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REVIEW PAPER

Review of Singapore's air quality and greenhouse gas emissions: Current situation and opportunities

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Singapore has many environmental accomplishments to its credit. Accessible data on air quality indicates that all criteria pollutants satisfy both U.S. Environmental Protection Agency (EPA) and World Health Organization (WHO) air quality standards and guidelines, respectively. The exception is $PM_{2.5}$ (particles with an aerodynamic diameter ≤ 2.5 μm), which is not currently considered a criteria pollutant in Singapore but may potentially be the major local air pollution problem and cause for health concern. Levels of other airborne pollutants as well as their physical and chemical processes associated with local formation, transformation, dispersion, and deposition are not known. According to available emission inventories, Singapore's contribution to the total atmospheric pollution and carbon budget at the regional and global scales is small. Emissions per unit gross domestic product (GDP) are low compared with other countries, although Singapore's per-capita GDP and per-capita emissions are among the highest in the world. Some information is available on health effects, but the impacts on the ecosystem and the complex interactions of air pollution and climate change at a regional level are also unknown. This article reviews existing available information on atmospheric pollution and greenhouse gas emissions and proposes a multipollutant approach to greenhouse gas mitigation and local air quality. Singapore, by reducing its per-capita emissions, increasing the availability of information (e.g., through regularly publishing hourly and/or daily $PM_{2.5}$ concentrations) and developing a research agenda in this area, would likely be seen to be a model of a high-density, livable, and sustainable city in Southeast Asia and other tropical regions worldwide.

Implications: Singapore is widely recognized for its environmental achievements and often cited as a model of a high-density, livable, and sustainable city. This article reviews available information with the aim to provide a reference for future scientific research of strategic relevance for Singapore's air quality and greenhouse gas mitigation management under a multipollutant framework. However, the limited publicly accessible data and little scientific information prevent a comprehensive assessment of the local air quality and greenhouse gas emissions. Singapore's dynamic economy and strong profile in advanced science and technological innovation have the potential to enhance the research agenda in this area, which is not yet well developed in tropical cities.

Introduction

Singapore has a well-deserved international reputation as a clean and green city due to many important environmental accomplishments, particularly in water resources and urban landscape management. According to the National Environmental Agency (NEA) of Singapore, the local air quality compares well with that of major cities in developed countries and Singapore has reduced its carbon intensity (Carbon dioxide [co_2] emissions per unit of gross domestic product [GDP]) (Ministry of the Environment and Water Resources, 2009). Local air quality is affected by the usual urban pollution sources (vehicular traffic and industrial activity), cargo ships crossing the nearby Singapore Strait, natural emissions from the abundant vegetation and ocean, and episodic transboundary pollution originating from wildfires and land-clearing activities in neighboring countries. The tropical climate together with complex local meteorological conditions further results in unique chemical transformation characteristics that affect the formation of secondary pollutants from primary emissions and deserves further scrutiny.

Reviews of the status of air quality in Asian cities cite Singapore's air quality management as a useful example of good practice (Clean Air Initiative for Asian Cities Center, 2006; Haq et al., 2002). Comparative reports of air quality levels and trends indicate that Singapore's ambient air pollution is considerably lower than in other cities of Southeast Asia (Clean Air Initiative for Asian Cities Center, 2010). These studies are based on annual average concentrations of the six criteria pollutants (particles with an aerodynamic diameter ≤ 10 μm [PM_{10}], sulfur dioxide [SO_2], ozone [O_3], carbon

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monoxide [CO], nitrogen dioxide [NO_2], and lead [Pb]) and a pollutant standard index (PSI; similar to the index developed by the U.S. Environmental Protection Agency [EPA]), which is published on a daily basis by NEA. Ambient concentrations of the criteria pollutants satisfy air quality standards set locally and by both the EPA and World Health Organization (WHO), respectively. $PM_{2.5}$ (particles with an aerodynamic diameter $\leq$2.5 μm) is monitored but is not currently regarded as a criteria pollutant in Singapore. Only annual average concentrations are published in the yearly NEA report and they exceed the EPA standards and WHO guidelines. Other pollutants that are known to have significant health effects, such as ultrafine particles (particles with an aerodynamic diameter $\leq$100 nm), black carbon, benzene, mercury, etc., are not included in the monitoring program, hence their concentrations are unknown.

The 24-hr PSI is an efficient tool to advise the public about the general effects associated with atmospheric pollution if the appropriate pollutants (e.g., $PM_{2.5}$) are included. However, this metric does not provide information about the diurnal variability and spatial distribution of air pollution across a city, exposure to short-term events of high emissions (e.g., during traffic jams and from seasonal wildfires), or during periods of intense formation of secondary pollutants (i.e., midday and early afternoon). The lack of publicly available data on ambient concentrations of pollutants at sufficient temporal (hourly or daily) and spatial resolution prevents a thorough and comprehensive assessment of local air quality. Further, ambient monitoring in conjunction with emission inventories and mathematical models is needed to evaluate air quality changes, control measures, future scenarios, and greenhouse gas mitigation strategies. An emissions inventory is necessary to provide current, accurate, and comprehensive accounting of all pollutant emissions and correlated emission sources, including their temporal and spatial distributions. Air quality models are necessary to quantify the links between emissions of primary pollutants, meteorology, atmospheric chemistry, urban morphology, and ambient pollutant concentrations. In many countries, there is a beneficial overlap between research and regulatory activities.

Singapore's stringent environmental regulations and emission controls based on the ambient monitoring of six criteria pollutants have been effective in keeping concentrations below EPA standards and WHO guidelines with the exception of $PM_{2.5}$. Singapore's generally flat but rough topography and tropical wet and convective weather (except during transboundary haze events) also help in the efficient dispersion and deposition of air pollutants. However, the lack of a threshold below which pollutant concentrations have no health impact, reported illnesses in Singapore that may be aggravated by air pollution (Pearce et al., 2007; Seow et al., 2004), Singapore's high per-capita emissions of pollutants (Bradshaw et al., 2010; Hertwich and Peters, 2009), and the complex interactions of those pollutants suggest that an holistic approach is needed to evaluate the full impact of emissions at local and regional levels. The purpose of this review article is to demonstrate the need for a science-based management system following a multipollutant approach to improve local air quality and greenhouse gas mitigation as described by Hidy and Pennell (2010). Air pollution consists of a mixture of different species, and the adverse effects of this mixture may be greater than the sum of its parts. Few sources emit a single pollutant, and the secondary pollutants formed in the atmosphere, such as O_3 and a portion of fine aerosols, do not necessarily change in response to reductions in the primary sources from which they form (e.g., Blanchard et al., 2008; Fujita et al., 2003). A multipollutant approach will improve the effectiveness of air quality and greenhouse mitigation programs by prioritizing actions that reduce human and ecological risks on the basis of exposure to a mixture of pollutants rather than of single pollutants (Hidy and Pennell, 2010; Hidy et al., 2011). Such an approach needs to be supported by ambient monitoring, emissions characterization, and air quality modeling as mentioned above, as well as an understanding of chemical and physical processes (particularly those that are local in nature) driving air pollution, and the human and ecological responses to air pollution exposure.

