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RESEARCH ARTICLE

Regional emissions and climate impact: analysing carbon dioxide and methane effects on temperature and sea levels in Asia

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Abstract

Climate change and its impacts are felt worldwide, and with increasing anthropogenic emissions, many international efforts are centred around mitigating emissions and meeting climate targets. The Asian continent has made the most significant contributions to global emissions, with China, India, and Russia generating the largest share of emissions. Given Asia's vulnerability to climate change, the study addresses the literature gap by examining the regional impact of anthropogenic carbon dioxide (CO_2) emissions and methane (CH_4) emissions on mean surface temperature (MST) and the effects of MST on mean sea levels (MSL) through panel regressions focusing on the period from 1993 to 2020, considering 45 countries. The study found that regional CO_2 and CH_4 emissions had a significant positive impact on MST at a 1% significance level, and MST had a positive impact on MSL at a 5% level of significance. The study has focused on continental sources of anthropogenic emissions and applied econometrics over traditional climate models to enable a more nuanced, granular, region-specific understanding of emission impacts for targeted policy development. It has proposed targeted policy measures to mitigate emissions, highlighting the importance of regional collaboration among Asian countries in achieving emission reduction goals.

Keywords CO_2 emissions · CH_4 emissions · Anthropogenic emissions · Mean sea level · Mean surface temperature · Global warming · Panel regression analysis · Policy implications

Introduction

The climatic consequences of anthropogenic emissions are visible across Asia, affecting ecosystems, societies, and economies. The world's largest continent, Asia, encompasses fifty-one countries spread over the six regions of Central Asia, East Asia, North Asia, South Asia, Southeast Asia, and West Asia (IPCC 2023b). Asia is the world's most populated region, with an estimated population of 4.7 billion people, comprising more than half the world's population, with more than 30% of the world's GDP and above 45% of global energy consumption (Calvin et al. 2012). Most countries in the region depend significantly on climate-sensitive sectors, such as agriculture, tourism, fisheries, and forestry. Additionally, they are compelled to depend on infrastructure vulnerable to climate change. Moreover, developing and least-developed countries in the region cannot adapt to climate-related challenges and impacts (Ford et al. 2015). Hence, Asia is a crucial region to consider when evaluating climate change, its implications, and developing policies to meet climate targets.

Climate change affects the oceanic environment, resulting in rising sea levels. Specifically, South Asia is highly sensitive and vulnerable to climate change (Dong et al. 2024). Mean sea level (MSL) can be defined as the average height

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of the entire ocean surface measured and averaged over an extended period (IPCC 2023a). The Asian continent has the world's longest coastline and is surrounded by the Arctic, Pacific, and Indian Oceans (Britannica 2021). Rising sea levels pose a critical challenge to small island developing countries, as their landmasses could be easily submerged or rendered uninhabitable (UN 2023). Countries like Thailand, Malaysia, Singapore, Sri Lanka, Maldives, Indonesia, Philippines, Vietnam, and the coastlines of China and India are most vulnerable to the rise of MSL.

IPCC defines mean surface temperature (MST) as the estimated average temperature of the Earth's surface, including both land and ice areas, and ocean surface without ice (IPCC 2023a). MST is recorded in a reference baseline period from 1951 to 1980. MST increases due to anthropogenic climate change can be observed across the Asian continent, with the highest record of 0.91 °C above the 1991 to 2020 average in 2023, with many areas having warmed incrementally more than the global average (WMO 2024b). Both natural and anthropogenic emissions affect MST, with anthropogenic emissions primarily dominating the impact on MST (IPCC 2014; Mehmood et al. 2025; Shi et al. 2025). Carbon dioxide (CO_2) and methane (CH_4) are the primary greenhouse gases (GHG) responsible for influencing global warming. CO_2 has been identified as the primary contributor to anthropogenic climate change, followed by CH_4 (Lindsey 2024; Allen et al. 2018; Filonchyk et al. 2024). The world is confronting climate change due to heavy reliance on fossil fuels (Bulut 2017). The increased consumption of fossil fuels due to economic and social developments has intensified concerns about global warming. The growth in the industries, transportation sector, and power generation has significantly raised the levels of emissions that contribute to severe consequences in health. Among fossil fuels, coal is particularly detrimental, while being proven to produce enormous amounts of CO_2, making it aggressive towards the long-term climate changes (Martins et al. 2021). Emissions are closely linked with environmental degradation. Thus, the resulting climate dynamics play a crucial role in the future of humanity. Notably, the transportation industry is accountable for one-third of the global emissions of CO_2, which is further influenced by the growth of the economy, population, urbanisation, and evolving social and leisure activities (Choudhury et al. 2023). Global climate change being a threat to the well-being of all people, the contribution of emissions towards environmental concerns varies across continents.

Furthermore, fossil fuel combustion, conversion of natural ecosystems to agricultural or urban areas, the resulting deforestation, chemical reactions from industrial activities, and solid wastes are the primary contributors to the observed changes in atmospheric CO_2 concentrations. Production of coal and oil, agriculture, animal husbandry, and decay of organic matter primarily emit CH_4 (EPA 2024). Both CO_2 and CH_4 emissions have made significant contributions since the pre-industrial era, which encourages attention towards CO_2 emissions alongside the other highly influential non-CO_2 gases (WMO 2024a). In accordance with the global warming potentials (GWP), indices which attempt to capture the instantaneous ability to trap heat among the GHGs, CO_2 has a GWP of 1, whereby CO_2 emissions tend to cause an increase in atmospheric concentration of CO_2, which may remain in the climate system for longer time spans. In contrast, it is estimated for CH_4 to have a GWP of 27 to 30 over 100 years, indicating CH_4 has a higher potential to absorb more energy relative to CO_2 emissions. Hence, alongside the prevailing emphasis on CO_2 emissions, it is critical to examine the joint implication of CO_2 and CH_4 on global warming (Jones et al. 2023; EPA 2025; C2ES 2003; J. Xie and Xiao 2024). The study's primary objective is to examine climate change in the Asian region by considering the impact of CO_2 and CH_4 emissions on MST and the resulting impact on MSL to bring about novel findings related to regional climate dynamics. Further, the study is aimed at emphasising the importance of policy implications to bring about regional climate stability. Given the rapid increase of GHG emissions in the Asian continent, this study contributes to the existing literature in three ways. Firstly, most of the extant studies for the Asian continent focus their research on the topmost emitting countries, sources of their emissions, and mitigation of those emissions. This study considered primary sources and mitigation of emissions through policy implications for not only the developed countries but also the developing, industrialised, and least-developed countries in the region. Secondly, most of the existing climate-related literature on human-induced climate change was centred on CO_2 emissions or considered the impact of either CO_2 or CH_4 emissions individually. However, this study quantifies the dual effects of CO_2 and CH_4 emissions on MST, providing broader coverage to capture the synergistic effect between these two primary GHG emissions. Despite a significant body of literature in this research domain, the most relevant studies on climate variables are based on climate models and simulations. The use of econometrics in climate-related literature is minimal. Hence, the study employs econometrics to quantify the impact of the incorporated variables and facilitates a broader understanding of regional climate dynamics contributing to the existing body of literature in the domain.

The remaining sections of this paper are organised as follows. The 'Literature Review' section covers the existing studies and empirical evidence from an Asian perspective. The 'Data and Methodology' section presents the data sources used in the study and interprets the methodology employed. The 'Results and Discussion' section assesses the empirical findings. Finally, the study concludes by exploring the 'Policy Implications', considering the potential areas

for addressing the challenges posed by climate change, and examining the study's 'Limitations'.

Literature review

The Asian continent is experiencing significant climate changes due to the increasing temperature levels (You et al. 2022; Kim and Byun 2009). Respectively, global warming response can be assessed by two key metrics: transient climate response to cumulative CO_2 emissions and net zero CO_2 emissions (Vakilifard et al. 2022). Transient climate response to cumulative CO_2 emissions explains how much the temperature will increase because of the CO_2 emissions. Net-zero CO_2 emissions describe how much the temperature will increase even after CO_2 emissions are stopped. Increasing CO_2 concentrations in the atmosphere will cause an increment in temperature levels, destroying the habitats for life on earth, including human beings, plants, and animals. Studies show a continuous increase in CO_2 emissions since the Second Industrial Revolution (Hashimoto 2019). The results derived from Community Climate Model version 02 from the National Centre of Atmospheric Research show a significant influence of atmospheric CO_2 on East Asia's climate in the late Cretaceous period. Furthermore, the study shows how the air surface temperature decreases when CO_2 concentrations are reduced (J. Chen et al. 2013). According to a study conducted by employing the regional climate model (RegCM4), when CO_2 levels are higher in certain regions due to regional emissions, it leads to a decrease in net longwave radiation flux to the upper atmosphere from the lower troposphere, resulting in an observed temperature increment of 0.18 K occurring from trapped heat (X. Xie et al. 2018).

Several studies investigate CO_2 emission sources, the impact of CO_2 on climate change, and CO_2 policy implications in major emitting countries such as China, India, and Russia (Ahmed et al. 2023). Some studies have been undertaken to identify China's contribution and vulnerabilities in climate change (P. Chen et al. 2023; Gao et al. 2022). However, a gap exists in the geographical focus on identifying the diverse challenges faced by other Asian nations. Developed nations in Asia, like Japan and Russia, have better resources to overcome these underlying threats caused by the temperature rise and fluctuating sea levels. In contrast, developing countries would face difficulties in adapting new strategies due to a lack of resources and financial burdens.

The importance of implementing international policies and measures suggested by the Kyoto Protocol, a landmark agreement focused primarily on developed nations to reduce CO_2 emissions (Mar et al. 2022). However, not much emphasis has been placed on addressing developing countries' emissions, most notably the Southeast Asian countries. CO_2 emissions have become one of the significant issues in China, while the country contributes to the highest percentage of CO_2 emissions globally (Gao et al. 2022). The Paris Agreement allows all nations to set their individual emission reduction targets and reduce GHG emissions (Larry 2019). It is evident that a focus on developing and least-developed nations, and not only the developed nations, is necessary to adapt different strategies to mitigate climate change. Hence, this study analyses the data for forty-five Asian countries, including most of the developing, industrialised, and least developed countries in the region. Further, credible local and regional case studies and analogues can be used to analyse the causes of climate vulnerability and how to adapt to climate change. It would help policymakers create an effective plan to address the challenges of climate change (Ford et al. 2010).

The results derived from examining the emissions of ninety major industrial carbon producers using a simple climate model show that CO_2 and CH_4 emissions from these major emitters substantially contributed to global MST and MSL rise (Ekwurzel et al. 2017). CH_4 has a higher radiative efficiency than CO_2, indicating that CH_4 is more effective at trapping heat in the atmosphere. Since the pre-industrial era, CH_4 concentration in the atmosphere has increased by approximately 150%. Reducing CH_4 emissions can be challenging due to its strong correlation with livestock numbers and their link to the global population. However, controlling CH_4 emissions is crucial for mitigating climate change (Tuckett 2009; Kumari et al. 2018). The removal of CH_4 effectively delays the rate of increasing MST and is a complement to CO_2 removal and mitigation efforts (Abernethy et al. 2021; del Prado et al. 2023). Related studies from the past mostly focus on CO_2 emissions and their impact on rising temperature levels. However, continuously increasing CH_4 emissions also significantly affect the Asian temperature levels. Hence, it is crucial to assess the regional impact of both CO_2 and CH_4 emissions on temperature levels and MSL rise in the Asian context to address this gap.

