NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

EARTH OBSERVATORY OF SINGAPORE

PRUDENTIAL

Past Trends and Future Projections of **Air Quality and Health Implications** in Different Countries/Cities

earthobservatory.sg

This study is carried out by the research team led by *Assoc. Prof. Steve Hung-Lam YIM* from Earth Observatory of Singapore (EOS), Nanyang Technological University (NTU), Singapore with a collaboration with *Ms. Yue Li* and *Dr. Tao Huang* from The Chinese University of Hong Kong.

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PRUDENTIAL'S OBJECTIVES

According to the World Health Organisation, climate change affects the social and environmental determinants of health including clean air, safe drinking water, sufficient food and secure shelter. Between 2030 and 2050, approximately 250,000 additional deaths per year from malnutrition, malaria, diarrhoea and heat stress are expected to occur. Reducing emissions of greenhouse gases through decarbonisation efforts can result in improved health, particularly through reduced air pollution.

Prudential's objectives for this research are to:

a. Continue to expand our focus on the intersection of climate change and health;
b. Contribute to wider public policy discussions on the health impacts of climate change; and
c. Drive meaningful conversations with government using science-based research.

In summary, we want to better understand the impacts of climate change on air quality and its associated public health impacts in different countries over a long period by systematically reviewing past studies and assessing long-term air quality trends based on robust, science-based data. This will not only help form the basis of future assessments of effective management and mitigation of climate change, particularly air pollution, but also help us identify areas for potential product innovation, including digital tools, or enhancements to health and protection products.

A Study: The effects of air quality on health in countries/cities across Asia and Africa

Air pollution is a complex problem affecting millions of people around the world each year

Air pollution has drawn attention from all around the world due to its pervasiveness, harm to the environment, and potential health dangers (Bickerstaff, 2004). Numerous studies conducted in the past have reported the worsening of global air quality, particularly in developing countries (Han and Naeher, 2006; Thuong et al., 2022).

The United Nations Environment Programme has highlighted that air pollution is a critical environmental and public health concern. Air pollution has been also identified as the biggest environmental health risk of our time (Desai, 2017). Long-term exposure to air pollution can cause severe respiratory diseases, lung cancer, cardiovascular disease and premature death. A recent study reported that 8.8 million people worldwide die each year due to air pollution. The report by the World Bank published in 2022 estimates that the cost of the health damage caused by air pollution amounts to $8.1 trillion a year, equivalent to 6.1% of global GDP (Lelieveld et al., 2019; Lim et al., 2020; Lončar et al., 2022).

Air pollution is a complex issue influenced by a range of factors that can be broadly categorised as emission-related and climate-related.

- Emission-related factors are diverse and include natural and human-made activities such as burning of fossil fuels, household fires, road traffic and deforestation, which are often linked to urbanisation and economic development.
- Climate-related factors include different types of atmospheric activities, such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which can affect winds and rainfalls and the distribution of air pollutants.

Air pollutant emissions are an important source of air pollution. Increase in global population, industrialization and land cover changes i.e., urbanization are reported to be the critical contributors to degradation of air quality. During the past

few decades, numerous countries have worked hard to develop emission reduction technology and set specific air quality standards (Pai et al., 2022). The World Health Organization (WHO) has issued global air quality guidelines since 1987 for controlling global air pollution and associated mortality. These guidelines were subsequently updated in 1997, 2005 and 2021. Nevertheless, annual fine particulate matter ($PM_{2.5}$) exposure levels in many countries are still significantly higher than the 2005 WHO annual guidelines of 10 $\mu g/m^3$ (WH, 2005). According to the latest update of the WHO's air quality guidelines, the standard for annual $PM_{2.5}$ exposure is limited to 5 $\mu g/m^3$, which means that the majority of the global population lives in polluted areas (World Health Organization, 2021). In 2021, WHO revealed that Southeast Asia, Africa and the Eastern Mediterranean are the most severely affected air pollution hotspots globally. The data demonstrates that only 17% of the 117 countries in the three regions analysed have air quality that meets the WHO air quality guidelines for particulate matter (PM), and that these countries are primarily high-income countries (World Health Organization, 2021). In stark contrast, less than 1% of low- and middle-income countries have air quality that meets the recommended WHO thresholds for small particles, thus, urgent action is required to address this issue.

Air pollution is also closely linked to climate change. Air pollutants and greenhouse gases often come from same sources. Any greenhouse gases emission policies may have co-effect on air quality. Also, changes in climate can influence air quality. For example, warmer atmosphere may enhance the ozone formation (Adame et al., 2022). The Fifth Assessment Report of IPCC shows that climate change will primarily exacerbate existing health problems by 2050 and that the populations currently most affected by climate-related diseases will also be at greatest risk in the future (Barros et al., 2017). Although public health and climate change adaptation have appeared in medical literature and related reports before, the intersection between these two areas of research has received less attention to date. This is because the incidence of climate change impacts on health is complex (Paavola, 2017).

Air pollution can vary over different timescales and across seasons. Due to the spatial diversity, some areas may experience more severe pollution than others. Additionally, air pollution can be transboundary, with pollutants moving across borders and affecting neighbouring countries.

The complexity of air pollution has yet to be fully understood. This calls for a comprehensive study to systematically understand the recent and current situation status of the air pollution, and the relationships between air pollutant emission sources, air pollution and health impact based on holistic datasets. Given these diverse factors that contribute to air pollution, each country/region has its own unique set of characteristics and health impacts. These should be better evaluated.

Local study of air pollution among countries/cities reveals common main drivers but different effects on human health depending on countries/city

This report assesses the air quality and the resultant health impacts over two decades (2000-2020) in Hong Kong and nine countries, namely Singapore, Indonesia, Malaysia, Philippines, Thailand, Vietnam, Côte d'Ivoire, Nigeria and Kenya. A preliminary assessment is also provided for Hong Kong and the full assessment will be completed in the next phase of the project. This study aims to provide useful references for policy formulation, and thus target to provide air pollution information as detailed as possible.

For each country and territory studied, this report first presents a review of historical records of air quality and health impacts related to $PM_{2.5}$, black carbon (BC) and organic carbon (OC), which are the important indicators of air quality. The following section presents the air quality trend analyses of each studied location as a function of time and space in relation to climate events and emission control measures. The report also estimates health impacts of exposure to the studied air pollutants in terms of premature deaths due to diseases including cardiovascular diseases such as stroke, chronic obstructive pulmonary disease (COPD) and ischemic heart disease (IHD), lower respiratory infections (LRI) and lung cancer (LC).

The data used in this report are from open sources and widely used in air pollution studies. The data include global reanalysis of aerosol with spatial and temporal distributions (Modern-Era Retrospective analysis for Research and Applications, Version 2, MERRA2), emissions data from the Community Emissions Data System and the Hong Kong Air Pollutant Emission Inventory, modelled effect of ENSO, IOD and effect of pollution on health, population data from The WorldPop Open Repository and health data from the Global Health Data Exchange.

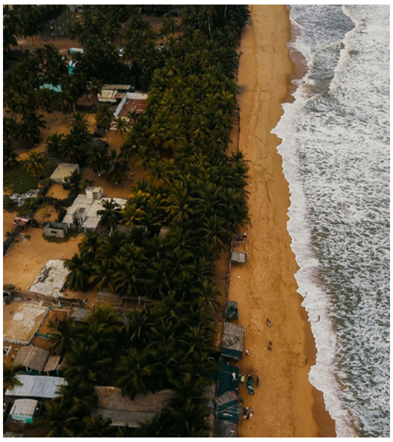
Given the diverse factors that contribute to air pollution, each country and city studied in this report has its own unique set of characteristics and challenges for their air pollution issues. The main results of each country/territory are summarised as follows:

AFRICA

Nigeria

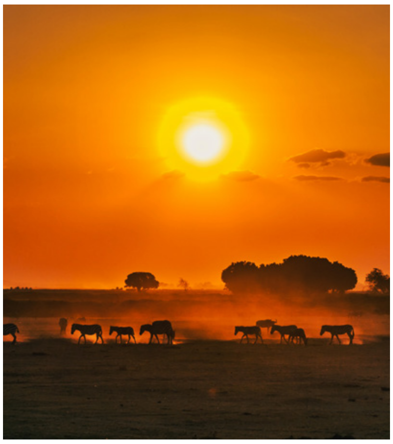
Nigeria has experienced high $PM_{2.5}$ concentration over the last 20 years with an annual average of 62.30 μg/m^3. The trend of $PM_{2.5}$ concentration shows a clear seasonality, with higher $PM_{2.5}$ concentration in the dry season (January and February). Anthropogenic biomass burning is the major direct source of air pollution in this region followed by households, transportation and industry. In addition to local sources, the northern region is more vulnerable to dust storms from the Sahara Desert and natural grassland fire sources. The total number of all-cause premature deaths due to $PM_{2.5}$ exposure in Nigeria over the last 20 years was 2,669,142 (95% UI: 1,953,013 - 3,232,595). LRI, stroke and IHD were the top three diseases to the resultant premature deaths. The total number of premature deaths due to $PM_{2.5}$ in Nigeria remained at a high level. Therefore, more effective emission control measures are required to be implemented in Nigeria, especially in the northern region that is affected not only by local emissions, but also by transboundary air pollution.

Côte d'Ivoire



The average annual concentration in Côte d'Ivoire was 35.83 μg/m^3 over the recent two decades. Côte d'Ivoire shares the same arid climate as Nigeria and is heavily impacted by large amounts of mineral dust from the Sahel and Sahara, as well as by human-induced biomass burning. The main sources of air pollutant emissions in Côte d›Ivoire are the residential, transportation and industrial sectors. Côte d'Ivoire has a clear north-south pattern of $PM_{2.5}$ concentration, with a higher $PM_{2.5}$ level in the north (up to about 35 μg/m^3 in 2020). In addition, air quality in Côte d'Ivoire has become better during the last two decades, with maximum $PM_{2.5}$ concentration in the north decreasing from 45 μg/m^3 in 2000 to 35 μg/m^3 in 2020. The trend of $PM_{2.5}$ concentration in Côte d'Ivoire has a clear seasonality, with January and February being the dry season. The total number of all-cause premature deaths due to $PM_{2.5}$ exposure in Côte d'Ivoire over the past 20 years is 182,301 (95% UI: 109,381-243,133). LRI, stroke, and IHD are the top three diseases contributing to the resultant premature deaths. There is a clear upward trend in the total number of deaths and incidence caused by $PM_{2.5}$ in Côte d'Ivoire. Therefore, Côte d'Ivoire should seek to reduce air pollution in the region, especially in the north, by controlling anthropogenic emissions.

Kenya



$PM_{2.5}$ concentration in Kenya had a distinct episode which occurred in the winter of 2008. The $PM_{2.5}$ episode coincided with the strong La Niña event in 2008, during which the ocean surface in the central and eastern tropical Pacific w as c ooler, rainfall in eastern Africa decreased significantly a nd e asterly w inds a long t he equator became stronger, favouring the long-range transport and accumulation of pollutants in the country. Rapid urbanisation with the corresponding increase in vehicle ownership and the continued use of solid fuels as an energy source have also contributed to the deterioration of air quality in Kenya. The $PM_{2.5}$ concentration in some parts of Nairobi (such as the industrial areas) has been at dangerously high levels since the 1980s, exceeding the WHO guidelines. Kenya shows an upward trend in negative health impacts due to $PM_{2.5}$, both in premature deaths and incidence of various diseases. Over the past 20 years, the total number of all-cause premature deaths due to $PM_{2.5}$ exposure in Kenya was 250,427 (95% UI: 150,456-333,581) and the incidence was 8,618 (95% UI: 4,048-12,524) (in thousands). In Kenya, stroke was the largest contributor to premature deaths due to $PM_{2.5}$. In addition, there was a clear trend of simultaneous increase in the total number and incidence of premature deaths due to $PM_{2.5}$ in Kenya from 2000 to 2020. Therefore, the air quality in Kenya remains serious.

SOUTHEAST ASIA

Indonesia

Indonesia showed an average of annual $PM_{2.5}$ concentration of 10.33 μg/m^3 from 2000 to 2020. The $PM_{2.5}$ concentration in Indonesia showed significant episodes in September 2002 (48.05 μg/m^3), October 2006 (62.00 μg/m^3), October 2015 (42.90 μg/m^3), and September 2019 (30.70 μg/m^3). There was an increasing trend for all emissions in Indonesia, especially an accelerating trend for SO_2 and NO_x. $PM_{2.5}$ concentration in Indonesia tended to be higher in northern Sumatra and Riau, mainly due to the effects of frequent wildfires (up to about 35 μg/m^3 in 2020). The two $PM_{2.5}$ peaks occurring in the fall of 2002 and 2015 coincided with simultaneous El Niño and positive IOD, and the other two $PM_{2.5}$ peaks in 2006 and 2010 coincided with positive IOD. In Indonesia, a total of 3,165,156 (95% UI: 2,013,987 - 4,111,831) premature deaths due to $PM_{2.5}$ occurred during the study period. Stroke, IHD, and COPD were the top three diseases. As for the total incidence, attributable to $PM_{2.5}$ exposure, it is estimated that $PM_{2.5}$ caused 45,158 (95% UI: 21,651-65,242) (in thousands) all-cause incidence in Indonesia over the past 20 years. There was a clear upward trend in the total number of premature deaths and incidence due to $PM_{2.5}$. Therefore, Indonesia is suggested to implement more effective measures to mitigate the impact SO_2 and NO_x emissions on air quality by controlling emissions from the energy and transportation sectors, as well as to improve control and early warning of wildfires.

Malaysia

The average of annual $PM_{2.5}$ concentration in Malaysia during the study period was 10.33 μg/m^3, with significant episodes in September 2002 (26.21 μg/m^3), October 2006 (37.36 μg/m^3), September 2015 (41.31 μg/m^3) and September 2019 (40.82 μg/m^3). In Malaysia, transportation was a significant source of air pollution which involved different modes of transportation such as road, rail, air and sea. Anthropogenic emissions of BC and NO_x were mainly from the transportation sector, whereas OC and SO_2 emissions were mainly from the residential and energy sectors. Air pollutant concentration tended to be higher in Peninsular Malaysia than in East Malaysia in Borneo (peak $PM_{2.5}$ concentration can reach around 25 μg/m^3 in 2010). Southerly winds in the summer months of June to August provided favorable meteorological conditions for the long-range transport of $PM_{2.5}$ from Sumatra northward to Peninsular Malaysia. As another typical maritime country in Southeast Asia, Malaysia is also strongly affected by ENSO and IOD. The two episodes in the fall of 2002 and 2015 coincided with the simultaneous occurrence of ENSO and positive IOD, whereas the two other episodes in 2006 and 2019 coincided with the occurrence of positive IOD. At the same time, the dry climate has led to an increase in wildfires and deteriorating air quality. The combined effects of ENSO and positive IOD exacerbated air quality there, making the climate drier and with less rainfall. During the study period, a total of 275,167 (95% UI: 156,142-374,230) premature deaths were attributed to $PM_{2.5}$ in Malaysia. IHD, stroke, and LRI were the top three diseases to the premature deaths due to $PM_{2.5}$. Our results show a clear and consistent upward trend in the total number of premature deaths due to $PM_{2.5}$ and the incidence of each disease in Malaysia. Therefore, the suggestion for the Malaysian Government is suggested to implement additional measures to control emissions from the transportation sector and to improve air quality monitoring network to monitor of the impact of atmospheric activities on air quality.

Singapore

In Singapore, the average of annual $PM_{2.5}$ concentration over the past 20 years was 15.70 μg/m^3. There were five significant episodes of $PM_{2.5}$ concentration in October 2002, October 2006, June 2013, September 2015 and September 2019, with monthly average $PM_{2.5}$ concentration of 33.70 μg/m^3, 61.27 μg/m^3, 42.77 μg/m^3, 61.83 μg/m^3, and 51.91 μg/m^3, respectively. Singapore has experienced a significant upward trend in total anthropogenic emissions of BC and OC over the past 20 years, while total SO_2 emissions have shown a downward trend. Due to the small size of Singapore, the spatial distribution of air pollution varied marginally and was more susceptible to influences from neighbouring countries. Singapore is strongly affected by both ENSO and IOD. The two episodes in the fall of 2002 and 2015 coincided with the simultaneous occurrence of ENSO and positive IOD, and the other two episodes in 2006 and 2019 coincided with positive IOD. Meanwhile, Singapore is often severely affected by haze and wildfires. The combined effects of El Niño and positive IOD result in a drier climate and less rainfall, causing serious transboundary haze. During the study period, a total of 27,424 (95% UI: 15,495-37,410) premature deaths in Singapore were attributed to $PM_{2.5}$. IHD, stroke and LRI were the top three diseases to the premature deaths due to $PM_{2.5}$. In Singapore, premature deaths and incidence due to $PM_{2.5}$ fluctuated widely with five distinct waves during the recent two decades. Four of which corresponded to high pollution weather caused by El Niño and positive IOD events. Therefore, to mitigate the premature deaths due to PM.5, more effort is suggested to address transboundary haze issue in Singapore.

Philippines

The Philippines showed an average of annual $PM_{2.5}$ concentration level of 9.68 μg/m^3 during the recent two decades, which is comparable to the global average. Over the past two decades, anthropogenic emissions of BC and SO_2 in the Philippines showed a decreasing trend until 2011. Air pollution was more severe in the major northern cities such as Manila, Quezon, Caloocan and Baguio. The air pollution in the major cities was mainly associated with vehicle emissions. The maximum $PM_{2.5}$ concentration in the Philippines remained around 35-40 μg/m^3 the highest value occurring in 2010. The Philippines is surrounded by sea in Southeast Asia and thus influenced by complex climate variability. The combined effects of El Niño and positive IOD exacerbated the serious $PM_{2.5}$ pollution levels in the country in 2015, whereas the effects were not significant in 2002. In addition, air pollution in the Philippines was more influenced by individual positive IOD events rather than individual El Niño events. The total number of all-cause premature deaths due to $PM_{2.5}$ in the Philippines over the past 20 years was estimated to be 988,137 (95% UI: 1632,566-1,282,200). In terms of total incidence, a total of 25,559 (95% UI: 12,430-36,714) (in thousands) were attributable to $PM_{2.5}$, with LRI being the largest contributor to the premature deaths due to $PM_{2.5}$. There was a significant upward trend in the total number and incidence of premature deaths due to $PM_{2.5}$ in the Philippines over the past 20 years. Therefore, the government is suggested to focus more on addressing traffic emissions in the northern part of the Philippines.

Thailand

Thailand is one of the countries in mainland Southeast Asia with annual average $PM_{2.5}$ concentrations below 20 μg/m^3, while its BC concentration was relatively high (1.12 μg/m^3). In Thailand, emissions of air pollutants except SO_2 have been increasing in the last 20 years. Air pollution in Thailand was severe in the northern and north-eastern cities, due to exposure to air pollutant emissions of agricultural activities and forest fires. There was no significant relationship between ENSO or IOD events and changes in air pollution in Thailand. The total number of all-cause premature deaths due to $PM_{2.5}$ in Thailand was estimated to be 830,045 (95% UI: 563,218-1,049,959), and the number of incidence was 15,900 (95% UI: 8,258-22,310) (in thousands) in the past 20 years. In Thailand, stroke was the largest contributor to premature deaths due to $PM_{2.5}$. There was a clear and continuous upward trend in the total number of premature deaths and incidence due to $PM_{2.5}$ in Thailand over the past 20 years. Thailand, especially its the northern part, still suffered from air pollution and thus needs to focus on improving the agricultural and transportation structures of the region to mitigate the associated air pollutant emissions.

Vietnam

During the past 20 years, the average of annual $PM_{2.5}$ concentration in Vietnam was below 20 μg/m^3, whereas the BC concentration level was relatively high (1.13 μg/m^3). Similar to Thailand, Vietnam is located in mainland Southeast Asia. Emissions of all air pollutants in Vietnam showed an accelerating trend, but the annual average $PM_{2.5}$ concentration showed the opposite trend. Air pollution in Vietnam was severe in the northern and north-eastern cities due to emissions of agricultural activities and forest fires. There was no significant relationship between ENSO or IOD events and changes in air pollution in Vietnam. The total number of all-cause premature deaths due to $PM_{2.5}$ in Vietnam over the past 20 years as estimated to be 1,618,314 (95% UI: 1,158,436-1,993,307) with incidence of 20,397 (95% UI: 11,178-28,032) (in thousands). In Vietnam, stroke was the largest contributor to premature deaths due to $PM_{2.5}$ with a total of 929,435 (95% UI: 692,191-1,119,425) premature deaths. In terms of the variations in health outcomes during the study period, the total number of premature deaths and incidence due to $PM_{2.5}$ in Vietnam showed a significant upward trend in the past 20 years. Hence, Vietnam particularly its northern area still experienced air pollution. The country is thus suggested to put more effort to enhance its transportation and agricultural infrastructures to reduce the associated air pollutant emissions.

Hong Kong (China)

Hong Kong experienced air pollution. Local emissions are the key contributor to the air pollution in the city. Road transportation is a particularly important emitter leading to serious roadside air pollution. Transboundary air pollution is another important contributor to local air pollution. The transboundary air pollution can be enhanced by La Niña. While the emission, topography and weather of Hong Kong are complicated, the corresponding analysis requires more time to be completed. The full analysis results for Hong Kong will be presented in the second phase.

Next Steps

Numerous datasets such as those in the report (emissions, meteorology, mapping of air pollutants, health outcomes) should be further improved in detail, monitored in the long-term and shared so that this study can be updated in a few years to assess progress.

Given the transboundary nature of air pollution, cooperation between different countries within ASEAN and across the world should be maintained and improved as appropriate.

Reporting of progress is recommended so that progress against UN SDGs, especially Goal 3, 7, 11 and 13, can be measured and directions undertaken to reach the goals by 2030.