The present article first reviews the existing public and scientific information on emissions of pollutants and greenhouse gases to the atmosphere, current ambient air quality monitoring efforts, and known air pollution health impacts in Singapore. Depending on the available information, the discussion is extended beyond the criteria pollutants to other air toxics. In terms of greenhouse gases, the discussion focuses on CO_2 emissions, since combustion is locally the main source of greenhouse gases. Singapore's $PM_{2.5}$ annual average concentrations and emissions per-capita and GDP are compared with those from other Asian countries and selected cities around the world to provide a reference of the air quality and emissions status. Finally, the article presents a list of scientific topics and research needs identified by a group of local and international experts in different areas of atmospheric sciences during a workshop organized by the National University of Singapore (NUS) about air quality in tropical urban environments.

Geographic Setting and Local Meteorology

Singapore is an island-state located at the southern tip of the Malay Peninsula with an area of 710 km^2. Since gaining independence from Malaysia in 1965, Singapore has undergone rapid urbanization. The population has increased from 1.8 million in 1965 to 5.08 million in 2010 and about 1 million tourists visit Singapore per month (Singapore Department of Statistics, 2010). Land-use change has been rapid, with a doubling of the built-up area between 1965 and 2000 and a corresponding decrease in forest and farm areas. Some of the general industrial areas (e.g., electronics, manufacturing, etc.) are located within residential estates, but most of the heavy industries (e.g., oil refining, petrochemical, steelworks, etc.) are concentrated in a large industrial estate in the western part of the island that includes several reclaimed offshore islands (Figure 1). Ten percent of Singapore's land is committed as green space, of which about half is gazetted nature reserves. Including the extensive tree cover (roadside greenery, park connector network), almost half of Singapore is covered by vegetation (Ministry of the Environment and Water Resources, 2009). The commercial and business center is located in the south of Singapore and primarily consists of a large commercial area with shopping malls, hotels, and entertainment complexes. These areas

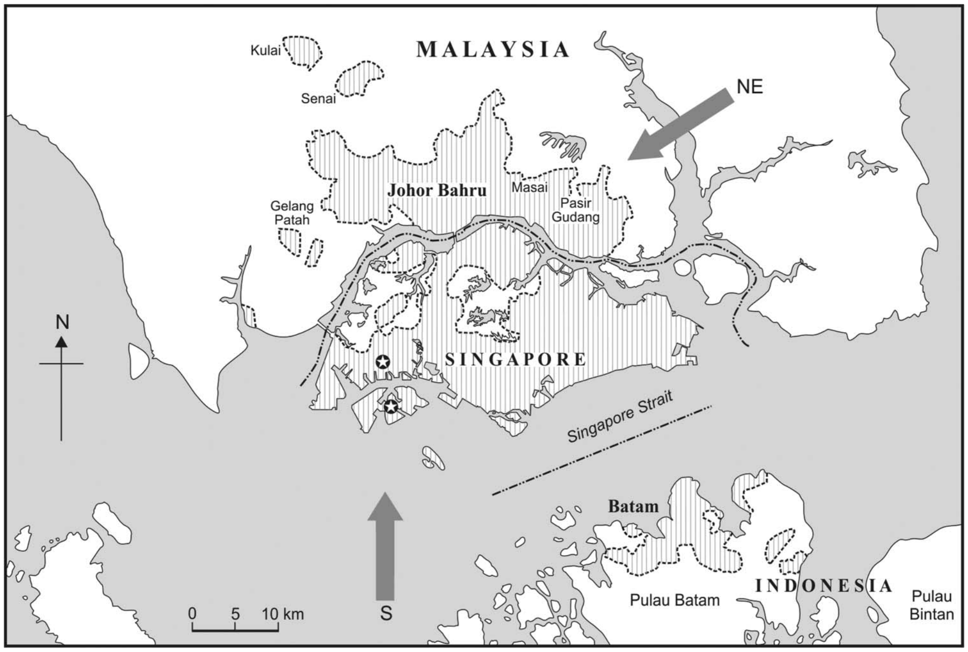

Figure 1. Map of Sijori Growth Triangle formed by the urban areas (indicated by line shading) of Johor Bahru, Malaysia (population ~1.8 million), Singapore (~5 million), and Batam, Indonesia (~1 million). Stars are locations of heavy industries in Singapore (Jurong Industrial Estate and Jurong Island). Solid thick arrows are main wind directions experienced during the SW and NE monsoons seasons, respectively.

generally have a high density of workers, visitors, and vehicular traffic that continues past midnight. The central business district, which houses the financial center and includes numerous tall skyscrapers, is located in the center of the southern part.

Because of its geographical location near the equator (~1.2°N) and coastal setting, Singapore's climate is characterized by perennial high temperatures, relative humidity, and rainfall, and low average wind speeds typical of a tropical climate. Temperatures range from ~25°C in the early morning to ~35°C in the afternoon, with an annual average of ~27.5 °C. Relative humidity is ~90% in the morning and remains above 60% during the rest of the day. The local wind climate is dominated by the reversal of wind direction between the two monsoon seasons (northeast [NE] and southwest [SW]) and modified by land/sea breezes and a possible urban heat island circulation. The NE monsoon occurs between November and January and is characterized by widespread heavy rainfall with monthly means ranging from 170 to 330 mm. The SW monsoon typically falls between May and September and is characterized by relatively drier conditions with average monthly rainfall between 130 and 160 mm. Given the high temperatures, humidity, and strong solar radiation, strong convection characterizes the daytime mixing dynamics of the atmosphere. The urban heat island (UHI), a regional-scale phenomena describing the urban-rural temperature difference, is well established and shows a seasonal variation with higher (lower) mean monthly nocturnal temperature differences, measured between the commercial district and a mostly undeveloped rural area in the northwest (NW) of Singapore, during the drier SW (wet NE) monsoon season of ~5.5 (3.5) °C (Chow and Roth, 2006). The presence of an UHI in combination with the rough city surface maintains predominantly unstable atmospheric stratification even at night.

Emissions to the Atmosphere

Emission of pollutant gases and aerosols

Singapore has a strong and dynamic industrial sector including chemical, electronic and metallurgic industries, the major petroleum refining center of Asia (world's third largest), power plants that supply the increasing consumption of electricity (produced primarily by burning natural gas and to a lesser extent oil), waste incinerators, one of the busiest ports in the world, and one of the largest airports in the region. All are important sources of pollutant gases and aerosols that combine with emissions from motor vehicles and private apartments (almost one million units of each) (Singapore Department of Statistics, 2010). Although Singapore accounts for only 0.39% of total Asian emissions (Ohara et al., 2007; compiling the emissions of six pollutants from 25 Asian countries for 2000), its relative affluence places it among the top two per-capita contributors of anthropogenic emissions to the atmosphere in Asia for each pollutant, with the exception of nonmethane hydrocarbon (NMHC) (Figure 2). The high per-capita SO_2 emissions in Singapore are due to oil-powered industrial plants (Arndt et al., 1997; Ministry of the Environment and Water Resources, 2008a). Orlic et al. (1999), based on a source apportionment study, also identified oil refineries as an additional source of SO_2.

