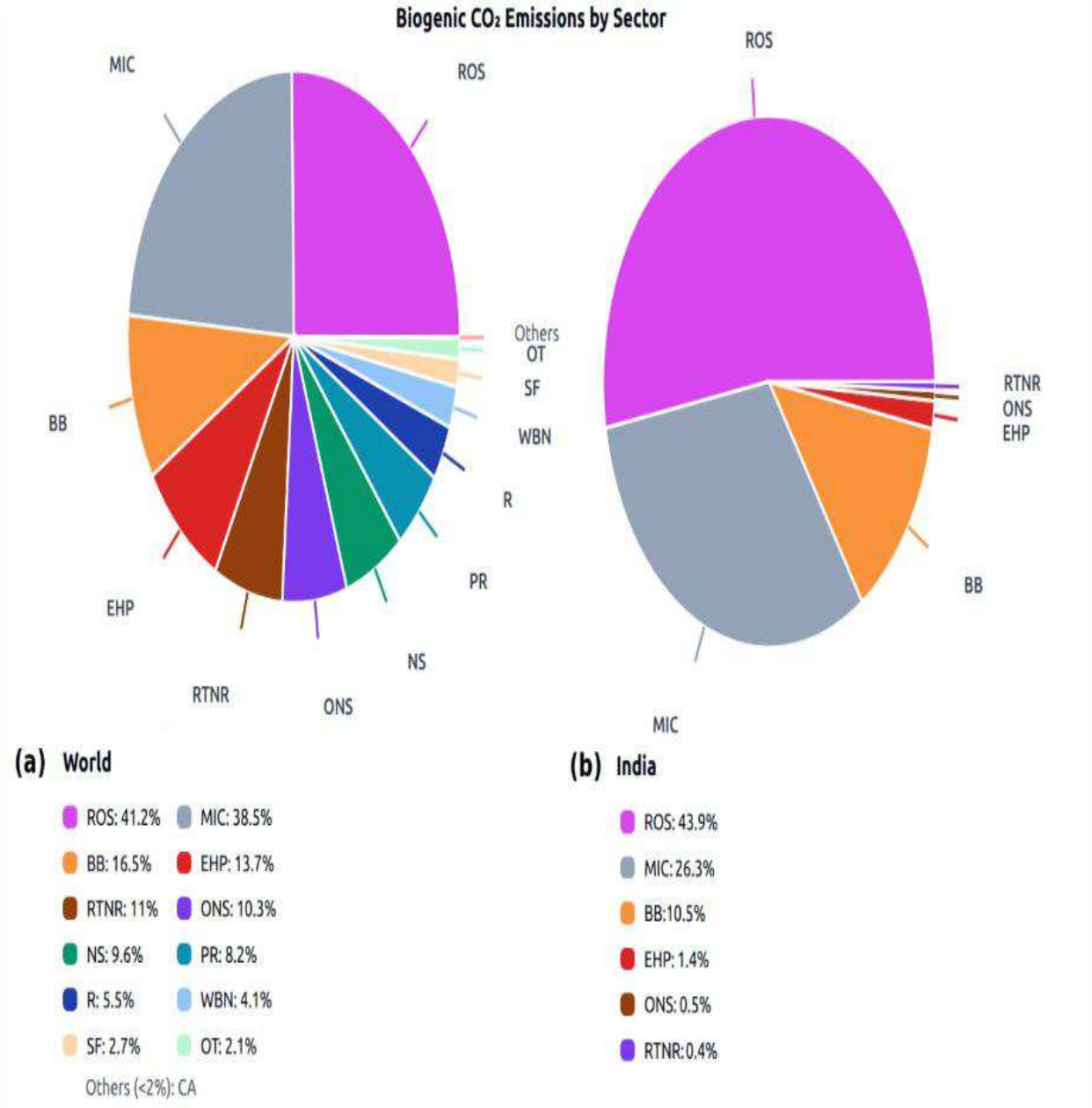


Figure 8. Comparison of the annual mean biogenic (or biofuel) CO_2 emission sectoral contributions (%) for (**a**) the World and (**b**) India.(where: **ROS:** residential and other sectors; **MIC:** manufacturing industries and construction; **BB:** biomass burning; **EHP:** electricity and heat production; **ONS:** oil and natural gas and **RTNR:** road transportation and no resuspension **NS:** non-specified; **PR:** petroleum refining; **R:** railways; **WBN:** water-borne navigation; **SF:** solid fuels; **OT:** other transportation; and **CA:** civil aviation).