Rising sea levels are a serious threat to Asia's densely populated coastlines, endangering infrastructure, ecosystems, and millions of lives. Understanding the mechanisms that cause this phenomenon is critical for developing effective mitigation and adaptation strategies. MSL and MST have exhibited a well-established relationship (Tebaldi et al. 2021; Jevrejeva et al. 2016). It has been stated that by 2100, the sea level will grow at a rapid pace, exceeding 80% of the coastline, which would particularly affect low-lying countries like Bangladesh, Vietnam, and the coastlines of India and China (Church et al. 2006; Lindsey 2023). The studies highlight the mechanisms contributing to the MSL rise, such as thermal expansion and melting glaciers. There has also been an emphasis on the urgency of climate actions that could be taken by focusing on global warming caused by

industrial levels. The importance of acknowledging regional variations for accurate sea level rise projections has been highlighted in the past (Hamlington et al. 2020). Ocean currents, wind patterns, and variations in water salinity can impact how MSL responds to changes in MST (Martyr-Koller et al. 2021). However, while global climate models provide a large-scale picture of temperature rise, their estimates lack the specificity required for effective regional adaptation (Elshall et al. 2022). Integrating econometrics would offer a nuanced understanding of the regional impact of CO_2 and CH_4 emissions on the rising sea levels. It can provide the study with a powerful tool for shedding light on regional impacts and urging country-specific policy developments. Hence, this study contributes to the existing body of knowledge by applying econometric techniques to examine the relationship between these variables and their consequences, which is necessary for the domain, given that most research on the domain relies on climate model simulations.

Some of the past studies focused on one of the gases, not the separate effect of GHG on MST, and the effect on MSL (Kabir et al. 2023; Boucher et al. 2009). Therefore, analysing the impact of anthropogenic emissions on the regional temperatures and sea level rise of Asian countries' emissions can give a much better insight for policymakers to undertake effective mitigation strategies.

A study conducted for Southeast Asia across countries such as Brunei, Myanmar, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, and Vietnam highlights the alarming increasing trends in CO_2 emissions, underlying the crucial need for a regional analysis (Lee et al. 2013). Many research studies focused on GHG emissions' influence on sea level rise, particularly on a global basis (Hansen et al. 1981; Humlum et al. 2013). There is an increasing need for a localised analysis, particularly in susceptible regions such as Asia. Ocean currents, coastline terrain, and socioeconomic development differ from location to location; henceforth, it is crucial to emphasise the significance of recognising Asia's unique vulnerabilities and investigating specialised solutions for the Asian continent (IPCC 2022).

Asia's trade has increased significantly over the past two decades, and most of the Asian countries have experienced a great increment in GDP and population during the twentieth century (Su et al. 2011; Guisan and Exposito 2002). Further, the transportation sector in the region has also grown significantly in the last 25 years and remains one of the main sources of CO_2 emissions (Timilsina and Shrestha 2009). Emissions have increased by more than 45% since the year 2000 (Statista 2025). Many studies state that, given the economic growth, population growth, and increment in transportation, CO_2 and CH_4 emissions in the region have also increased significantly (Magazzino et al. 2024; Rahman and Alam 2022; Jorgenson and Clark 2013). Hence, this study employs the emissions data from the years 1993 to 2020 to analyse the impact of anthropogenic emissions on MST and the resulting impact on MSL to highlight the importance of policy implications to mitigate the emissions in the next two decades.

A concern overlooked in existing research is the link between human-induced GHG emissions and the developing temperature variations that affect sea levels. Some studies accept this link but devote little space to examining the sources and trends of these emissions (Mimura 2013; Shivanna 2022). This study is aimed at examining the primary sources of these emissions, highlighting and understanding the policy implications of the findings as an integral objective for guiding policy decisions to reduce emissions and mitigate the hazard of rising sea levels. By quantifying the individual and combined effects of CO_2 and CH_4 on Asian sea levels, the study is aimed at providing policymakers with a strong foundation for devising successful mitigation and adaptation strategies.

Accordingly, as shown in Fig. 1, a conceptual framework was developed based on the reviewed literature. The first hypothesis (H1) suggests that the MST is influenced by CO_2 emissions. The second hypothesis (H2) proposes that MST is further influenced by CH_4 emissions. Finally, the third hypothesis (H3) examines the impact of the average predicted values of MST, derived from CO_2 and CH_4 emissions, on the MSL.

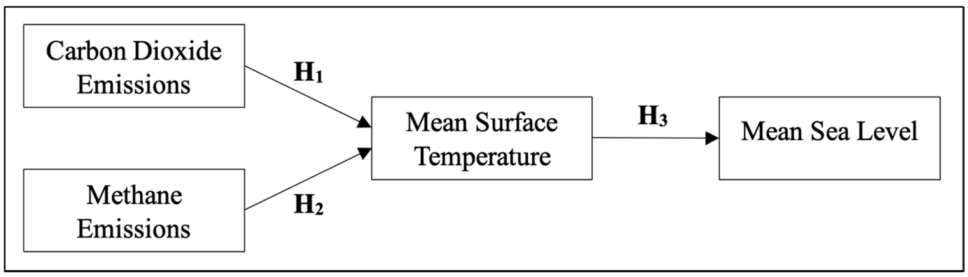


Fig. 1 Conceptual framework. H1 denotes the first hypothesis, H2 denotes the second hypothesis, and H3 denotes the third hypothesis. Source: Authors' composition

Data and methodology

The study uses a strongly balanced panel dataset based on secondary data, consisting of cross-sectional data across annual time intervals for forty-five Asian countries. Considering the limitations in data availability and accessibility for the variables, the study is conducted from 1993 to 2020. Table 1 shows the data utilised for the research and their sources. Country-wise emissions of CO_2 and CH_4 are measured in kilotons (kt) and kilotons of carbon dioxide equivalent (ktCO2e), respectively. The data of MST change are measured in degrees Celsius (°C), taking the average temperature between 1951 and 1980 as a baseline. Furthermore, the MSL change measured in millimetres (mm) was used in the study. Four countries in the Asian continent (Turkey, Taiwan, Palestine, and Timor-Leste) were excluded from the study due to the unavailability of data.

Before the analysis, the gathered data for the study was averaged to produce annual values for each year to observe any trends for the considered period with line graphs. Furthermore, decadal comparisons for CO_2, CH_4, and MST are made with choropleth maps. Descriptive statistics were generated for each variable, and the analysis was conducted using the STATA software. Altogether, 1260 observations were collected for the study; the data file used for the analysis is presented in S1 Appendix.

The analysis is conducted in four steps. Accordingly, in the first step, the impact of CO_2 on MST is derived as shown in Eq. (1), where MST1 is the predicted MST change derived from the impact of logCO2 which is the logarithmic value of CO_2 emissions.

$$MST1_{it} = \beta_0 + \beta_1 logCO2_{it} + \varepsilon_{it} \quad (1)$$

Secondly, the impact of CH_4 on MST is derived from Eq. (2), where MST2 is the predicted MST change derived from the impact of logCH4 emissions, which indicates the logarithmic value of CH_4 emissions.

$$MST2_{it} = \beta_0 + \beta_1 logCH4_{it} + \varepsilon_{it} \quad (2)$$

Followed by the individual panel analyses and, thirdly, the predicted MST changes. MST1 obtained from Eq. (1) and MST2 obtained from Eq. (2) are averaged to derive the average MST change represented by $\widehat{MST}$ as shown in Eq. (3).

$$\widehat{MST}_{it} = (MST1_{it} + MST2_{it})/2 \quad (3)$$

Finally, to determine the impact of MST change on MSL, a panel analysis will be conducted from the average MST change as shown in Eq. (4).

$$MSL_{it} = \beta_0 + \beta_1 \widehat{MST}_{it} + \varepsilon_{it} \quad (4)$$

In Eqs. (1), (2), (3), and (4), 'i' represents the country, with 't' denoting the period. The logarithmic transformation of CO_2 and CH_4 emissions in Eqs. (1) and (2) are to account for the diminishing effect of emissions on MST, thus capturing the nonlinear relationship between emissions and MST.

Among the independent variables in Eqs. (1) and (2), mainly CO_2 and CH_4, the existence of significant correlation tends to cause an issue of multicollinearity, which is a concern that can be addressed by increasing the study's sample size. Accordingly, the present research utilises a larger sample size with data collected for forty-five countries over 28 years from 1993 to 2020. Moreover, the study investigates the impact of CO_2 and CH_4 emissions on MST change separately by developing two separate equations, mentioned in Eqs. (1) and (2). Thus, it is likely to mitigate the issues of multicollinearity and strengthen the credibility of the respective findings.

Given the variability of data across time with country-specific impact, the study employs panel regressions using Eqs. (1), (2), and (4) to determine the regional effects of MST change on MSL via CO_2 and CH_4 emissions. Subsequently, simple linear regressions (SLR) were implemented to examine the effects of CO_2 and CH_4 emissions on MSL through MST across individual countries in Asia. Panel data sets have various advantages over cross-sectional datasets, such as offering many data points, improving the precision of estimates, providing the ability to formulate robust hypotheses, and revealing dynamic

Table 1 Data sources and variables

Variable	Measurement	Source
Mean sea level	Millimetres	International Monetary Fund – Climate Change Indicators Dashboard https://climatedata.imf.org/datasets/b84a7e25159b4c65ba62d3f82c605855/explore
Mean surface temperature	Degree Celsius	International Monetary Fund – Climate Change Indicators Dashboard https://climatedata.imf.org/datasets/4063314923d74187be9596f10d034914/explore
Carbon dioxide emission	Kilotons	World Bank (World Development Indicator Archives) https://databank.worldbank.org/source/wdi-database-archives
Methane emission	Kilotons of CO_2 equivalent	World Bank (World Development Indicator Archives) https://databank.worldbank.org/source/wdi-database-archives

Source: Authors' composition

relationships over time (Hsiao 2014). For the analysis of Eqs. (1), (3), and (4), the study considers three-panel regression analysis models: pooled ordinary least squares estimation (POLS), random effect estimation (RE), and fixed effect estimation (FE). The conduct of the analysis using panel regression analysis enabled the control of the unobserved heterogeneity across the forty-five Asian countries in the study. Additionally, it supports the conduct of a comprehensive analysis in capturing complex trends over an extended period to uncover the dynamic fluctuations, which is an essential component associated with climate-related studies. Panel regressions perform temporal and spatial analysis, where this study considers the cross-sectional data across forty-five countries and time series data for twenty-eight years in the Asian region. Hence, it enables the development of a statistical model to quantify the impact of emissions on climate-related variables of MST and MSL. Individual sensitivity analysis tests are conducted with three specification tests to determine the most suitable model among the estimation models. Accordingly, the *F* test was performed to examine the FE and POLS models, and the Hausman test was employed to determine between the FE and RE models. Finally, the Breusch-Pagan test was used to distinguish between the POLS and RE models. The RE estimation model is favoured when it is assumed that the country-specific effects do not correlate with anthropogenic emissions.

