7-SEAS Urban-AQ

Whitepaper*

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State of Science and Scientific Background

Air quality is closely related to atmospheric chemistry, climate, and the global environment. Air pollution refers to the release of pollutants into the air that are harmful to human and other living beings' health and cause negative consequences for the climate and the environment. It is also the contamination of outdoor or indoor surroundings, either by physical, chemical, or biological agents, that changes the normal features of the atmosphere. There are many types of air pollutants, such as particulates (both organic and inorganic), gases (including ammonia, carbon monoxide, sulfur dioxide, nitrous oxides, methane, and chlorofluorocarbons), and biological molecules. Air pollution is caused by both natural phenomena and human activities. Natural sources of air pollution include fires, dust storms, volcanic eruptions, and others. Human activities such as burning fossil fuels (including coal, petroleum, natural gas, oil shale, bitumens, tar sands, and heavy oils), alcohol-based fuels, biomass, biofuels, and other solid materials (like plastics, medical, and hazardous waste) also emit toxic air pollutants into the atmosphere. This also includes power plants, oil refineries, and chemical manufacturing factories that emit toxic gases, particulate matter, and radioactive substances into the air. Air pollutants could be criteria pollutants (particulate matter, ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, and lead) and hazardous contaminants including trace metals (mercury, chromium, cadmium, nickel, aluminum, iron, etc.), BTEX (benzene, toluene, ethylbenzene, and xylene), formaldehyde, dioxins and polychlorinated biphenyls (PCBs), benzo[a]pyrene (BaP), polycyclic aromatic hydrocarbons (PAH), Volatile organic compounds (VOC). These air pollutants cause critical environmental issues like poor indoor/outdoor air quality, urban smog or haze, visibility degradation, acid rain, ozone depletion/holes, and global warming. Exposure to high levels of air pollution (short- or long-term) can cause a variety of adverse health outcomes such as nervous system damage, cardiovascular damage, chronic obstructive pulmonary disease, Alzheimer's disease, lung cancer, asthma, and lower respiratory infections leading to premature death. The International Agency for Research on Cancer has classified air pollution, in particular $PM_{2.5}$ (particulate matter ≤ 2.5 μm in aerodynamic diameter), as a leading cause of cancer. Ambient $PM_{2.5}$ caused 4.2 million (95% UI: 3.7–4.8 million) deaths and 103.1 million (95% UI: 90.8–115.1 million) disability-adjusted life years (DALYs) in 2015 (Cohen et al., 2017).

Wildlife also experiences the same detrimental health effects of air pollution that humans do. Moreover, air pollution seriously affects plant growth and crop yield.

Urban air quality is one of the most important concerns for city residents and regulatory authorities. Urban air quality is deteriorating due to rapid urban infrastructure development, industrial activities, and economic development. Many cities around the world are suffering from poor air quality, which has a pernicious impact on public health, the economy, agriculture, and livestock. Urban air quality is greatly aggravated by gaseous and particulate emissions from a variety of sources, including industries, traffic activities, construction, waste incineration, and household emissions. Urban landscape and local meteorology significantly affect the urban air quality. Urban heat island (UHI) effects on human health are profound and manifest through extreme temperatures, heatwaves, and air pollution (Figure 1; Singh et al., 2020). The process of air quality deterioration also follows temporal and spatial differences. Therefore, a comprehensive understanding of the characteristics and causes of air pollution is important, which led to the development of systematic air quality monitoring.