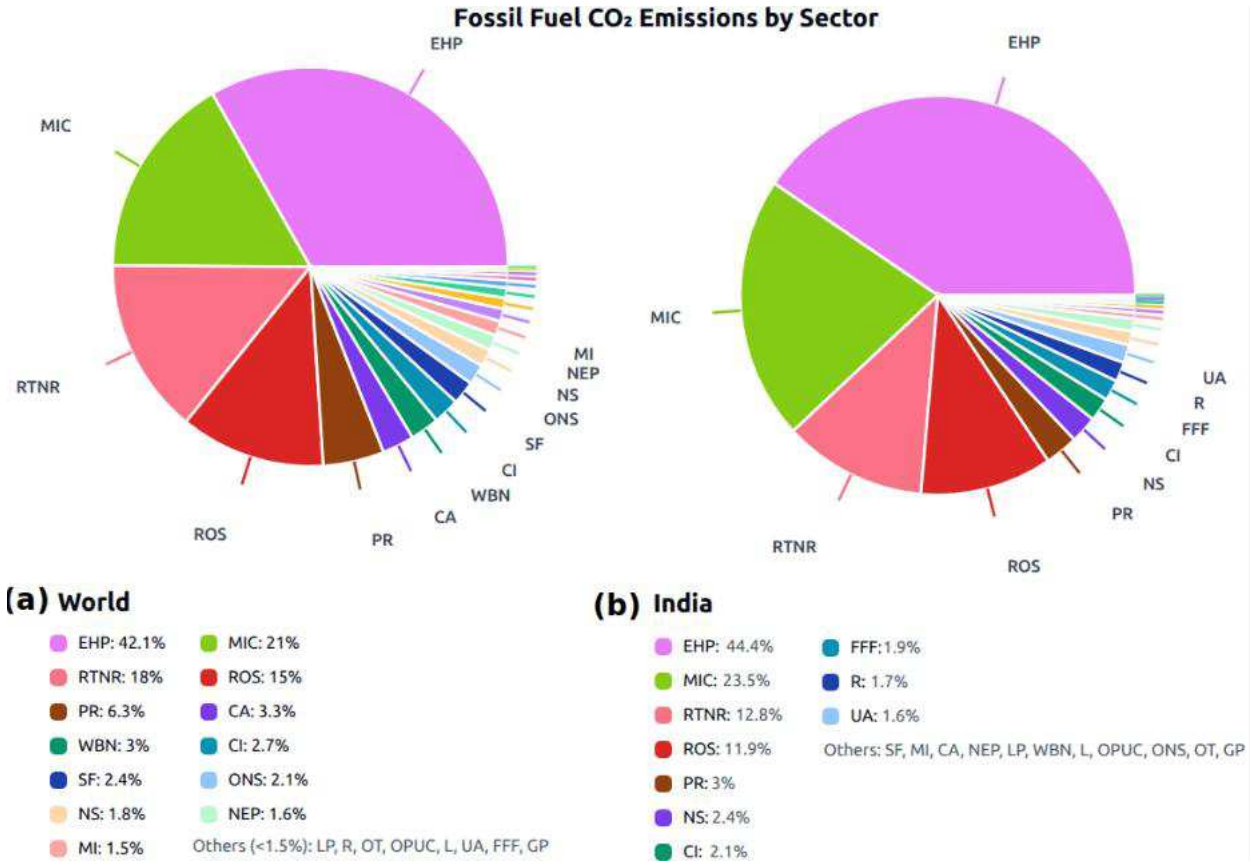


Figure 9. Comparison of the annual mean fossil fuel sectoral contributions to CO_2 emissions (%) for (a) World and (b) India region.(where: **PR**: petroleum refining; **NS**: non-specified; **CI:** chemical industry; **FFF:** fossil fuel fires; **R:** railways; **UA:** urea application; **SF:** solid fuels; **MI:** metal industry; **CA:** civil aviation; **NEP:** non-energy products; **LP:** lime production; **WBN:** water-borne navigation; **L:** liming; **OPUC:** other process uses of carbonates; **OT:** other transportation; **GP:** glass production; **EHP:** electricity and heat production; **MIC:** manufacturing industries and construction; **RTNR:** road transportation and no resuspension; **ROS:** residential and other sectors; **ONS:** oil and natural gas).