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INTRODUCTION

Project Background

Long-term exposure to ambient air pollution has been reported to increase the risk of developing respiratory disease, chronic obstructive pulmonary disease (COPD), lung cancer and cardiovascular disease (CVD), as well as other health problems that might be related to premature deaths (Anenberg et al., 2011; Gu et al., 2018; Southerland et al., 2022). A recent study has reported that 8.8 million people worldwide die each year due to air pollution, indicating that the $PM_{2.5}$ problem is a global challenge (Lelieveld et al., 2019; Lim et al., 2020). A growing number of epidemiological studies on air pollution in recent years have evaluated exposure levels using a variety of models and techniques, from macroscope to microscope (Bauwelinck et al., 2022; Glasgow et al., 2016; Zou et al., 2009). Despite the fact that many countries are aware of the issue and have taken steps to lessen air pollution, exposure assessment studies on this topic in developing countries are still limited, especially in some countries of Africa and Southeast Asia (Han and Naeher, 2006; Thuong et al., 2022).

The largest-ever data released by World Health Organization (WHO) reveals that Southeast Asia, Africa, and the Eastern Mediterranean are the world's air pollution hotspots (WHO, 2021). The data show that only 17% of the 117 studied countries had air quality meeting the recently updated WHO air quality guidelines for particulate matter (PM), and these countries are mainly in high-income countries. By contrast, less than 1% of low- and middle-income countries with WHO recommended thresholds for small particles (Goshua et al., 2022). These pinpoint the important spatial heterogeneity of air pollution particularly in low- and middle-income countries. In Southeast Asia, air pollution is primarily caused by two potential sources: one is biomass burning and volcanic activities that can easily be intensified by El Niño Southern Oscillation (ENSO), whereas the other one is human activity (Sakti et al., 2023). Although summer monsoon precipitation variability in East Asia is mainly regulated by ENSO events (Wu et al., 2009), Indian Ocean Dipole (IOD) has also been found to significantly influence summer precipitation in Southeast Asia (Yang et al., 2010). IOD events begin with anomalous cooling of sea surface temperature (SST) along the Sumatra-Java coast in the eastern Indian Ocean during May-June (Feng and Meyers, 2003), which affects the climate of Australia and other countries surrounding the Indian Ocean Basin, and it is also a significant contributor to rainfall variability in these regions (N. Saji and Yamagata, 2003; Saji et al., 1999). In West Africa, biomass burning is a large direct source of air pollution, which predominates in dry seasons (Wu et al., 2022). Previous studies have confirmed that the population in West African region has continued to grow at about 2% per year in recent years. This population trend indicated that anthropogenic emissions was the main source of pollution in the region (Keita et al., 2018; Knippertz et al., 2015). Hence, specific, and scientific analysis methodologies are needed to assess and evaluate air quality in different regions by combining different chemical components of emissions over a long period.

AFRICA

Nigeria

The ambient air quality (lead, particulate matter, nitrogen oxides, sulfur dioxide, volatile organic compounds) observed in Nigeria fails to fulfil the WHO air quality standards, clearly indicating the unsafe levels and the attendant health risks (Osuji and Avwiri, 2005). Air pollution has a direct impact on the health of the local population, especially among the rural population in Nigeria (Nwachukwu et al., 2012).

Côte d'Ivoire

According to a study on the environment and epidemiology in 2014, high levels of gaseous and particulate air pollution in Abidjan (city of Côte d'Ivoire) are mainly from household fires and traffic. These emissions and their associated deaths and morbidity are likely to increase over the next decade unless action is taken to regulate the sources of emissions (Becerra et al., 2020).

Kenya

Rapid urbanisation, the corresponding increase in vehicle ownership, and the continued use of solid fuels as an energy source have contributed to the deterioration of air quality in Kenya. $PM_{2.5}$ concentration in some parts of Nairobi (such as industrial areas) has been at dangerously high levels since the 1980s, exceeding the WHO guidelines (deSouza, 2020).

SOUTHEAST ASIA

Indonesia

Southeast Asia accounts for approximately 15% of the world's tropical forests. Most of the forests are in Indonesia, where peatland fires are the world's leading CO_2 emitters (Jaenicke et al., 2008; Stibig et al., 2014). El Niño amplifies the impact of wildfires, for example, during the El Niño period in 1997 and 1998, the extensive wildfires in Indonesia released around 0.95 Gt of carbon (Page et al., 2002). Large wildfires also occurred in Indonesia during the 2002 and 2006 El Niño events. The average annual CO_2 emissions from peatland fires in Indonesia reached 1.4-4.3 Gt from 1997 to 2006, equivalent to 19-60% of the global average annual carbon emissions from fossil (Hooijer et al., 2006).

Malaysia

Malaysia is a major contributor to pollutant emissions in Southeast Asia, just below Indonesia and Thailand, where the main sources of air pollution are the increased demand of motor vehicles and rapid industrialisation (Sentian et al., 2019). Besides, over the years, the air quality in Malaysia has suffered from transboundary haze caused by forest fires outside the country. In 2005 and 2013, higher air pollution records were measured in Malaysia due to the regional haze problems (Forsyth, 2014).

Singapore

Singapore is a highly urbanised country in Southeast Asian, which suffers from the seasonal exposure to transboundary haze (Ho et al., 2019). Singapore's haze problem usually coincides with the dry season from July to September, when the southwest monsoon transfers haze from forest fires outside the country (Vadrevu et al., 2014). During the haze exposure period, the load of particulate matter and other aerosol pollutants in the atmosphere increases (Wiggins et al., 2018; Xu et al., 2015).

Philippines

Air pollution in the major cities such as Manila mainly comes from mobile sources, power plants and industrial plants, whereas most of the hazardous pollutants in Manila come from transportation or mobile sources (Krupnick et al., 2003). Data from the Land Transportation Office (LTO) show that the number of registered motor vehicles in Manila increased by 16.41% in 1990 compared to 1989. Of these, only 16% were new vehicles and the rest were older vehicles. 73.4% were gasoline vehicles, whereas 25.2% were diesel vehicles (Gallardo, 2008).

Thailand

Thailand's air pollution has reached unsafe levels due to its fast economic growth and the construction of petrochemical facilities since 2006. (Guo et al., 2014). Due to rapid economic development and urbanisation, Bangkok has experienced serious air pollution problems. The main source of air pollution in Bangkok is vehicle emissions. The PM10 emissions of vehicles accounts for more than 30% of the total PM10 emissions in the country (Chuersuwan et al., 2008).

Vietnam

Forest biomass burning in north-western Vietnam affects air quality in Hanoi during the peak Ultraviolet Aerosol Index (UVAI) in March and April. BC in Hanoi peaked in December and January, especially during December 2013 and January 2014, and wind patterns suggest that pollutants during this period were mainly transported from large urban areas in southern China. Serious pollution events were observed in Hanoi. In addition to this, BC concentration was significantly higher at night than during the day, with peaks generally after 21:00 local time (Lasko et al., 2018).

EAST ASIA

Hong Kong (China)

In Hong Kong, La Niña enhances air pollution levels to a certain extent (Yim et al., 2019). Massive levels of PM emissions from biomass burning, which can have a regional or global impact on climate. The major aerosols produced by biomass combustion are organic carbon (OC) and black carbon (BC) (Yin et al., 2019). Many studies have demonstrated that transboundary air pollution is an important contributor to air pollution in Hong Kong, which has caused a great concern due to its significant role in air quality (Gu et al., 2018; Gu and Yim, 2016; Huang et al., 2021).

Objectives of the Study

This project focuses on nine countries and one city, including Singapore, Indonesia, Malaysia, Philippines, Thailand, Vietnam, Côte d'Ivoire, Nigeria, Kenya, and Hong Kong (China). Our analyses target to assess the air quality changes and the resultant health impacts in the recent two decades (2000-2020). Three objectives are designed as follows:

To review historical records of air quality and health impacts
A systemic literature review is conducted to review air quality and health assessment studies in the studied countries/cities in the recent two decades. The literature review includes global, regional, country and even local studies. The targeted air pollutants include particulate matter with an aerodynamic diameter ≤ $_{2.5}$µm ($PM_{2.5}$), black carbon (BC) and organic carbon (OC). Past emission control measures related to the studied air pollutants are discussed, whereas past studies assessing the air pollution-attributable health impacts in the studied countries/cities are summarised.

To analyse trend of air quality in studied countries/city
Past trends of air quality in the aforementioned countries/city in the recent two decades are analysed. Any climate/weather events are incorporated into the analyses to explain the past trend. Moreover, based on the literature review results, past implemented emission control measures are considered to explain the past changes in the concentration levels of the air pollutants. In addition, the spatial distribution of the air pollutants is assessed.

To estimate the health impacts of exposure to the studied air pollutants in terms of deaths and incidence
The health impacts of air pollutant exposure are evaluated in term of premature deaths and morbidity. This project estimates the premature deaths due to the diseases including cardiovascular diseases (CVD), chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), and lung cancer (LC). With the estimated health impact results, this project describes the trend of the health impacts during the past two decades. Similar to air quality trend analyses, past climate/weather events and emission control measures are considered in this health impact assessment.

LITERATURE REVIEW

The purpose of the literature review is to establish a comprehensive understanding regarding the past trend of air pollutants of the selected nine countries and a city in the recent two decades. This review mainly collects the information from peer-review journal papers, government reports, and other relevant scientific documents.

Past air pollution trend analysis

A long-term trend analysis study of global air pollution shows that $PM_{2.5}$ concentration tended to increase in most developing countries (such as countries in Asia, South America, and sub-Saharan Africa) between 1998 and 2016, whereas the $PM_{2.5}$ concentration tended to decrease in developed countries. $PM_{2.5}$ concentration is strongly correlated with the increase in total population in India and sub-Saharan Africa (Lim et al., 2020). Moreover, the trend of $PM_{2.5}$ concentration from 2000 to 2019 varied between different regions. Africa was the region with the largest decrease in annual average concentration from 43 μg/m^3 in 2000 to 35 μg/m^3 in 2019 (Southerland et al., 2022). In contrast, Southeast Asia showed the largest average increase in air pollution concentration, with urban population-weighted average concentration increasing by 27% over the last two decades (from 49 μg/m^3 to 62 μg/m^3). Intra-regional variation was evident in both regions.

Official air quality monitoring data are lacking or unavailable in most Economic Community of West African States, such as Kenya, which is one of the selected countries in this study (deSouza, 2020; Mir Alvarez et al., 2020). Thus, studies of long-term pollution trends in Africa are very limited.

AFRICA

Nigeria

$PM_{2.5}$ level in Nigeria is as high as 125 μg/m^3, well above recommended levels and the world average (Urhie et al., 2020). Sonibare and Jimoda (2009) observe an increasing trend of air pollution in densely populated cities in Nigeria such as Lagos, Abuja, and Port Harcourt in 2009.

Côte d'Ivoire

A 14-year aerosol fingerprint impact study conducted in Daloa, Côte d'Ivoire shows that the aerosol optical depth (AOD) increased from 0.8 to 1.3 between 2000 and 2010. Seasonal variations were detected during the study period, with AOD increasing from January to April and decreasing from October to December in Daloa (Emetere et al., 2019).

Kenya

$PM_{2.5}$ concentration in Nairobi, Kenya was found to consistently elevate during 2014-2015, with slightly elevated values during dry periods (Kirago et al., 2022).

SOUTHEAST ASIA

Indonesia

Siregar et al. (2022) measured long-term (2000-2007) $PM_{2.5}$ concentration in Indonesia based on satellite-derived aerosol optical depth measurements. The study reported that air quality of Sumatra has been deteriorating, from a low of 8.71 μg/m^3 in 2000 to a high of 17.48 μg/m^3 in 2006.

Malaysia

A study conducted by Rahman et al. examined long-term air pollution in the capital city of Malaysia. The average $PM_{2.5}$ concentration in the study area consistently exceeded the annual standard (15 μg/m^3) of the United States Environmental Protection Agency (USEPA) during the study period 2002 to 2011, with an average of 25 µg/m^3. Higher $PM_{2.5}$ concentration levels were found in 2002, 2005, and 2006, which may be due to regional haze pollution.

Singapore

The air quality in Singapore was affected from transboundary haze over the years. Research reported that the transboundary haze was caused by forest fires from Indonesia. During 1991-1994, total suspended particulate matter (TSP) levels peak at certain moments. For example, the peak in June 1991 was associated with the eruption of Mount Pinatubo, and the peak in mid-August to early November 1991 was mainly influenced by forest fires in Indonesia (Chew et al., 1999). Singapore experienced another severe haze between August and October 1994, when PM10 levels increased sharply and atmospheric ozone levels exceeded the US EPA ozone standard, also due to transboundary pollution from large forest fires in parts of Sumatra and Kalimantan (Awang et al., 2000). In 2005 and 2013, higher air pollution records were measured in Singapore due to the haze problems outside the country (Forsyth, 2014).

Philippines

Previous studies reported that $PM_{2.5}$ concentrations in urban areas in the Philippines consistently exceeded the WHO guideline. In Philippines, air quality in summer is better because the summer southwest monsoon brings relatively heavy precipitation to most of the archipelago during May through October. The northeast winter monsoon is generally associated with lower precipitation amounts. So, during the dry season, the average $PM_{2.5}$ concentration at traffic sites in Metro Manila can reach 58.4 µg/m^3 (Tantengco and Guinto, 2022). Air quality is worse in the northern Philippines, especially in Luzon, where the port of Manila is located at, which is highly influenced by polluted air masses from the southern part of Taiwan's highly industrialized region (Tseng et al., 2021).

Thailand

A study of long-term pollution trends in Bangkok, Thailand reported that about half of the monitoring stations showed a slight decrease in PM10 concentration from 2006 to 2016, which may indicate that Bangkok's strategies to address long-term urban PM10 issues, such as strengthening fuel and vehicle standards and monitoring mobile sources in Bangkok, are being effectively implemented. (Chirasophon and Pochanart, 2020). However, in 2017, the average $PM_{2.5}$ concentration in the Bangkok still exceeded the Thailand standard of 50 µg/m^3 in 24 hours (http://air4thai.pcd.go.th/webV2/download_book.php? bookid=33(in Thai)).

Vietnam

As the most populated city in Vietnam, Ho Chi Minh City had air quality deteriorating rapidly over the past 20 years due to increases in its anthropogenic emissions (Nguyen et al., 2022). During 2014-2017, the daily level of PM10 in Ho Chi Minh City was 74 µg/m^3, which was lower than the standard of the Vietnamese National Technical Regulation on Ambient Air Quality (150 µg/m^3), but higher than the European Air Quality Standard or the WHO guidelines (50 µg/m^3). The number of days exceeding the Vietnamese national standard was 36 days, or $_{2.5}$% of the study period, while the number of days exceeding the WHO standard guidelines was 1126 days, or 79% of the study period. PM10, NO2 and O3 levels were higher in the dry season than in the rainy season (Phung et al., 2016).

EAST ASIA

Hong Kong (China)

Ambient $PM_{2.5}$ in Hong Kong showed different trends before and after 2005. There was an increasing trend in PM before 2005 with average PM10 and $PM_{2.5}$ concentration of 51.4 µg/m^3 and 34.2 µg/m^3 in 2005, respectively. From 2006-2016, the PM concentration started to decline ; nevertheless the lowest annual average PM concentration observed in 2016 was still higher than the WHO guideline value (Liao et al., 2018).

Health impacts of exposure to air pollutants

From 2000 to 2020, the premature death rate due to $PM_{2.5}$ in Southeast Asia increased by 33%, while cities in Africa experienced the greatest decline, with a 40% reduction. The global average urban premature death rate due to $PM_{2.5}$ in 2019 was approximately 61 per 100,000 inhabitants. The regional averages of Africa were below the global urban average whereas the Western Pacific and Southeast Asia averages were above the global urban average (Southerland et al., 2022).

In Southeast Asia, the average annual number of premature deaths caused by $PM_{2.5}$ increased by 38% from 1999 to 2014, with stroke and IHD being the two major contributors, accounting for 39% and 35% of the total, respectively. High values were concentrated in the metropolitan areas of Southeast Asia except for North India, Bangladesh (Shi et al., 2018).

In addition, excess deaths in adults, new-borns, and children due to $PM_{2.5}$ were high in emerging and middle-income countries in Africa and South Asia. In 2012, approximately 97.6% of the South African population was exposed to $PM_{2.5}$ concentration levels above the 2005 WHO guidelines (10 μg/m^3). From 2000 to 2012, the number of deaths due to $PM_{2.5}$ rose from 15,619 to 19,507, an increase of 25%; while the number of deaths due to ozone pollution increased by 31% (Roomaney et al., 2022). The State of Global Air 2019 report revealed that air pollution was the eighth leading risk factor for premature death in Kenya, with nearly 19,000 deaths in 2017, 5,000 of which were due to ambient air pollution and the rest due to indoor pollution (https://www. stateofglobalair.org/).

AFRICA

Nigeria

In the African countries of Niger, Chad and Nigeria, 59%, 55% and 54% of excess deaths occurred in children and new-borns (Chowdhury et al., 2022). Nwachukwu et al., (2012) studied the impact of air pollution on diseases among the people of Rivers State, Nigeria by analysing data from the Nigerian National Ministry of Health and National Ambient Air Quality. Their study reported that a total of 30,435 cases of diseases were reported from 2003 to 2008, of which 61 patients died. A number of diseases prevalent in the study area (e.g., tuberculosis, pneumonia, chronic bronchitis, and upper respiratory tract infection (URT)) were significantly correlated with air pollution (Nwachukwu and Ugwuanyi, 2010).

Côte d'Ivoire

A study of different sources of air pollution in neighbourhoods within Abidjan (the city of Côte d'Ivoire) found that household cooking fires, garbage burning, and vehicle emissions were associated with the incidence of specific diseases. The study estimated that by reducing annual $PM_{2.5}$ emissions to meet the WHO standards, the hospitalisation rates could be reduced by 3.6% for people living near garbage burning sites, 3.8% for those living near heavy traffic, and up to 24.9% for those living near high levels of home fire emissions (Maesano et al., 2018).

Kenya

A study on indoor air pollution and acute respiratory infections from biomass burning in Kenya found acute respiratory infections and acute lower respiratory infections as an increasing concave function of average daily exposure to PM10, with the rate of increase accelerating when exposed to PM_{10} at concentrations below 1000-2000 μg/m^3 (Ezzati and Kammen, 2001).

SOUTHEAST ASIA

Indonesia

Previous studies have shown that air pollution is currently responsible for 50% of the morbidity in Indonesia and the overall rate is expected to increase by 26% by 2030 (Haryanto, 2018; Haryanto and Franklin, 2011).

In addition, long-term exposure to higher levels of $PM_{2.5}$ has a greater chance of having CVD, especially in women and the elderly (Siregar et al., 2022).

Malaysia

A previous study in Malaysia on the possible health effects of the 1997 forest fires found that the number of outpatient clinics increased two to three times during the peak smoke haze period in Kuching, Sarawak (Afroz et al., 2003). There was an increase in the number of respiratory outpatient clinics from 250 to 800 per day in the Kuala Lumpur General Hospital, and some major hospitals in Kuala Lumpur also saw an increase in asthma, acute respiratory infections, and conjunctivitis during August-September 1997 (Brauer and Hisham-Hashim, 1998). In terms of respiratory diseases, Selangor and Sarawak recorded a significant increase in the total number of cases during the September haze. In addition, the daily incidence of conjunctivitis in Sarawak in September was found to be positively correlated with PM10 concentration. In Malaysia, short-term exposure to high levels of PM10 is harmful to human health, particularly affecting children, the elderly, and people with respiratory problems the most (Awang et al., 2000).

Singapore

Ho et al. (2020) studied the effect of air pollution on mortality in Singapore and demonstrated a significant association between increased Pollutants Standards Index (PSI) and mortality, especially in the short term, where PSI in the very unhealthy range had a detrimental effect on mortality. This may be due to the fact that PSI mainly affected the frail population, and the depletion of this writing population led to a reduction in potential mortality after a few days, thus temporarily reducing the impact of PSI (Yeo et al., 2014). Previous studies in Singapore have also shown an increase in haze-related inpatient and outpatient visits (e.g., respiratory illnesses) during haze periods (Emmanuel, 2000).

Philippines

The Institute for Health Metrics and Evaluation reported that the Philippines was one of the ten nations with the highest burden of air pollution-related mortality, with 64,000 deaths in 2019 and a predicted rise in the following years (Macatangay and Hernandez, 2020).

Thailand

In Bangkok, from January 2006 to December 2014, increased in 10 $\mu g/m^3$ in O3, NO2, SO_2, PM10, and CO at a lag of 0-1 days were associated with increases in cardiovascular admissions of 0.14%, 1.28%, 8.42%, 1.04%, and 6.69%, respectively; and respiratory admissions of 0.69%, 1.42%, 4.49%, 1.18%, and 7.69%, respectively. Older adults (≥65 years) appear to be the most vulnerable group to air pollution (Phosri et al., 2019).

Vietnam

In Ho Chi Minh City, changes in NO2 and PM10 levels were strongly associated with hospital admissions for respiratory and CVD; SO_2 levels were only moderately associated with respiratory and CVD admissions, while O3 concentration was not associated with either of these. The risk of respiratory admission increased from 0.7% to 8% and the risk of CVD admission increased from 0.5% to 4% for each 10 $\mu g/m^3$ increase in each air pollutant. The study found that women were more sensitive to air pollutants than men with respect to respiratory disease. The risk of hospital admission for cardiovascular disease from NO2 exposure was slightly higher in women than in men. In contrast, men had a higher risk of hospital admission for cardiovascular disease due to PM10 exposure than women (Phung et al., 2016).

EAST ASIA

Hong Kong (China)

In Hong Kong, both health risk and mortality burden have shown a continuous decreasing trend in recent years (2001-2016), which may be associated with relevant air pollution control measures (Liao et al., 2018). The beneficial population health improvements of reducing air pollution in Hong Kong have been confirmed by Hedley et al. (2002). Their study reported a 2.0%, 3.9%, and 2.1% reduction in cardiovascular, respiratory, and all-cause deaths, respectively, in the first 12 months after the implementation of fuel sulfur content limits in Hong Kong.

MATERIALS AND METHODS

Air pollutant dataset for a trend analysis

In this study, regional surface $PM_{2.5}$, BC, and OC concentration data were obtained from monthly Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) dataset managed by NASA. Compared with previous version (MERRA-1), MERRA-2 is the latest version of global atmospheric reanalysis for the satellite era produced by NASA Global Modeling and Assimilation Office (GMAO) using the Goddard Earth Observing System Model (GEOS) version 5.12.4 (GMAO, 2015). Other applications of MERRA-2 dataset can be found in (Stauffer et al., 2018; Fang et al., 2020; Yim et al., 2022). This dataset was monthly data starting from January 2000 to December 2020, with a spatial resolution of 0.5°×0.625°. It should be noted that monthly rainfall data was also derived from MERRA-2 dataset.