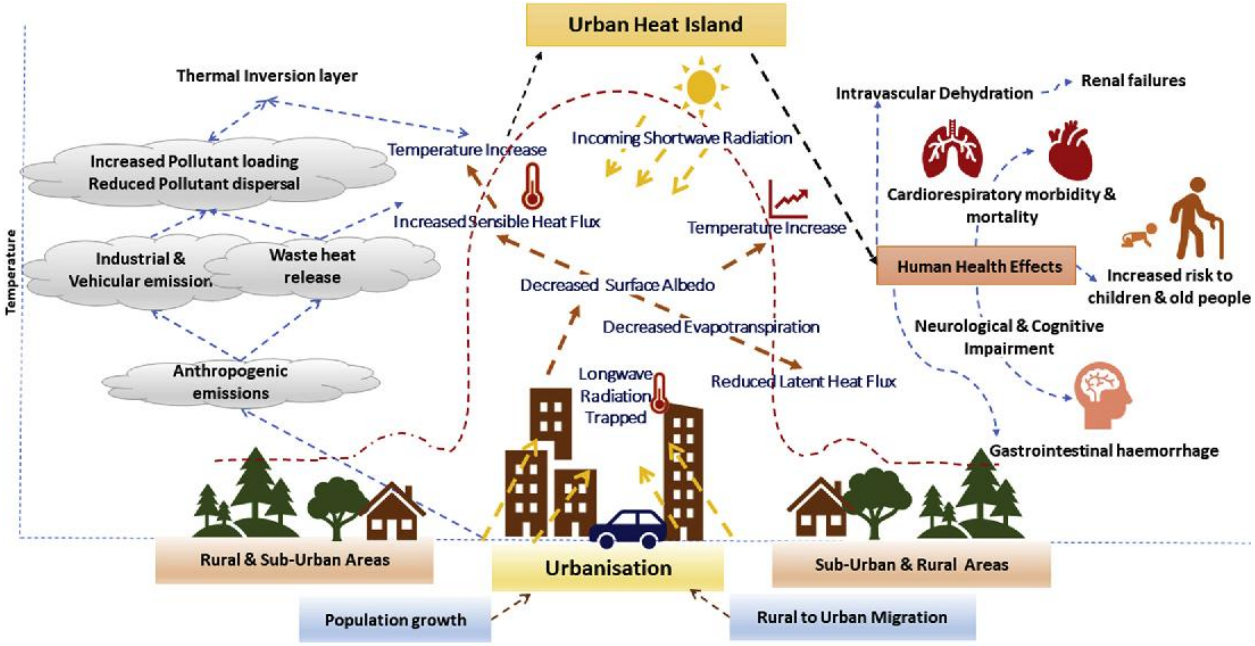

Figure 1. Urban Heat Island effects and their health impacts (taken from Singh et al., 2020).

Air quality monitoring is effective for determining the air quality status of a specific location at a particular time. Effectively monitoring urban air quality and analyzing the source terms of the major air pollutants is important for public authorities to take air quality management actions. The benefits of urban air quality monitoring are as follows.

1. Better understanding the air quality status and the contributing source origins
2. Proper framing of mitigating and control strategies to combat urban air pollution
3. Taking actions to improve the quality of life and health of the public
4. Protect public health and thus reduce healthcare costs
5. Increase environmental awareness among the public
6. Promote new forms of sustainable mobility
7. Increase the attractiveness of the city for tourism
8. Framing a healthier ecosystem
9. Enhance the city's ability to attract talent, innovation, and investment

Urban air pollution in Southeast Asia

Southeast Asia (SEA; here defined as Singapore, Indonesia, the Philippines, Malaysia, Thailand, Vietnam, Myanmar, Cambodia, and Laos) is a well-known region for its high pollution loadings and complex meteorology (Lin et al., 2013; Salinas et al., 2013; Kusumaningtyas et al., 2018; Pani et al., 2018; Hien et al., 2019; Tham et al., 2019; Dahari et al., 2020). Air pollution has been one of the most serious environmental problems in Southeast Asia in recent years. It is a subject of interest from both regulatory and scientific perspectives, as regional emissions are growing rapidly due to population growth, economic development, and urbanization. Regional air pollution problems such as reduced visibility and acid deposition are already apparent in the region. The great majority of Southeast Asia's urban population is exposed to unsafe levels of air pollution. Regional air quality varies widely across Southeast Asia with space and time.

Air pollution in Southeast Asia can arise from natural or unnatural sources. Sources of natural air pollution include volcanic eruptions and biomass-burning activity. There are 750 active volcanoes in Southeast Asia, and volcanic eruptions occur frequently in this region (Whelley et al., 2015). Fires in equatorial SEA are mostly due to peat burning during August–October and are highly affected by droughts induced by the El Niño–Southern Oscillation

(ENSO). Over the past four decades, three devastating forest fires have occurred in Sumatra and Borneo in 1982/1983, 1997/1998, and 2015. These ENSO-driven forest fires released massive GHGs into the atmosphere, and the most severe fire, which occurred in 1997/1998, was estimated to emit 0.95 Gt of carbon.