Compared to its GDP, Singapore's emission rates are in general slightly higher than those of countries with similar economies such as Japan, Taiwan, and South Korea, but lower than other Asian countries (Figure 3). The only exception is Singapore's SO_2 emission rate, which is comparable to that of several developing economies. In terms of economic metrics, Singapore emits less pollution than the majority of Asian

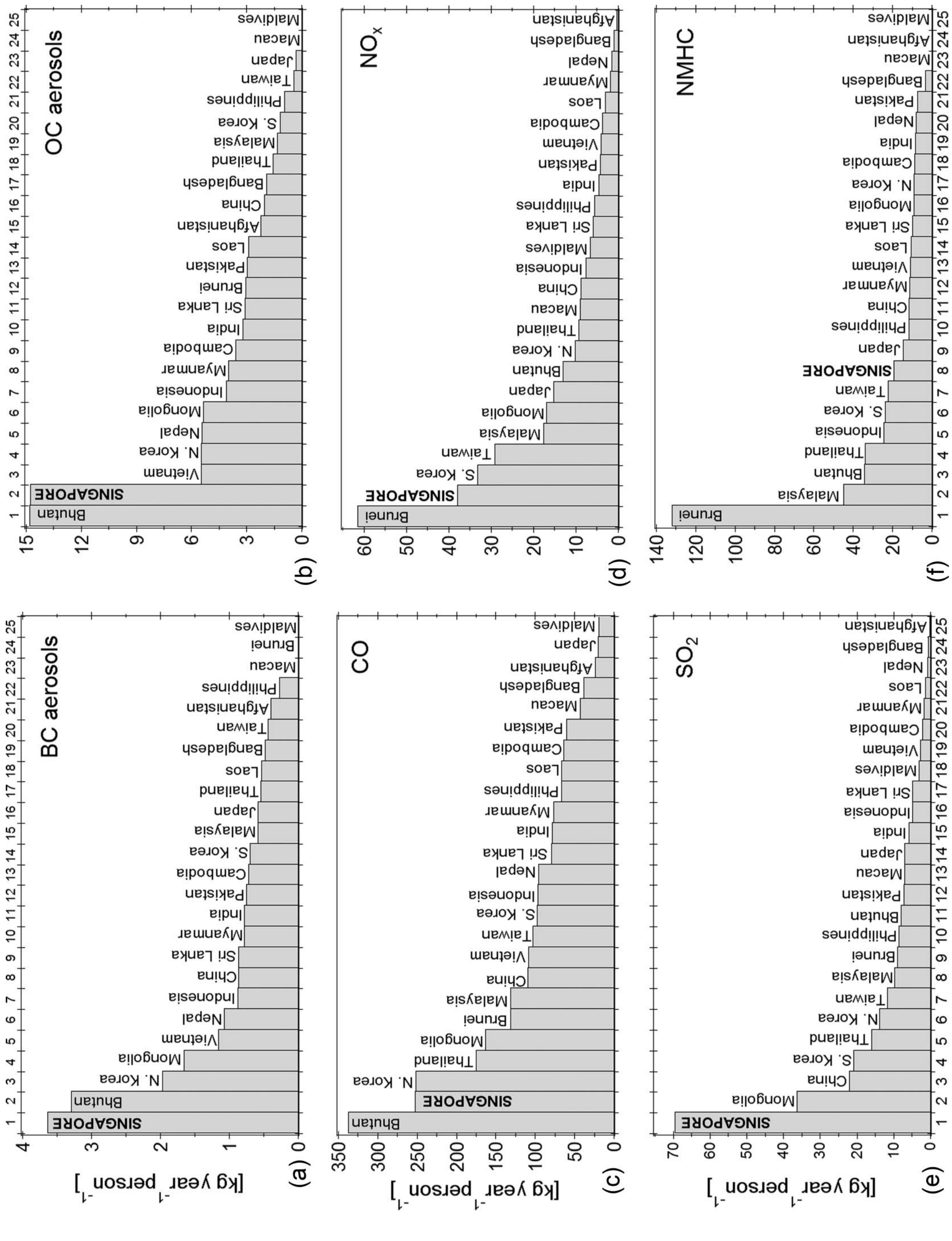

Figure 2. Per-capita anthropogenic emissions of (a) black carbon aerosols, (b) organic carbon aerosols, (c) CO, (d) NO_x, (e) SO_2, and (f) NMHC from 25 Asian countries. The national emissions were taken from Ohara et al. (2007) and divided by the corresponding country populations using 2000 as reference year. National emissions do not include contributions from aviation and shipping.