Emission dataset for a trend analysis

Emission data was obtained from the Community Emissions Data System (CEDS), which produces consistent estimates of global air emissions species (BC, OC, NO_x, SO_2, NH_3) since 1750. Detailed information can be found in Hoesly et al. (2018). Emission data in Hong Kong was derived from Hong Kong Air Pollutant Emission Inventory, which can be found in Environmental Protection Department (EPD) official website (https://www.epd.gov.hk/epd/english/top.html).

Air pollutant dataset for a health implication analysis

The annual high-resolution ground-level $PM_{2.5}$ data for a health implications analysis was derived from a hybrid dataset from the Atmospheric Composition Analysis Group at Washington University in St. Louis, with a high spatial resolution of 0.01°×0.01° (van Donkelaar et al., 2021). This data estimated $PM_{2.5}$ concentration from 1998 to 2021 by combining Aerosol Optical Depth (AOD) retrievals from the NASA MODIS, MISR, and SeaWIFS instruments with the GEOS-Chem chemical transport model, and then calibrating to global ground-based observations using a Geographically Weighted Regression (GWR).

Land-use regression model for a health implication analysis in Hong Kong

Since the high spatial resolution (0.01° × 0.01°) dataset was gridded at the finest spatial resolution of the incorporated information sources, the $PM_{2.5}$ gradient at the gridded resolution may not be fully resolved due to the influence of coarser resolution information sources. Therefore, the $PM_{2.5}$ data for Hong Kong was replaced by the predicted results from the more explanatory land-use regression (LUR) model in order to improve the accuracy and interpretability. Detailed information of LUR model building and evaluation can be found in previous research (Li et al., 2022; Nduka et al., 2022).

El Niño-Southern Oscillation (ENSO)

One of the mostly utilised ENSO index is the Oceanic Niño Index (ONI) from NOAA. It was defined as the 3-month moving mean of sea surface temperature anomaly index in Niño 3.4 region (5°N to 5°S, 150°W to 90°W). In this study, an ENSO event was defined as five consecutive ONI in boreal winter at or above + 1 for El Niño and at or below – 1 for La Niña during 2000 to 2020. Neutral period was defined as – 0.5 ≤ ONI ≤ 0.5.

Indian Ocean Dipole (IOD)

Monthly Dipole Mode Index (DMI) was used in this study to characterise Indian Ocean Dipole (IOD) from 2000 to 2020. The Index represents the anomalous SST gradient between the western equatorial Indian Ocean (50°E - 70°E and 10°S - 10°N) and the Southeastern equatorial Indian Ocean (90°E - 110°E and 10°S - 0°N), and was calculated at NOAA/PSL using the HadISST1.1 SST dataset (Ashok et al., 2001; N. H. Saji and Yamagata, 2003). Following the definition in Hague 2021, Positive (negative) IOD events were identified when the three-month running mean DMI was + 0.4°C or above (– 0.4°C or below) for at least three consecutive months between June and November. Neutral period was defined when the DMI is sustained between – 0.4°C and 0.4°C.

Gridded population data

Gridded population data in this study used The WorldPop Open Repository (WOPR) dataset, which provides gridded population estimates for individual countries from 2000 to 2020 at a spatial resolution of 3 arc (~ 100m). Detailed methodology used to estimate the population can be found in Lloyd et al. (2019). It should be noted that the spatial resolution of the final population data was aggregated to 0.01°× 0.01° to satisfy the resolution of air pollution data to fit the IERs model.

Health impact assessment

The death and incidence rate can be obtained in GBD 2019 through the Global Health Data Exchange (GHDx) query tool (http://ghdx.healthdata.org/gbd-results-tool), which is an online query tool of GBD 2019. Data of cases and the rates were reported as numbers with 95% uncertainty intervals (UIs). This study estimated the burden due to $PM_{2.5}$ for lower respiratory infections (LRI), Tracheal, bronchus, and lung cancer, Chronic obstructive pulmonary disease (COPD), Stroke, and ischemic heart disease (IHD). Age modification was applied to calculate the relative risk (RR) for IHD and Stroke as described in previous epidemiological study (Burnett et al., 2014). We applied integrated exposure-response functions (IERs) developed by Burnett et al. (2014) and updated by Cohen et al. (2017) to estimate the global relative risk for each disease due to $PM_{2.5}$. Population-attributable fraction (PAF) was used to estimate the health outcomes E (Mansournia and Altman, 2018). The formulas are show as follows:

$$RR(z) = 1, z < z_{fc} , \quad (1)$$

$$RR(z) = 1 + \alpha \cdot \left(1 - exp(-\beta \cdot (z - z_{fc})^{\delta}\right), z \geq z_{fc} , \quad (2)$$

$$E = \Sigma_k (RR_k - 1)/RR_k \cdot f_k \cdot P_k , \quad (3)$$

where z_fc is counterfactual scenario of theoretical minimum risk exposure level (TMREL) below which we assumed there is no additional risk. TMREL for each pollutant was defined in Cohen et al. (2017); k refers to the index of the domain grid; P refers to the population size based on various population datasets, and f refers to the baseline death and incident rate. α, β, δ were estimated using nonlinear regression.

Uncertainties

The uncertainty of health impact estimations included air pollutant estimations and empirical coefficients adopted in the IER model. Uncertainty calculation in air pollution estimation was presented in the hybrid dataset, which was represented by the range of $PM_{2.5}$ values obtained from the variation between individual AOD datasets or the common uncertainty, including the sensitivity of the GWR-based adjustment to monitor selection. The uncertainties of IER model came from the parameters (α, β, δ) in the RR calculation. Uncertainties for these parameters were obtained by the central estimation of fitted functions with 95% UIs based on GBD calculations. The ultimate uncertainty was estimated based on the mean and 95% UIs of the effective distribution.

RESULTS

Trends of different air pollutants

This sub-section aims to analyse the trends of annual average concentration levels of air pollutants ($PM_{2.5}$, BC, and OC) in nine selected countries, see Figure 4-1. Of the countries, six are in Southeast Asia, whereas three are in Africa. The concentration trends of the air pollutants of each country and city are discussed below with an analysis of their emission trends.

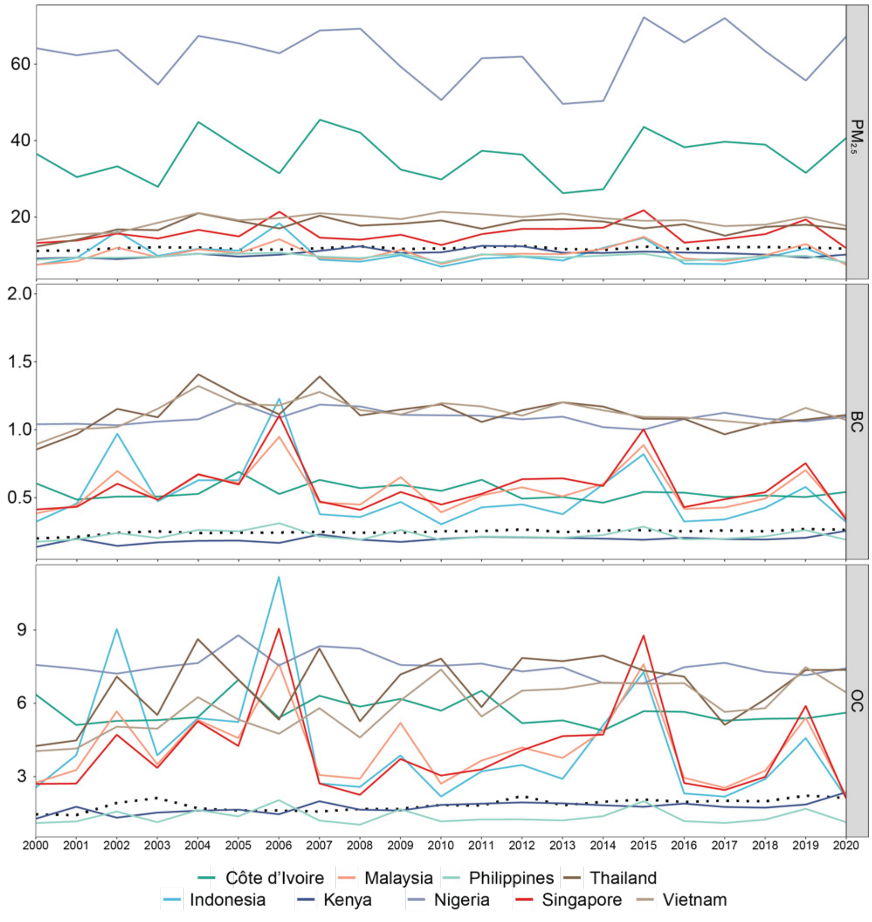

Figure 4-1. The trends of annual average air pollutant concentration levels (unit: µg/m³) in the nine studied countries in terms of (a) $PM_{2.5}$, (b) BC, and (c) OC. The black dotted line represents the global mean values of the three pollutants.

Nigeria (Africa)

Nigeria, which is located in the West Africa, had high $PM_{2.5}$ concentration during the past two decades with an average of annual $PM_{2.5}$ concentration of 62.30 μg/m^3 (Figure 4-1). Arid climate, large amounts of mineral dust from the Sahel and Sahara combined with human-induced biomass burning contributed to the persistent haze in West Africa (Knippertz et al., 2015; Sultan and Janicot, 2003). Biomass combustion was a major direct source of air pollution in West Africa, which can not only lead to an increase in concentration of nitrogen oxides and carbon monoxide but can also indirectly affect climate by disturbing ozone and methane concentration and producing secondary aerosol particles. The biomass burning in this country was almost anthropogenic (e.g., two-wheeled taxis) (Liousse et al., 2010). Besides, another important source of air pollution in West Africa was the anthropogenic emissions from households, transportation and industry (UN population, 2013). As shown in Figure 4-2, the main air pollutants emission contributors in Nigeria were residential, transport and industrial sectors.

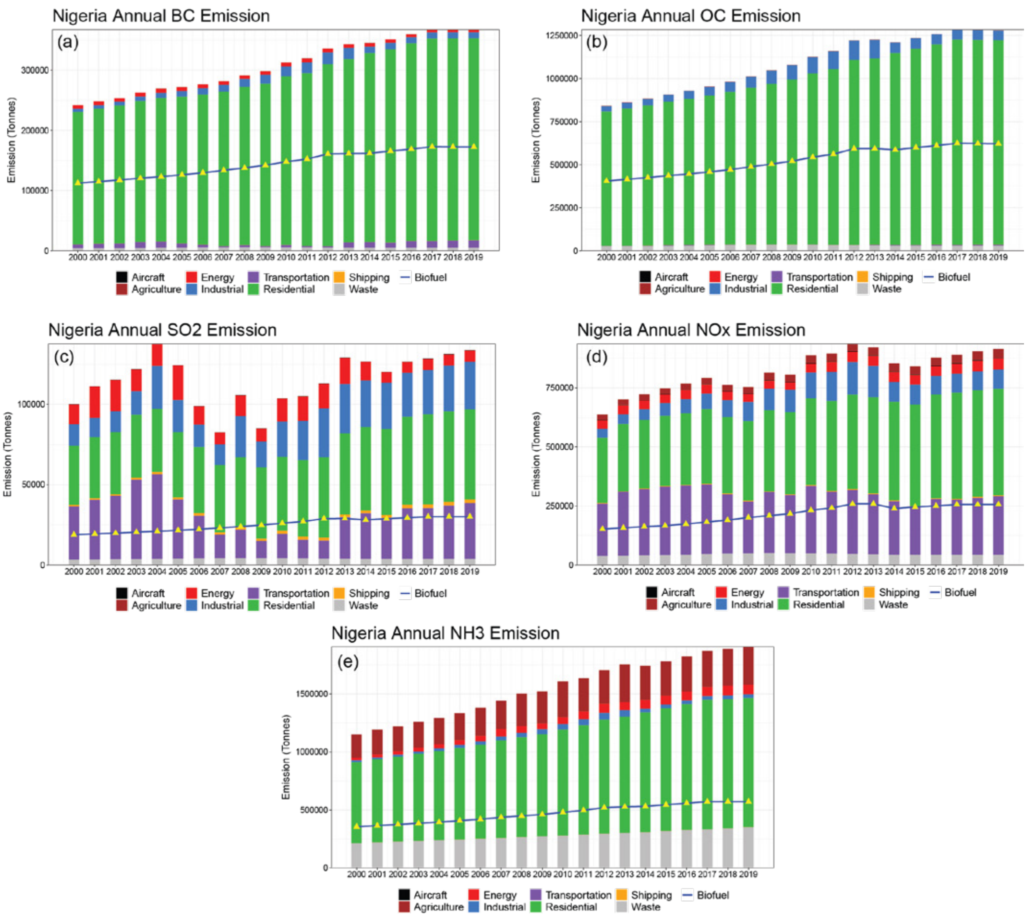

Figure 4-2. The trends of annual total anthropogenic emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Nigeria from 2000 to 2019. The blue line represents the total anthropogenic emissions from biofuel.

Côte d'Ivoire (Africa)

Côte d'Ivoire had an average of annual $PM_{2.5}$ concentration of 35.83 µg/m^3 as shown in Figure 4-1. Located in the West Africa, Côte d'Ivoire shares the same climate with Nigeria with arid climate, which was heavily affected by large amounts of mineral dust from the Sahel and Sahara combined with human-induced biomass burning, resulting in frequent and persistent hazy events in West Africa (Knippertz et al., 2015; Sultan and Janicot, 2003). In the West Africa continent, biomass combustion was a major direct source of air pollution, leading to not only an increase in concentration of nitrogen oxides and carbon monoxide but indirect effects on climate by disturbing ozone and methane concentration and producing secondary aerosol particles. The biomass burning in this country was almost anthropogenic (e.g., two-wheeled taxis) (Liousse et al., 2010). Besides, another important source of air pollution in West Africa was the anthropogenic emissions from households, transportation and industry (UN population, 2013). Figure 4-3 shows that the main air pollutants emission contributors in Côte d'Ivoire were residential, transport and industrial sectors.

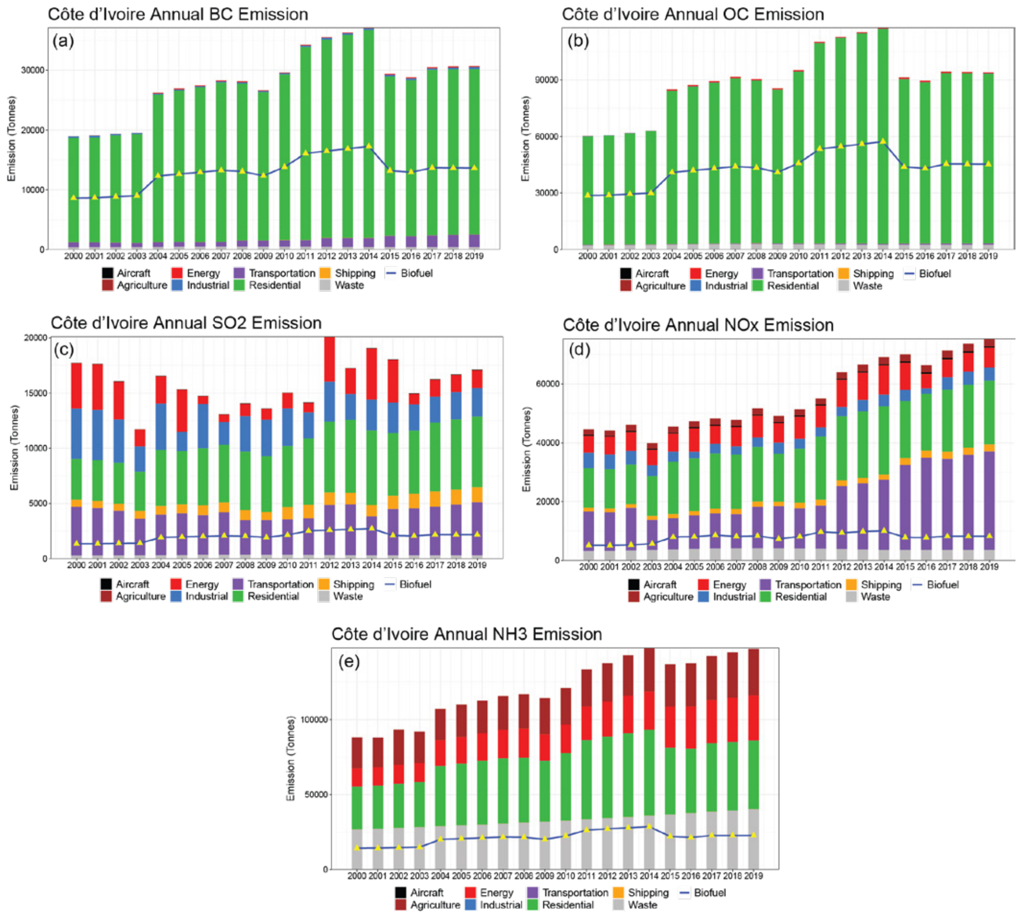

Figure 4-3. The trends of annual total anthropogenic emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Côte d'Ivoire from 2000 to 2019. The blue line represents the total anthropogenic emissions from biofuel.

Kenya (Africa)

As shown in Figure 4-1, Kenya had an average of annual $PM_{2.5}$ concentration of 10.51 μg/m^3 during the past two decades. The average values of $PM_{2.5}$ in Kenya were close to the global mean value (11.28 μg/m^3) as shown by the black dotted line in Figure 4-1. Additionally, the average BC and OC concentration in Kenya was also close to the global average level, with 0.19 μg/m^3 and 1.74 μg/m^3, respectively. Senelwa and Hall (1993) reported that, in Kenya, about 85% of energy demand came from biomass burning. and nearly 100% of the rural and 75% of urban population relied on biomass for energy, respectively, in 1993 (Senelwa and Hall, 1993). Biomass burning played an important role in the global carbon cycle (Pennise et al., 2001). Therefore, the total biofuel emissions from BC and OC accounted for approximately 50% of total anthropogenic emissions in Kenya as shown in Figure 4-4 a & b. Besides, all emissions in Kenya showed a clear increasing trend, except for SO_2 emission, which showed a higher total emission in 2011 and tends to decrease since then (Figure 4-4c). This result was consistent with a study conducted by Nyangena in 2012, where energy-related simulations were performed using Business As Usual (BAU) case, showing that the energy consumption from power generation will be reduced from 88% to 73%, whereas final energy consumption will decrease from 48% to 22% in 2030. It is because the renewable energy is expected to grow at 13.7% and 11.0% per year based on some government policies (Nyangena, 2012; Wambui et al., 2022).

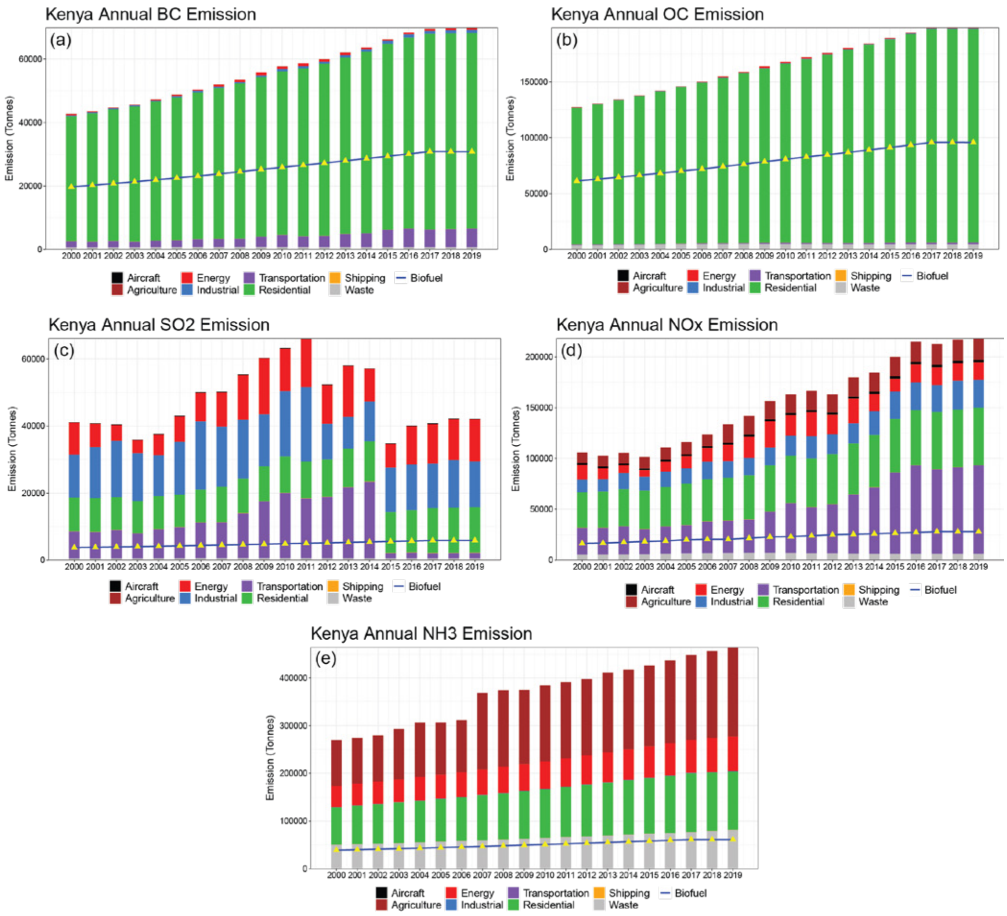

Figure 4-4. The trends of annual total anthropogenic emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Kenya from 2000 to 2019. The blue line represents the total anthropogenic emissions from biofuel.