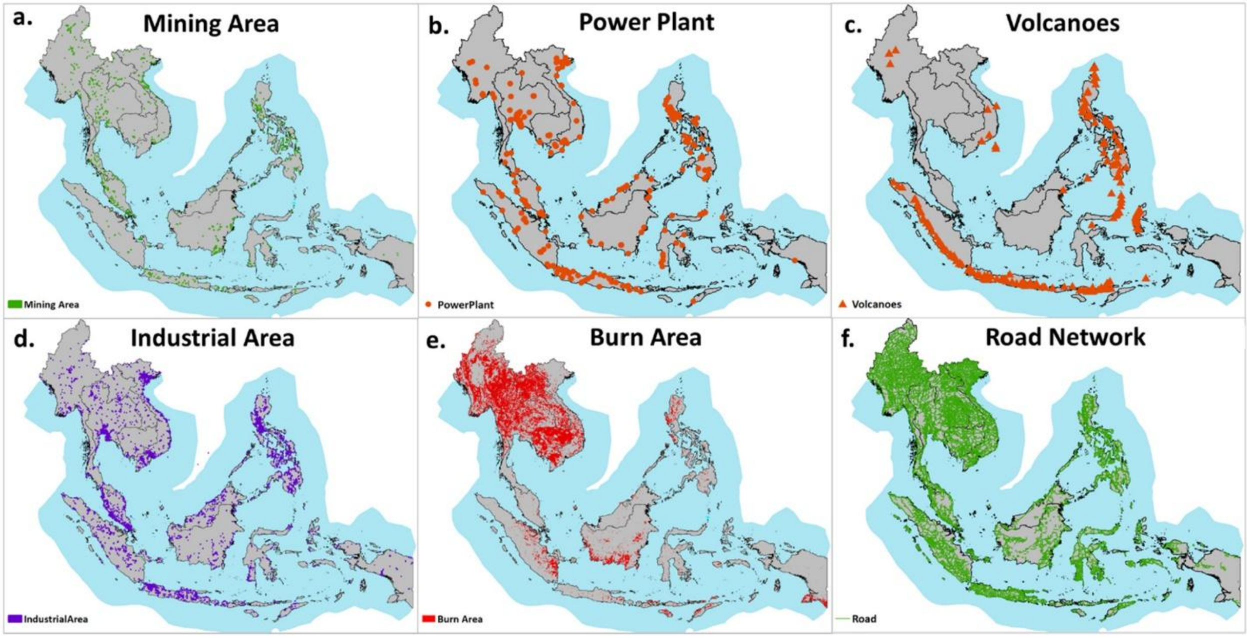

Figure 2. Distribution of air pollution sources in Southeast Asia (a) mining areas, (b) power plants, (c) active volcanoes, (d) industrial areas, (e) burned areas, and (f) road networks (taken from Sakti et al., 2023).

Unnatural air pollution is caused by human activities including vehicular emissions with mixed residential, commercial, and industrial emissions, and other anthropogenic activities, and burning forests for land clearing (Sakti et al., 2023). Across the northern peninsular Southeast Asia (PSEA; here defined as Thailand, Myanmar, Vietnam, Laos, and Cambodia), substantial open BB in the form of forest fire and agricultural burning, occurs in the dry season (February–April) and significantly influences the atmospheric composition and regional climate (Lin et al., 2023, 2014; Tsay et al., 2016). These fire activities in Southeast Asia emit a substantial amount of aerosol, containing a significant amount of water-soluble inorganic ions such as NH_4^+, K^+, and NO_3^- and carbonaceous aerosols composed of both elemental carbon (EC) and organic carbon (OC) into the atmosphere. Emissions from the vegetation fire severely impact the air quality, atmospheric chemistry, and climate over Southeast Asia. Complex meteorology and land terrain also play important role in air quality over Southeast Asia. Moreover, the increasing population in Southeast Asia also adds to the pollution levels.