On the other hand, the estimation model of FE is accompanied when the country-specific effects are correlated with CO_2 and CH_4 emissions, through which the time-invariant factors are controlled in the analysis. Alternatively, if the influence is neither of them, Eqs. (1), (2), and (4) will be estimated using the POLS estimation model. Before analysis, the Levin Lin and Chu test (LLC) was conducted to determine the stationarity of all variables in the study. The test is characterised by a null hypothesis that assumes panels containing unit roots and was tested at a 0.05 significance level (Levin et al. 2002). Furthermore, the stability of variables against exogenous shocks was tested using panel vector auto-regression (PVAR) (Sims 1980). The heteroskedasticity of the model was tested using the modified Wald test for groupwise heteroskedasticity in the FE regression model (Rathnayake et al. 2023).

Results and discussion

Asia's emission profile and regional significance

Global CO_2 and CH_4 emissions show a rapid upward trend for the period considered, as presented in Fig. 2. Similarly, CO_2 and CH_4 emissions from the Asian continent also show a rapid increase from 1993 to 2020. On average, for the study period, Asia accounted for more than 50% of global

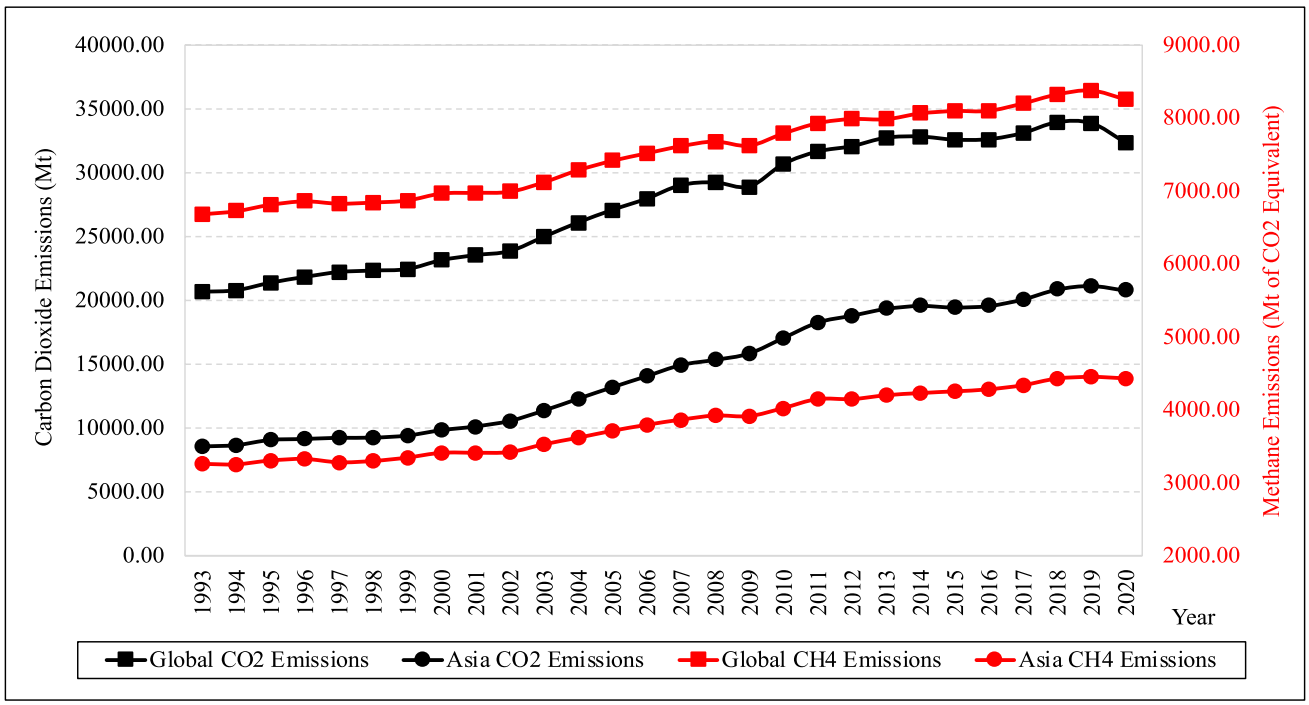


Fig. 2 Global vs. Asia comparison of yearly CO_2 emissions (Mt) and CH_4 emissions (Mt CO2e). CO_2 emissions show a significant growth, while CH_4 emissions exhibit a consistent yet slower growth across the period Source: Authors' illustration based on data from WB Indicators.

anthropogenic CO_2 and CH_4 emissions. In 1993, the region contributed around 41% to global CO_2 emissions, and by 2020, approximately 64%, indicating a 23% increase in contribution to global CO_2 emissions. Furthermore, Asia accounted for approximately 49% of global CH_4 emissions in 1993, and by 2020, an estimate of 54%, indicating an increase of around 5% in contribution to global CH_4 emissions.

Figures 3 and 4 show a continental comparison of CO_2 and CH_4 emissions from 1993 to 2020. According to Fig. 3, the Asian region has the highest anthropogenic CO_2 emissions, followed by North America and Europe. As per Fig. 4, the Asian region shows the highest CH_4 emissions for the period of study. Anthropogenic CO_2 emissions in Asia are primarily driven by industrialisation spurred by many developing countries in the area. The rapid increase in CO_2 emissions in the latter decade can be explained by population growth, increased energy demand, economic growth, and lack of mitigation strategies and regulations (Dharmapriya et al. 2024). Furthermore, according to IEA, the Asian continent heavily relies on coal for energy supply, around 48.3% of the total energy mix, and the energy intensity for the region shows a drastic increment of 201% from 2000 to 2021 (IEA 2021a).

From the period 2000 to 2017, most of the CH_4 emissions were due to agriculture in the regions of Asia, Oceania, Africa, and South America. Furthermore, many CH_4 emissions stem from fossil fuel consumption in China (Jackson et al. 2020). Given that Asia has the highest emissions of CO_2 and CH_4 relative to other continents, the region plays a primary role in developing global efforts to mitigate climate change by addressing the root causes of these emissions.

Figure 5 shows the annual MST change for the Asian region from 1993 to 2020. An upward trend of MST can be observed from 1993 to 2020. Considering MST from 1951 to 1980 as the baseline, MST in 1993 showed a difference of − 0.01 °C, whereas, in 2020, a significant difference of 1.53 °C was observed, denoting a temperature difference of 1.52 °C between 1993 and 2020. An average MST increase of 0.97 °C relative to the baseline for the study period was observed. These findings suggest a notable shift in MST patterns over the considered span of 28 years. According to Fig. 6, the MSL of the Atlantic, Indian, and Pacific Oceans shows an upward trend from 1993 to 2020, indicating a consistent rise in sea levels over the years. During the study period, the MSL of the Pacific Ocean showed the highest average increase of 3.4-fold, followed by the Indian Ocean and Atlantic Ocean with an average of 1.1-fold and 0.7-fold increase, respectively. Moreover, the average global MSL change further demonstrates a steady upward trend over the period. The global trends observed for the variables of CO_2, CH_4, MST, and MSL are presented in S2 Appendix. These findings highlight the urgent need for climate action

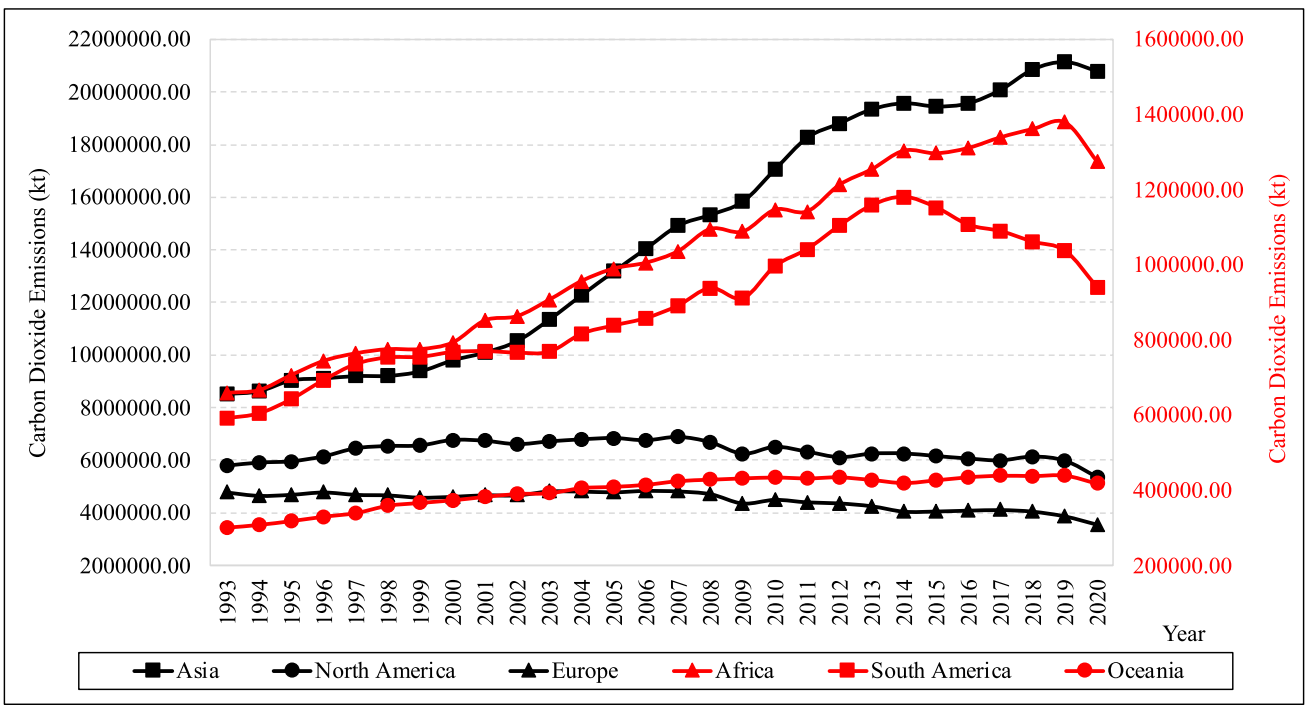


Fig. 3 Continental comparison of yearly CO_2 emissions (kt). Asia contributed approximately 64% to global CO_2 emissions in 2020 Source: Authors' illustration based on data from WB Indicators.