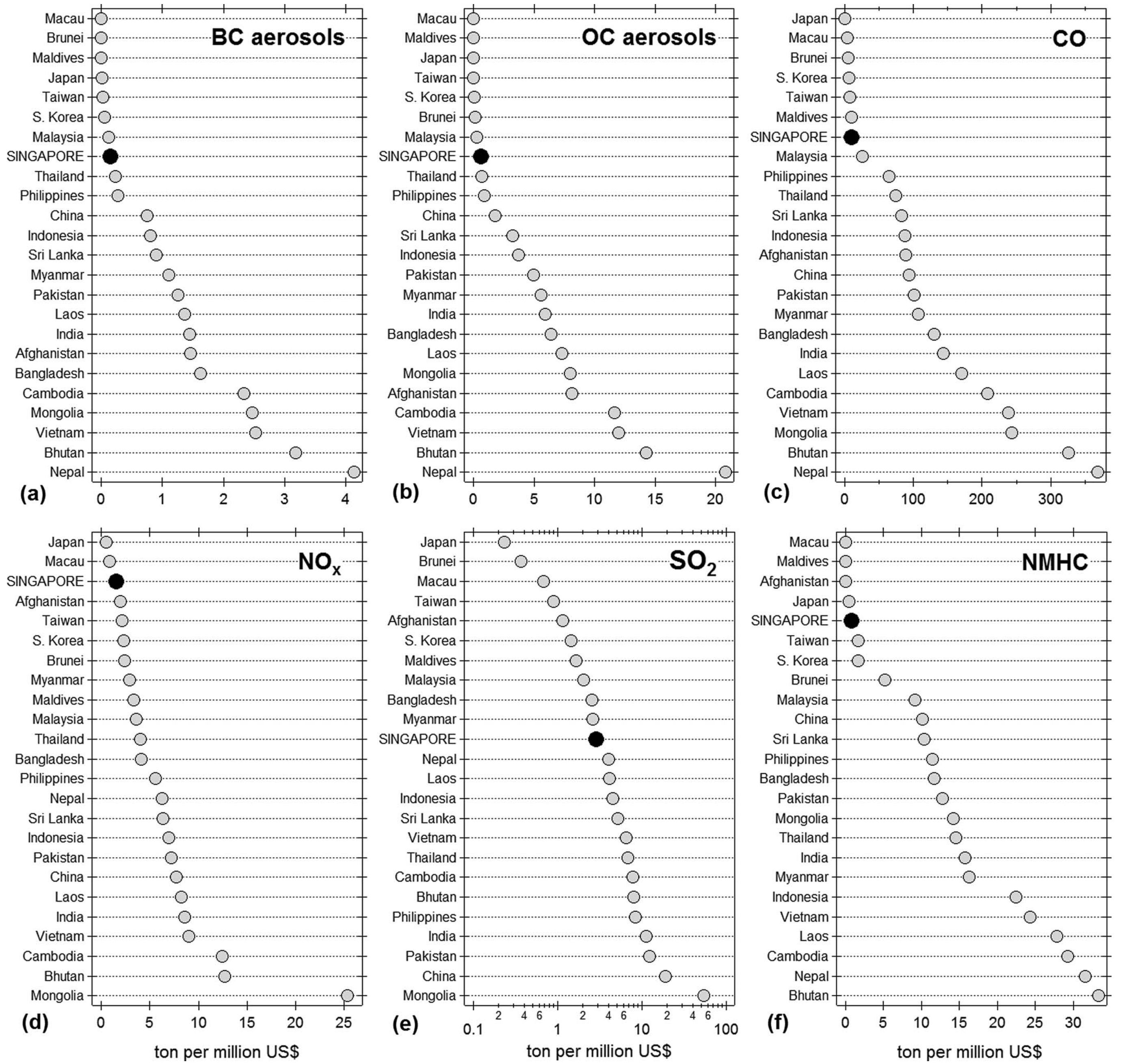

Figure 3. Anthropogenic emissions normalized by GDP for the six pollutants and 25 countries presented in Figure 2. National emissions were taken from Ohara et al. (2007) and divided by the corresponding country GDP using 2000 as reference year. The GDP data (in 2005 US$) were obtained from the International Macroenomic Dataset compiled by USDA-ERS (United States Department of Agriculture–Economic Research Service, 2010). National emissions do not include contributions from aviation and shipping. No GDP information is available for North Korea. Note the logarithmic scale for the SO_2 emissions in panel (e). Black markers correspond to Singapore's emissions.

countries, but if those countries could reach Singapore's economic activity and wealth, their emissions would presumably also increase significantly. Applying Singapore's per-capita emission rates listed in Figure 2 to the population of the Asian countries, the total emissions from Asia would increase by a factor of 5.7 for SO_2, 5.1 for nitrogen oxides (NO_x), 4.5 for black carbon (BC), 5.6 for organic carbon (OC) aerosols, 2.8 for CO, and 1.6 for NMHC.

Singapore's per-capita emissions are generally high when compared with cities rather than countries (Figure 4). Although this list is short and data were obtained from local emission inventories with the understanding that different methodologies were used, sources considered may differ (e.g., Mexico City's inventory includes contributions from aviation, whereas Singapore's inventory does not) and different baseline years were used in some cases, the summary provides a first comparison of Singapore's emissions with selected large cities around the world.

A comprehensive assessment of the local air quality must account for anthropogenic emissions from neighboring cities, cargo ships crossing Singapore Strait, transboundary pollutants from seasonal wildfires in nearby Sumatra and Kalimantan, and natural emissions from the ocean, rainforests, and oil palm plantations in the region. For example, the city of Johor Bahru (population of ∼1.8 million) borders Singapore to the north in Malaysia, whereas Batam (∼1 million) is located 20 km off the Singapore south coast in Indonesia. These two cities concentrate a large number of labor-intensive industries. Similar to Singapore, both are characterized by growing population making the Sijori Growth Triangle, as this region is known, almost a megacity given its total population of close to 8 million people (Figure 1).

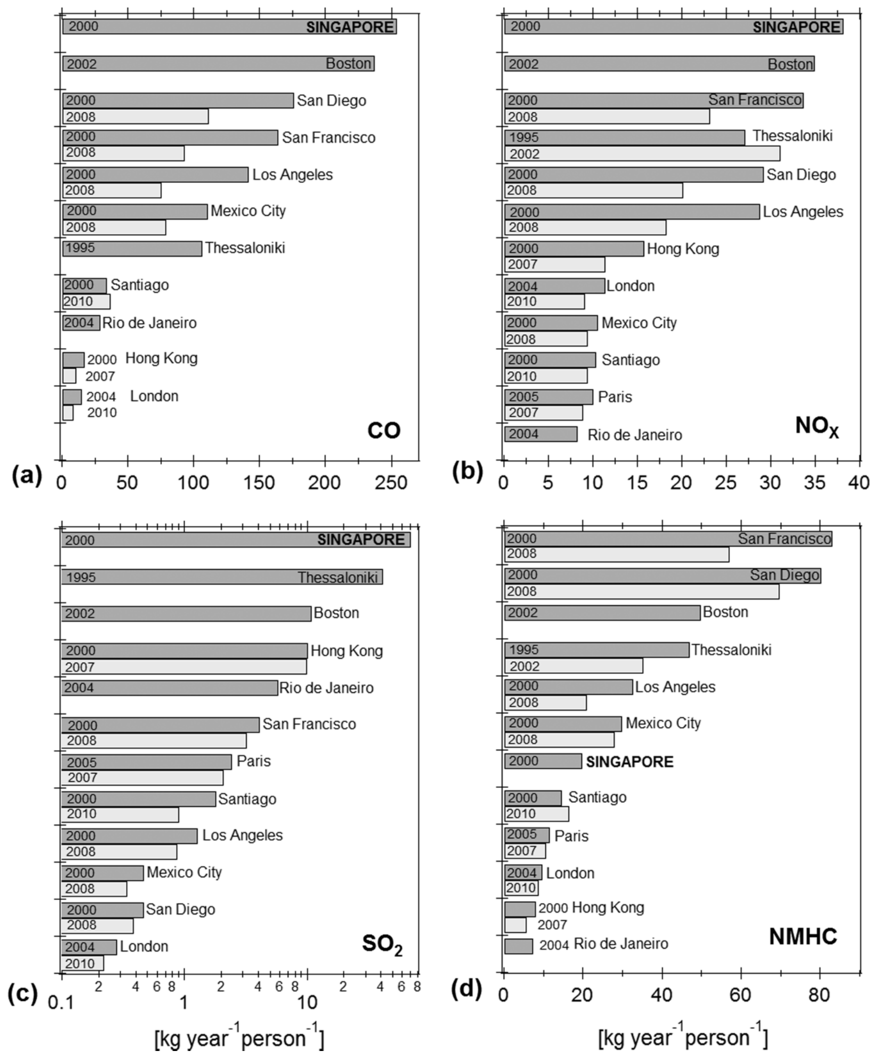

Figure 4. Per-capita emissions of (a) CO, (b) NO_x, (c) SO_2, and (d) NMHC from selected cities worldwide. Data were obtained from local emission inventories and normalized by the corresponding populations of the respective cities as reported in their own emission inventories: Mexico City (Secretaria del Medio Ambiente del Gobierno del Distrito Federal, 2010a); Hong Kong (Environmental Protection Department, 2009); Los Angeles (South Air Basin), San Francisco, and San Diego (Air Resources Board California Environmental Protection Agency, 2009); Boston (Massachusetts Department of Environmental Protection, 2007); Paris (Ile de France) (AIR PARIF, 2010); Rio de Janeiro (Fundação Estadual de Engenharia do Meio Ambiente, 2004); Thessaloniki (Tsilingiridis et al., 2002; Moussiopoulos et al., 2009); London (Greater London) (Mattai and Hutchinson, 2008); and Santiago (DICTUC, 2007; Universidad de Chile–Instituto de Asuntos Públicos, 2002). Singapore's emissions were obtained from Ohara et al. (2007). Note that Singapore's population is the same for the country and for the city.