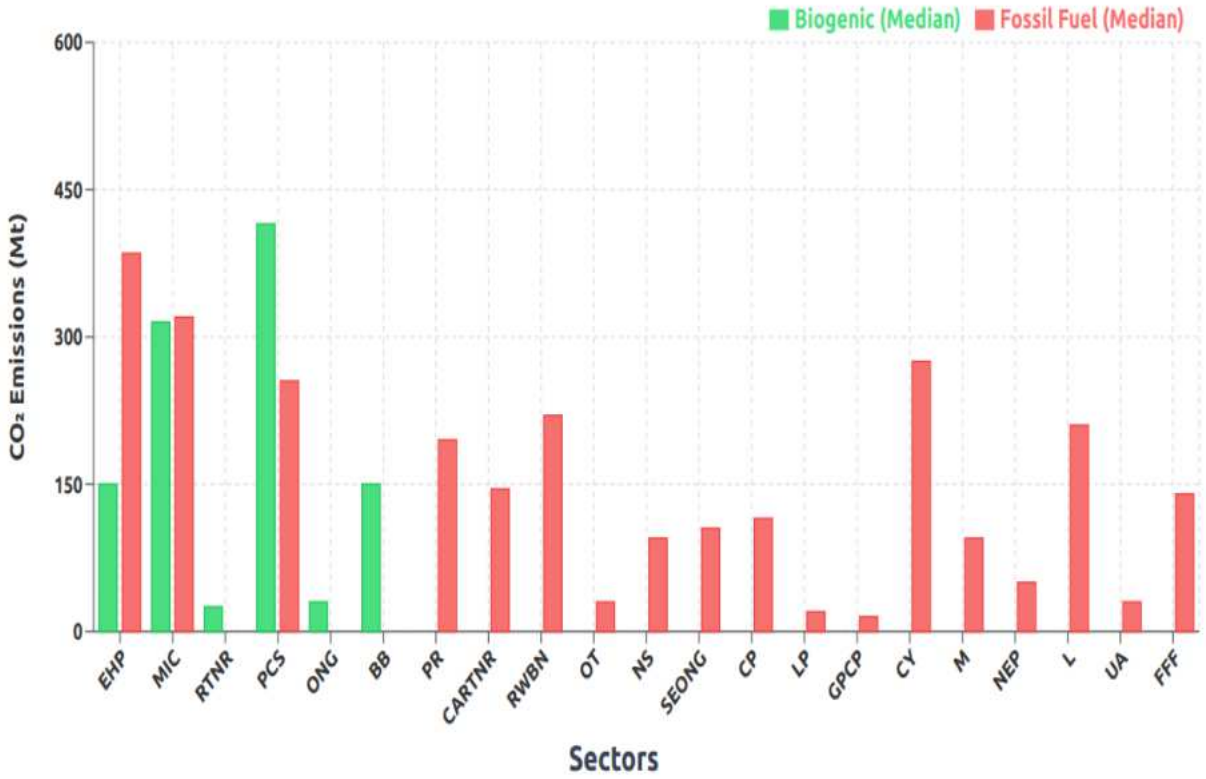
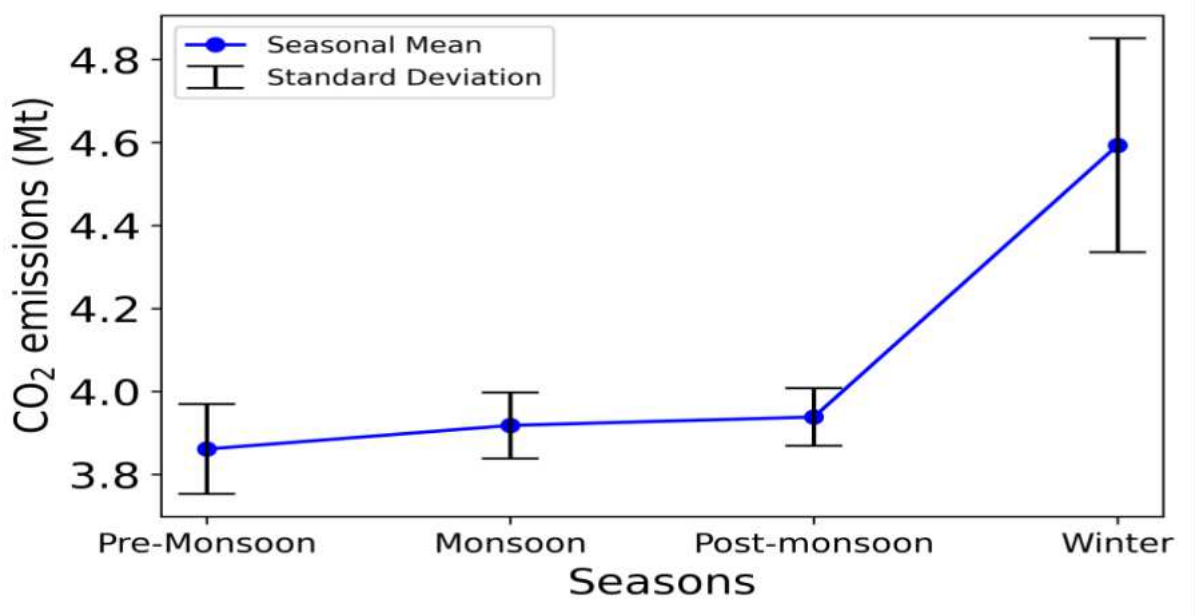