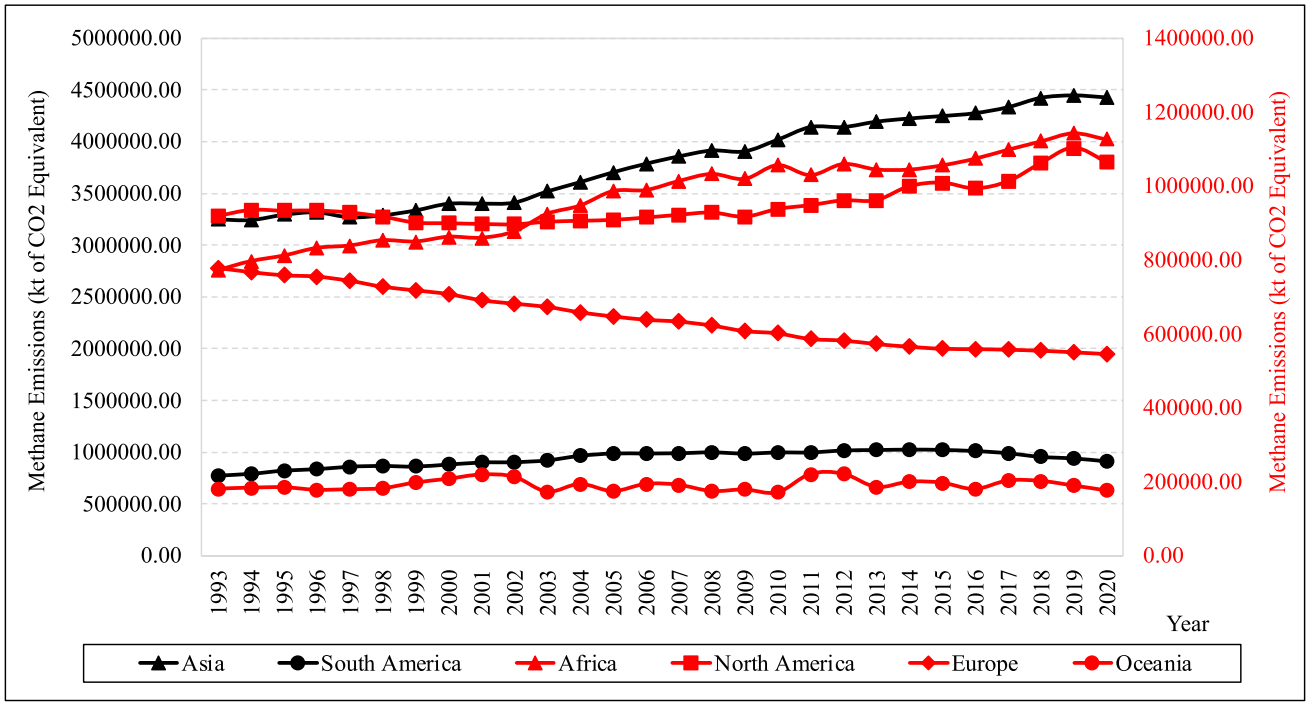


Fig. 4 Continental comparison of yearly CH_4 emissions (ktCO2e). Asia's contribution to global CH_4 emissions has increased by approximately 5% over the period Source: Authors' illustration based on data from WB Indicators.

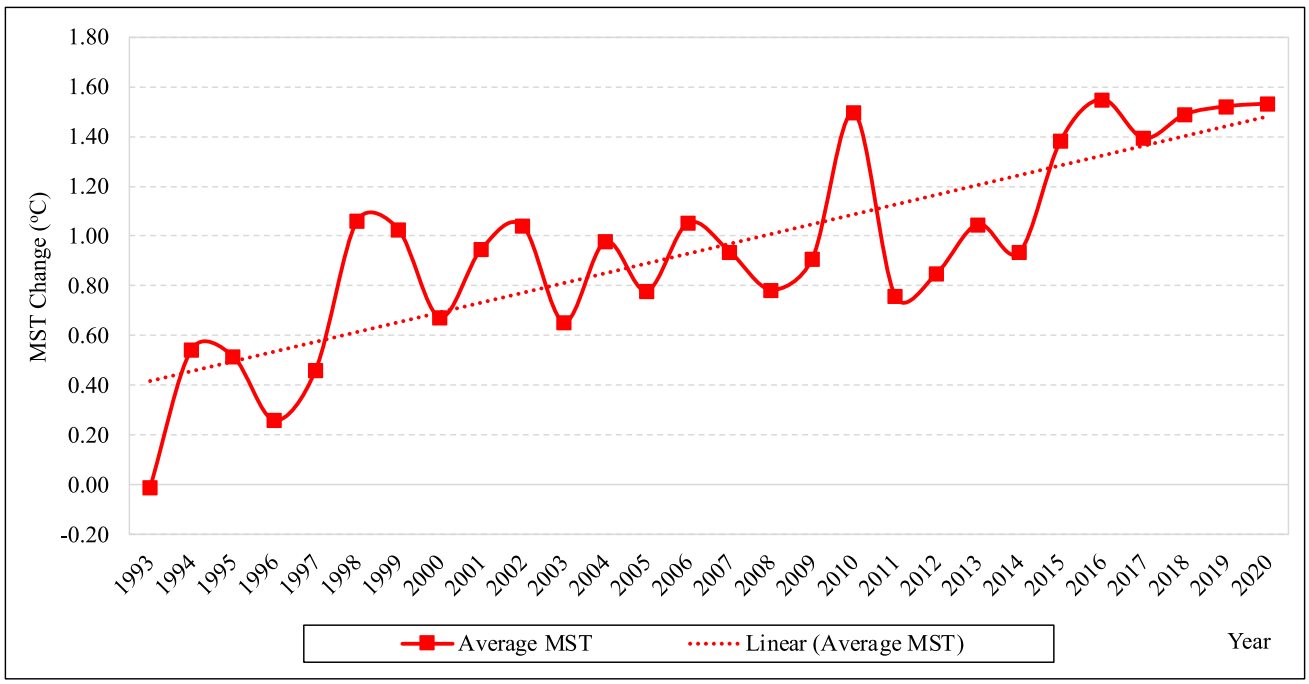


Fig. 5 Yearly MST change (°C). MST change denotes a difference of 1.52 °C from 1993 to 2020 with an average increase in MST of 0.97 °C relative to the baseline Source: Authors' illustration based on data from the IMF Climate Indicators Dashboard

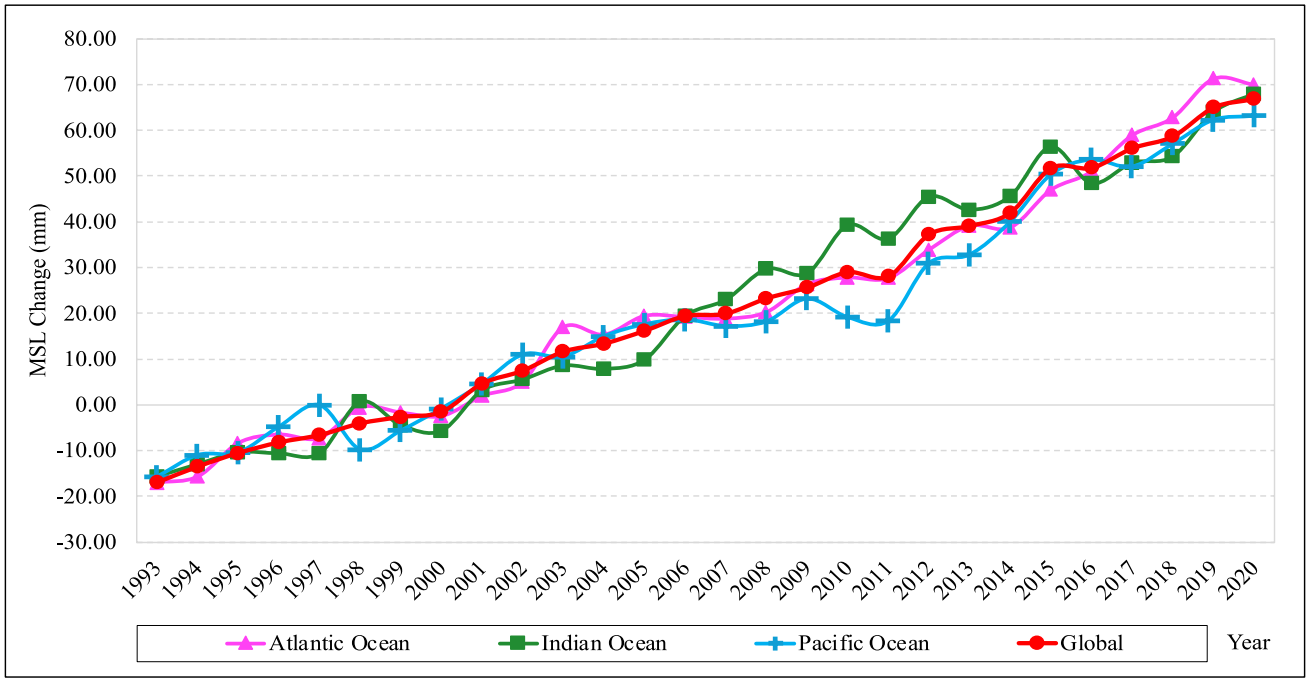


Fig. 6 Ocean-wise comparison of yearly MSL change (mm). MSL change illustrates an upward trend across all oceans, while the Pacific Ocean shows the highest average increase of 3.4-fold Source: Authors' illustration based on data from the IMF Climate Indicators Dashboard

Table 2 Descriptive statistics for Asia

	CO_2 (kilotons)	CH_4 (kilotons of CO_2 equivalent)	MST (degree Celsius)	MSL (millimetres)
Obs	1260	1260	1260	1260
Mean	321,811.11	84,465.74	0.95	21.57
SD	1,111,186.17	184,707.18	0.59	25.31
Min	177.05	47.49	−1.20	−16.98
Max	10,944,686.20	1,186,285.18	3.69	71.31

Note: Obs., SD, Min., and Max. represent the number of observations, standard deviation, minimum value, and maximum value, respectively

Source: Authors' calculations based on data from WB Indicators and IMF Climate Indicators Dashboard

to address the increasing MST and MSL and mitigate their impact.

Descriptive statistical analysis

Descriptive summary statistics are generated for each of the forty-five Asian countries (S3 Appendix) and the overall continent, as presented in Table 2 below.

The study covers the period from 1993 to 2020, with 1260 observations for forty-five Asian countries. Over the period of study, CO_2 emissions average to 321,811.11 kt, where the top 10 emitters of CO_2 are China, Russia, India, Japan, South Korea, Iran, Indonesia, Saudi Arabia, Thailand, and Kazakhstan, with the average CO_2 emissions ranging between 6,602,215.41 and 187,500.98 kt. As per the comparisons made over the first decade of 1993 to 2002 and the second decade of 2011 to 2020, the average change has been valued between 4.73 and 0.52 kt, indicating the average change in the per capita CO_2 emissions of the aforementioned top ten emitters to have increased over time, except in Japan. Based on the CH_4 emissions over the focused time frame, the top ten emitters of CH_4 have had average CH_4 emissions extending between 967,214.43 and 73,095.16 kt. These countries include China, India, Russia, Indonesia, Iran, Pakistan, Turkmenistan, Saudi Arabia, Bangladesh, and Thailand. Reflecting on the average change in per capita CH_4 emissions, six countries out of the top ten emitters, excluding Bangladesh, India, Indonesia, and Saudi Arabia, account for an increase in per capita CH_4 emissions within the range of 8.07 to 0.09 kt.