A noteworthy example of the effect of regional events on local air quality is the episodic occurrence of "smoke-haze" (a term used in Southeast Asia for large-scale air pollution events associated with wildfires) due to biomass burning on the Indonesian islands Sumatra and Kalimantan, and the Indonesian portion of the island of Borneo. In particular during the dry season (May–October), sporadic plumes of smoke from these wildfires can reach Singapore and increase the levels of PM_{10} and $PM_{2.5}$. In autumn 1997, for example, an unusually strong El Niño–Southern Oscillation event produced the typical dry meteorological conditions conducive to fire activity and the subsequent buildup of airborne particles in the region. An area of approximately 45,600 km^2 in Indonesia burned from August to December, producing a smoke-haze event unprecedented in extent and intensity (Heil and Goldammer, 2001; Koe et al., 2001). During this period, the average concentration of $PM_{2.5}$ in Singapore was 86 $\mu g\ m^{-3}$, exceeding the observed concentration in previous months by 3.5 times (Orlic et al., 1999). Two recent smoke-haze events occurred in 2006 and 2010, elevating the PSI during several days to the moderate or unhealthy air quality category. In October 2006, 12 days reported 24-hr PM_{10} concentrations over 100 $\mu g\ m^{-3}$, and 3 days exceeded the EPA air quality standard of 150 $\mu g\ m^{-3}$, with a maximum of 210 $\mu g\ m^{-3}$. In October 2010, 4 consecutive days exceeded 24-hr average concentrations of 100 $\mu g\ m^{-3}$, with a maximum of 146 $\mu g\ m^{-3}$ (National Environmental Agency, 2011).

Biomass burning emits particles and gases such as volatile organic compounds (VOCs) and oxides of sulfur and nitrogen. These gases react and produce plumes of secondary pollutants such as peroxide radicals, oxygenated VOCs, and secondary organic aerosols (SOAs) that are transported across the region with the prevailing winds. In addition, recent studies have found that the intense biogenic VOC emissions from Southeast Asia's tropical rainforests in the presence of anthropogenic emissions of NO_x and other pollutants might produce significant perturbations in the atmosphere at the regional scale in terms of atmospheric pollution, cloud formation, and rainfall, with a possibility to affect global climate dynamics (Hewitt et al., 2010; Integrated Land Ecosystem–Atmosphere Process Study, 2005). Furthermore, it has been found that the vast oil palm plantations in the region might emit large amounts of highly reactive oxygenated VOCs to the atmosphere that have not been accounted for previously (Misztal et al., 2010); nothing is known about their interaction with anthropogenic urban emissions.

Emission of greenhouse gases

Singapore's Second National Communication under the United Nations framework Convention on Climate Change reports total greenhouse gas emissions of 38,790 kt yr^{-1} of carbon dioxide equivalents (CO_2e, i.e., including emissions of CO_2, nitrous oxide [N_2O], methane [CH_4], perflurocarbons [PFCs], hydrofluorocarbons [HFCs], and sulfur hexafluoride [SF_6]) for 2000, in which CO_2 accounts for 97.3% (37,756 kt yr^{-1}) (National Environmental Agency, 2010). This is an increase of 45% in 6 yr as reported in the initial communication (Ministry of the Environment and Water Resources, 2000). According to Singapore's National Climate Change Strategy, CO_2 emissions increased to 40,337 kt yr^{-1} in 2005, contrary to the carbon intensity in terms of GDP, which decreased 30% compared to 1990 levels due to a rapid switch to natural gas for power generation (Ministry of Environment and Water Resources, 2008b). These figures do not include contributions from international bunkers and are ~20% lower than those reported in the Millennium Development Goals Indicators (United Nations, 2011a). The same report indicates that Singapore reduced its CO_2 emissions by 31% between 1990 and 2008, and 53% since 1997 when Singapore's emissions peaked. This decrease is consistent in terms of per-capita emissions since 1997, and compares favorably to the null changes or slight increases observed in the majority of countries, as shown in Figure 5. In this period Singapore's per-capita emission decreased 64%, although the actual rate of 6.8 ton $person^{-1}\ yr^{-1}$ is still above the Asian average of 3.3 ton $person^{-1}\ yr^{-1}$, as shown in Figure 6. Including CO_2 emissions from international bunkers, Singapore has the third largest emission rate, with 33.4 ton $person^{-1}\ yr^{-1}$ in 2007,

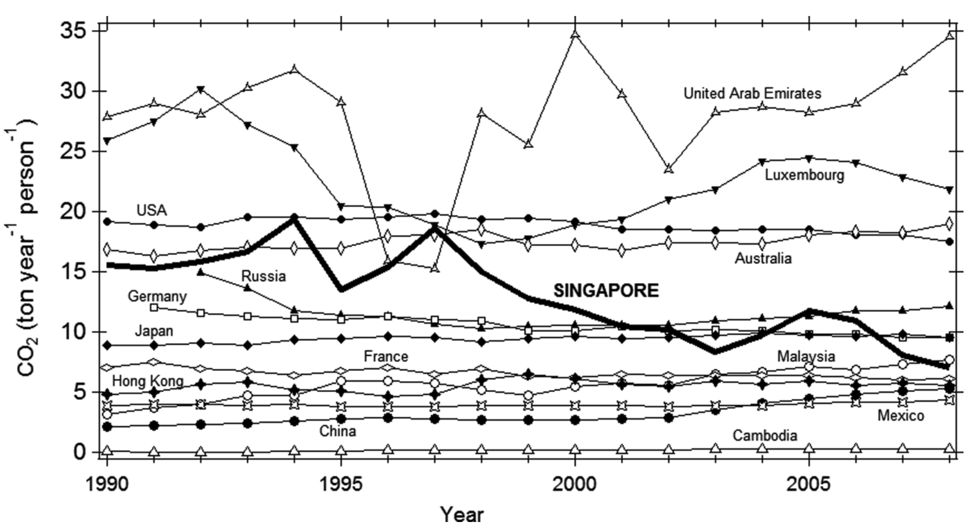

Figure 5. Annual trends of per-capita emissions of CO_2 for Singapore and selected countries around the world. Data were obtained from the United Nation's Millennium Development Goals Indicators updated on July 2011 (United Nations, 2011a).

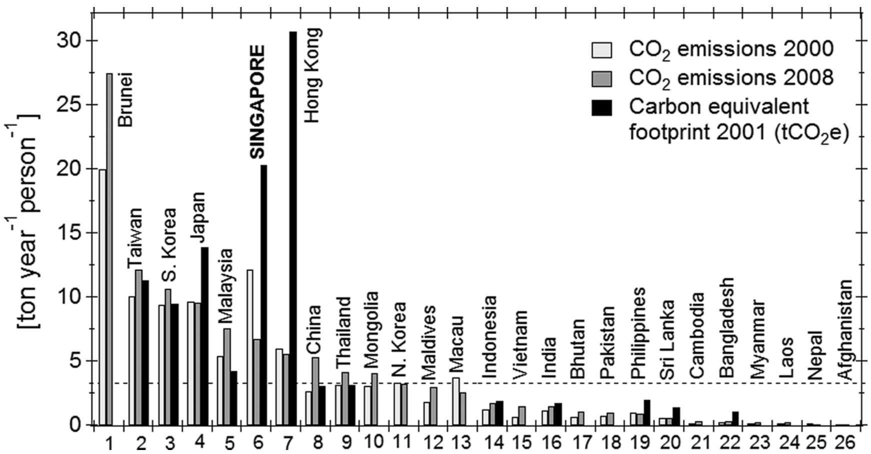

Figure 6. Per-capita anthropogenic emissions of CO_2 and carbon equivalent footprints from 26 Asian countries. National CO_2 emissions correspond to the emissions reported in the United Nation's Millennium Development Goals Indicators updated on July 2011 (United Nations, 2011a). Per-capita carbon equivalent footprints include contributions from CO_2, CH_4, N_2O and HFCs, PFCs, and SF_6, and were adapted from Hertwich and Peters (2009). Population data from the United Nations (United Nations, 2011b) were used to calculate the per-capita CO_2 emissions and carbon equivalent footprints. Only contributions from fossil fuels and process emissions are considered. Emissions related to land-use change are excluded. CO_2 emissions do not include international bunker fuel storage. The dashed line indicates the average CO_2 per-capita emission of 3.3 ton person^{-1} yr^{-1} in Asia.

surpassed only by Qatar and United Arab Emirates (World Resources Institute, 2011). Comparing these emission rates with those reported by Kennedy et al. (2011) for a number of selected cities worldwide, Singapore ranks at the top, followed closely by Rotterdam, another city with a major port (Figure 7).