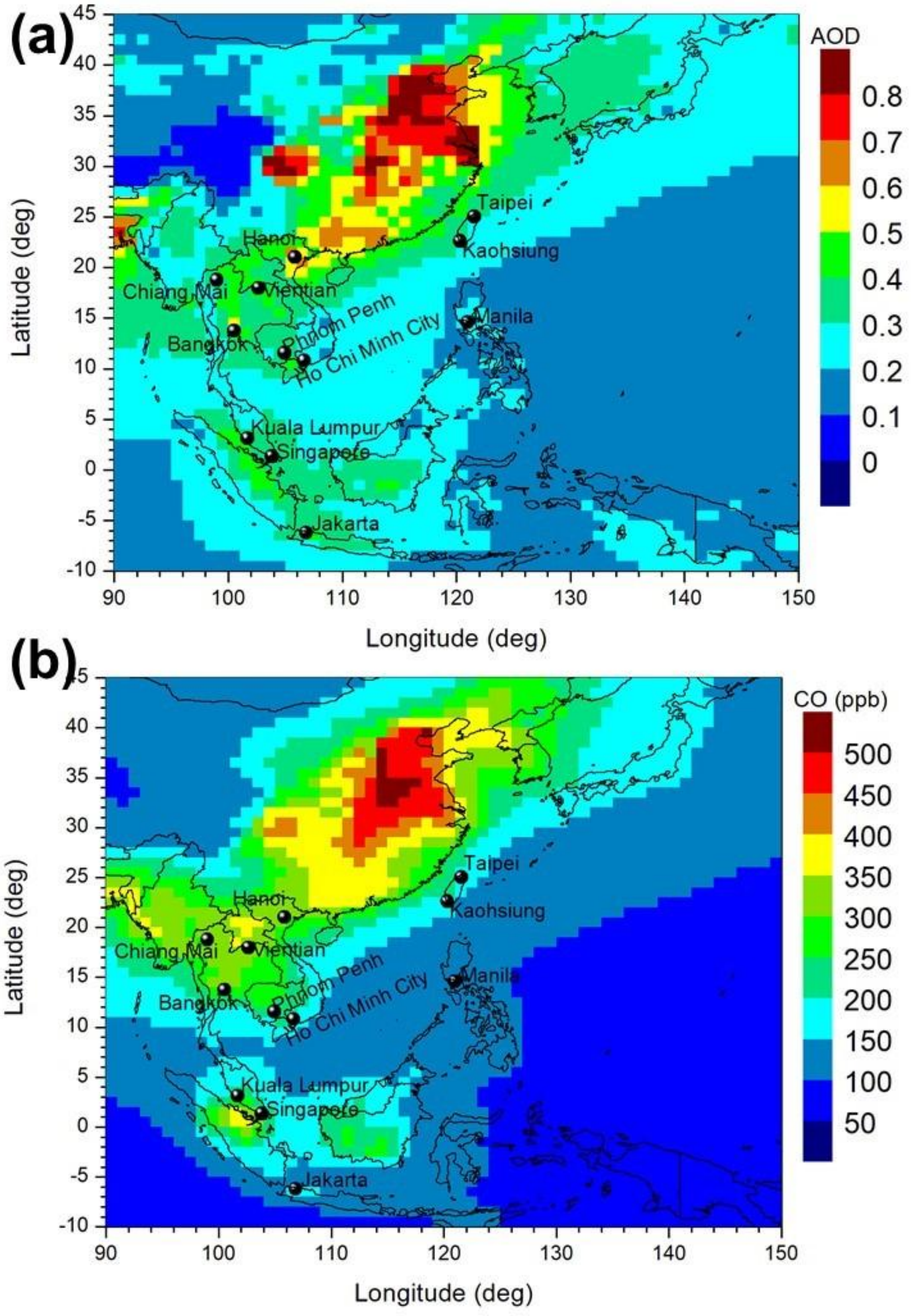

Figure 3. Spatial distribution of annual average(2001–2022) (a) aerosol optical depth at 550 nm from MODIS Terra satellite and (b) carbon monoxide (CO) mass concentration in ppb at surface level from MOPITT over Southeast Asia.

7-SEAS Urban-AQ Science Goals

7-SEAS Urban-AQ will enhance our understanding of urban air quality, the controlling factors, and the associated risks/impacts on climate and public health across different cities in Southeast Asia and Taiwan. Initially targeted cities are Chiang Mai and Bangkok in Thailand, Hanoi and Ho Chi Minh City in Vietnam, Kuala Lumpur in West Malaysia and Kota Kinabalu in East Malaysia, Singapore, and Taipei and Kaohsiung in Taiwan. Major cities such as Jakarta, Indonesia; Vientiane, Laos; Phnom Penh, Cambodia; and Manila, the Philippines, will be included at a later stage.

1. Air Quality Assessments
2. Defining/understanding the AQ problems
3. Aerosol chemistry and physics: visibility and source apportionment
4. Impact on regional climate
5. Impact on public health and economic burden
6. Air pollution control strategies
7. Planning and discussion workshops and training
8. Publications and public relationships

The abovementioned science goals are applicable to each city in Southeast Asia. More detailed discussions of each topic and associated science goals are provided below to explain the specific relevance of 7-SEAS Urban-AQ.

1. Air Quality Assessments

There are three types of air quality assessments: direct observation or in situ measurements, remote-sensing retrievals, and air quality modeling. Long-term data on criteria pollutants (particulate matter, ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, and lead) will be collected as available and analyzed to understand the status, patterns, and trends of air pollutants across different cities. For example, long-term air quality and meteorological parameters are available over Taiwan (https://airtw.epa.gov.tw/ENG/default.aspx), Thailand (https://www.pcd.go.th/), and Singapore (https://www.nea.gov.sg/) measured at air quality monitoring stations across the countries. Air quality data ($PM_{2.5}$ mass concentrations) measured at Hanoi, Ho Chi Minh City, Jakarta, Vientiane, Kuala Lumpur, and Manila with US Embassy monitors are also available (https://www.airnow.gov/international/us-embassies-and-consulates/). Observations made at a location represent only one point and depend on the site and number of monitoring sites available. Air pollution retrievals made using remote sensing have the advantage of a relatively wide and geographically uniform coverage area. This supports large-scale observations and produces average air pollution concentrations over a specific location or landmass. Various satellite retrievals will be assessed and analyzed to understand the spatial heterogeneity or variability of various air pollutants over Southeast Asia. For example, the MOPITT (Measurement of Pollution in the Troposphere; https://terra.nasa.gov/about/terra-instruments/mopitt) provides the carbon monoxide surface concertation. The TROPOMI (TROPOspheric Monitoring Instrument; https://www.tropomi.eu/) onboard the Sentinel-5 Precursor satellite (S5P) monitors a range of chemical species (SO_2, NO_2, O_3, HCHO, and H_2O) crucial to the climate and other atmospheric processes. The AIRS (Atmospheric Infrared Sounder; https://airs.jpl.nasa.gov/) also provides tropospheric CO concentrations. Different aerosol optical properties will be retrieved from MODIS (Moderate Resolution Imaging Spectroradiometer; https://modis.gsfc.nasa.gov/). Moreover, the reanalysis model MERRA-2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/) provides spatial distribution of various aerosol components and meteorological parameters over the globe. Air quality modeling (WRF-Chem and/or CMAQ) can be used to produce the air pollutants dataset during the important missing periods and to validate the existing emission inventories over Southeast Asia. Several questions can be answered by analyzing the long-term air pollutant data in different cities and over the whole of Southeast Asia.