Indonesia (Southeast Asia)

Indonesia showed an average of annual $PM_{2.5}$ concentration of 10.33 μg/m^3 from 2000 to 2020, see Figure 4-1. Indonesia showed obvious peaks in $PM_{2.5}$ concentration, with clear episodes in September 2002 (48.05 μg/m^3), October 2006 (62.00 μg/m^3), October 2015 (42.90 μg/m^3) and September 2019 (30.70 μg/m^3). Its annual OC concentration (SD: 2.38 μg/m^3) showed a more obvious increase than $PM_{2.5}$ and BC. Figures 4-5 shows that all emissions in Indonesia had an increasing trend, in particular to an accelerating upward trend for SO_2 and NO_x. In Indonesia, the residential sector accounted for the largest proportion of anthropogenic emissions of black carbon. At the same time, 50% of the total anthropogenic emissions came from biofuels (Figure 4-5 a & b). In contrast, emissions from the energy and transportation sectors dominated total anthropogenic emissions of SO_2 and NO_x, respectively (Figure 4-5 c & d). A study on pollutant emission assessment in Indonesian city (Jakarta) during 2005-2015 showed that the largest contributor to NO_x emission was the road transport sector, with heavy-duty vehicles being the largest proportion, whereas SO_2 emissions were mainly from industrial combustion (Lestari et al., 2020).

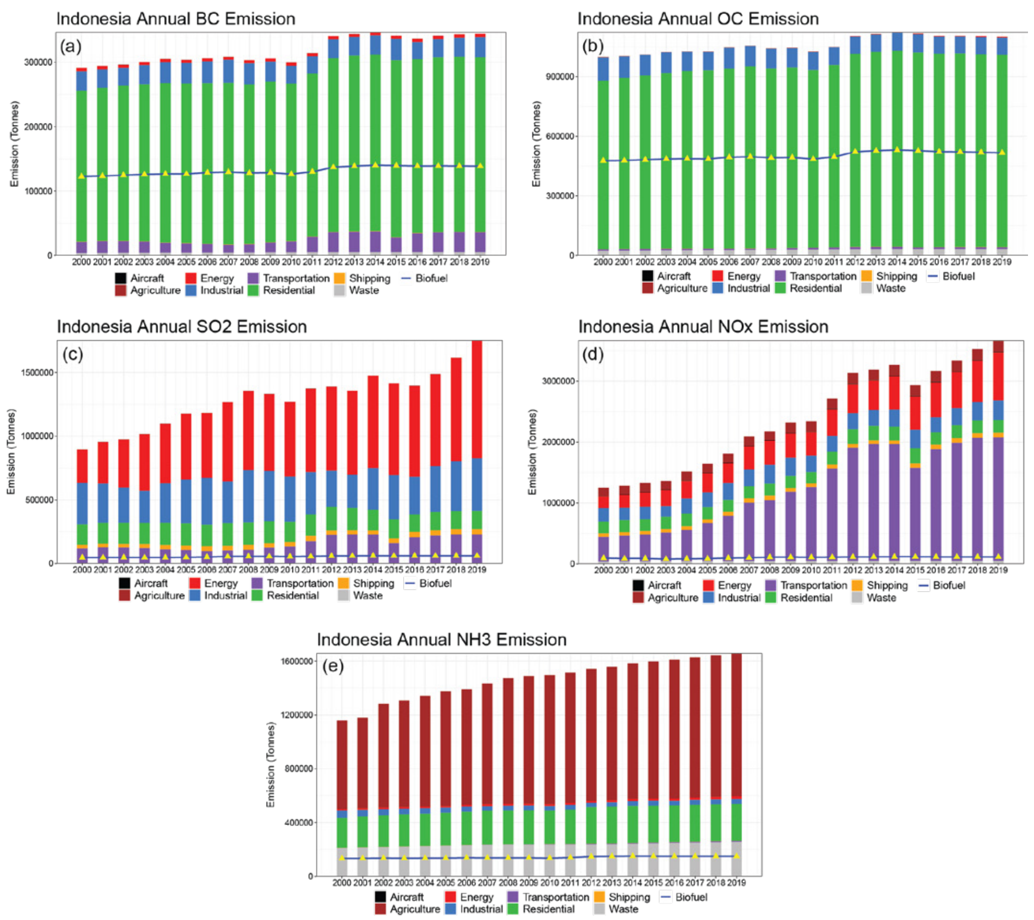

Figure 4-5. The trends of annual total anthropogenic emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Indonesia from 2000 to 2019. The blue line represents the total anthropogenic emissions from biofuel.

Malaysia (Southeast Asia)

Malaysia as one of the countries in the maritime continent of Southeast Asia. Figure 4-1 shows that Malaysia had an average of annual $PM_{2.5}$ concentration of 10.33 μg/m^3 during the studied year period, with clear episodes in September 2002 (26.21 μg/m^3), October 2006 (37.62 μg/m^3), September 2015 (41.31 μg/m^3), and September 2019 (40.82 μg/m^3) and a more obvious increase in annual OC (SD: 1.55 μg/m^3), which were consistent with the other countries in the maritime continent. In Malaysia, transportation became a significant source of air pollution which involved different modes of transportation such as road, rail, air and sea (Ong et al., 2011). Figure 4-6 shows the total anthropogenic emissions from different sectors in Malaysia. The anthropogenic emissions of BC and NO_x were mainly from transportation sector, whereas the emissions of OC and SO_2 were mainly from residential and energy sectors, respectively.

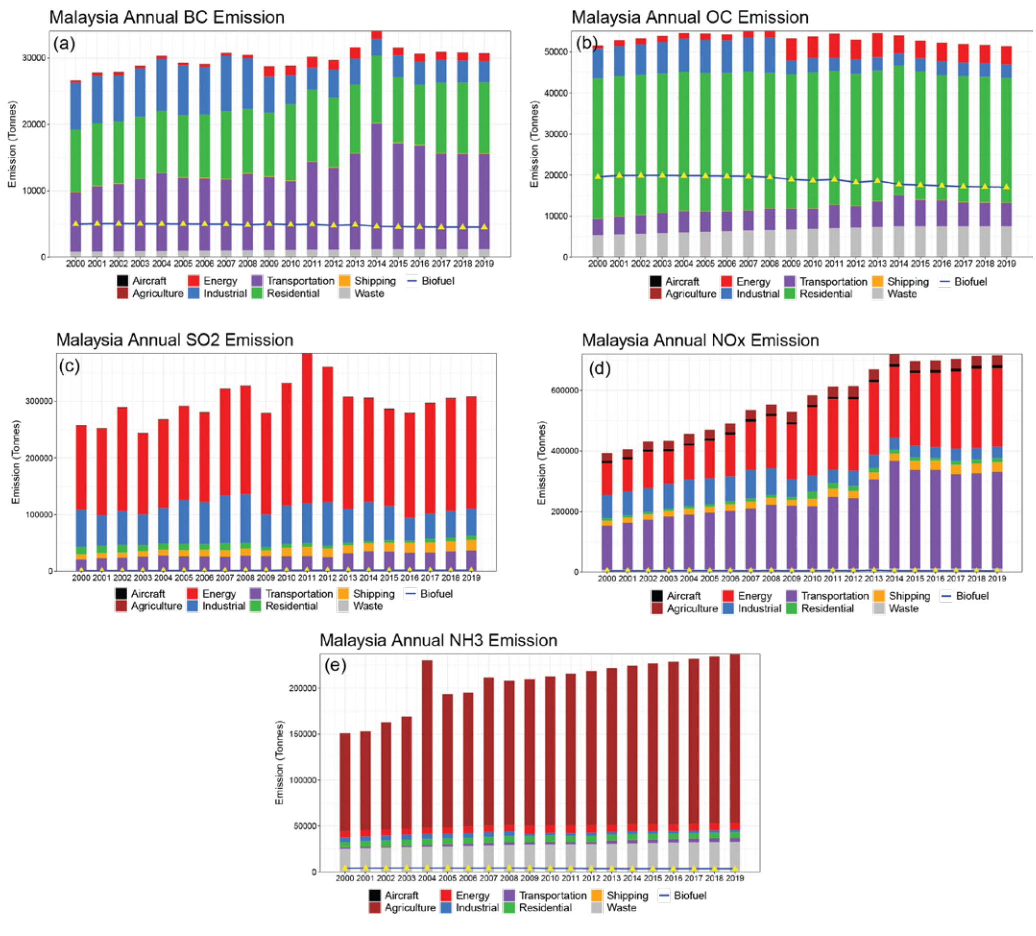

Figure 4-6. The trends of annual total emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Malaysia from 2000 to 2019. The red line represents the total anthropogenic emissions, whereas the blue line represents the total biofuel emissions.

Singapore (Southeast Asia)

Figure 4-1 shows that Singapore had an average of annual $PM_{2.5}$ concentration of 15.70 μg/m^3 during the past two decades. There were five clear episodes in $PM_{2.5}$ concentration in October 2002, October 2006, June 2013, September 2015 and September 2019, with the monthly average $PM_{2.5}$ concentration of 33.70 μg/m^3, 61.27 μg/m^3, 42.77 μg/m^3, 61.83 μg/m^3 and 51.91 μg/m^3, respectively. It should be noted that its annual OC concentration had a wide variation (SD: 1.92 μg/m^3). Figure 4-7 shows the total anthropogenic emissions from different emission sectors in Singapore. The results show that the total anthropogenic emissions of BC and OC had a significant upward trend during the past 20 years, whereas the total emissions of SO_2 showed a decreasing trend. Almost all SO_2 emissions in Singapore came from the energy sector. To diversify its energy sources, Singapore started using natural gas to generate electricity in 1992, and the share of natural gas in total electricity generation rose rapidly from 16% in 1993 to 61% in 2003. Singapore optimised its energy structure by converting old steam turbine plants into combined cycle plants (Kannan et al., 2007).

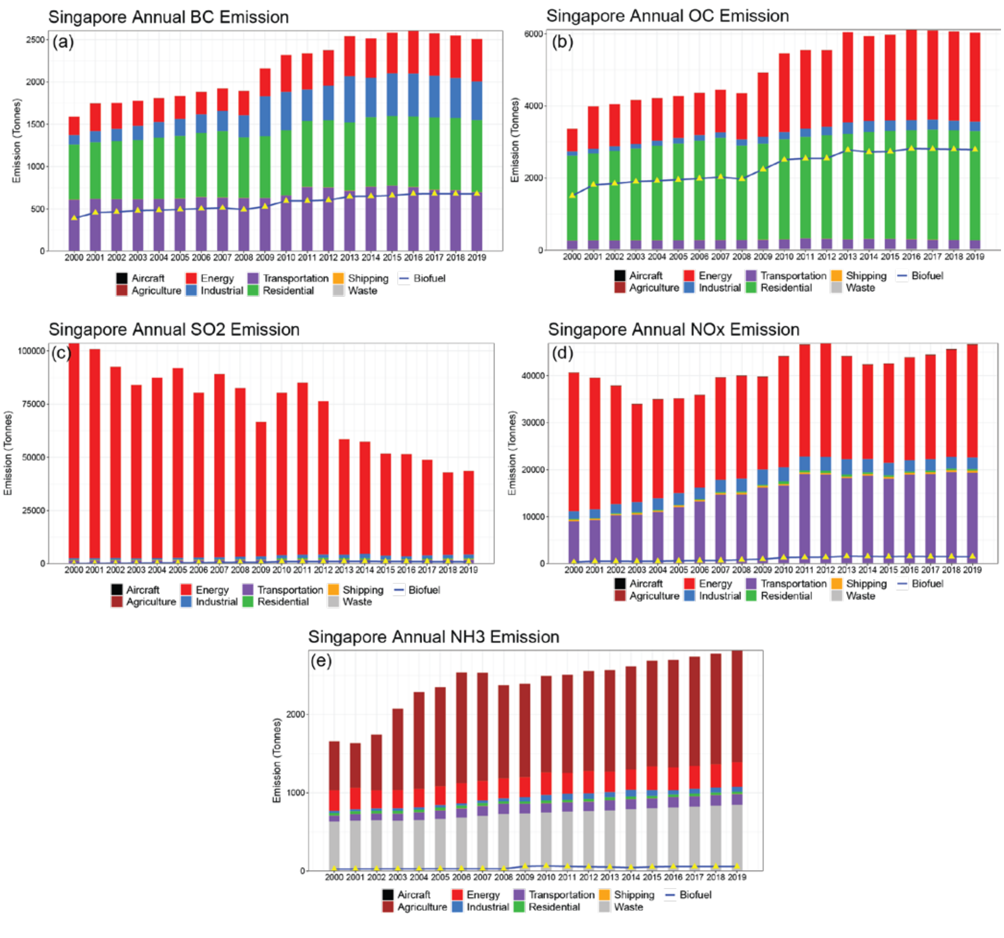

Figure 4-7. The trends of annual total emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Singapore from 2000 to 2019. The red line represents the total anthropogenic emissions, whereas the blue line represents the total biofuel emissions.

Philippines (Southeast Asia)

Philippines, which is located in the eastern Southeast Asia, showed a 9.68 μg/m³ of average of annual $PM_{2.5}$ concentration during the past two decades, see Figure 4-1. Its $PM_{2.5}$ concentration level was comparable with the global mean displayed by the black dotted line in the figure. The total anthropogenic emissions from different sectors in Philippines showed that the BC and SO_2 emissions had a similar trend, with a decreasing trend until 2011, after which emissions started to increase (Figure 4-8 a & c). Total anthropogenic emissions of OC had a decreasing trend over the last two decades, whereas in contrast, total NO_x emissions had a significant increase after 2011 (Figure 4-8 b & d).The year 2011 as a turning point may be related to the enactment of the Renewable Energy Act in 2008 to promote the development, utilisation and commercialization of renewable energy in the Philippines through different incentives (Sumabat et al., 2016).

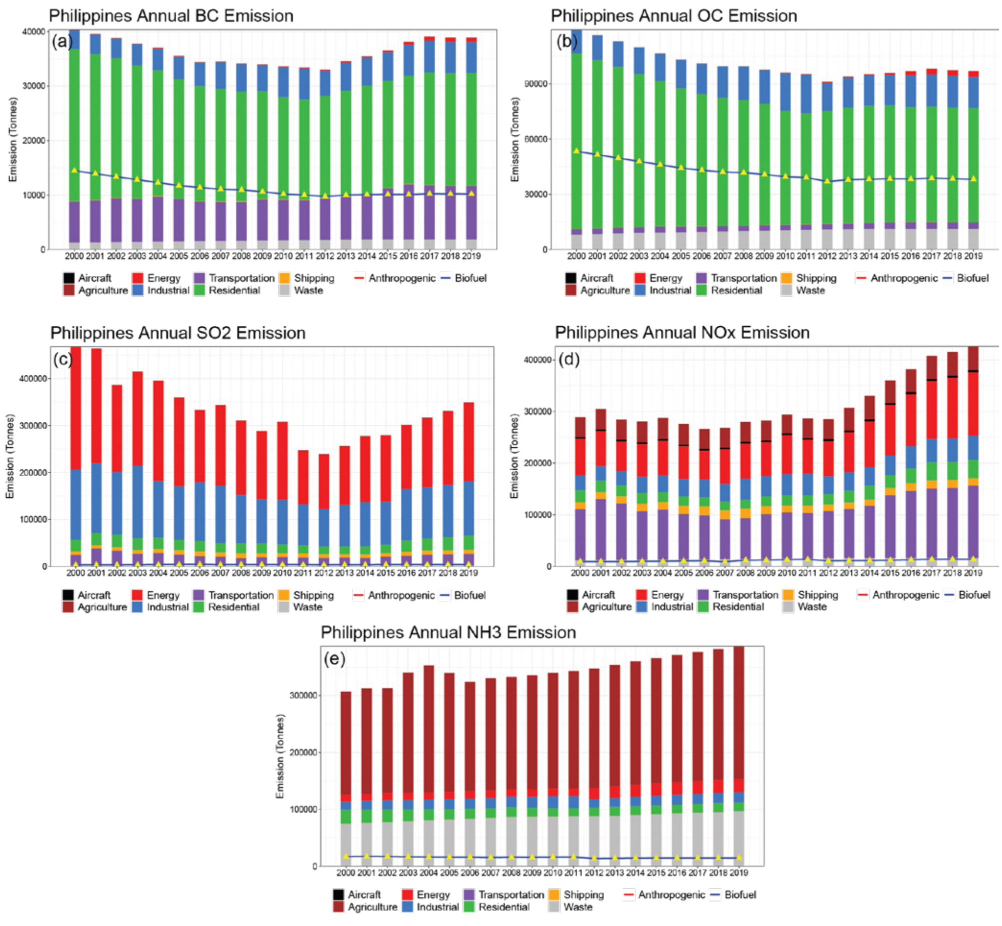

Figure 4-8. The trends of annual total emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Philippines from 2000 to 2019. The red line represents the total anthropogenic emissions, whereas the blue line represents the total biofuel emissions.

Thailand (Southeast Asia)

Thailand, which is one of the countries in the continental Southeast Asia, had an average of annual $PM_{2.5}$ concentration lower than 20 µg/m³, whereas it had a relatively high BC concentration (1.12 µg/m³) during the past two decades. In Thailand, emissions of air pollutants except SO_2 increased for nearly 20 years. SO_2 emissions in this country were mainly from the energy sector and the transportation sector, which means that the structure of energy production in this country was gradually being optimised, probably in relation to some renewable energy policies enacted and implemented in Thailand (Figure 4-9). For example, the Thailand government promoted renewable energy production by purchasing electricity from renewable sources at a higher-than-normal price (Keyuraphan et al., 2012).

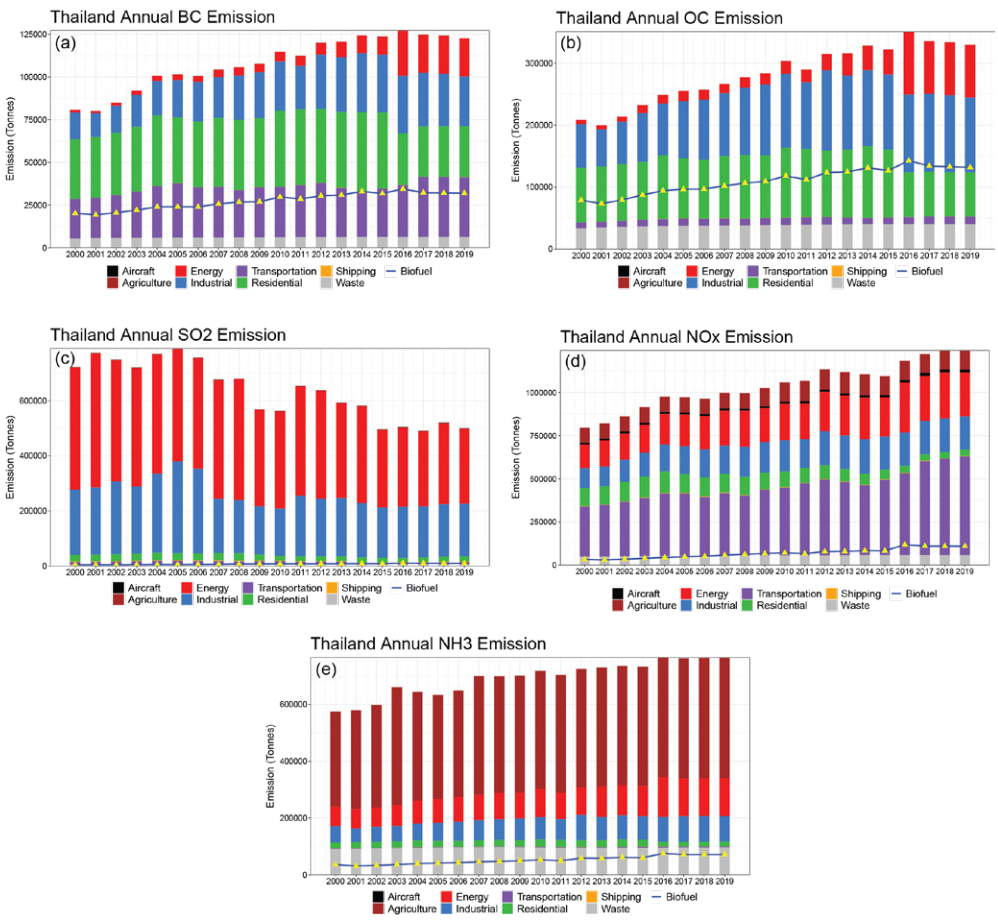

Figure 4-9. The trends of annual total emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Thailand from 2000 to 2019. The red line represents the total anthropogenic emissions, whereas the blue line represents the total biofuel emissions.

Vietnam (Southeast Asia)

Vietnam has annual average $PM_{2.5}$ concentration lower than 20 μg/m^3, whereas a relatively high BC concentration level (1.13 μg/m^3) as shown in Figure 4-1. Similar to Thailand, Vietnam is also located in the continental Southeast Asia. Emissions of all air pollutants in Vietnam showed an accelerating increase rate (Figure 4-10). It is noted that the trend of average of annual $PM_{2.5}$ concentration during the past two decades did not show the same trend of emissions despite of the climate policy (Zimmer et al., 2015) and promotion of renewable energy (Nguyen et al., 2019).