The emission data in Figures 5 and 6 were extracted from emission inventories based on spatially limited geographic boundaries that only include emission sources within the country or city of interest. Hertwich and Peters (2009) calculated the total greenhouse gas emissions associated with the production of all goods consumed by 73 countries using a "consumer" approach. Here the emissions occurring outside the geographic boundaries of the region of interest, but which are still directly caused by activities occurring within the actual country, are also included (i.e., imports and international transport). According to this measure, Singapore's carbon footprint is lower than those of Luxembourg, Hong Kong, United States, Australia, and Canada (not shown) and higher than other countries considered in the analysis. Within Asia, Singapore's carbon footprint of 19.3 ton CO_2e person^{-1} yr^{-1} (considering a population of 4.1 million as in 2001) is only surpassed by that of Hong Kong and is much larger than the corresponding values for neighboring Malaysia and Indonesia of 4.2 and 1.9 ton CO_2e person^{-1} yr^{-1}, respectively (Figure 6). The numbers for Singapore include emissions related to purchases by tourists that are mistakenly accounted as domestic consumption, which may have an impact on the statistics, particularly for city-states (E. G. Hertwich, personal communication).

Ambient Monitoring

Singapore has 14 stations that measure air quality across the city. This monitoring network measures hourly ambient concentrations of the Singaporean criteria pollutants and $PM_{2.5}$. The observations are used to calculate the PSI, which is published on a daily basis. As mentioned before, $PM_{2.5}$ levels are also monitored daily, but only the annual and 24-hr (based on a 3-yr average of yearly 98th percentile 24-hr values) average $PM_{2.5}$

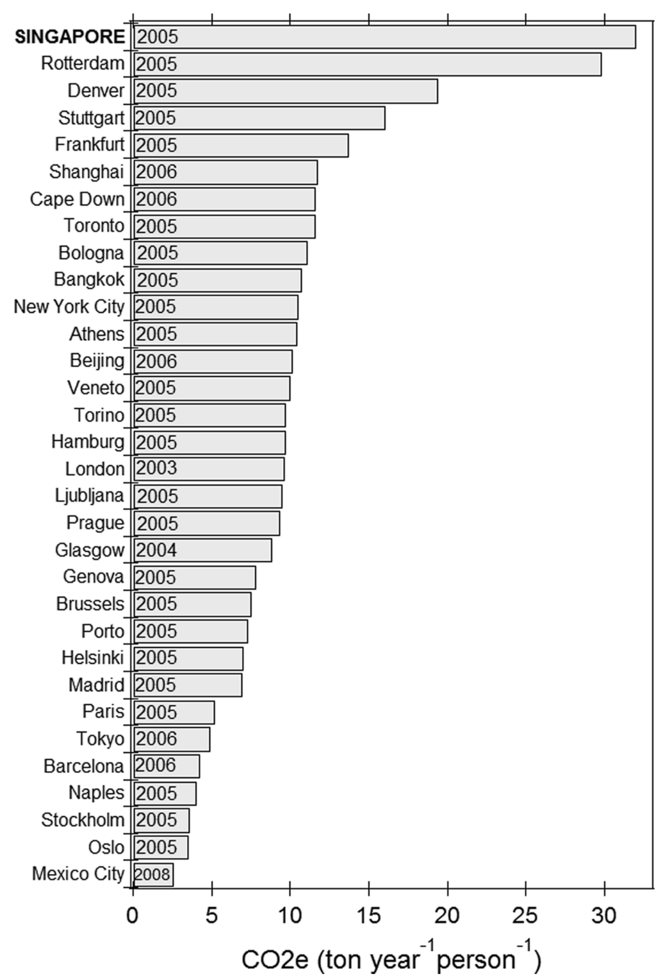

Figure 7. Per-capita greenhouse gas emissions for selected cities around the word. Numbers inside bars correspond to baseline years. The emissions were adapted from Kennedy et al. (2011) with the exception of Singapore and Mexico City, whose emissions were taken from elsewhere (World Resources Institute, 2011; Secretaria del Medio Ambiente del Gobierno del Distrito Federal, 2010b). Emissions include contributions from transportation, energy use, industrial processes, waste, aviation, and international bunkers.

concentrations are available in the yearly NEA report. Figures 8 and 9 and Table 1 show the annual trends and 2007 mean concentrations of $PM_{2.5}$ reported by the NEA as part of its annual Key Environmental Statistics Report (Ministry of the Environment and Water Resources, 2011), together with data from selected other cities and WHO and EPA thresholds. During the last 9 yr, the annual average $PM_{2.5}$ concentrations have exceeded the thresholds set by both the EPA and WHO by up to 53% and 130%, respectively. The 24-hr average $PM_{2.5}$ concentrations have exceeded the EPA standard in 6 of the last 7 yr and the WHO guidelines every year by up to of 29% and 80%, respectively, in years not affected by transboundary smoke-haze. Similar to other large and industrialized cities, fine aerosols seem to be the major air pollution problem in Singapore. The $PM_{2.5}$ annual average concentration in Singapore is lower than that observed in large cities of Latin America and Asia (e.g., Santiago and Hong Kong), similar to some European cities (e.g., Rotterdam, Berlin, and Prague), similar or higher than U.S. cities, and higher than cities located in Canada and Australia. Oanh et al. (2006) reported daily average $PM_{2.5}$ concentrations for six Asian cities (Bangkok, Beijing, Chennai, Bandung, Manila, and Hanoi) ranging from18 to 104 $\mu g\ m^{-3}$ and 44 to 168 $\mu g\ m^{-3}$ during the wet and dry seasons, respectively. Table 1 shows that the 24-hr average $PM_{2.5}$ concentrations in Singapore are within the range of those observed in Asian cities during the wet season, and generally lower during the dry season, with the exception of periods affected by transboundary smoke-haze from wildfires in neighboring countries, such as in 2006, for example.