- What are the emission patterns of gaseous pollutants including greenhouse gases?
- What are the emission pattern of particulate matter ($PM_{2.5}$ and PM_{10})?
- What are the trends in gaseous pollutants and particulate matter?
- What are the emissions of toxics air pollutants?
- Does meteorology affect the emissions of trace gases and aerosols?
- What are the diurnal behaviors of gaseous pollutants and particulate matter?
- What is the difference between daytime and nighttime pollution levels/scenarios?
- What are the levels of air pollutants during BB seasons?

- How significant are the impacts of ENSO or other climate drivers on air quality?
- How well do existing emission inventories represent BB emissions?

2. Defining and Understanding the AQ problems for each city

The abovementioned analyses of air pollutants will be beneficial to understand and define the exact AQ problems in Southeast Asia and in particular for a specific city. The most contributing pollutants to the urban haze and air quality degradation and the important controlling factors in different cities can be identified. Long-term analysis will also be helpful to know the seasonal pattern and trend (percentage of increasing or decreasing) of specific air pollutants in cities in Southeast Asia.

3. Aerosol chemistry and physics: visibility and source apportionment

Visibility reduction is probably the most apparent symptom of air pollution. Visibility degradation is caused by the absorption and scattering of light by atmospheric particles and gases before it reaches the observer. As the number of fine particles increases, more light is absorbed and scattered, resulting in less clarity, color, and visual range. Aerosol chemical constituents such as mineral dust, elemental carbon (EC) or black carbon (BC), and brown carbon (BrC; the light-absorbing organic carbon (OC)) are key absorbers of solar radiation contributing significantly to visibility degradation and net warming. In contrast, SO_4^{2-}, NO_3^-, a major part of organic matter (OM), and sea salt are light scattering aerosols and importantly contribute to net cooling by counteracting the global warming caused by greenhouse gases and light-absorbing aerosols. Scattering by aerosols impairs visibility much more readily. Visibility standards are based on extinction coefficients, which is a measure of the light attenuation due to both absorption and scattering. A detailed knowledge of aerosol chemistry and physics is vital to better understanding the visibility impairment in different cities or Southeast Asia. Source apportionment is conducted to identify and quantify the impact of different sources of air pollutants at the sampling sites. Source apportionment of aerosol by receptor model such as positive matrix factorization (PMF) requires large data of aerosol composition. Overall, knowledge of aerosol chemistry and physics will be beneficial for understanding primary emissions, secondary formation, chemical transformations, and the life cycles of different aerosol species across different cities. Comprehensive measurements of atmospheric composition will be required to fully explore the links between aerosols, their sources, and the meteorological conditions that lead to haze and visibility degradation. Such measurements include gaseous pollutants, aerosol physical and chemical properties, and meteorological parameters. Several questions can be answered with the knowledge of aerosol chemistry and physics in different cities in Southeast Asia.

- What are the formation mechanisms and rates for secondary inorganic aerosols (SO_4^{2-}, NO_3^-, and NH_4^+) and what meteorological conditions control their relative importance?
- Are there any differences in daytime and nighttime in formation mechanisms?
- What are the O_3 formation and production mechanisms? Are they different for different cities?
- What are the mechanisms that lead to PAN formation during daytime/nighttime and BB/non-BB seasons?
- How does the chemical transformation change during BB seasons?
- What are the sources contributing to $PM_{2.5}$? What are the contributions of biomass burning to heavy $PM_{2.5}$ loadings during the burning seasons?
- What are the contributions of different chemical species to $PM_{2.5}$ and light extinction budgeting?
- How do BC and BrC contribute to total light extinction? What are the differences between BB and non-BB scenarios?
- How important is O_3 chemistry for BrC light absorption?
- What are the contributions of biomass burning to BrC light absorption during the burning seasons?

4. Impact on regional climate

An accurate understanding of aerosol radiative forcing is crucial for estimating the aerosol climate effect at regional and global scales. The quantification of the radiative impact of atmospheric aerosols over a region requires information on their physical, chemical, and optical properties, as well as their spatiotemporal variability. Measurements of aerosol physical, chemical, and optical properties (discussed in the abovementioned sections) will be used in quantifying the aerosol radiative effects over different cities in Southeast Asia.