Additionally, the MST averaged to 0.95 °C for the study timeframe from 1993 to 2020, with the average MST being at its highest in the countries of Russia, Mongolia, Kuwait, Bahrain, Kazakhstan, Iran, Qatar, Iraq, Turkmenistan, and Uzbekistan. These countries' average change in MST ranged between 1.15 and 0.26 °C, respectively. Finally, the dependent variable of MSL averaged 21.57 mm from 1993 to 2020. The highest change in MSL was seen in

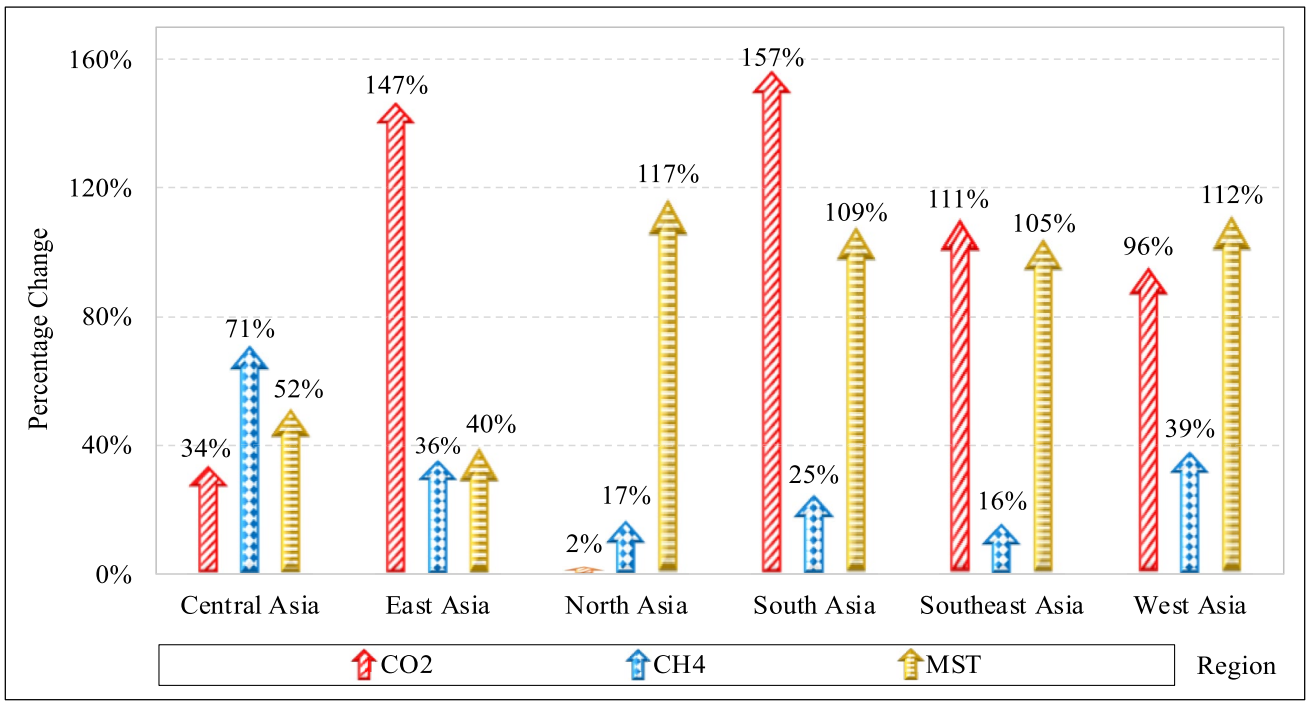


Fig. 7 Decadal comparison of regional CO_2 emissions, CH_4 emissions, and MST Source: Authors' illustration based on data from WB Indicators and IMF Climate Indicators Dashboard

Afghanistan, Bahrain, Bangladesh, Bhutan, India, Indonesia, Iran, Iraq, and Israel.

A decadal comparison between the periods of 1993 to 2002 and 2011 to 2020 in CO_2 emissions, CH_4 emissions, and MST across the six Asian regions is presented in Fig. 7. Accordingly, South Asia recorded the highest increase in CO_2 emissions, followed by East Asia and Southeast Asia, suggesting a significant rise in industrialisation and energy-related activities in these regions during the recent decade. In contrast, the highest percentage change in CH_4 emissions was observed in Central Asia, followed by West Asia, and East Asia. This highlights an increased emphasis on agriculture-related activities in these regions compared to other regions in Asia. The overall trend reflects a concerning alignment between rising emissions and increasing MST, indicating that all Asian regions are experiencing accelerated climate change impacts.

The choropleth maps in Fig. 8 visually represent the average change in CO_2 emissions across Asia for two decades. The first decade is from 1993 to 2002, and the latter is from 2011 to 2020. Figure 8B illustrates the average CO_2 emissions from 2011 to 2020, which shows that CO_2 emissions have increased compared to the first decade in most Asian countries from 1993 to 2002, as shown in Fig. 8A. Specifically, thirty-one countries have shown an increase in average per capita CO_2 emissions over the two decades.

China, the leading CO_2 emitter in the world, accounts for an average CO_2 emission of 6,602,215.41 kt from 1993 to 2020, with an average change in per capita CO_2 emissions by 7 kt between the first decade of 1993 to 2002 and the latter decade of 2011 to 2020. With economic growth in China, moving closer to its final phases of industrialisation and swift urban development, by the year 2020, China has contributed to 30.7% of the global carbon emissions, where one primary cause of the situation is China's transport sector, with a growth rate of the average annual number of private cars by 14.14% from 2010 to 2020 (Lu et al. 2022; Li et al. 2024; Azam et al. 2016). Moreover, by the year 2021, 63% of the total electricity generation in China is through coal, from which the industrial sector consumes around 58.5% of the total electricity generated (IEA 2021b). Additionally, other industrialised countries, including India, Thailand, the Philippines, and Indonesia, have an increased reliance on fossil fuels in energy generation, causing a rise in anthropogenic CO_2 emissions. As per the first decade, India's average per capita CO_2 emissions are 0.81 kt, which has driven up to 1.61 kt by the latter decade. This represents that the average per capita CO_2 emissions have increased by 0.80 kt. According to IEA, in 2021, 72% of the total electricity generation and 50% of the domestic energy production in India are from coal, encouraging the rising trend in CO_2 emissions (IEA 2021c).

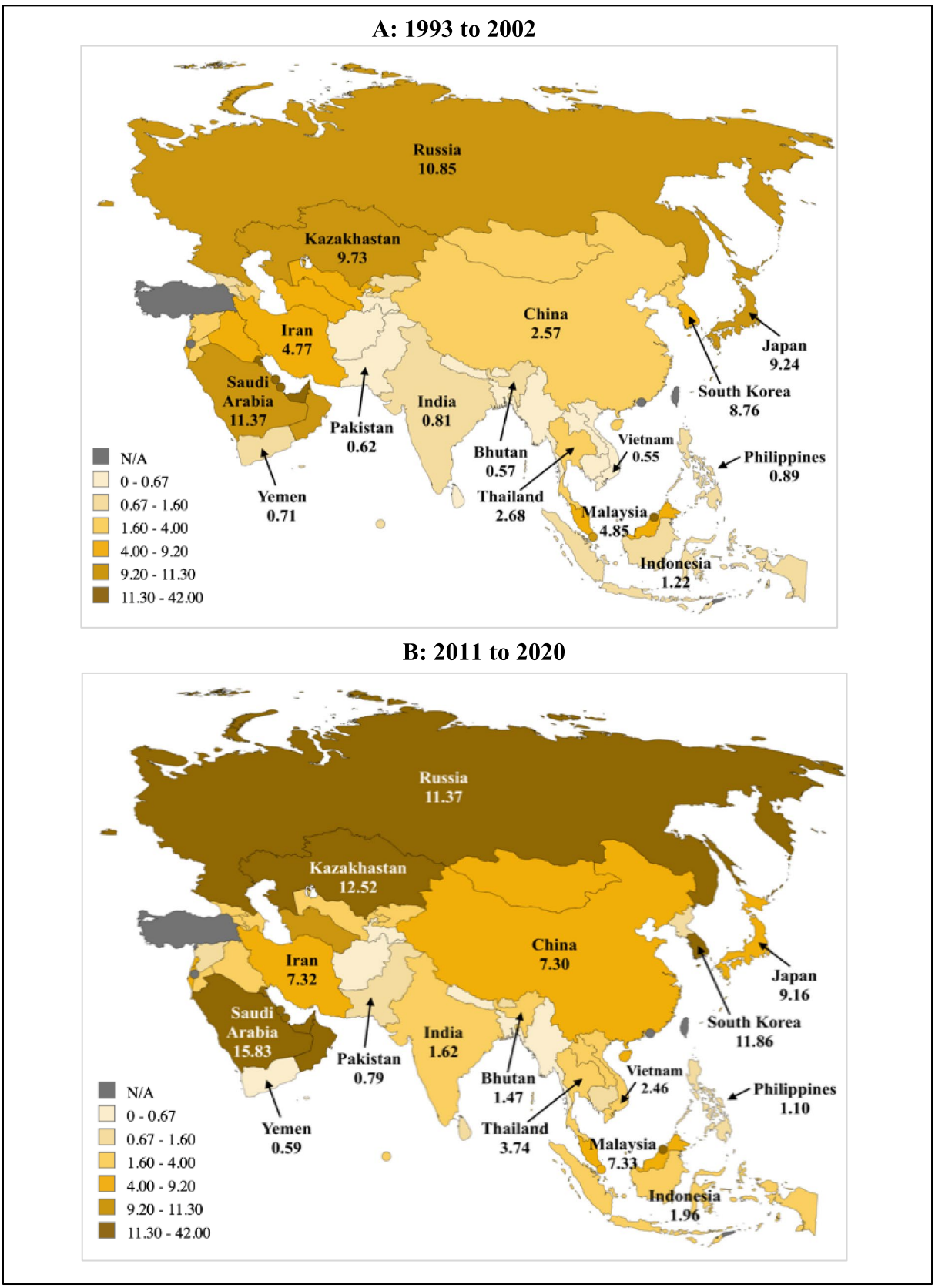


Fig. 8 Average change in per capita CO_2 emissions between two decades from 1993–2002 and 2011–2020 Source: Authors' illustration based on data from the IMF Climate Indicators Dashboard

Along with the economic growth, India's transportation sector is the cause of 80% of the country's CO_2 emissions, indicating a positive correlation between the demand for private vehicles, energy consumption, and total CO_2 emissions. Thus, India is ranked third among the world's top ten CO_2 emitters (Jain and Rankavat 2023). Furthermore, by 2021, the IEA reports that oil contributed to 40% of the total CO_2 emissions from fuel combustion in Thailand (IEA 2021i). This was further led by the country's increased trade openness to 125% from 1990 to 2015, when the country's exports were the cause of the increased CO_2 emissions, forming environmental concerns (Ninpanit et al. 2019). Indonesia and the Philippines have set an average CO_2 emission of 378,440.17 kt and 86,081.67 kt from 1993 to 2020, with an average increase of 0.73 kt and 0.20 kt of per capita CO_2 emissions over the two decades. Accordingly, the largest source of CO_2 emissions in Indonesia and the Philippines is coal combustion (IEA 2021d, f). In Malaysia, the average change in per capita CO_2 emissions over the two decades is 2.48 kt. One of the critical forms of currency inflows into Malaysia is through tourism, which has contributed to 13.3% of the country's GDP in the year 2019, creating a vast amount of job opportunities, which in contrast, led to a rise in CO_2 emissions due to significant utilisation of energy for traveling, accommodation, and entertainment (Raihan 2024).