A number of papers have investigated the chemical composition of airborne particles in Singapore during the last decade. Concentrations of trace metals, ions, elemental carbon, organic carbon, polycyclic aromatic hydrocarbons (PAHs), and water-soluble organic compounds in $PM_{2.5}$ have been determined at ambient conditions (Balasubramanian and Qian, 2004; Balasubramanian et al., 2003; See et al., 2006a) and in selected microenvironments such as bus interchanges, hawker centers, and residential buildings (Kalaiarasan et al., 2009; See and Balasubramanian, 2008; See et al., 2006b) using gravimetric and analytical methods. More recently, the gas/particle partitioning of semivolatile organic compounds including PAHs, polychlorinated biphenyls (PCBs), mono- and dicarboxylic acids, methoxylated phenols, and other polar organic compounds has also been investigated (He and Balasubramanian, 2009; He et al., 2010). These studies have reported daily mean $PM_{2.5}$ concentrations larger than 50 $\mu g\ m^{-3}$ during transboundary smoke-haze episodes and between 20 and 40 $\mu g\ m^{-3}$ during normal days. The major components making up the aerosols are water-insoluble carbonaceous materials (21%), sulfate (19%), elemental carbon (11%), water-soluble carbonaceous material (10%), ammonia (9%), and trace metals (9%). During smoke-haze events, the aerosol mass increment is due mainly to contributions of OC, BC, and sulfates (Balasubramanian et al., 2003). Emission sources that contribute to the fine aerosol loading include vehicular traffic, power plants, oil refineries, petrochemical industries, construction activities, marine aerosols, and biomass burning from wildfires in Indonesia. The contribution of SOAs to the total local aerosol loading could be also important. Recent studies show that SOAs account for a large fraction (up to ~60%) of the aerosol burden in urban atmospheres (Jimenez et al., 2009).

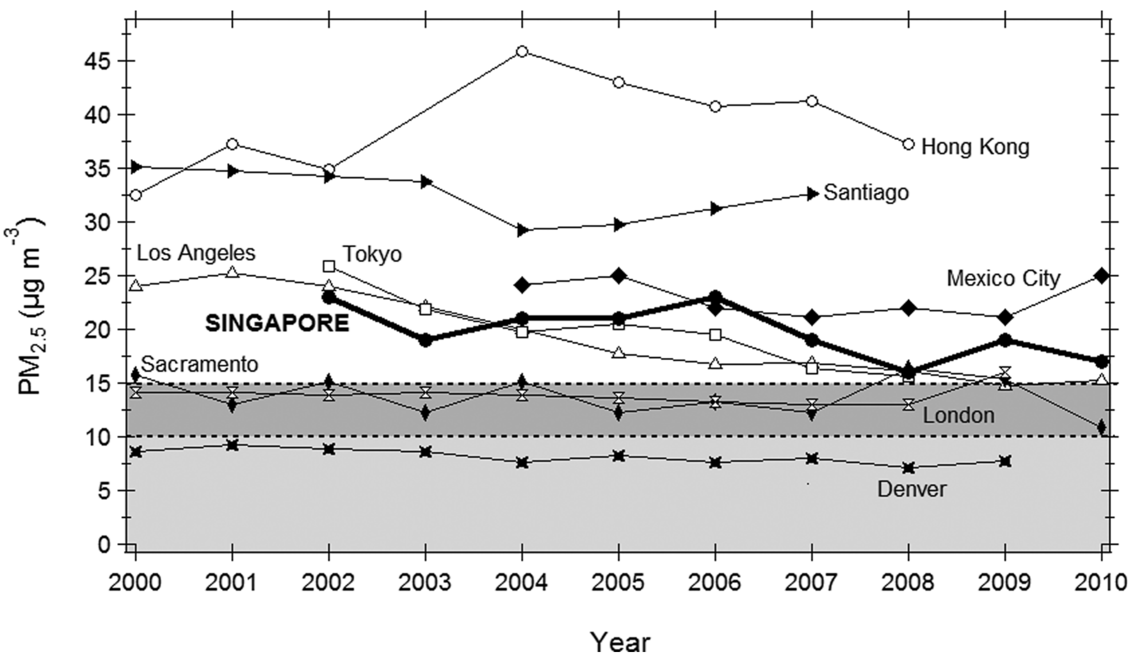

Figure 8. Annual average concentrations of $PM_{2.5}$ between 2000 and 2010 for selected cities. Light and dark shaded areas indicate $PM_{2.5}$ levels below the WHO guidelines and EPA standards, respectively. Data were obtained from historical databases of air quality monitoring networks and local air quality reports: Singapore (Ministry of the Environment and Water Resources, 2011), London (Griffin et al., 2010), Hong Kong (Environmental Protection Department, 2009), Mexico City (Secretaria del Medio Ambiente del Gobierno del Distrito Federal, 2011), Santiago (Sistema Nacional de Información Ambiental, 2010), Tokyo (Tokyo Metropolitan Government, 2010), Californian cities (Air Resources Board California Environmental Protection Agency, 2011), and other U.S. cities (EPA, 2011).

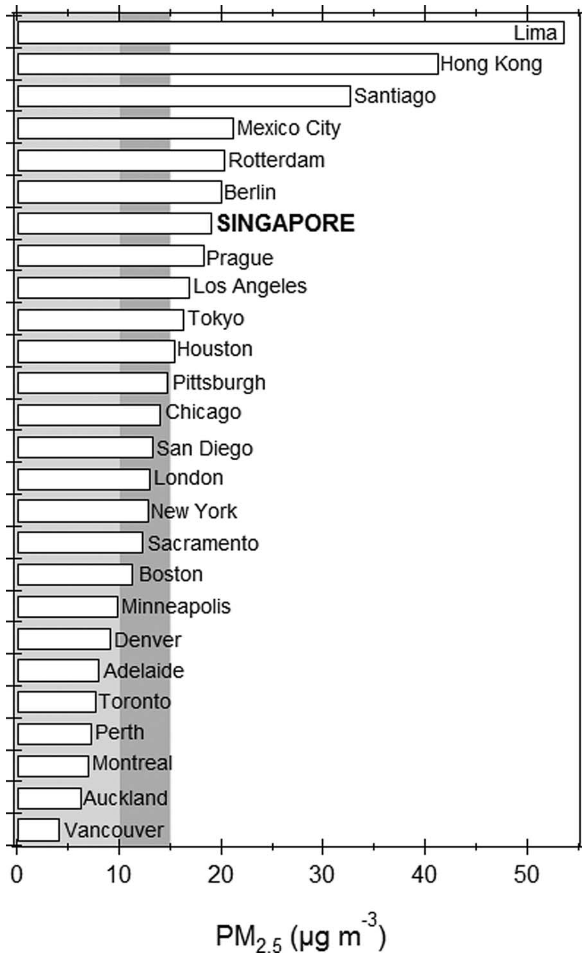

Figure 9. Annual average concentrations of $PM_{2.5}$ in 2007 for selected cities. Vertical light and dark shaded areas indicate $PM_{2.5}$ levels below the WHO guidelines and EPA standards, respectively. Data cities included in Figure 8 were obtained from the same references, for Lima and remaining cities from additional references (Dirección General de Salud Ambiental, 2010; Ontario Ministry of the Environment, 2008).

Air Quality Modeling

Air quality models for simulating pollutants formation, transformation, and dispersion are widely available for predicting air pollution concentrations, particularly those of secondary pollutants. These models are increasingly used to develop air quality policies, because they can evaluate control measures under present and future emission and climatic scenarios. A literature and Internet search on air quality modeling in Singapore produced a nil result. Nevertheless, we are aware that the Association of Southeast Asian Nations (ASEAN) Specialized Meteorological Centre (ASMC) hosted by NEA runs the open software Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model of National Oceanic and Atmospheric Administration's (NOAA's) Air Resources Laboratory on a daily basis to forecast the occurrence of transboundary smoke-haze from wildfires in the region. The HYSPLIT model simulates the smoke-haze dispersion from fire hotspots in Southeast Asia that are detected by NOAA's satellites (ASEAN Specialized Meteorological Centre, 2010).