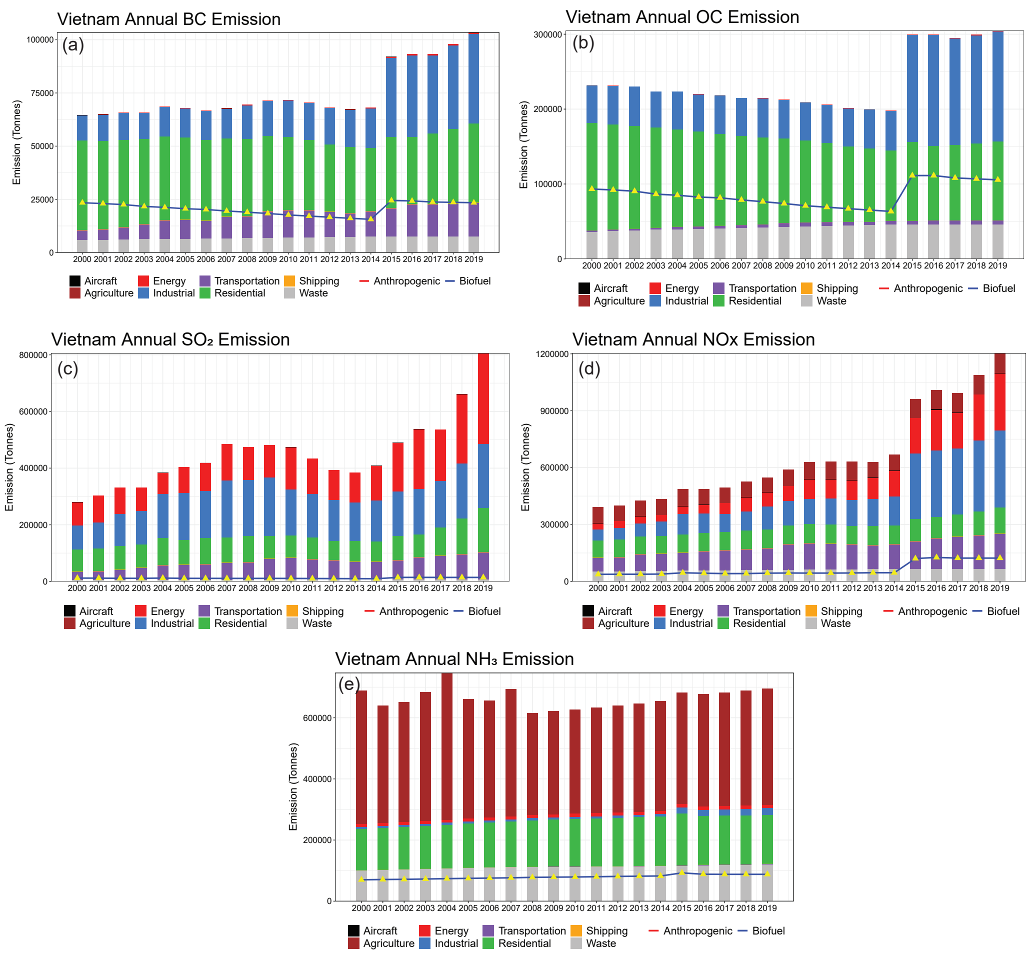

Figure 4-10. The trends of annual total emissions (unit: tonnes) of (a) BC, (b) OC, (c) SO_2, (d) NO_x, and (e) NH_3 in Vietnam from 2000 to 2019. The red line represents the total anthropogenic emissions, whereas the blue line represents the total biofuel emissions.

Spatial distribution of $PM_{2.5}$ during the past two decades

This subsection focuses on the discussion of the spatial distribution of $PM_{2.5}$ in each country in 2000, 2010 and 2020. The three years were selected for evaluating the changes of $PM_{2.5}$ concentration level during the past two decades. The results are displayed in Figures 4-11 – 4-20.

Nigeria (Africa)

Figure 4-11 shows that Nigeria showed a high annual average $PM_{2.5}$ concentration level in the three years up to 120 µg/m^3. Nigeria had limited air quality management policies and was highly influenced by emissions from old fleets of vehicles using poor quality fuels and traditional stoves burning wood (Keita et al., 2021). Moreover, Nigeria showed a clear north-south pattern in the annual average concentration of $PM_{2.5}$. In addition to local sources, the northern region was more vulnerable to dust storms from the Sahara Desert, natural savannah fire sources from prevailing Harmattan wind, and marine aerosols brought by monsoon flow (Gnamien et al., 2021b). According to the spatial distribution maps in Nigeria, the air quality maintained poor and even gets worse during the past twenty years. The maximum $PM_{2.5}$ concentration observed in 2000 and 2020 was approximately 120 µg/m^3, whereas the maximum value in 2010 was just around 100 µg/m^3.

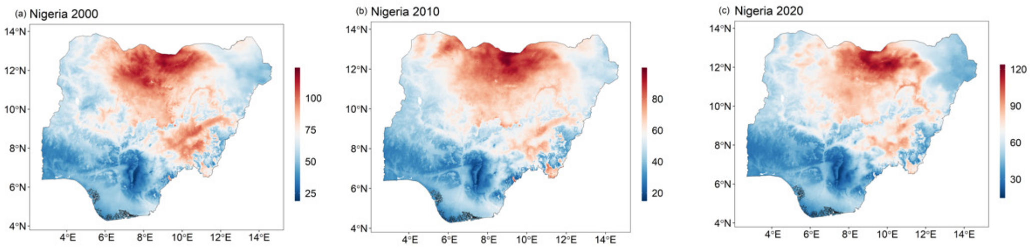

Figure 4-11. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: µg/m^3) in Nigeria in (a) 2000, (b) 2010, and (c) 2020.

Côte d'Ivoire (Africa)

Côte d'Ivoire had a clear north-south pattern with the higher $PM_{2.5}$ concentration (up to around 35 µg/m^3 in 2020) in north (Figure 4-12). This West African country had limited air quality management policies during the studied period. The country was highly influenced by emissions from old fleets of vehicles using poor quality fuels and traditional stoves burning wood (Keita et al., 2021). In addition to local sources, the northern region was more vulnerable to dust storms from the Sahara Desert, natural savannah fire sources from prevailing Harmattan wind, and marine aerosols brought by monsoon flow (Gnamien et al., 2021b). A previous study focused on the spatial distribution of air pollutants in two typical cities of Côte d'Ivoire (i.e. Abidjan and Korhogo) found that PM10 and $PM_{2.5}$ concentration was higher in the neighbourhoods without paved roads and in the area affected by traffic or wood from home fires, respectively. The results also show a strong correlation between particulate matter concentration and living standards. Peak air pollutant concentration in both cities often occurred in the morning and afternoon time. In Abidjan, road traffic intensity was less spread out in the morning than in the evening. In Korhogo, firewood use and dust resuspension increased particulate matter concentration in the evening. Serious public health problems may occur in these regions (Gnamien et al., 2021a). Additionally, the air quality became better in Côte d'Ivoire during the past two decades, with the maximum concentration of $PM_{2.5}$ in the northern area decreasing from 45 µg/m^3 in 2000 to 35 µg/m^3 in 2020.

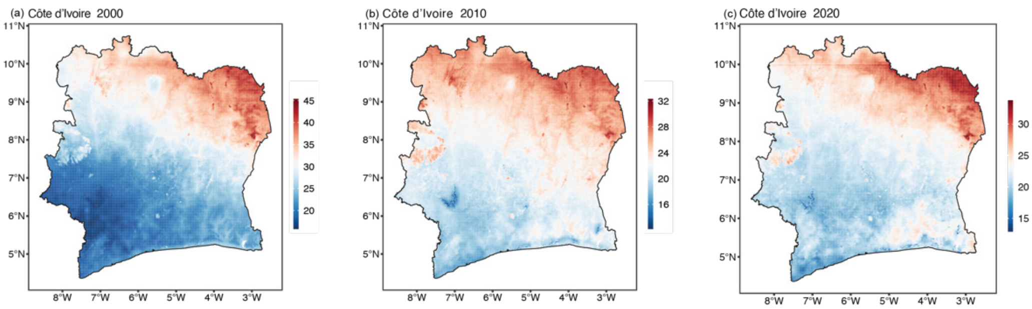

Figure 4-12. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: µg/m^3) in Côte d'Ivoire in (a) 2000, (b) 2010, and (c) 2020.

Kenya (Africa)

As shown in Figure 4-13, Kenya had a clear spatial variation in 2000, whereas the spatial variation became less clear in 2010 and 2020 although the western part had a hotspot with the maximum $PM_{2.5}$ concentration of around 40 µg/m^3 and 50 µg/m^3, respectively. As reported in previous study, the higher $PM_{2.5}$ concentration level in western part of the country was mainly related to the use of traditional stoves in rural areas (Yip et al., 2017). Although the highest $PM_{2.5}$ level was observed in a small area of western part in Kenya in 2020, the air pollutant concentration in Kenya had a significant decreasing trend, especially in the northern part, with an average concentration of 30 µg/m^3 recorded in 2000 to 20 µg/m^3 recorded in 2020.

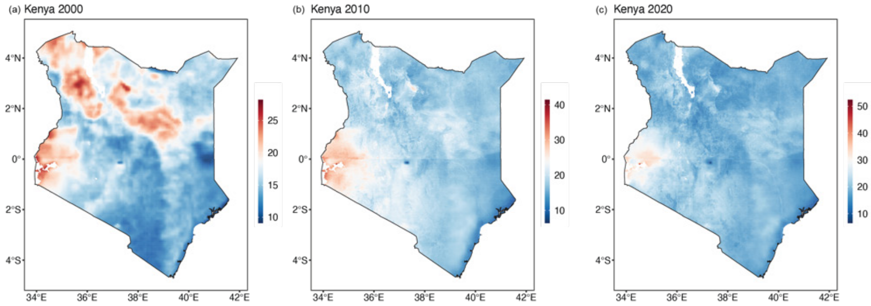

Figure 4-13. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: µg/m^3) in Kenya in (a) 2000, (b) 2010, and (c) 2020.

Indonesia (Southeast Asia)

As shown in Figure 4-14, $PM_{2.5}$ concentration in Indonesia tended to be higher in northern Sumatra and Riau, largely due to the impact of frequent wildfires (Fujii et al., 2014). The $PM_{2.5}$ level can be up to approximately 35 µg/m^3 in 2020 over there. In addition, air pollution was also more evident in the southern peninsula of Indonesia, i.e., Jakarta and Bandung. Jakarta is the capital of Indonesia and a mega-city with a large population. A large number of buildings, highways and small to large factories are located in and around the city (Santoso et al., 2020). Tangerang is an industrial city near Jakarta with many small factories located around the city. Commercial activities were concentrated in the city center, while industrial activities were concentrated in the west and east of Bandung (Sani et al., 2022). It should be noted that the most active volcano (Mount Merapi) close to the southern cities in Indonesia was one of the major causes of air pollution affecting its surrounding area (Warsini et al., 2014). The spatial distribution of $PM_{2.5}$ concentration in Indonesia did not have too many changes from 2000 to 2020, with the highest concentration that often happened in the western and southern peninsulas in Indonesia at around 30 µg/m^3.

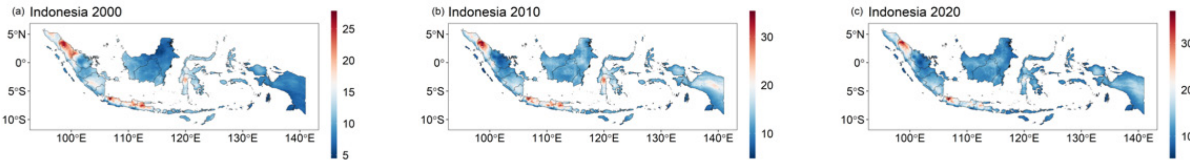

Figure 4-14. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: µg/m^3) in Indonesia in (a) 2000, (b) 2010, and (c) 2020.

Malaysia (Southeast Asia)

In Malaysia, the air pollutant concentration tended to be higher in the Peninsular Malaysia than in the Borneo's East Malaysia as shown in Figure 4-15. The peak $PM_{2.5}$ concentration can be up to around 25 µg/m^3 in 2010. Kuala Lumpur, which is the capital city of Malaysia located in the western peninsula, showed the annual $PM_{2.5}$ concentration of 21.69 µg/m^3, 19.64 µg/m^3 and 21.25 µg/m^3 in 2000, 2010 and 2020, respectively. Kuala Lumpur is the most densely populated and prosperous area in Malaysia. The population density in the peninsular area of Malaysia was much higher than that in the Borneo area, and the air pollution was therefore more serious in the western part (Figure 4-15). Previous research reported the susceptibility of air pollution in the Malay Peninsula to the effects of regional transboundary haze (Latif et al., 2018). In particular, southerly winds during the summer months of June to August provided a favorable meteorology for the transport of $PM_{2.5}$ from Sumatra long distances northward to Singapore and Peninsular Malaysia. The drier climatic condition during El Niño made the regional haze pollution problem even worse (Tangang et al., 2007).

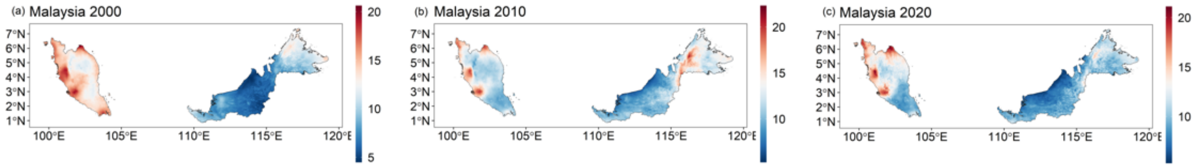

Figure 4-15. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: μg/m^3) in Malaysia in (a) 2000, (b) 2010, and (c) 2020.

Singapore (Southeast Asia)

It should be noted that the spatial distribution of air pollution varied very little and was more susceptible to the influence of surrounding countries because of the small size of Singapore (Figure 4-16). The northern part of Singapore tended to have higher concentration, which may be mainly due to the direction effects from Peninsular Malaysia. According to the spatial figures, the air pollution concentration showed a decreasing trend during the past 20 years, with the maximum value of 18 μg/m^3 in 2000 to 14 μg/m^3 in 2010 and to $1_{2.5}$ μg/m^3 in 2020.

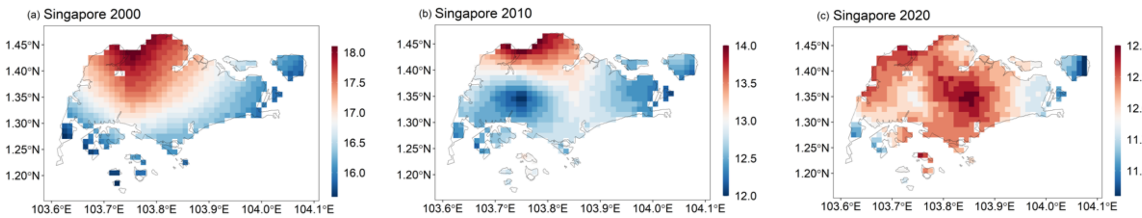

Figure 4-16. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: μg/m^3) in Singapore in (a) 2000, (b) 2010, and (c) 2020.

Philippines (Southeast Asia)

In Philippines, the northern cities such as Manila, Quezon, Caloocan and Baguio had more serious air pollution as shown in Figure 4-17, which was mainly related to vehicle emissions (Gallardo, 2008). The peak $PM_{2.5}$ concentration can be up to around 40 μg/m^3 in 2010. According to the spatial trend of air pollution in Figure 4-17, the maximum $PM_{2.5}$ concentration in Philippines was keeping around 35-40 μg/m^3 during the past two decades, with the highest value happened in 2010. In the Philippines, Jeepneys have long been an iconic form of public transportation, but the outdated design of traditional jeepneys was not only unsafe but can cause serious air pollution. The latest news showed that in response to these problems, the Philippine government has launched a modernisation programme, which aimed to replace the traditional jeepney with a greener, more efficient model (Quimba, 2022). But this modernisation plan encountered many complex issues that involved balancing the needs of the transportation industry, the environment, and society. Therefore, from a long-term perspective, there were still many problems in the implementation of the modernisation plan in the Philippines. This also means that the air pollution in the Philippines, especially in the northern cities, will continue to be affected by transport sector largely.

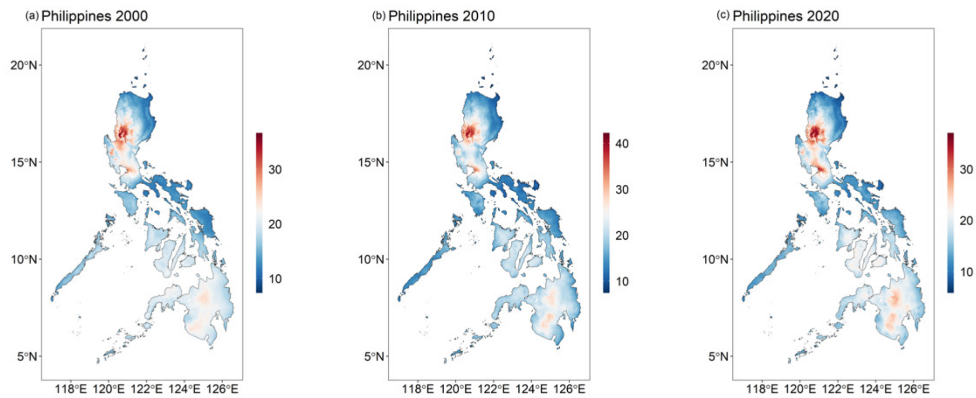

Figure 4-17. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: μg/m^3) in Philippines in (a) 2000, (b) 2010, and (c) 2020.

Thailand (Southeast Asia)

Thailand is a typical agriculture-based country in Southeast Asia, in which air pollution was more severe in the north than in the south (Figure 4-18). Phairuang et al. (2017) confirmed that agricultural activities and forest fires were strongly associated with ambient PM concentration in cities in northern and north-eastern Thailand. For example, sugarcane was a major commercial crop in North Central Thailand, which was used as a raw material for sugar production in the agro-industry. Bagasse as used as fuel for boilers after the crushing process to generate the energy needed to run the sugarcane plant, which in turn released large amounts of air pollutants (Sornpoon et al., 2014). The air quality remained poor in Thailand as shown in Figure 4-18. The highest $PM_{2.5}$ concentration observed in the northern was around 35 μg/m^3 in 2000, but it increased to around 42 μg/m^3 and 45 μg/m^3 in 2010 and 2020, respectively.

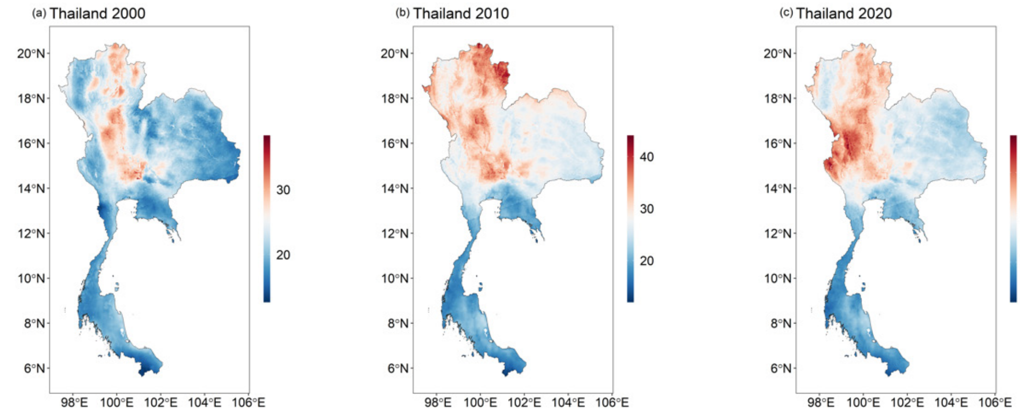

Figure 4-18. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: μg/m^3) in Thailand in (a) 2000, (b) 2010, and (c) 2020.

Vietnam (Southeast Asia)

As shown in Figure 4-19, $PM_{2.5}$ concentration in Vietnam was higher in the north than in the south (Figure 4-19). Since Vietnam is a typical agriculture-based country in Southeast Asia, agricultural activities and forest fires were strongly associated with ambient PM concentration in cities in northern part of the country as reported in Phairuang et al (2017). According to the Figure 4-19, the highest $PM_{2.5}$ happened in the northern part of Vietnam at around 52 μg/m^3 in 2010, but it decreased to 40 μg/m^3 in 2020.

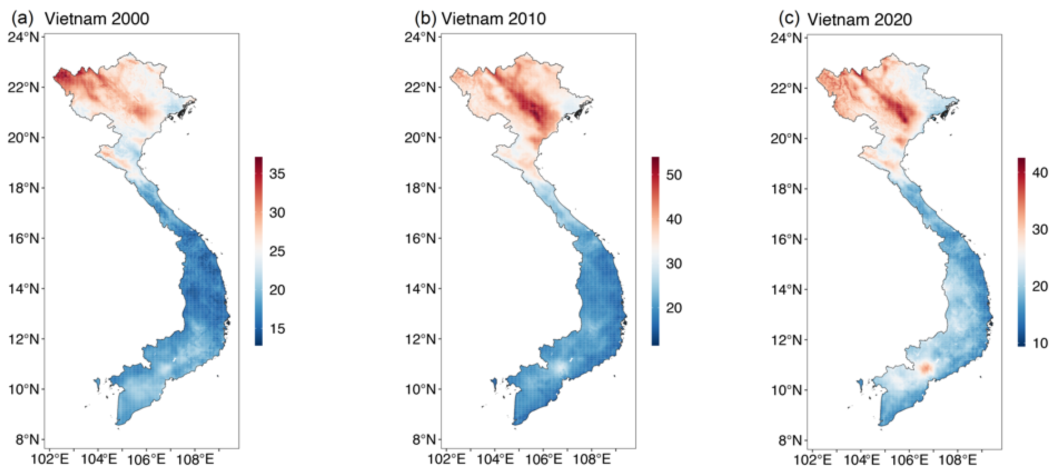

Figure 4-19. The spatial distribution of annual average concentration of $PM_{2.5}$ (unit: μg/m^3) in Vietnam in (a) 2000, (b) 2010, and (c) 2020.

Analysis of the association between air pollution episodes and the occurrence of ENSO and IOD in Africa

Air pollution in the two West African countries, Nigeria and Côte d'Ivoire, was often highly correlated with dry weather. While air pollution in the East African country, Kenya, was more likely to be vulnerable to the effects of a complex climate.

Nigeria (Africa)

It is clear that the trend of $PM_{2.5}$ concentration had remarkable seasonality in Nigeria, with January and February being the dry season (Figures 4-20). Weli and Chineze (2017) confirmed that high PM concentration in January and February may be associated with the dry season, but the influence of meteorological factors on PM concentration was very minor. In addition to the influence of meteorological factors, air pollution in Nigeria was more likely to be influenced by local fossil fuel combustion. Perri et al. (2021) reported that the high concentration months in Nigeria may be due to increased gas flaring activities during the dry season by several types of emission sources such as refineries, petrochemical plants, and fertiliser plants.