As per the developed countries, economic growth is correlated with higher energy use, leading to the elevation of anthropogenic CO_2 emissions. Russia, being one of the developed nations, the decadal comparison reveals an upsurge in the average per capita CO_2 emissions by 0.52 kt, where the average CO_2 emissions from 1993 to 2020 are 1,618,432.32 kt. Russia, the largest producer of oil and gas combined in the world and the fourth largest emitter in 2017, is experiencing significant impacts from climate change. By 2018, Russia's oil and gas production represented 12.1% and 17.3% of the total global oil and gas production (Xiao et al. 2021). Similarly, other developed nations, such as Saudi Arabia and South Korea, exhibit substantial emission of CO_2 emissions stemming from the massive reliance on energy consumption. In the first decade of the study, Saudi Arabia has had an average increase in per capita CO_2 emissions by 4.47 kt over the two decades. Along with the growth in industrialisation in Saudi Arabia, a massive oil exporting country, the level of energy consumption has led to upward trends along with the increased energy consumed for transportation purposes and due to the transfer of population into urban areas, whereas reported by IEA, 63% of the total CO_2 emissions from fuel combustion was from oil (Hamieh et al. 2022; Mahmood et al. 2020; IEA 2021h). At the same time, making comparisons across the decades, South Korea's change in average per capita CO_2 emissions over the two decades by 3.09 kt is due to the strong dependence on fossil fuels for energy generation, which further extends along with developments in infrastructure, increase in fuel used in transportation backed by economic growth.

The nexus between international trade and CO_2 emissions have been emphasised among developing countries where the export of goods produced in developing nations to developed nations for consumption is likely to increase the amount of energy utilised, air pollution, and land use, leading to intensifying levels of CO_2 emissions (Meng et al. 2023). Thus, thirteen developing countries and eight least developed countries, some of which are Iran, Pakistan, Vietnam, and Bhutan, show an increase in the average per capita CO_2 emissions, where the average change in the per capita CO_2 emissions over the two decades ranges from 7 to 0.17 kt. Among these countries, the primary cause has been the increased use of fossil fuels as their primary source of energy. Notably, during the early 2000 s, the environmental quality in Vietnam raised concerns as the country's use of coal increased due to foreign direct investments, causing rapid growth in the economy, accompanied by urbanisation and industrialisation, which led the country to experience fast-growing emissions of CO_2 (Bui Minh et al. 2023). Correspondingly, 48.1% of the energy supply in Vietnam is from coal, resulting in a carbon footprint comprising 78% of total CO_2 emissions from fuel (IEA 2021j).

On the contrary, Japan, a developed country; Yemen, a least developed country; along with twelve developing countries of Kuwait, Iraq, Jordan, Azerbaijan, Bahrain, Syria, Uzbekistan, North Korea, Singapore, Qatar, and the United Arab Emirates have shown a decrease in the average change in per capita CO_2 emissions over the two decades.

Around 69% of the countries indicate a rise in per capita CO_2 emissions. In contrast, the most significant change in average per capita CO_2 emissions can be observed in Oman, with an average of 42,905.66 kt for the time frame from 1993 to 2020. The lowest positive change compared to the values of Fig. 8A and B is in Pakistan, valuing an average change of 0.17 kt.

Figure 9 represents the choropleth maps of the average change in CH_4 emissions across the Asian continent for two decades, where the average per capita CH_4 emissions in the first decade of 1993 to 2002 increased by the latter decade of 2011 to 2020. As presented in Fig. 9A and B. Of the forty-five countries considered in the study, twenty-one countries indicate an increase in the average per capita CH_4 across the first and the latter decade.

In line with the first decade, it is evident that China and India are the top two emitters of anthropogenic CH_4 emissions. China is the highest emitter of per capita CH_4, similar to per capita CO_2 emissions in the continent. The comparison between the two decades indicates that the average change in per capita CH_4 emissions in China increased by 0.16 ktCO2e. The average CH_4 emissions from 1993 to 2020 were valued at 967,214.43 ktCO2e, with the highest CH_4

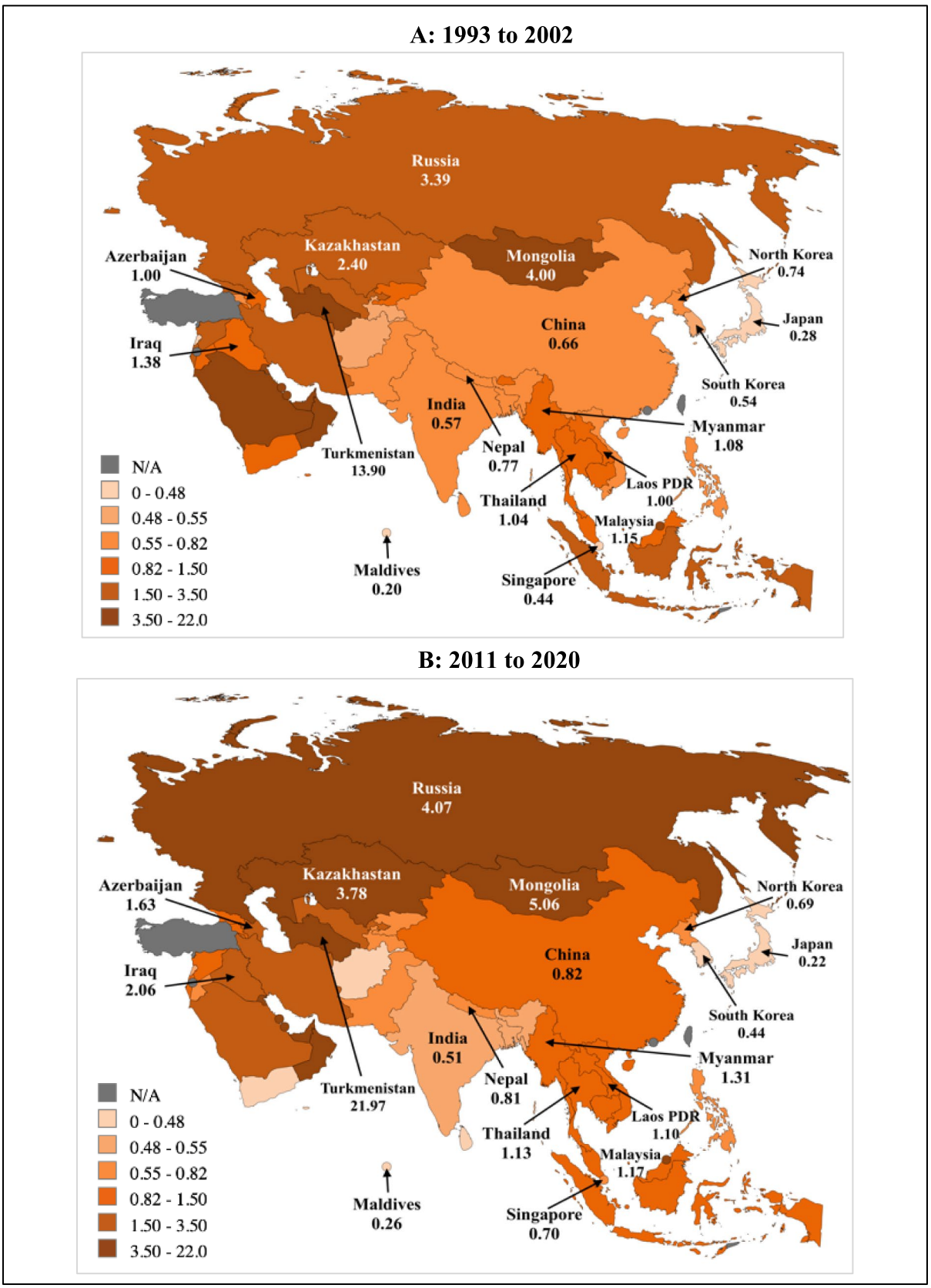


Fig. 9 Average change in per capita CH_4 emissions between two decades from 1993–2002 and 2011–2020 Source: Authors' illustration based on data from WB Indicators

emissions in China occurring in the year 2020. This has been led majorly by the rising demand for meat-based food and urban development, driving the demand for production in the livestock sector (Du et al. 2024). Furthermore, the growing population in China has resulted in poor agricultural management, leading to higher carbon emissions (Hongdou et al. 2018). There has been an increase in the global atmospheric CH_4 from 2006 to 2017, specifically in East Asia. The CH_4 emission growth was widely affected by the microbial sources of landfills and rice paddies while also being influenced by thermogenic emissions caused by the production of fossil fuels and the burning of biomass (Geum et al. 2024). Thailand and Malaysia, which are industrialised countries in Asia, also face increasing levels of CH_4 emissions due to flooded rice fields and other microbial sources, where the average change in per capita CH_4 emissions has increased over the two decades by 0.09 ktCO2e in Thailand and by 0.02 ktCO2e in Malaysia, respectively.

Additionally, Russia and Singapore, which are developed countries, show an increase in the average per capita CH_4 emissions over the two decades. Russia, one of the largest producers of fossil fuels, accounts for an average change in per capita CH_4 emissions of 0.68 ktCO2e. Accordingly, this elevated change results from coal, gas, and oil mining, in which around 95% of the domestic energy production is from natural gas, crude oil, and coal (IEA 2021g). During the latter decade, Singapore's mean CH_4 emissions reached a value of 2,706.05 ktCO2e. As a result of increased emissions from the economy's waste sector, the country experienced an average change of 0.26 ktCO2e in per capita CH_4 emissions (Wong 2022).

Moreover, the decadal comparison shows that twelve of the developing countries, importantly Turkmenistan, Mongolia, Iraq, and Azerbaijan, have had an elevation in the per capita CH_4 emissions over the decades of 1993 to 2002 and the latter decade of 2011 to 2020, ranging from 8.07 ktCO2e to 0.08 ktCO2e. The primary causes behind the rapid growth in CH_4 emissions are the production of fossil fuels to support energy generation, agricultural activities, poor waste management, and specific industrial processes of cement manufacturing. Among these developing nations, Turkmenistan has the highest change in per capita CH_4 emissions, of 8.07 ktCO2e, as per the decadal comparison. Additionally, the countries of Myanmar, Laos PDR, Maldives, and Nepal, identified to be the least developed nations, present to have a rise in the average change in the per capita CH_4 emissions, with the average CH_4 emissions accounting for 58,471.21 ktCO2e, 6,307.48 ktCO2e, 83.32 ktCO2e, and 20,424.09 ktCO2e, respectively. This increase was mainly driven by the livestock and energy generation sectors. Importantly, as reported by IEA, 92% of the energy production in Nepal is from biofuels and waste, which indicates the potential for a rise in CH_4 emissions over time (IEA 2021e).

Nevertheless, twenty-three countries, which include Cambodia, Bangladesh, North Korea, India, Japan, Philippines, Kyrgyzstan, South Korea, Uzbekistan, Georgia, Sri Lanka, Bhutan, Indonesia, Yemen, Israel, Saudi Arabia, Jordan, Oman, Brunei, Qatar, Afghanistan, Syria, Kuwait, and the United Arab Emirates, have represented reductions in the average per capita CH_4 emissions over the two periods. Countries that significantly rely on agricultural sectors, such as North Korea, South Korea, and Japan, are to be accompanied by seasonal variations, where CH_4 emissions are likely to be substantial during the summer, predominantly due to microbial emissions (Geum et al. 2024). This explains the negative change in the average per capita CH_4 emissions in the countries of North Korea, accounting for a decrease of 0.05 ktCO2e, which has less rice cultivation, a reduction of 0.10 ktCO2e in South Korea, and 0.06 ktCO2e in Japan, since microbial emissions are limited in South Korea and Japan for its rice cultivating seasons. Similarly, India, the second in the top ten emitters of CH_4, has an average CH_4 emission for the time frame of 628,876.86 ktCO2e, driven by agriculture, livestock farming, and energy production. 50% of the domestic energy production in India was from coal, and 33% from biofuel and waste as per IEA records for the year 2021 (IEA 2021c). However, the average per capita CH_4 emissions change over the two decades shows a reduction of 0.06 ktCO2e.