Several questions could be answered by doing this in different cities in Southeast Asia.

- What are the magnitudes of radiation budget perturbation at the surface, at the top of the atmosphere, and in the atmosphere?
- What is the magnitude of the heating rate?
- What are the contributions of BC and BrC to composite aerosol radiative forcing?
- Was there any impact from dust on composite aerosol radiative forcing?
- What are the effects of surface or atmospheric radiative forcing on ambient temperature and observed solar radiation at the surface?
- How well do regional and global models predict the regional BB influence on climate?

5. Impact on public health and economic burden

Urban air quality greatly impacts public health. A significant number of epidemiological studies have found a correlation between air quality and a wide range of adverse health impacts, underscoring the considerable role of air pollution in the disease burden in the general population, ranging from subclinical effects to premature death. The health risk assessment for air pollution includes mathematical estimation and modeling of several processes, including population estimates, population exposure to pollutants, and adverse health impact assessment using specific concentration-response functions. Generally, population data, air quality data, baseline mortality or disease rates, and risk estimates (changes in health effects associated with changes in air pollutant concentrations) from epidemiological studies quantify the association between health effects and exposure to air pollution. The health risk assessment method can facilitate policy decision-making by evaluating the costs and health risks associated with air pollution (Hassan Bhat et al., 2021).

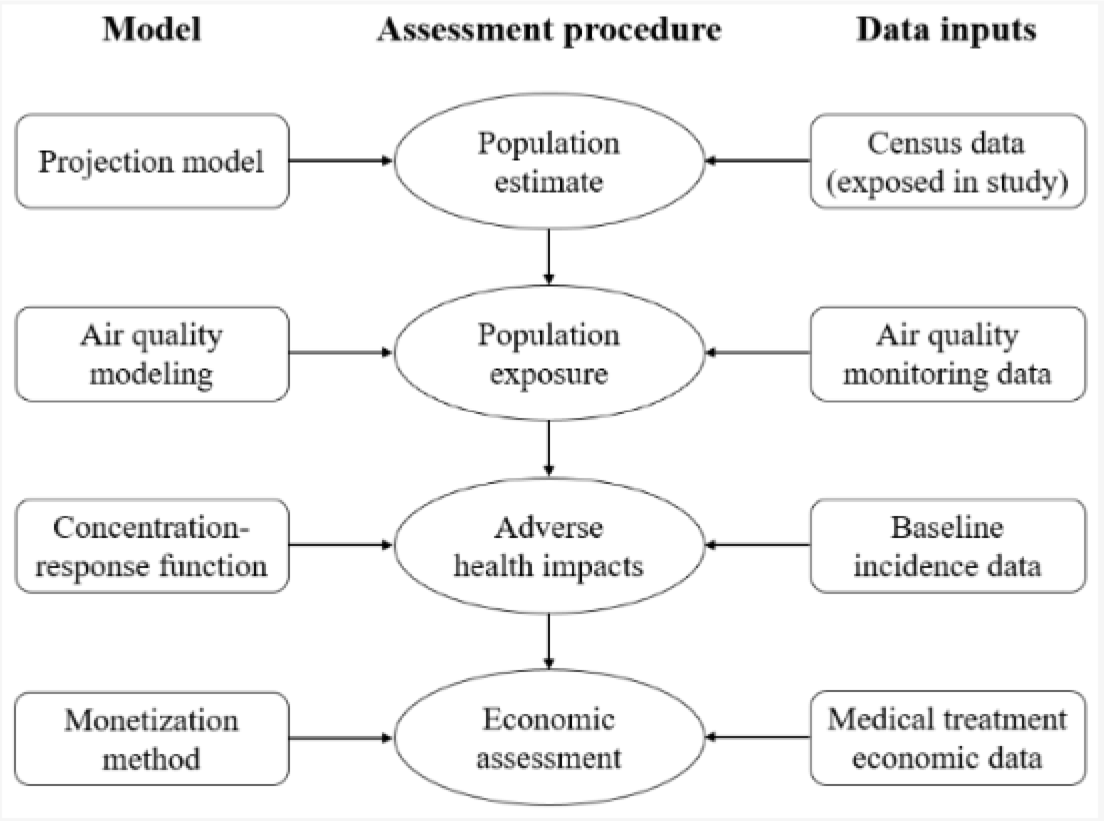

Figure 4: The flow diagram of Air Pollution Health Risk Assessment methods, typical models, and data inputs (taken from Hassan Bhat et al., 2021).

Several questions could be answered by estimating health impacts of air pollution in different cities in Southeast Asia.

- What are the adverse health impacts of various air pollutants?
- What are the deposition fraction at different respiratory tracts of humans?
- When and where to exercise?
- What is the best possible time for tourism?
- What are the potential health risks of the inhabitants?