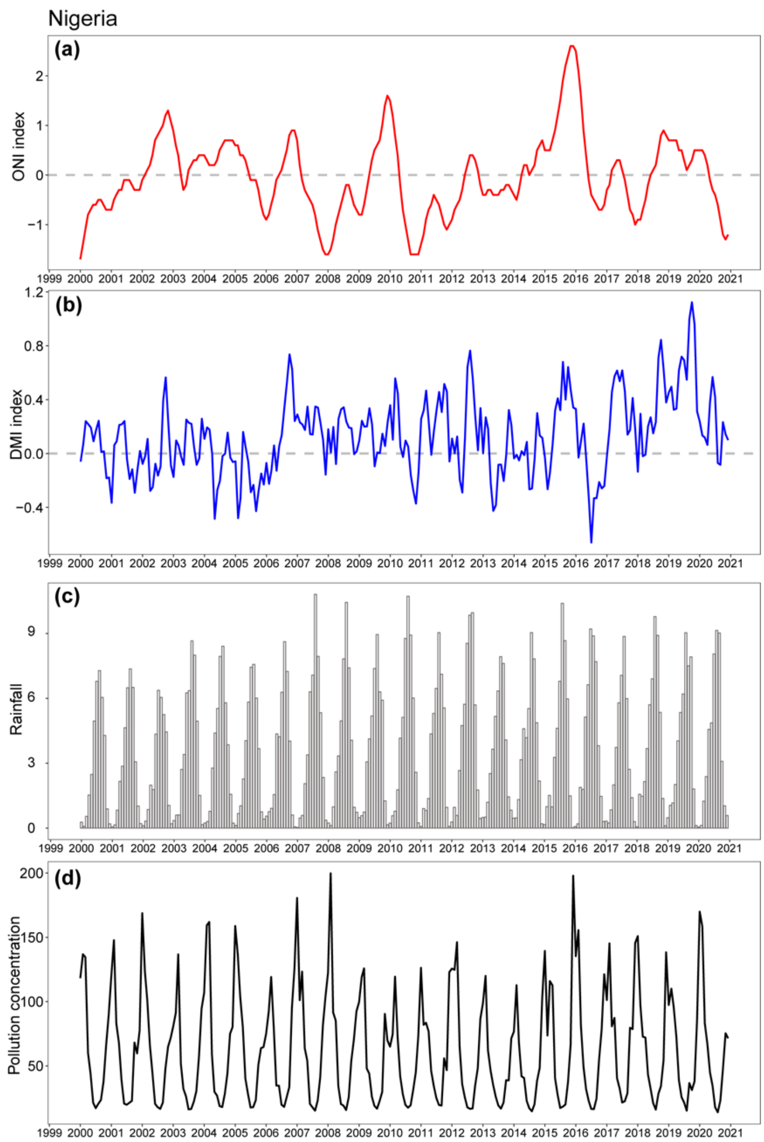

Figure 4-20. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: $\mu g/m^3$) in Nigeria during 2000-2020.

Côte d'Ivoire (Africa)

The trend of $PM_{2.5}$ concentration in Côte d'Ivoire also had remarkable seasonality, with January and February being the dry season (Figures 4-21). Weli and Chineze (2017) confirmed that the high PM concentration in January and February may be associated with the dry season, but the influence of meteorological factors on PM concentrations was very minor. In addition to the influence of meteorological factors, air pollution in Côte d'Ivoire was more likely to be influenced by local fossil fuel combustion.

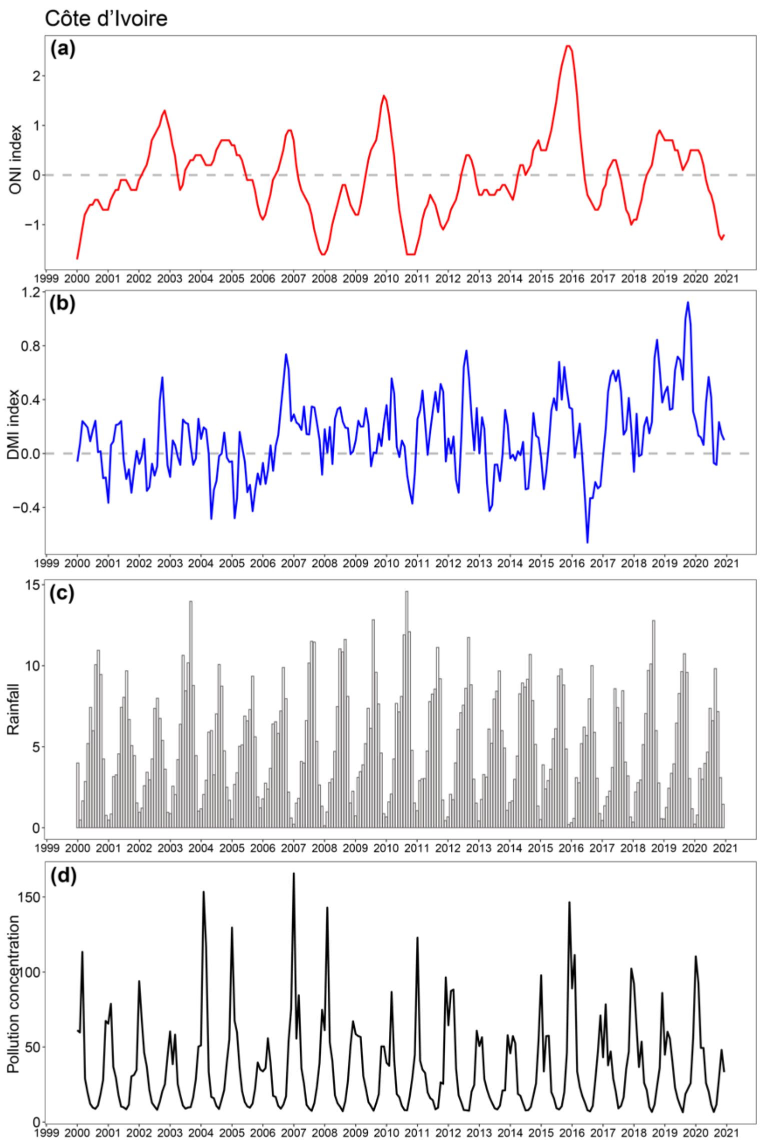

Figure 4-21. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: µg/m^3) in Côte d'Ivoire during 2000-2020.

Kenya (Africa)

Kenya is located on the eastern coast of Africa, bordering the Indian Ocean, and is therefore more likely to be vulnerable to the effects of a complex climate compared to the other two African countries. Larson et al. (2014) reported that a Pearson correlation of 0.70 between the annual average of $PM_{2.5}$ and the annual average of precipitation in Kenya, confirming that $PM_{2.5}$ concentration was highly associated with precipitation. Air pollution in Kenya was not severe over the past two decades with small fluctuations in $PM_{2.5}$ concentration, but there was a significant peak moment of high polluted period in the winter of 2008 when the air pollutant concentration exceeded the average concentration (8.29 μg/m^3), reaching 25 μg/m^3 (Figure 4-22). This period coincided with the strong La Niña event of 2008, during which the ocean surface in the central and eastern tropical Pacific Ocean tended to be cool, rainfall increased over Indonesia and decreased significantly in eastern Africa, and the easterly wind along the equator became stronger, which favour long-range transport and accumulation of pollutants in the Eastern region. This result was also consistent with a previous study that the variability of rainfall in the Kenyan region was higher during El Niño than La Niña events (Shisanya et al., 2011). The study also showed that ENSO events were characterised by higher rainfall during October to December, but not all ENSO events resulted in extreme weather events in south-eastern Kenya. Abnormalities in southern Kenya were not always expected to be caused by ENSO occurrences, which supported the findings by Amissah-Arthur et al. (2020) that reported El Niño events had different regional impacts on the rainfall in Kenya.

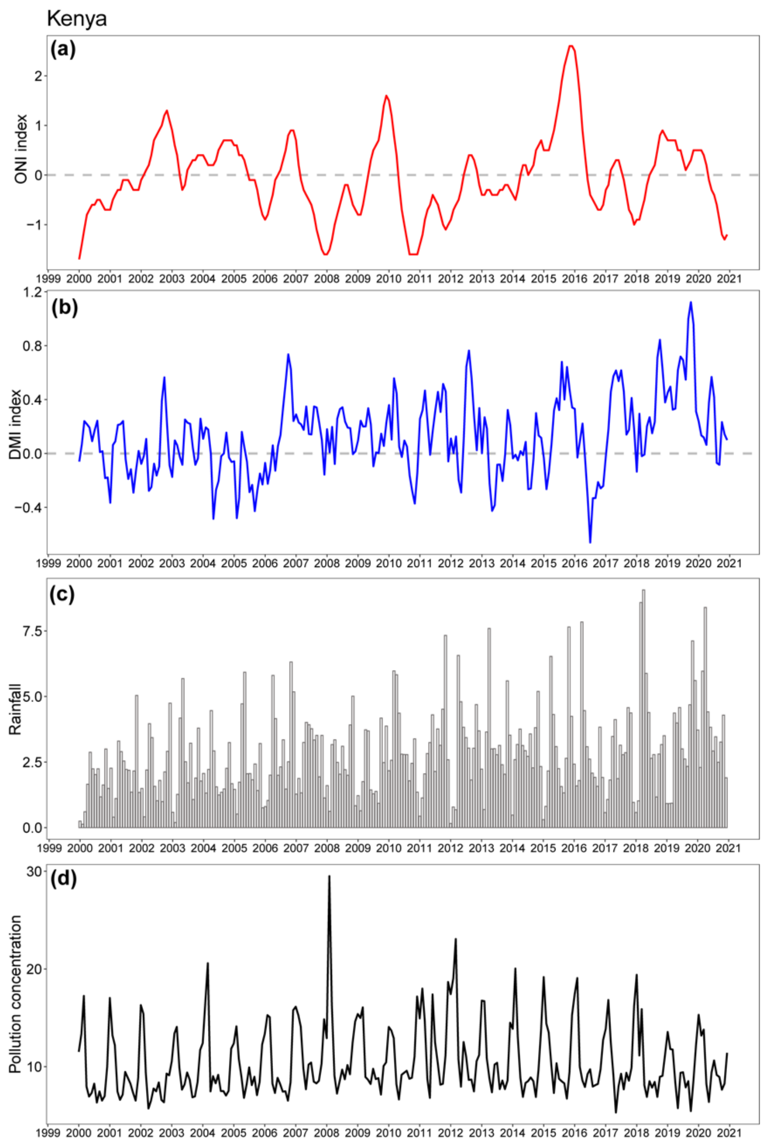

Figure 4-22. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: μg/m^3) in Kenya during 2000-2020.

Analysis of the association between air pollution episodes and the occurrence of ENSO and IOD in Southeast Asia

The analysis showed consistent peaks in Indonesia, Malaysia, and Singapore. This subsection further studied the consistent peaks along with the two climate patterns, ENSO and IOD events.

Indonesia (Southeast Asia)

In Indonesia, two $PM_{2.5}$ peaks occurring in the fall of 2002 and 2015 coincided with the simultaneous El Niño and positive IOD occurrences, and other two $PM_{2.5}$ peaks in 2006 and 2009 coincided with positive IOD (Figures 4-23). This was because positive IOD shifted warm water from Southeast Asia to Africa, lowering atmospheric humidity in southern part of Southeast Asia, making the region less rainy (Amirudin et al., 2020). El Niño, on the other hand, warmed the ocean surface in the central and eastern tropical Pacific, reducing rainfall (Meehl, 1996). Thus, the combined effect of El Niño and positive IOD exacerbated this phenomenon, making the climate drier and rainfall less. Meanwhile, parts of Indonesia, especially in Sumatra and Riau, were often affected by severe haze caused by forest fires, and the arid climate contributed to increased wildfires and deteriorating air quality (Jayachandran, 2009; Mead et al., 2018).

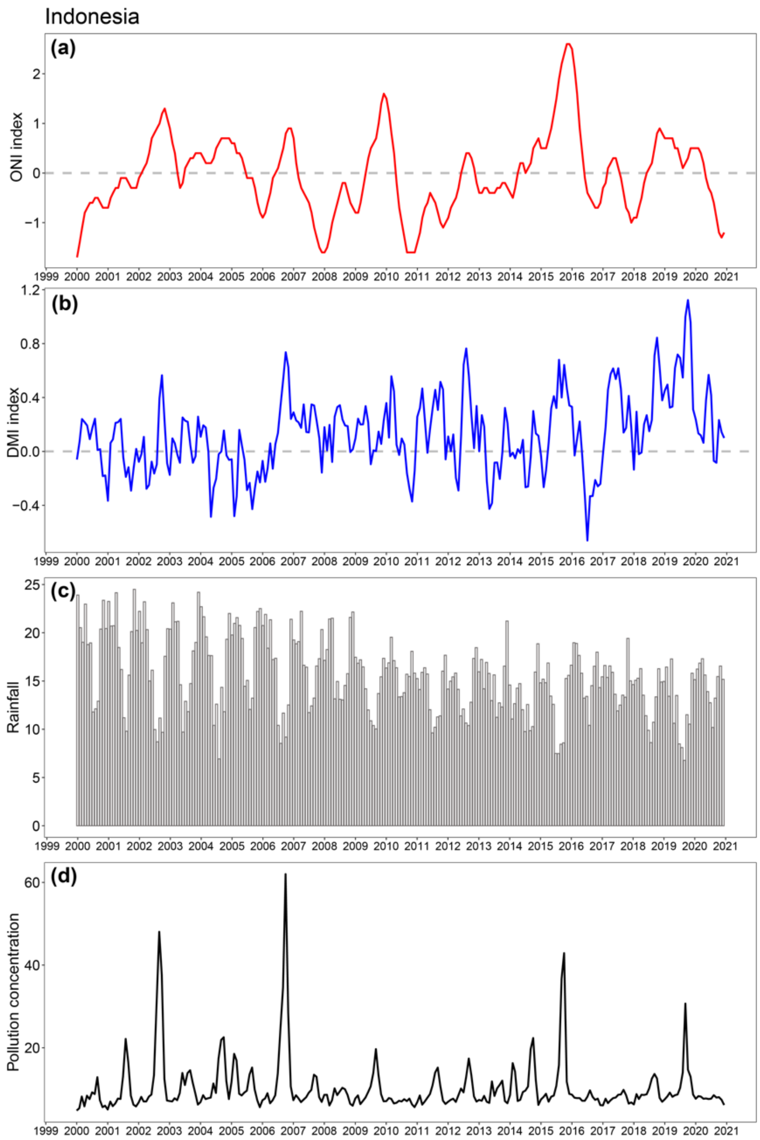

Figure 4-23. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: µg/m^3) in Indonesia during 2000-2020.

Malaysia (Southeast Asia)

As another typical maritime country in Southeast Asia, Malaysia was also suffering from the strong effects of ENSO and IOD. Two $PM_{2.5}$ peaks occurring in the fall of 2002 and 2015 coincided with the simultaneous El Niño and positive IOD occurrences, and other two peak time in 2006 and 2019 coincided with positive IOD alone (Figure 4-24). Meanwhile, Malaysia was often under the severe effects of haze and wildfires, and the arid climate contributed to increased wildfires and deteriorating air quality (Jayachandran, 2009; Mead et al., 2018). The combined effect of El Niño and positive IOD exacerbated the air quality there, making the climate drier and rainfall less (Amirudin et al., 2020).

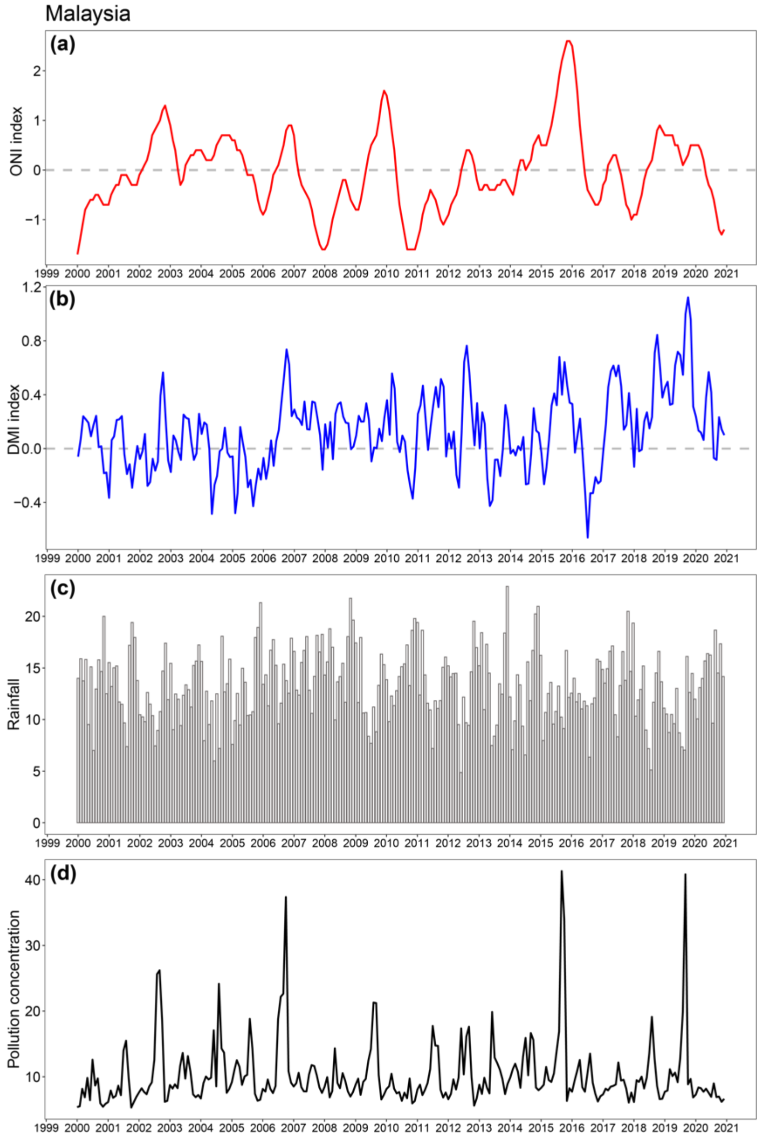

Figure 4-24. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: μg/m^3) in Malaysia during 2000-2020.

Singapore (Southeast Asia)

Singapore was under the strong effects of ENSO and IOD. Two $PM_{2.5}$ peak times occurring in the fall of 2002 and 2015 coincided with the simultaneous El Niño and positive IOD occurrences, and other two peak times in 2006 and 2019 coincided with positive IOD alone (Figure 4-25). Meanwhile, Singapore has often experienced haze and wildfires. The arid climate contributed to increased wildfires and deteriorating air quality (Jayachandran, 2009; Mead et al., 2018). The combined effect of El Niño and positive IOD exacerbated the air quality in the country, making the climate drier and rainfall less (Amirudin et al., 2020).

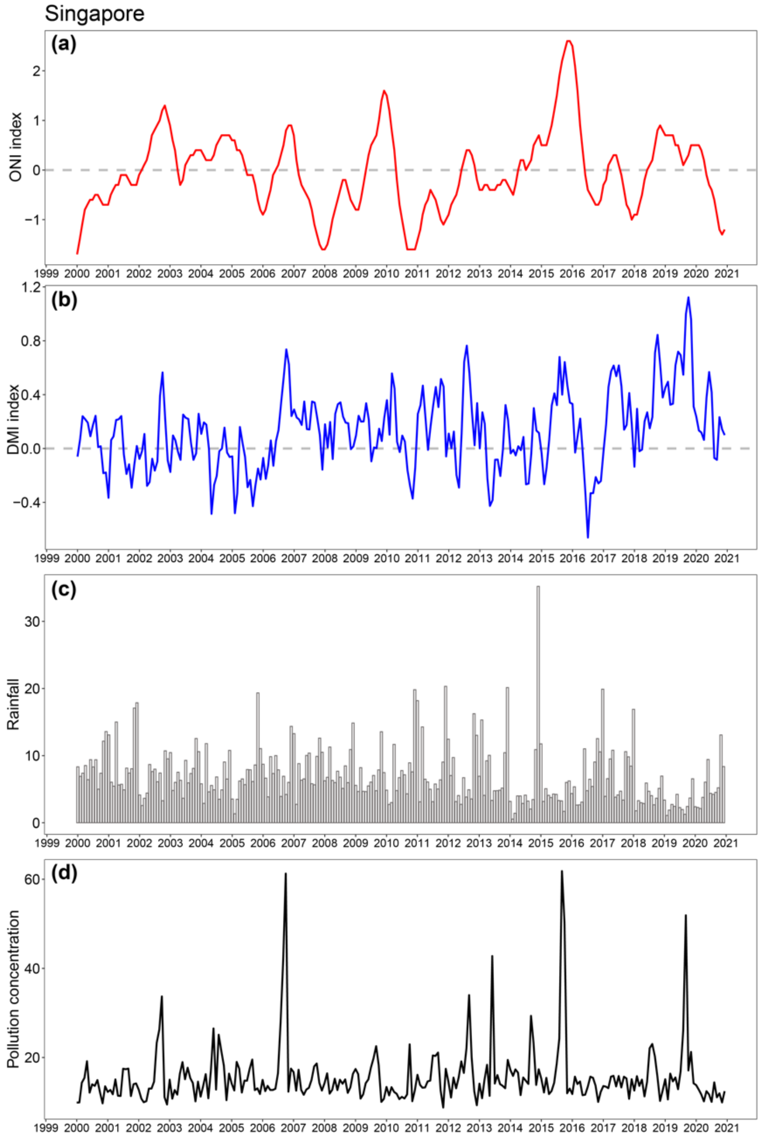

Figure 4-25. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: $\mu g/m^3$) in Singapore during 2000-2020.

Philippines (Southeast Asia)

The Philippines is a country surrounded by sea in Southeast Asia, and thus largely affected by climate variability such as El Niño and IOD. In 2015, the combined effect of El Niño and positive IOD exacerbated PM2.5 pollution levels in the country in 2015 (Figure 4-4). The episode in 2019 particularly highlighted the important impact of positive IOD on the $PM_{2.5}$ concentration in the Philippines. This may be related to the location of the Philippines in the western Pacific Ocean, where diverse and complex climatic effects are present (Hu et al., 2015; Weng et al., 2007).