Figure 10. Combined emissions analysis showing biogenic (green) and fossil fuel (red) CO_2 contributions across all sectors.

647 **Supplementary figures list**

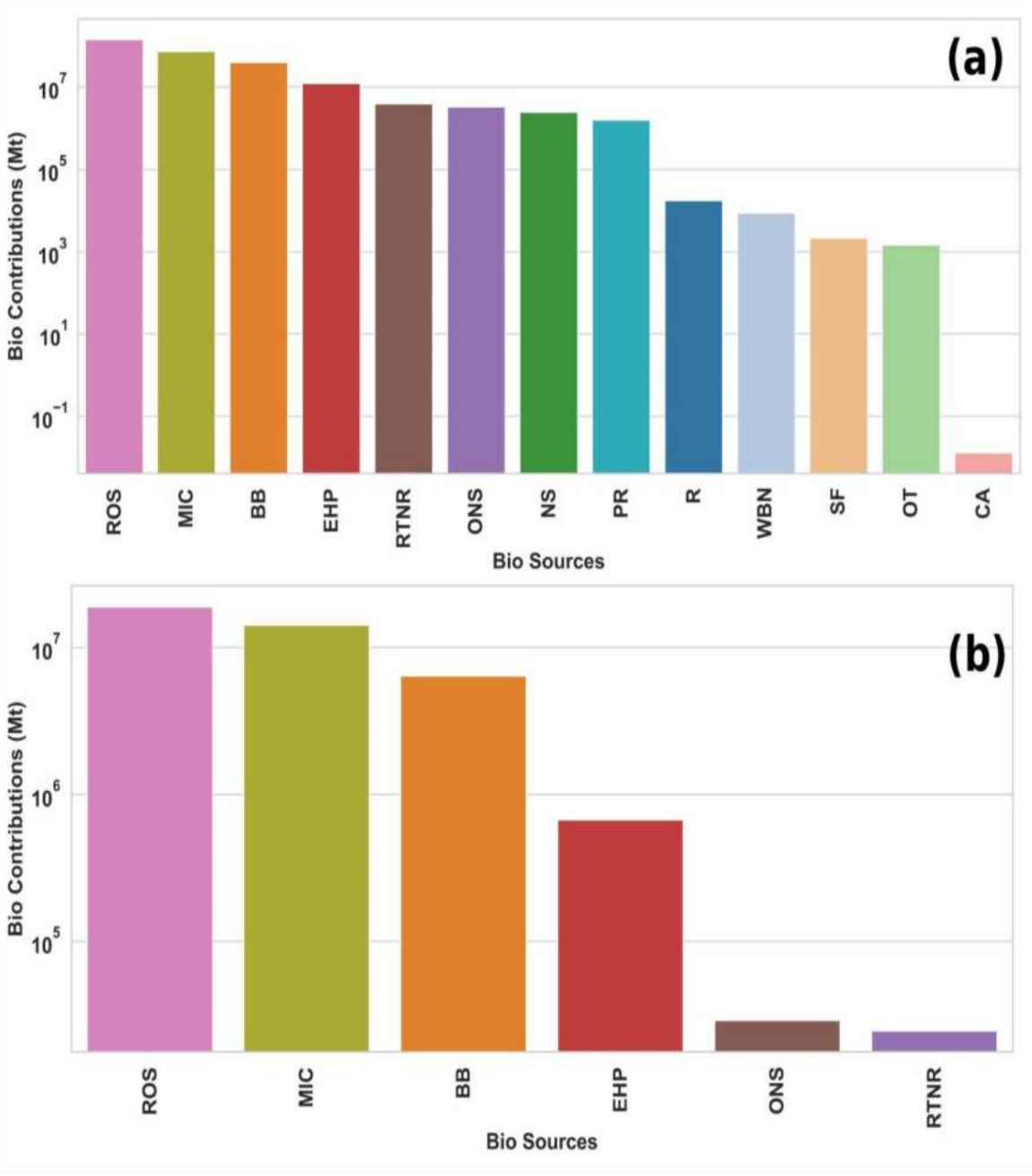
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649