6. Air pollution control strategies

A wide range of policies, strategies, and interventions have been implemented worldwide to improve air quality. Air pollution control strategies are mostly site-specific. Understanding the current state of air pollution will be beneficial to construct a better blueprint to mitigate air quality issues. Also, this study will be helpful in shaping effective control strategies for open burning management in Southeast Asian countries.

7. Planning and discussion workshops and training

Workshops are a great way to facilitate meaningful discussion and tap into collective wisdom. Annual workshops and training will be planned to (a) decide the sampling locations, (b) discuss data collection, analysis, and sharing, (c) deliberate about scientific results and findings, and (d) proceed with report/manuscript writing.

8. Publications and public relationships

Outcomes of 7-SEAS Urban AQ will be published in peer reviewed journals as scientific and technical writings.

Communicating to the public about urban air pollution is a complex task. It requires careful consideration of the goals and objectives of the communication, the target audience, the type of information and the messages to be conveyed. Communicating about air pollution to the public is essential for reducing exposure by increasing awareness and promoting precautionary actions.

Field campaigns, modeling and assessment

1. Ground-based Measurements

Close integration with ground measurements is fundamental to this study. Measurements of meteorological parameters, criteria air pollutants (PM_{10}, $PM_{2.5}$, O_3, SO_2, NOx, and CO), and VOCs will be conducted in different cities across Southeast Asia. Simultaneous in situ measurements of aerosol physical, chemical, and optical properties will also be done. Gravimetric sampling of 24-hourly $PM_{2.5}$ will be carried out using high- or low-volume air samplers. The filter papers will be analyzed for water-soluble ions, OC, EC, WSOC, trace metals, anhydrous sugars, and isotopes. Real-time BC light absorption and mass concentrations will be made using a multi-wavelength (370–950 nm) aethalometer (e.g., AE33). Aerosol scattering coefficient measurements will be done using a three-wavelength (450, 550, and 700 nm) nephelometer. The scanning mobility particle sizer (SMPS) will be used size and number concentration of aerosol particles with diameters from 2.5 nm to 1000 nm. Ground-based networks such as AERONET (https://aeronet.gsfc.nasa.gov/), MPLNET (https://mplnet.gsfc.nasa.gov/), and Pandora (https://pandora.gsfc.nasa.gov/) play a critical role linking surface, satellite, and modeling results during the field campaigns at local and regional scales. Various optical properties of columnar aerosols will be obtained from the AERONET site available in Southeast Asia. Likewise, the vertical distribution of aerosols in the atmospheric column will be obtained from the MPLNET sites. Moreover, vertical column densities of trace gases (NO_2 and O_3) and HCHO in the atmosphere will be obtained from PANDORA instrument sites.

2. Satellite remote sensing observations

Satellite remote sensing of land plays a critical role in monitoring aerosols, gaseous pollutants, and vegetation fires at regional scales. Observations of CO will be obtained from MOPITT (https://terra.nasa.gov/about/terra-instruments/mopitt) and AIRS (https://airs.jpl.nasa.gov/). Likewise, various chemical species (SO_2, NO_2, O_3, HCHO, and H_2O) will be retrieved from TROPOMI (https://www.tropomi.eu/). Information about open vegetation fires and several aerosol optical parameters will be retrieved from MODIS (https://modis.gsfc.nasa.gov/).

3. Air quality modeling

Air quality models use mathematical and numerical techniques to simulate the physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere. The Community Multiscale Air Quality (CMAQ) and Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) models will be used to estimate the concentration of air pollutants in different cities based on inputs of meteorological and emission datasets. The PMF model will be used to quantify different source contributions to ambient aerosols using measured aerosol chemical compositions in different cities.

4. Assessment of climatic and health impacts

The aerosol "direct effect" refers to the interaction of aerosols through scattering and absorption with solar (shortwave) and, to a lesser extent, with thermal infrared (longwave) radiation. The clear-sky shortwave (SW; 0.25–4 μm) direct aerosol radiative forcing for composite aerosols will be estimated by following the methodology presented in Pani et al. (2016). The approach (Figure 5; Pani et al., 2016) involves (i) the reconstruction of various aerosol optical properties such as aerosol optical depth (AOD), single scattering albedo (SSA), and asymmetry parameter (AP) in the Optical Properties of Aerosols and Clouds (OPAC 3.1) model (Hess et al., 1998) by using available observations and (ii) the incorporation of the reconstructed/estimated aerosol optical properties in the Santa Barbara Discrete Ordinate Radiative Transfer (SBDART) model (Ricchiazzi et al., 1998). Aerosol radiative forcing (ARF, W m^{-2}) at the surface (ARF_{SFC}) and at the TOA (ARF_{TOA}) will be calculated as the change in the net (difference between downward and upward) fluxes with and without aerosol conditions as

$$ARF_{SFC} = (\text{NetFlux})\ \text{with aerosol at SFC} - (\text{NetFlux})\ \text{without aerosol at SFC} \quad (1)$$

$$ARF_{TOA} = (\text{NetFlux})\ \text{with aerosol at TOA} - (\text{NetFlux})\ \text{without aerosol at TOA} \quad (2)$$