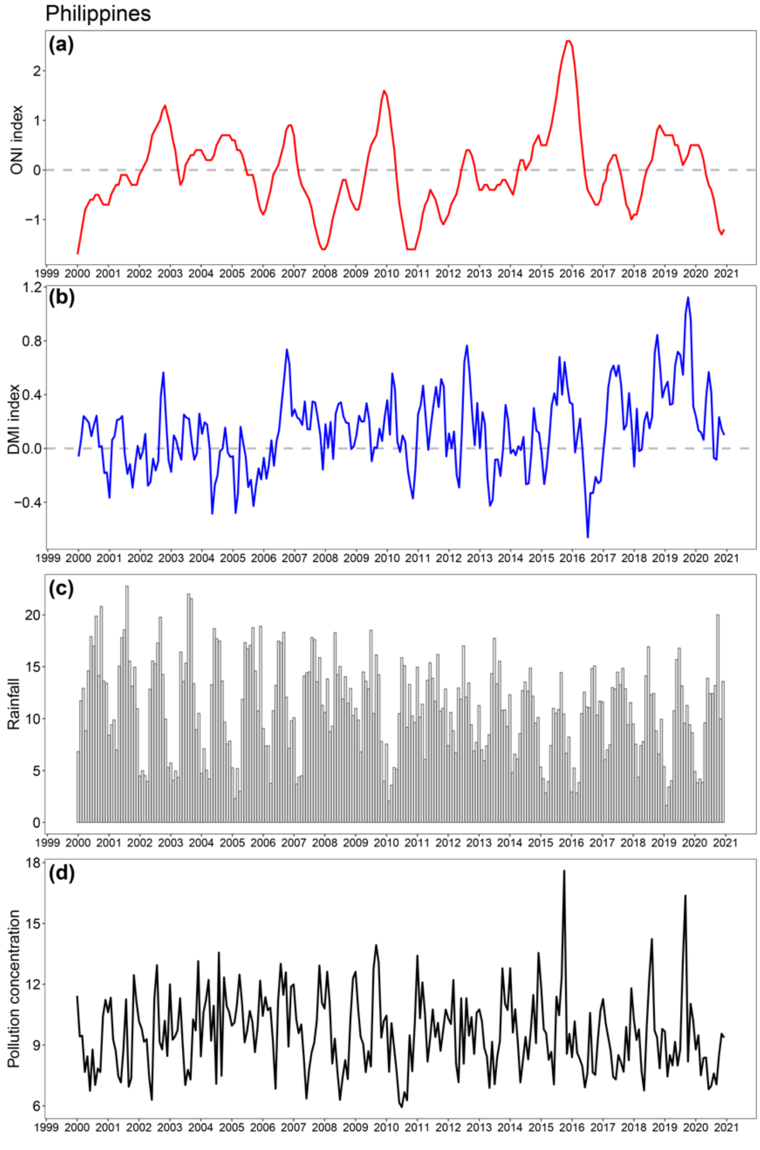

Figure 4-26. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: μg/m^3) in Philippines during 2000-2020.

Thailand (Southeast Asia)

In contrast, there was no significant relationship between ENSO or IOD events and air pollution changes in Thailand, as shown in Figure 4-27. It is clear that high air pollution was usually associated with low rainfall and dry season. This is because the dry season favors the occurrence of forest fires and the burning of crop residues, which are the main sources of air pollutants in Southeast Asia. However, neither ENSO nor IOD events had a significant driving effect on precipitation in this region. A study about haze in northern Thailand showed that rainfall may be the main cause of haze reduction in Thailand, and there was no significant association between ENSO and haze phenomena (Sooktawee et al., 2015). Another climate study into the 2011 floods in Thailand also confirmed that La Niña had only a minor effect on rainfall in this region (Van Oldenborgh et al., 2012).

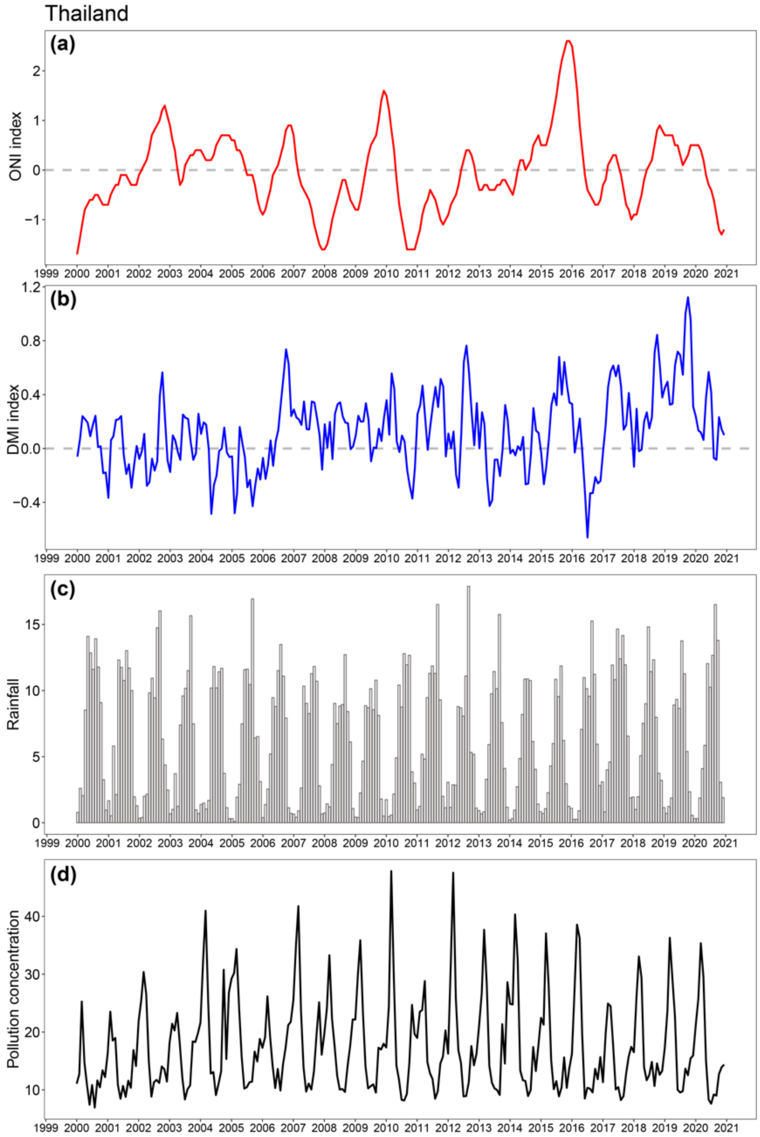

Figure 4-27. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: μg/m^3) in Thailand during 2000-2020.

Vietnam (Southeast Asia)

In Vietnam, there was no significant relationship between ENSO or IOD events and air pollution changes. According to the Figure 4-28, high air pollution was usually associated with low rainfall and dry season. This is because the dry season favors the occurrence of forest fires and the burning of crop residues, which are the main sources of air pollutants in Southeast Asia. However, neither ENSO nor IOD events had a significant driving effect on precipitation in this region. Takahashi et al. (2011) also demonstrated that ENSO had minor effect on rainfall for the entire Indochina Peninsula, including Vietnam.

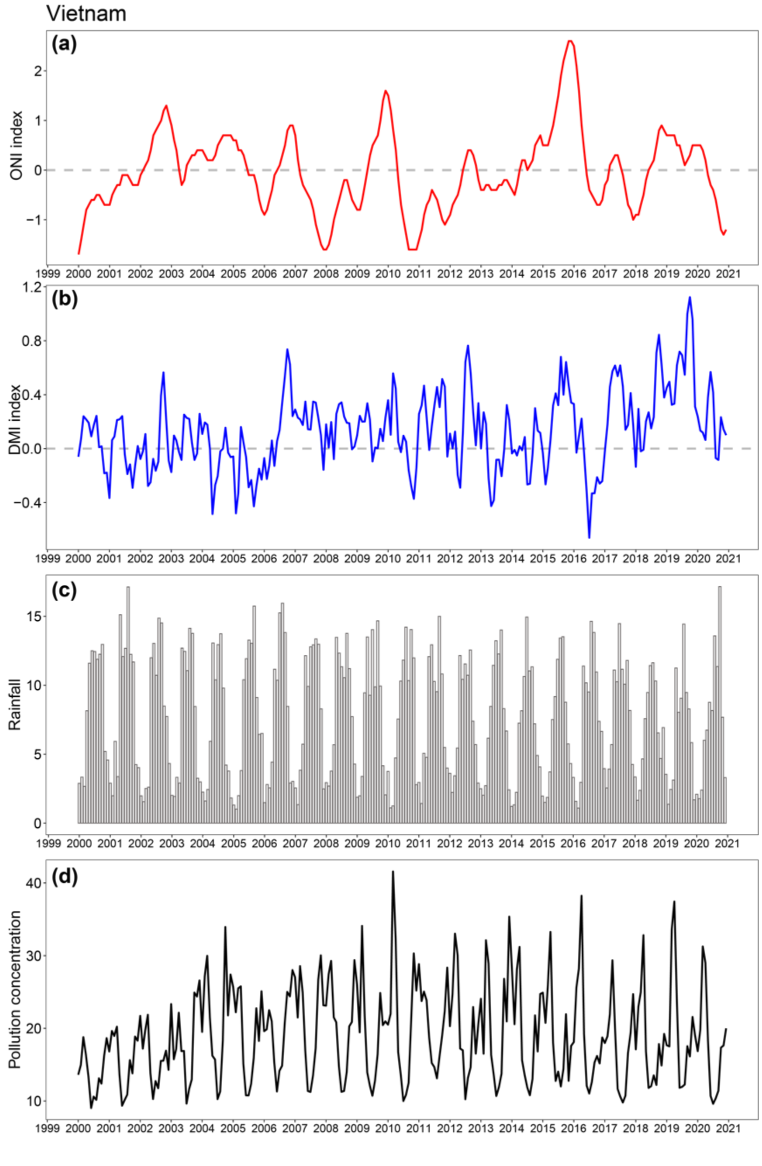

Figure 4-28. (a) the trends of ONI index (red line), (b) DMI index (blue line), (c) the monthly average rainfall represented in the column bars (unit: mm), (d) monthly average $PM_{2.5}$ concentration (black line) (unit: μg/m^3) in Vietnam during 2000-2020.

Human health impacts of $PM_{2.5}$

This sub-section summarizes the main results of the premature deaths and incidences in each country due to $PM_{2.5}$ through different diseases over the past two decades, see Table 4-1 and Table 4-2.

Region	All-cause	COPD	IHD	LC	LRI	Stroke
Indonesia	3,165,156 (2,013,987-4,111,831)	253,213 (138,621-349,293)	994,541 (635,902-1,291,284)	171,553 (110,090-224,256)	150,608 (68,991-220,638)	1,595,241 (1,060,383-2,026,361)
Nigeria	2,669,142 (1,953,013-3,232,595)	103,914 (70,829-128,985)	544,003 (454,203-620,215)	38,734 (30,059-46,026)	1,371,250 (891,228-1,743,295)	611,241 (506,693-694,075)
Vietnam	1,618,314 (1,158,436-1,993,307)	133,203 (79,486-176,881)	368,265 (269,855-450,366)	99,394 (70,511-124,100)	88,017 (46,391-122,535)	929,435 (692,191-1,119,425)
Philippines	988,137 (632,566-1,282,200)	70,357 (39,440-96,101)	375,279 (251,429-477,850)	47,026 (31,298-60,502)	146,049 (69,073-211,575)	349,426 (241,326-436,172)
Thailand	830,045 (563,218-1,049,959)	87,549 (50,717-117,860)	252,179 (178,633-313,329)	94,972 (65,868-119,892)	78,866 (39,259-112,161)	316,478 (228,741-386,717)
Malaysia	275,167 (156,142-374,230)	18,222 (9,426-25,712)	120,563 (70,222-162,072)	15,806 (9,501-21,217)	36,400 (15,254-54,836)	84,176 (51,739-110,393)
Kenya	250,427 (150,456-333,581)	20,155 (11,134-27,704)	60,253 (39,451-77,452)	4,405 (2,888-5,705)	69,831 (32,150-102,093)	95,783 (64,833-120,627)
Côte d'Ivoire	182,301 (109,381-243,133)	7,941 (4,485-10,811)	47,007 (32,012-59,432)	5,326 (3,590-6,814)	72,722 (34,800-104,904)	49,305 (34,493-6,112)
Singapore	27,424 (15,495-37,410)	1,639 (853-2,307)	11,727 (6,899-15,705)	3,529 (2,139-4,721)	4,573 (1,913-6,894)	5,956 (3,691-7,783)

Table 4-1. The estimated total number of premature deaths of each disease due to $PM_{2.5}$ in each country during 2000-2020. The ranges in parentheses are 95% confidence interval.

Country or Cities	All-cause	COPD	IHD	LC	LRI	Stroke
Nigeria	74,680 (48,910-94,671)	573 (390-711)	1,115 (931-1,272)	37 (29-44)	72,009 (46,776-91,570)	947 (785-1,075)
Indonesia	45,158 (21,651-65,242)	1,200 (657-1,655)	829 (529-1,077)	167 (107-218)	39,967 (18,368-58,487)	2,995 (1,990-3,805)
Philippines	25,559 (12,430-36,714)	403 (226-550)	714 (479-910)	47 (31-60)	23,696 (11,212-34,322)	699 (483-873)
Vietnam	20,397 (11,178-28,032)	686 (409-910)	636 (466-777)	99 (71-124)	17,872 (9,411-24,890)	1,103 (821-1,330)
Thailand	15,900 (8,258-22,310)	488 (283-657)	560 (397-696)	93 (65-118)	14,066 (7,012-19,994)	693 (501-847)
Kenya	8,618 (4,048-12,524)	101 (56-139)	176 (115-227)	4 (3-5)	8,176 (3,766-11,951)	161 (109-202)
Côte d'Ivoire	5,521 (2,682-7,929)	49 (28-67)	99 (68-126)	5 (4-7)	5,269 (2,515-7,608)	97 (68-121)
Malaysia	5,277 (2,287-7,875)	104 (54-147)	176 (103-237)	16 (9-21)	4,794 (2,006-7,225)	187 (115-245)
Singapore	352 (161-517)	19 (10-27)	32 (19-43)	5 (3-6)	269 (113-405)	26 (16-35)

Table 4-2. The total incidence outcomes (unit: thousand) of each disease due to $PM_{2.5}$ in each country during 2000-2020. The ranges in parentheses are 95% confidence interval

Nigeria (Africa)

Nigeria was found to have the total number of 2,669,142 (95% UI: 1,953,013 – 3,232,595) all-cause premature deaths due to $PM_{2.5}$ in the past decades. Among diseases, LRI, Stroke and IHD were the top three contributors to the total number of 1,371,250 (95% UI: 891,228-1,743,295), 611,241 (95% UI: 506,693-694,075) and 544,003 (95% UI: 454,203-620,215) premature deaths in Nigeria during 2000-2020.

As for the total incidence, Nigeria had the highest all-cause incidences [a total of 74,680 (95% UI: 48,910 – 94,671) (unit: thousand) incidences due to $PM_{2.5}$]. LRI was the largest contributor causing 72,009 (95% UI: 46,776-91,570) (unit: thousand).

Figure 4-29 shows the total number of premature deaths due to $PM_{2.5}$ in Nigeria. This is not a significant upward trend, which could link with a significant decline in premature deaths caused by LRI. The incidence due to $PM_{2.5}$ showed a slight upward trend.

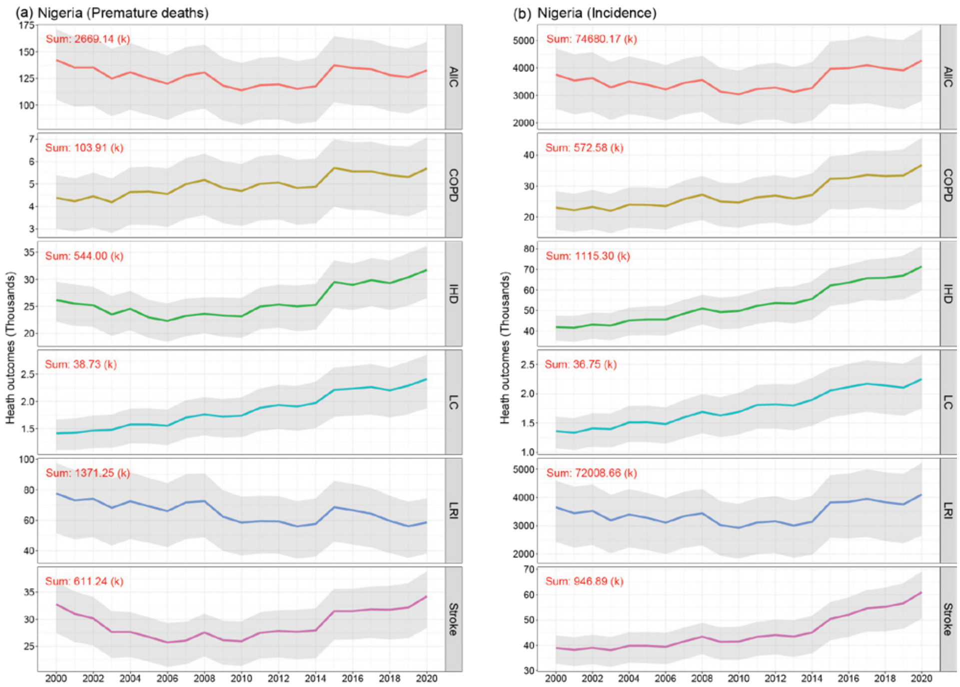

Figure 4-29. The trend of (a) premature deaths and (b) incidences in Nigeria through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Côte d'Ivoire (Africa)

In Cote d'Ivoire, the total number of all cause premature deaths due to $PM_{2.5}$ in the past two decades was 182,301 (95% UI: 109,381-243,133). Among diseases, LRI, Stroke and IHD were the top three contributors to the premature deaths due to $PM_{2.5}$, respectively causing the total number of 72,722 (95% UI: 34,800-104,904), 49,305 (95% UI: 34,493-6,112) and 47,007 (95% UI: 32,012-59,432) premature deaths during 2000-2020. The highest number of incidences of LRI was associated with the high incidence rate of this disease in this country (Shi et al., 2017).

Figure 4-30 shows there were clear upward trends in total deaths and incidences due to $PM_{2.5}$ in Côte d'Ivoire during the past two decades. The number of all-cause premature deaths due to $PM_{2.5}$ showed a slightly increasing trend. The increasing trend was particularly obvious in the premature deaths due to $PM_{2.5}$ through COPD, IHD and LC, whereas the premature deaths in due to LRI shows a decreasing trend.

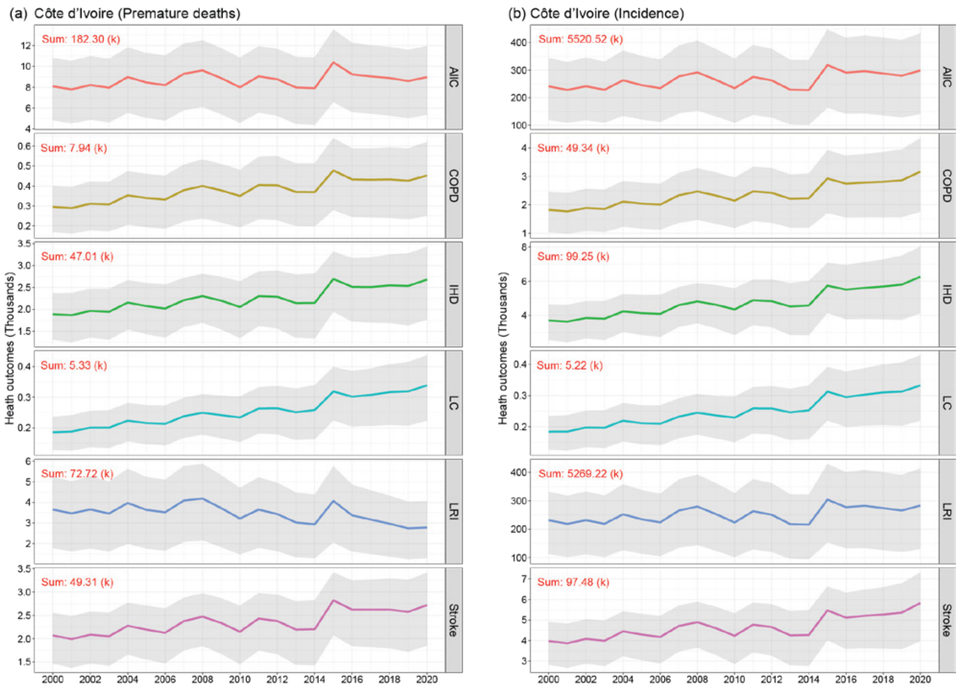

Figure 4-30. The trend of (a) premature deaths and (b) incidences in Côte d'Ivoire through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence intervall.

Kenya (Africa)

Kenya was estimated to cause the total number of 250,427 (95% UI: 150,456-333,581) all-cause premature deaths and 8,618 (95% UI: 4,048-12,524) (unit: thousand) incidences due to $PM_{2.5}$ during the past two decades. Stroke was the largest contributor in premature deaths due to $PM_{2.5}$ in Kenya, accounting for a total number of 95,783 (95% UI: 64,833-120,627). LRI was the largest contributor in incidences due to $PM_{2.5}$ in Kenya, with a total number of 8,176 (95% UI: 3,766-11,951) (unit: thousand). The highest number of incidences of LRI was associated with the high incidence rate of this disease (Shi et al., 2017).

Besides, there were significant synchronous increasing trends in both total premature deaths and incidence in Kenya, due to $PM_{2.5}$ from 2000 to 2020 in Kenya as (Figure 4-31).