Comprehensively, 47% of the countries indicate that the per capita CH_4 emissions escalated over the two decades, in which the most significant change in average per capita CH_4 can be observed in Turkmenistan, with an average of 95,264.54 ktCO2e for the period of study from 1993 to 2020. The lowest positive change is in Malaysia, valuing an average change of 0.02 ktCO2e.

The choropleth maps presented in Fig. 10 portray the average change in MST across the Asian continent for two decades. Comparing the averages of the first decade from 1993 to 2002, presented in Fig. 10A, with that of the latter decade presented in Fig. 10B, reveals an increase in the average MST of all forty-five countries. MST change was highest in Russia, with a value of 1.52 °C from 1993 to 2020, representing an increase of 1.15 °C over the two decades. Mongolia has the second-highest temperature, with an average change of 0.260 °C between the two decades. China, which was identified to be the highest emitter of average CO_2 emissions and CH_4 emissions, has had an average increase in the MST by 0.51 °C.

Additionally, the average MST in developed countries of Saudi Arabia, Israel, Singapore, South Korea, and Japan had escalated from 0.83 to 0.33 °C, respectively. Similarly, the twenty-three developing Asian countries considered in the study had an average change in MST between 0.22 and 0.89 °C. Accordingly, Azerbaijan, a landlocked country, Iraq, and Iran had an increase in the average change in MST by

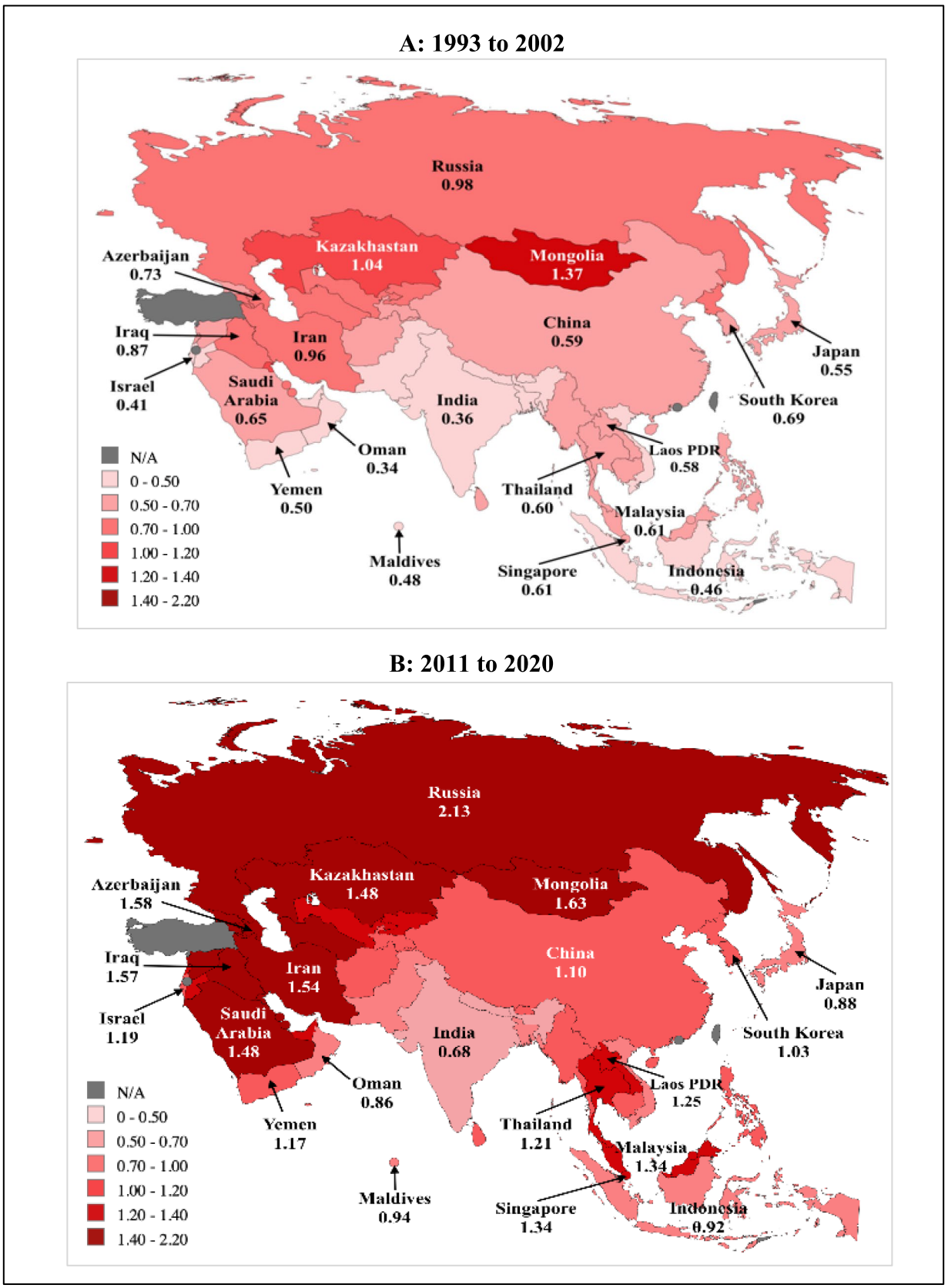


Fig. 10 Average change in MST between two decades from 1993–2002 and 2011–2020 Source: Authors' illustration based on data from the IMF Climate Indicators Dashboard

0.86 °C, 0.70 °C, and 0.57 °C over the two decades. Importantly, Oman had the most significant variation in the average change in per capita CO_2 emissions of 6.99 kt, in which the average MST change in the country depicts an increase of 0.52 °C.

Malaysia, Thailand, Indonesia, and India, which are industrialised countries, further illustrate the average MST rise over the two decades. The average change in MST in these countries has ranged between 0.73 and 0.32 °C. At the same time, Yemen, Laos PDR, and the Maldives, some of the least developed countries, had a rise in average MST where the average change in the countries was 0.67 °C, 0.66 °C, and 0.45 °C, respectively.

Over the past two decades, around thirty-one countries experienced an increase in per capita CO_2 emissions, while around twenty-one countries experienced a rise in per capita CH_4 emissions. This foreshadows that, along with the emission of CO_2 and CH_4, the temperature has increased over the past 28 years. Overall, all forty-five countries considered in the study show that the average MST has increased over the two decades.

Econometric estimation of emission-induced impacts

Followed by the decadal comparisons, the LLC test was conducted for all variables. As per the results, the null hypothesis of all variables except MSL was rejected at a 0.05 significance level. Whereby, MSL was stationary at its first difference. For the stability test of the variables conducted with panel vector autoregression (PVAR), the eigenvalues of all were less than one, indicating the presence of a stable system resilient to any exogenous shocks. S4 Appendix shows that none of the eigenvalues are outside the unit circle.

Equations (1), (2), and (4) used in the study rejected the null hypothesis of the Hausman test, indicating a systematic difference in coefficients; thereby, FE estimation was chosen over RE estimation. Breusch Pagan test was conducted to decide between FE and POLS estimation for Eqs. (1), (2), and (4) indicate the presence of significant variability in the unobserved fixed effects. Thus, FE estimation was identified as the most suitable estimation model over RE and POLS to determine the continental impact of MST change on MSL rise via CO_2 emissions and CH_4 emissions (Jayathilaka et al. 2022).

Table 3 presents the FE estimates for the impact of $LogCO_2$ on MST_1, $LogCH_4$ on MST_2, and $\widehat{MST}$ on MSL with their respective coefficients, standard errors, and significance levels. Accordingly, $LogCO_2$ shows a positive effect on MST_1 at a 1% level of significance. Indicating that when CO_2 emissions increase by 1%, MST_1 would increase by 0.44 °C. Similarly, $LogCH_4$ showed a significant positive impact on MST_2 at a 1% significance level. Hence, a 1% increase in CH_4 emissions would increase MST_2 by 0.62 °C. The model findings suggest the presence of a regional impact of anthropogenic emissions causing a temperature change in the range between 0.4 and 0.6 °C. Furthermore, $\widehat{MST}$ showed a positive effect on MSL at a 5% significance level. This suggests that when MST in the region increases by 1 °C, the result is an increase of 2.24 mm in MSL over time. In other words, indicating a significant sea level rise with the increase of MST change in the region. The modified Wald test for groupwise heteroskedasticity tested on Eqs. (1), (2), and (4) rejected the null hypothesis, indicating the existence of heteroskedasticity, which was addressed by obtaining the robust standard errors.

Extensive studies conducted by other scholars outline similar findings and phenomena aligning with the study results. Akhter et al. (2021) identified that there exists a moderate positive correlation between sea level rise and temperature in the northern Bay of Bengal and elaborated that the thermosteric component driven by MST change is increasing at a rate of 0.8 mm per year, and MST change was primarily responsible for the observed increase in MSL.

Table 3 Panel regressions results

Equation (4)—FE		Equation (2)—FE		Equation (1)—FE	
Variable	MSL	Variable	MST_2	Variable	MST_1
$\widehat{MST}$	2.2483**	$LogCH_4$	0.6276***	$LogCO_2$	0.4412***
	0.9340		(0.1750)		(0.0523)
Constant	0.9204	Constant	−5.2821***	Constant	−3.7402***
	0.9019		(1.7372)		(0.5560)
Observations (NxT)	1215	Observations (NxT)	1260	Observations (NxT)	1260
No. of countries (N)	45	No. of countries (N)	45	No. of countries (N)	45
No. of years (T)	27	No. of years (T)	28	No. of years (T)	28
F-value	5.80**	*F*-value	12.86***	*F*-value	71.10***

Note: *significant at 10%, **significant at 5%, ***significant at 1%. FE denotes fixed effect model. Parenthesis indicates the robust standard error

Source: Authors' calculations based on data from WB Indicators and IMF Climate Indicators Dashboard

Frederikse et al. (2020) further show that the accelerated rise in MSL is attributable to the thermal expansion of oceans and the decrease of ice mass from Greenland resulting from rising MST. A past study developed a semi-empirical model for MSL and MST. It estimated a proportionality coefficient indicating a 4.6 mm rise in MSL per 1 °C rise in MST (Grassi et al. 2013). This confirms the positive and noticeable impact of MST on MSL despite the region considered.

A study which uses regional CO_2 emissions validates the study findings of the impact of CO_2 emissions on MST and shows that CO_2 accounts for 43.7% of Asia's MST increase (Y. Chen et al. 2014). Furthermore, the study shows that a 1% rise in CO_2 emissions can cause a 0.01% rise in MST. FE estimates for Eq. (3) show a positive impact of logCH_4 on MST at a 1% significance level. These findings can be supported by a similar study related to rising MST, which states that CO_2 is the primary causal driver of global warming and that continuous emission of CO_2 and CH_4 will lead to an increase in MST (Larsson and Persson 2023). A dynamic panel analysis was performed to affirm the outcomes of the static panel estimation, with the detailed results provided in Appendix S5.