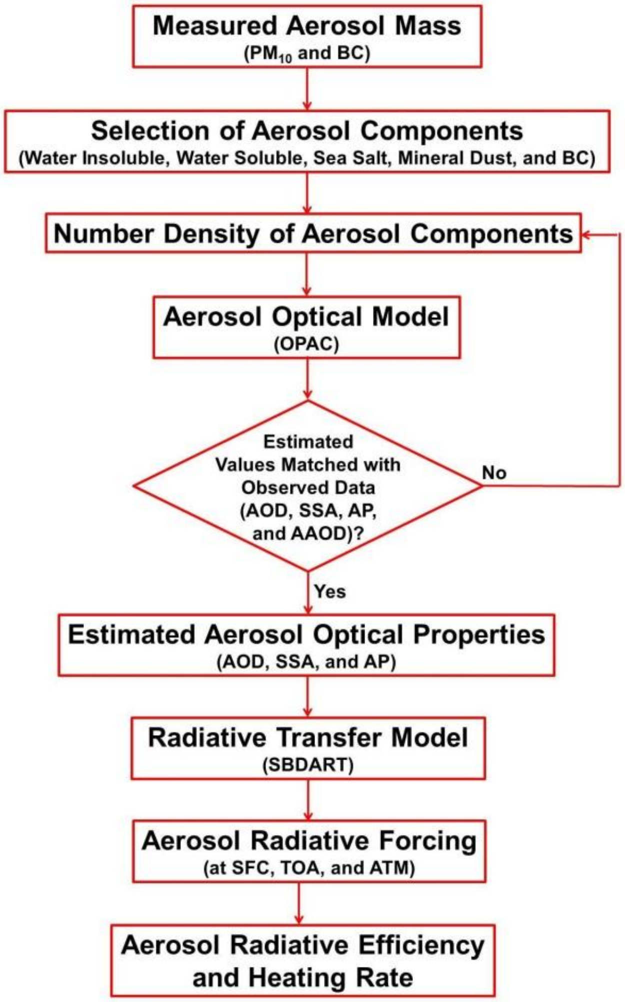

Figure 5: A flow diagram of the methodology adopted for the estimation of aerosol radiative forcing using SBDART model, in conjunction with the aerosol optical properties estimated from the OPAC in the shortwave range (taken from Pani et al., 2016).

The amount of energy trapped by the aerosols present in the atmosphere (ARF_{ATM}), will be estimated as the difference between the ARF_{TOA} and ARF_{SFC}. Furthermore, the aerosol radiative efficiency and heating rate for composite aerosol and its individual components will be estimated and compared at upwind and downwind locations. ARF_{ATM} in the shortwave region will be further used to estimate atmospheric heating rate at each layer (ΔP) is given by

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{\mathrm{g}}{\mathrm{C_p}} * \frac{\mathrm{ARF_{ATM}}}{\Delta \mathrm{P}} \qquad (3)$$

Where ($\frac{\partial \mathrm{T}}{\partial \mathrm{t}}$) is the heating rate (Kelvin per day; K d^{-1}), g is the acceleration due to gravity (9.8 m s^{-1}), $\mathrm{C_p}$ is the specific heat capacity of air at constant pressure (1006 J kg^{-1} K^{-1}), and P is the atmospheric pressure difference.

$PM_{2.5}$-bound trace metals, PAHs, and BC are major contributors to human health damage. Measurements of aerosol chemical composition and size distribution would help estimate the associated health risks/impacts on human health. Health risk assessments will be done using different methods. For instance, the Multiple-Path Particle Dosimetry Model (MPPD) can be used to estimate aerosol deposition in the human respiratory tract (e.g., Chow et al., 2023). Health risks of air pollutants ($PM_{2.5}$, NO_2, BC) can be assessed in terms of passive cigarette smoking equivalence (e.g., van der Zee et al., 2016; Pani et al., 2020). Health risks/impacts of trace metals will also be estimated.

Expected Benefits

Air quality monitoring is effective for a timely understanding of the current air quality status of a region or city. The outcomes from 7-SEAS Urban-AQ will provide the scientific basis for:

- Improved understanding of air quality status and its controlling factors in different cities in Southeast Asia
- Better understanding of the impact of local meteorology on air quality
- Improved understanding of visibility impairment and contributing sources in different cities
- Quantitative assessment of population exposures in different cities
- Better descriptions of fire dynamics and transport on a local-to-regional scale
- Quantitative assessment of the impact of BB-derived aerosols on regional climate with greater accuracy

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