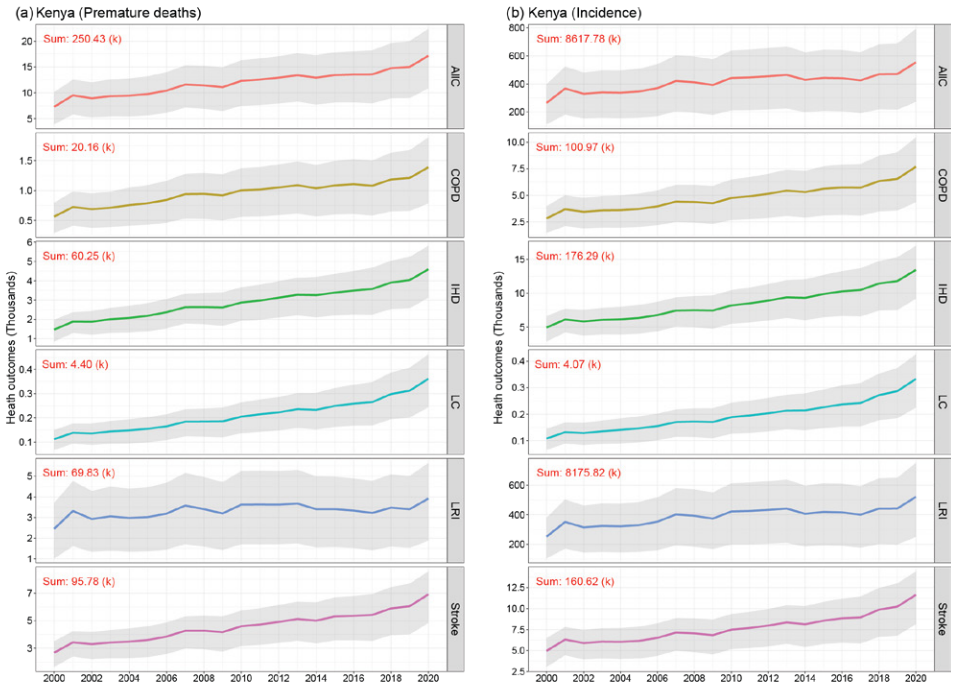

Figure 4-31. The trend of (a) premature deaths and (b) incidences in Kenya through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Indonesia (Southeast Asia)

Indonesia had a total of 3,165,156 (95% UI: 2,013,987 – 4,111,831) premature deaths due to $PM_{2.5}$ during the study period. Among diseases, Stroke, IHD, and COPD were the top three contributors to the premature deaths due to $PM_{2.5}$, respectively causing 1,595,241 (95% UI: 1,060,383-2,026,361), 994,541 (95% UI: 635,902-1,291,284), and 253,213 (95% UI: 138,621-349,293) premature deaths during 2000-2020. For the total incidence attributable to $PM_{2.5}$, Indonesia was estimated to cause the total number of 45,158 (95% UI: 21,651-65,242) (unit: thousand) all-cause incidence during the past two decades.

Figure 4-32 shows there were clear upward trends in total premature deaths and incidences due to $PM_{2.5}$. Although air quality in Indonesia was highly influenced by ENSO and IOD, it was not fully reflected in the final health outcomes. Previous studies confirmed that the public health in Indonesia was not only affected by climate but also by the local emission sources (e.g., population and human activities) (Sumarga, 2017; Uda et al., 2019).

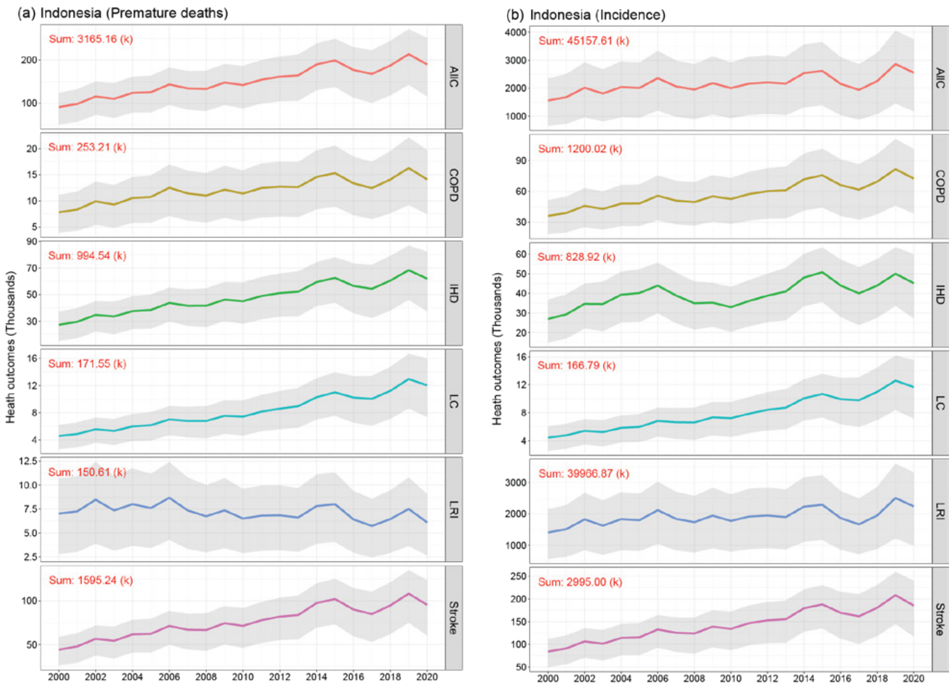

Figure 4-32. The trend of (a) premature deaths and (b) incidences in Indonesia through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Malaysia (Southeast Asia)

Malaysia had a total of 275,167 (95% UI: 156,142-374,230) premature deaths due to $PM_{2.5}$ during the study period. Among diseases, IHD, Stroke and LRI are the top three contributors to the premature deaths, causing a total number of 120,563 (95% UI: 70,222-162,072), 84,176 (95% UI: 51,739-110,393), and 36,400 (95% UI: 15,254-54,836) premature deaths during 2000-2020. For the total incidence due to $PM_{2.5}$, Malaysia was estimated to cause the total number of 5,277 (95% UI: 2,287-7,875) (unit: thousand) all-cause incidence during the past two decades.

There were clear consistent upward trends in total premature deaths and incidences for each disease in Malaysia, see Figure 4-33. Although air quality in Malaysia was highly influenced by ENSO and IOD, it was not fully reflected in the final health outcomes. Previous studies confirmed that the public health in Malaysia was not only affected by climate but also by the local sources (e.g., population and human activities) (Sumarga, 2017; Uda et al., 2019).

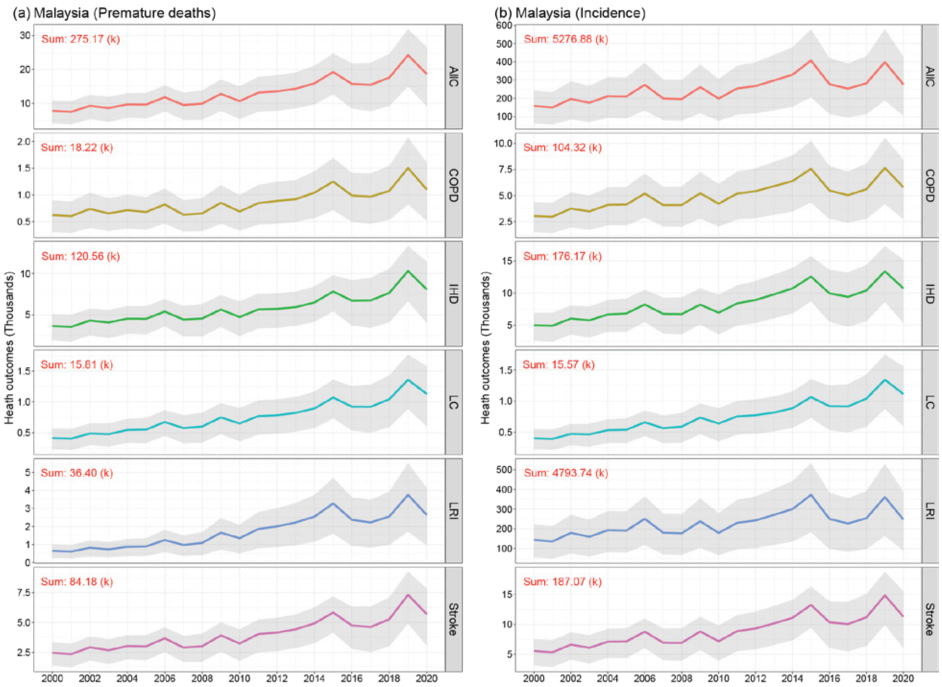

Figure 4-33. The trend of (a) premature deaths and (b) incidences in Malaysia through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Singapore (Southeast Asia)

Singapore had a total of 27,424 (95% UI: 15,495-37,410) premature deaths due to $PM_{2.5}$ during the study period. Among diseases, IHD, Stroke and LRI were the top three contributors to the premature deaths due to $PM_{2.5}$, respectively causing 11,727 (95% UI: 6,899-15,705), 5,956 (95% UI: 3,691-7,783), and 4,573 (95% UI: 1,913-6,894) premature deaths due to $PM_{2.5}$ during 2000-2020. For the total incidence due to $PM_{2.5}$, Singapore was estimated to cause the total number of 352 (95% UI: 161-517) (unit: thousand) all-cause incidence during the past two decades.

In Singapore, as shown in Figure 4-34, the premature deaths and incidence were more volatile, with a total of five distinct waves. Four of the waves corresponded to high polluted weather caused by El Niño and positive IOD events, and the remaining wave was influenced by the large wildfires in Indonesia according to previous analyses. This result indicates that the public health in Singapore was more sensitive to the severe and extreme weather (Aik et al., 2018).

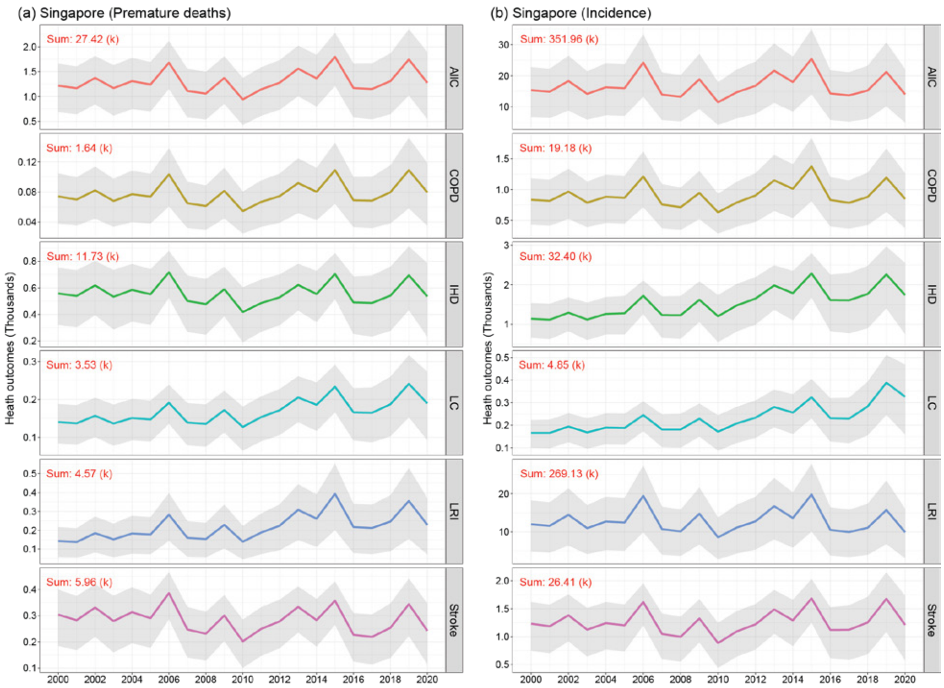

Figure 4-34. The trend of (a) premature deaths and (b) incidences in Singapore through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Philippines (Southeast Asia)

Philippines was estimated to cause the total number of 988,137 (95% UI: 1632,566-1,282,200) all-cause premature deaths due to $PM_{2.5}$ during the past two decades. Among diseases, IHD, Stroke, and LRI were the top three contributors to the premature deaths due to $PM_{2.5}$, causing the total number of 375,279 (95% UI: 251,429-477,850), 349,426 (95% UI: 241,326-436,172) and 146,049 (95% UI: 69,073-211,575) premature deaths due to $PM_{2.5}$ during 2000-2020. For the total incidence, Philippines had the highest all-cause incidences, with a total of 25,559 (95% UI: 12,430-36,714) (unit: thousand) incidences due to $PM_{2.5}$ exposure, with LRI 23,696 (95% UI: 11,212-34,322) is the largest contributor.

Figure 4-35 shows the total number of premature deaths and incidence due to $PM_{2.5}$ in Philippines. The results show clear upward trends during the past two decades.

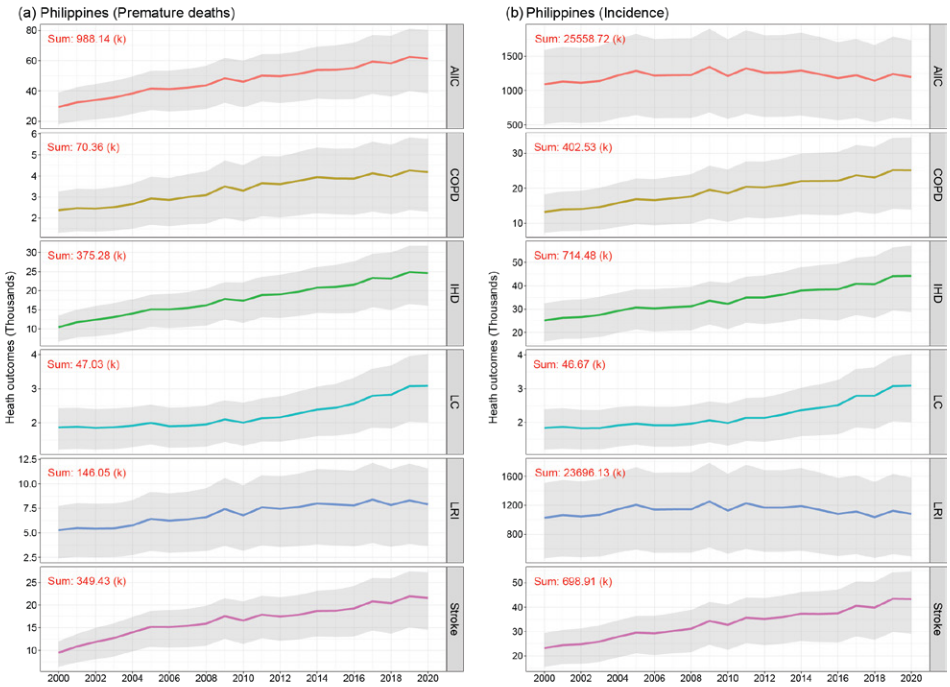

Figure 4-35. The trend of (a) premature deaths and (b) incidences in the Philippines through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

<u>Thailand (Southeast Asia)</u>

Thailand was estimated to cause the total number of 830,045 (95% UI: 563,218-1,049,959) all-cause premature deaths and 15,900 (95% UI: 8,258-22,310) (unit: thousand) incidences due to $PM_{2.5}$ during the past two decades. Stroke was the largest contributor in premature deaths due to $PM_{2.5}$ in Thailand with a total number of 316,478 (95% UI: 228,741-386,717) premature deaths. LRI was the largest contributor in incidences due to $PM_{2.5}$ in Thailand, with a total number of 14,066 (95% UI: 7,012-19,994) (unit: thousand). The highest number of incidences of LRI was associated with the high incidence rate of this disease (Shi et al., 2017).

Figure 4-36 shows the total number of premature deaths and incidence due to $PM_{2.5}$ in Thailand had clear and consistent upward trends during the past two decades, which is also confirmed in previous study (Shi et al., 2018). Shi et al. also calculated that the premature deaths due to $PM_{2.5}$ increased by an average of 38% in South and Southeast Asian countries including Thailand during 1999 to 2014.

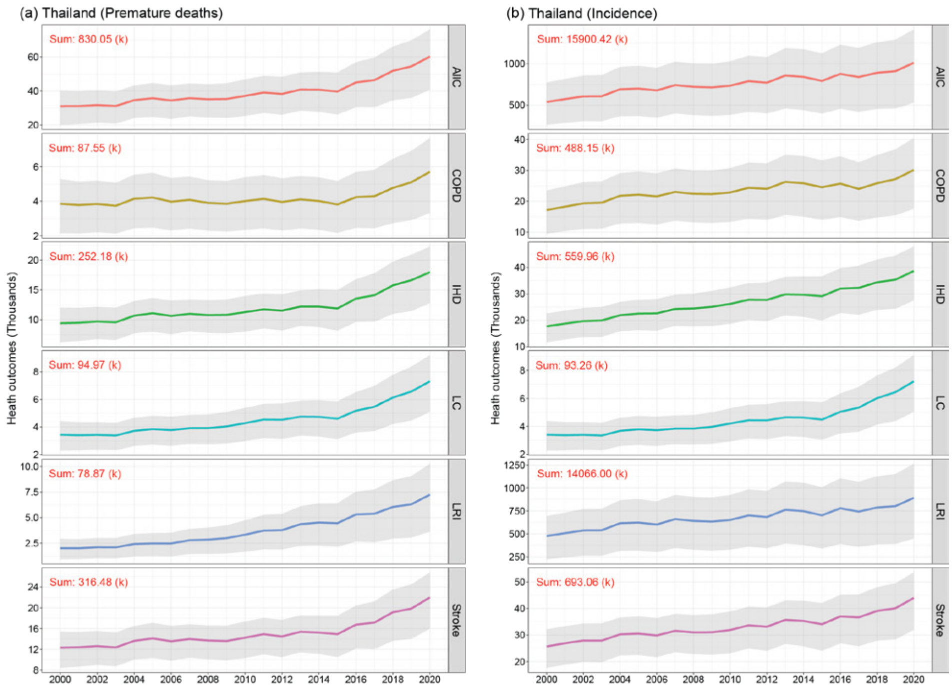

Figure 4-36. The trend of (a) premature deaths and (b) incidences in Thailand through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

Vietnam (Southeast Asia)

Vietnam was estimated to cause the total number of 1,618,314 (95% UI: 1,158,436-1,993,307) all-cause premature deaths and 20,397 (95% UI: 11,178-28,032) (unit: thousand) incidences due to $PM_{2.5}$ during the past two decades. Among diseases, Stroke was the largest contributor to premature deaths due to $PM_{2.5}$ in Vietnam, causing a total number of 929,435 (95% UI: 692,191-1,119,425). In addition, LRI was the largest contributor in incidences due to $PM_{2.5}$ in Vietnam, with a total number of 17,872 (95% UI: 9,411-24,890) (unit: thousand). The highest number of incidences of LRI was associated with the high incidence rate of this disease (Shi et al., 2017).

Figure 4-37 shows that the total number of premature deaths and incidence due to $PM_{2.5}$ in Vietnam showed clear upward trends during the past two decades. This result was also confirmed in previous study (Shi et al., 2018). Shi et al. also calculated that the premature deaths due to $PM_{2.5}$ increased by an average of 38% in South and Southeast Asian countries including Vietnam from 1999 to 2014.

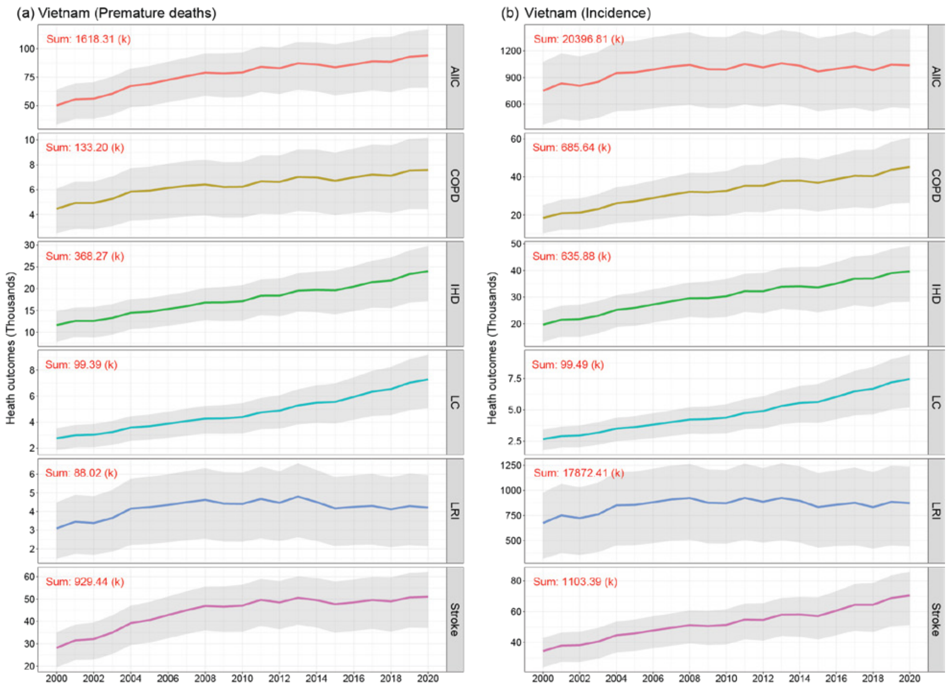

Figure 4-37. The trend of (a) premature deaths and (b) incidences in Vietnam through different diseases from 2000 to 2020. The shaded areas represent the 95% confidence interval.

CONCLUSION

Air pollution in Indonesia, Malaysia, Singapore, and Philippines was more influenced by individual positive IOD events than by individual El Niño events. The simultaneous occurrence of El Niño and positive IOD events contributed to the increase in air pollution in the countries in maritime Southeast Asia. There was no significant relationship between ENSO or IOD events and changes in air pollution in Thailand and Vietnam. The impact of ENSO on the Asian monsoon was limited over Indochina and the Indian subcontinent. The total number of premature deaths and incidence due to $PM_{2.5}$ in most Southeast countries, except Singapore, showed a clear upward trend. The premature deaths and incidence due to $PM_{2.5}$ in Singapore had a strong association with El Niño and positive IOD events, implying that public health in Singapore was more sensitive to severe and extreme weather, but this phenomenon was not evident in Indonesia and Malaysia. In Thailand and Vietnam, there were increasing trends of premature deaths and incidence due to $PM_{2.5}$. Stroke and IHD were the major diseases in Thailand and Vietnam. Regarding the African countries in this study, Nigeria and Côte d'Ivoire had relatively high $PM_{2.5}$ concentrations over the past 20 years, with local biomass burning likely to be the main source. The main pollutant emissions in Nigeria and Côte d'Ivoire were mainly from residential, transportation and industrial sources. High $PM_{2.5}$ levels in both countries were likely to be associated with the dry season, and meteorological factors had a minor effect on $PM_{2.5}$ concentration. By contrast, Kenya was more vulnerable to the complex climate effects coming from the Indian Ocean. Kenya showed an upward trend in health outcomes due to $PM_{2.5}$ among the three African countries, whereas Nigeria and Côte d'Ivoire showed slightly upward trends, which may be related to the significant decline in premature deaths through LRI due to $PM_{2.5}$ in these two countries.

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