Furthermore, exploring the heterogeneity across the Asian region, the country-specific SLR results generated for the forty-five countries incorporated in the study are presented in S6 Appendix. The findings demonstrate significant regional differences, indicating that CO_2 emissions significantly impact MST in thirty-one Asian countries. In Singapore, CO_2 emissions have the most substantial effect on MST, with a 1% increase in CO_2 emissions likely leading to a 3.56 °C rise in MST at a 1% significance level. Israel and Jordan also show significant increases, with MST rising by 2.09 °C and 1.51 °C, respectively, for a 1% increase in CO_2 emissions at a 1% significance level. Additionally, CH_4 emissions significantly affect MST in thirty countries. Notably, a 1% rise in CH_4 emissions is expected to cause a 6.65 °C increase in MST in Russia at a 1% significance level. Uzbekistan follows with a significant potential increase of 4.50 °C in MST for a 1% rise in CH_4 emissions, also at a 1% significance level. Resultingly, across forty-four countries, the average MST is presented to have a significant positive impact on MSL, underscoring the sensitivity of local temperature fluctuations on MSL.

Policy implications

Based on the above analysis results, the main recommendation is that all Asian countries, particularly the countries with the higher CO_2 and CH_4 emission rates, including China, India, Russia, Japan, Korea, and Indonesia, should take necessary measures to reduce the emission rates of CO_2 and CH_4 gases, which significantly contribute to climate change in the region. Mitigating emissions across the different areas of the Asian continent may present different countries with specific challenges and opportunities. It is important to tailor the mitigation efforts of various countries according to the regional variations in emission profiles, economic structures, and policy contexts. Specially, in the top five emitting countries. There is also a significant need for coordinated action and collaboration among Asian countries to address shared environmental challenges and achieve collective emissions reduction goals. Current policies implemented by high emitters can be an example for low-emitting countries to mitigate their emissions. When considering only the top five emitters of the Asian region, the two biggest emitters of the region, China and Russia, should mainly focus on accelerating the transition to renewable clean energy and industrial decarbonisation through carbon capture, utilisation, and storage. India should promote sustainable development and clean energy access, particularly in rural areas. Japan should encourage technological innovations for the mitigation of GHG emissions, improve hydrogen technology, implement carbon taxes, and support smart city initiatives. In addition, South Korea should mainly focus on electric mobility, green transitioning, and carbon pricing.

The Asian continent accounts for the most growth in global transport demand and contributes significantly to global transportation emissions. Hence, emerging Asian countries, including China, India, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, and frontier and developing Asian countries, including Bangladesh, Cambodia, the Lao People's Democratic Republic, Mongolia, Myanmar, Nepal, and Sri Lanka, must employ economic growth strategies that align with reducing transport emissions in their countries. Accordingly, all countries in Asia can use and adopt road regulations policies, improve transportation structures, and improve the efficiency and technology of transportation vehicles to reduce carbon emissions.

Economically developed regions in Asia have high energy-related per capita CO_2 emissions depending on their economic structure and energy system. It is crucial to change the energy consumption structure in the Asian Pacific region in favour of alternative energy sources and actively develop climate projects and energy-saving technologies to achieve low-carbon economies. The low-carbon strategies of many countries aim to establish an ecosystem capable of absorbing CO_2 emissions and developing clean technologies instead of entirely replacing fossil fuel energy carriers. Further, the developed countries in the Asian continent can share their emission-mitigating technologies with the developing and least developed countries. This will help Asian countries to reduce GHG emissions in the long term.

Fossil fuel burning from coal, oil, and gas causes most global GHG emissions. Hence, it is evident that Asian

countries which highly contribute to these anthropogenic emissions should employ necessary actions, including transitioning to renewable energy sources such as solar, wind, hydro, and geothermal powers, improving energy efficiency in industries such as heavy industry and engineering, chemicals and petrochemicals, textile, and other light manufacturing. Further, Asian countries can implement carbon pricing mechanisms such as carbon taxes and cap and trade mechanisms.

The Republic of China, which is currently the largest exporter in the world, is in Asia, the continent with the highest global exports. Apart from China, other Asian countries, such as India, Japan, South Korea, Malaysia, Indonesia, Singapore, and Vietnam, are also contributing significantly to the export quantities. Hence, Asian countries should employ different policies to mitigate emissions from export activities, such as optimising transportation routes and modes, implementing sustainable supply chain practices, and investing in upgrading the ports, cargo handling, and shore power facilities.

The Asian continent has the most significant CH_4 emissions from rice cultivation. Therefore, the top rice cultivation countries in the Asian continent, including China, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, and Japan, should employ necessary regulatory actions to reduce the regional emission of CH_4 from microbial sources. Asian countries should implement alternate wetting and drying water management, which allows the rice cultivating fields to dry periodically instead of continuously flooding the rice fields. Also, Asian countries should consider mid-seasonal draining, the use of aerobic rice varieties that can tolerate non-flooded cultivation, an integrated crop-livestock system, crop rotation, and increased use of crop-controlled released fertilisers to reduce CH_4 emissions. Further, to mitigate the CH_4 emissions occurring from the livestock in Asian countries, leading agricultural economies, including China and India, can improve feed efficiency, proper manure management, rotational grazing management to improve healthy soil, and use agroforestry and Silvo pastural practices.

Further, emerging technologies and innovations in the Asian continent will potentially play a crucial role in the mitigation of future GHG emissions. Asia is leading in renewable energy deployment in the world. New technologies such as floating solar farms used in countries like China and India that maximise land use in densely populated areas, 'Perovskite solar cells' which make solar panels cheaper and more efficient, are new solutions tailored to the region's needs. Offshore wind farms and floating wind turbine technologies are deployed to generate large-scale wind power in coastal areas and deeper waters. Countries like Japan and South Korea are investing heavily in 'Green Hydrogen' to decarbonise heavy industries and the transport sector. This innovation, 'Green Hydrogen', holds the potential to become a clean fossil fuel source for numerous industries. Indonesia and the Philippines are considering the use of geothermal energy resources and technologies to significantly reduce emissions in the countries.

Modern energy storage and grid modernisation innovations and technologies, such as lithium-ion and solid-state battery technologies, are being used to store energy from renewable sources like solar and wind. China has been scaling up larger-scale battery storage projects that balance the grid demand, which enables better integration of renewables. Countries like Singapore and South Korea are implementing smart grid systems that utilise sensors, artificial intelligence, and real-time data analytics to improve energy distribution. Moreover, demand response systems, which allow consumers to adjust their energy usage, smart meters, and artificial intelligence-driven platforms, are used to enable demand side management.

Asia is also focusing on carbon capture and storage technologies to mitigate emissions. China has been developing 'Carbon Capture and Utilisation' technologies to capture CO_2 emitted from different industries to convert it into synthetic fuels, chemicals, and plastics. Further, 'Direct Air Capture' systems are piloted in China to offset emissions to decarbonise some industrial sectors. The Asian transportation sector also utilises some of the most transformative innovations for the mitigation of emissions. There is a rise in the manufacturing and use of electric vehicles and innovations in battery technology. Countries like India, China, and Southeast Asia encourage the use of electric two-wheelers, three-wheelers, electric scooters, and rickshaws. Japan has been innovating hydrogen-powered vehicles, and some countries like China and Japan have been experimenting with their extensive high-speed rail networks.

Further, the agricultural sector of the Asian continent also focuses on innovative technologies and practices such as precision agriculture practices, including drones, sensors, and satellite imagery to monitor crops, CH_4 digester technologies to capture and use the gas as an energy source, agroforestry, and soil carbon sequestration to increased sequestration of the land. In some developed cities like Tokyo and Singapore, waste-to-energy technologies are being deployed to convert waste into energy. The developed countries in the region need to share these modern innovations and technologies with the developing and less developed countries in Asia to maximise the collective and collaborative mitigation efforts. Hence, future policy implications tangled and used with these emerging technologies and innovations in the Asian continent have the potential to significantly mitigate emissions in the region which ultimately affects the MST and MSL.

Conclusion

In summary, the Asian continent has a significant contribution to global CO_2 and CH_4 emissions, which impact both MST and MSL. Through the panel regressions analysis, it was discovered that anthropogenic emissions of CO_2 and CH_4 have a significant positive regional impact on MST, and MST has a considerable positive effect on MSL, indicating the increasing levels of MST and MSL on account of increasing anthropogenic emissions. This conclusion is visually aided using the line graphs and choropleth maps, which showcase the growing trend in increasing CO_2, CH_4, MST, and MSL levels. It should be highlighted that CO_2 and CH_4 emissions are continuously growing and can be identified as the main reasons for the increasing MST and MSL. Developed countries emit the highest amount of CO_2 and CH_4 in the Asian region. However, the other country categories, such as developing, industrialised, and least-developed countries, also show an increasing trend in CO_2 and CH_4 emissions. Transportation, fossil fuel combustion, energy generation and consumption, and trade activities have been highlighted in the study as the main CO_2-emitting industries in the Asian continent.

On the contrary, the agricultural sector, livestock maintenance, and waste management contribute the highest CH_4 emissions in the region. These CO_2 and CH_4 emissions trap the heat inside the atmosphere, affecting the MST of the Earth's surface. This leads to thermal expansion and melting glaciers, which ultimately causes an increase in MSL.

Accordingly, the finding of this study has a direct implication for climate adaption and mitigation strategies, particularly for the vulnerable regions in the Asian continent, as highlighted in the policy implication section of the study. The study findings postulate the necessity for critical mitigation of anthropogenic emissions, specifically, given that the consequences of these regional emissions impact the rise in MST change and MSL on the global climate change. This study proves that despite the unaccountable efforts in reducing GHG implemented in Asian countries, the drastic increasing trend of CO_2 and CH_4 emissions is yet to divert to decreasing trends. This highlights the significance of implementing anthropogenic emission mitigation policies in the least-developed and developing countries, which are low polluters compared to developed, industrialised leading emitters in the Asian continent, with more coordination and collaboration among the Asian countries. Hence, this study contributes to the existing body of literature by providing recommended policies for the Asian continent and for specific countries in the region that can be referred to by policymakers and future researchers.

However, the conclusions drawn are subject to several limitations. The authors consider only anthropogenic CO_2 and CH_4 emissions in this study to emphasise the policy implications. However, future researchers can incorporate other variables and GHGs to test MST and MSL according to their research objectives. Even though the model shows stability for the period considered, climate systems are dynamic and can exhibit nonstable behaviour in the long term. Also, the study focuses on the long-term impacts of CO_2 and CH_4 emissions on MST and MSL, it may overlook short-term, intra-annual, and seasonal variations in MST and MSL responses to emissions, which could be addressed by future research. The study recognises the inherent uncertainty in projecting MST and MSL, as these climate variables are subject to a range of natural and human-induced influences that may not be fully captured through econometric modelling. To address this limitation, a robust methodological framework was adopted, incorporating FE estimation, robust standard errors, LLC, and PVAR testing. Although these techniques enhance the reliability of the findings, it is important to note that the projections remain conditional on the continuation of historical patterns and relationships observed in the data. Further, future researchers may utilise interdisciplinary research collaborations and the integration of advanced analytical techniques to enhance their understanding of the complex interactions between emissions, MST, MSL, and climate change dynamics in any specific region.

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Author contribution All authors contributed to the conception and design of the project. CP, SL, SB, and TG composed the writing of the manuscript. CP and TG carried out a significant share of the tasks on statistical work in the manuscript. SL and SB provided critical knowledge in drafting the paper. RJ did the overall supervision of the study. The authors have read and approved the final manuscript.

Data availability All data generated or analysed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval This is not applicable.

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Competing interests The authors declare no competing interests.

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