650 **Figure S1.** EDGAR CO_2 emission of seasonal variation over the Indian region for

651 mentioned period**.**



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653

654 **Figure S2.** Comparison of the annual logarithmic mean biogenic (or biofuel) CO_2 emission
655 sectoral contributions (in Mt) for (**a**) World and (**b**) India.

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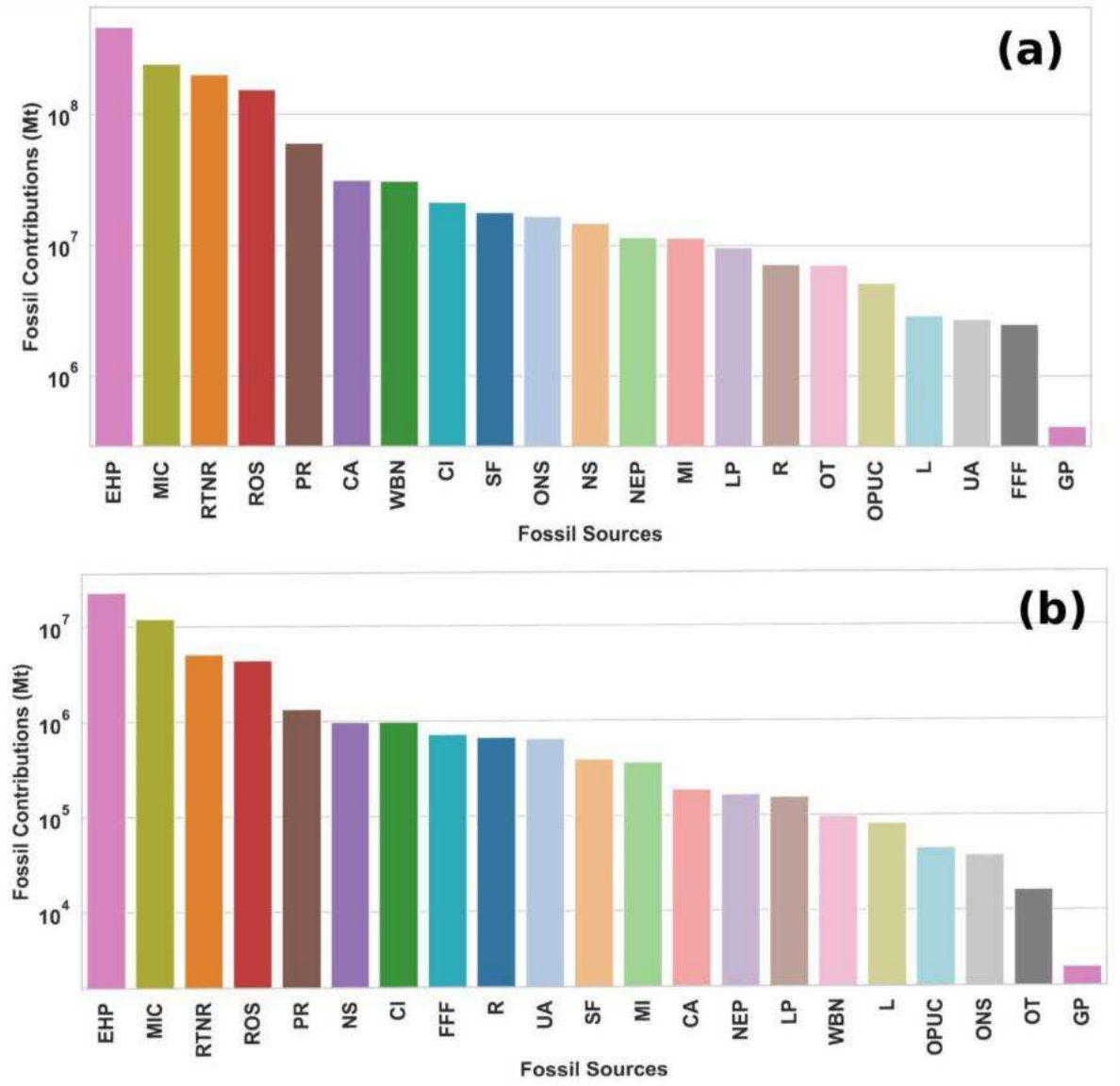


Figure S3. Comparison of the annual logarithmic Mean fossil fuel sectoral contributions to CO_2 emissions (in Mt) for (a) World and (b) India.

Table list

Table 1. shows the EDGAR abbreviation used for CO_2 bio and fossil emission sources.

Abbreviations	Sources
EHP	Main Activity Electricity and Heat Production
MIC	Manufacturing Industries and Construction
CA	Civil Aviation
RTNR	Road Transportation No Resuspension
WBN	Water-Borne Navigation
OT	Other Transportation
ROS	Residential and Other Sectors
NS	Non-Specified
ONS	Oil and Natural Gas
SWD	Solid Waste Disposal
IOBW	Incineration and Open Burning of Waste
WTD	Wastewater Treatment and Discharge
SF	Solid Fuels
EF	Enteric Fermentation
MM	Manure Management
CI	Chemical Industry
PR	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries
BTSW	Biological Treatment of Solid Waste
BB	Emissions from biomass burning
FFF	Fossil fuel fires
MI	Metal Industry
R	Railways
RC	Rice cultivations
GP	Glass Production
OPUC	Other Process Uses of Carbonates
NEP	Non-Energy Products from Fuels and Solvent Use
L	Liming
UA	Urea application
LP	Lime production

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669

670 **Table 2.** EDGAR CO_2 seasonal emission variations over India showing winter peak emissions
671 19% higher than pre-monsoon minimum with maximum variability in winter period.

672

Season	Period	Mean (Mt)	STD (±Mt)	Coefficient of Variation (%)	Characteristics

Pre-Monsoon	March–May	**3.86**	±0.12	3.1%	High temperatures, low humidity, dust storms
Monsoon	June–September	**3.92**	±0.08	2.0%	Heavy rainfall, high humidity, cloud cover
Post-Monsoon	October–November	**3.95**	±0.05	1.3%	Moderate temperature, decreasing humidity
Winter	December–February	**4.59**	±0.27	5.9%	Low temperatures, stable atmospheric conditions