Impacts on Public Health

A number of studies have investigated the complex relationship between human health and pollution exposure in Singapore, finding the same spectrum of adverse health outcomes associated with air pollution as in North American and European cities (Chew et al., 1995, 1999a, 1999b; Emmanuel, 2000; Goh et al., 1986; Neo et al., 2000; Ooi et al., 1991; Tan et al., 2000). Their findings have been summarized by the Health Effects Institute (2008). In particular, Emmanuel (2000) reported that the 1997 smoke-haze episode produced a 30% increase in hospital attendance and an increase in PM_{10} levels from 50 to 150 $\mu g\ m^{-3}$ was associated with increases of 12% in upper respiratory tract illnesses, 19% in asthma, and 26% in rhinitis cases.

Limited research is available on human exposure and possible health effects due to particulate air pollution in a number of specific local microenvironments (Kalaiarasan et al., 2009; Karthikeyan et al., 2006; See and Balasubramanian, 2006, 2008; See et al., 2006b). For example, Kalaiarasan et al. (2009) found that dwellers living in multistory buildings next to expressways were exposed to 24-hr average $PM_{2.5}$ concentrations between 27 and 75 $\mu g\ m^{-3}$. The mid-floors occupants were found to experience the highest concentrations. See et al. (2006) reported average $PM_{2.5}$ concentrations up to 68 $\mu g\ m^{-3}$ at a bus interchange during the operating hours (5:30 a.m. to 0:30 a.m.). Finally, See and Balasubramanian (2006) report that people involved in cooking activities in hawker centers can be exposed to concentrations of over 300 $\mu g\ m^{-3}$. Long-term exposure to such levels of particulate matter may pose adverse health effects. For example, the estimated carcinogenic risk of workers in hawker centers is up to 2 orders of magnitude higher than what is considered to be acceptable (i.e., the value whereby there is no

Table 1. Annual and 24-hr concentrations ($\mu g\ m^{-3}$) of $PM_{2.5}$ in Singapore

Averaging time	2002	2003	2004	2005	2006	2007	2008	2009	2010	EPA Standard[a]	WHO Guidelines[b]
24-hr	—	—	45	42	80	35	30	39	40	35	25
Annual	23	19	21	21	23	19	16	19	17	15	10

Notes: 2006 levels were affected by transboundary smoke-haze from wildfires in Sumatra and Kalimantan. Data were obtained from yearly NEA Key Environmental Reports (Ministry of the Environment and Water Resources, 2011).

[a]The 24-hr standard is attained when 98% of the daily concentrations averaged over 3 consecutive years are equal to or less than the standard. The annual standard corresponds to the 3-yr average of annual arithmetic mean concentrations.

[b]The 24-hr guideline is not to be exceed during more than 3 days per year. The annual guideline corresponds to the annual arithmetic mean concentration.

appreciable risk of adverse health effects over a lifetime) (See and Balasubramanian, 2006).

Although ambient levels of the monitored criteria pollutants are below the EPA air quality standards, Singapore's air pollution might still pose a threat to human health. Advances in the understanding of air pollution and impacts on public health risk have demonstrated that there is no discernible threshold at which air pollution does not cause adverse health effects (Anderson, 2009). There is extensive scientific evidence of impacts on public health associated with short- and long-term exposure to ambient air pollution, even in areas where the air quality standards are already met (Craig et al., 2008). Recent findings also suggest that exposure to air pollution in extremely hot and humid environments tends to increase health effects risks (Qian et al., 2008). Consistent evidence shows that exposure to atmospheric pollutants, in particular fine aerosols, contributes to premature deaths caused by cardiovascular and respiratory illnesses (Craig et al., 2008; Pope and Dockery, 2006). Asthma and lung cancer are two respiratory illnesses enhanced by air pollution (Craig et al., 2008; Health Effects Institute, 2010; Koenig, 1999; Laden et al., 2006; Trasande and Thurston, 2005). According to the Health Promotion Board, about 5% of adults and 20% of children in Singapore have asthma (Health Promotion Board, Singapore, 2010). The prevalence of asthma in Singaporean children aged 13–14 yr is 24%, compared to 18% in the United States, 13% in Taiwan, 12% in Malaysia, and 11% in Hong Kong (Pearce et al., 2007). In the same context, cancer-related deaths have increased from 15% to 27% in the last 30 yr according to the National Cancer Centre of Singapore, with lung cancer being the leading cause of cancer in men and the second most common cause in women (Seow et al., 2004). Although causes other than air pollution may be primarily responsible, air quality needs to be considered in a holistic assessment of these diseases.

Opportunities for Scientific Research of Strategic Relevance to Singapore's Air Quality Management and Greenhouse Gas Mitigation Practice

The present review of Singapore's air pollution and its impacts on air quality, human health, and climate change suggests opportunities for an enhanced local air quality management and greenhouse gas mitigation strategy, through the application of science-based regulatory actions using a multipollutant framework. The clean air component of Singapore's Sustainable Development Blueprint (Ministry of the Environment and Water Resources, 2009) and other NEA reports on the state of the environment suggest that the current air quality regulatory strategy is constrained to a single-pollutant perspective. The focus is on meeting individual ambient standards, without formal consideration of coincident or cumulative benefits regarding other pollutants. For example, according to the Sustainable Development Blueprint (Ministry of the Environment and Water Resources, 2009) the objective is to reduce $PM_{2.5}$ and SO_2 annual ambient concentrations to 12 and 15 $\mu g\ m^{-3}$, respectively by 2020. A formal risk assessment, however, which evaluates the co-benefits for other pollutants of attaining these standards, is not apparent, nor is there an air quality management plan for addressing these goals. There are general strategies, such as promoting public transport, improving energy efficiency, or enhancing land use planning, but a technical analysis of their effectiveness to attain the proposed standards is also not apparent.

An ideal air quality management system would focus on achieving greatest risk reduction based on multipollutant exposure dose-response models as described by Hidy and Pennell (2010) for the recent NARSTO (formerly named the North American Research Strategy for Tropospheric Ozone) assessment of the technical needs to support multipollutant management. Management like this will seek to minimize risk of exposure for humans and ecosystems while providing for a quantitative evaluation of the effectiveness of the management process. Various possible emission reduction strategies can be evaluated on the basis of net risk reduction or maximum benefit, taking into account the synergistic effects of exposure to multiple pollutants when such effects exist. This management approach will rely on tools such as comprehensive ambient monitoring of criteria and noncriteria pollutants (including hazard air pollutants, oxidant precursors, end products such as peroxides and SOAs, and chemical aerosol speciation), complete quantification and characterization of natural and anthropogenic emissions, strong scientific knowledge of the physical and chemical processes translated into numerical models, and characterization of human and ecological responses to ambient pollutant exposure.

Singapore has implemented strong environmental regulations and land-use guidelines to manage pollution based on a long-term Conceptual Plan using a pragmatic and cost-effective approach that considers environmental, economic and social factors (Ministry of the Environment and Water Resources, 2009). This plan is reviewed every 10 yr and is translated to medium-term strategies through a Master Plan that is reviewed every 5 yr. Among the measures implemented to control pollution from industries, all heavy industries have been located in the southwest corner of the main island and on an offshore industrial park (see Figure 1), as far away from residential areas as possible. Regarding private transport management, Singapore was the first in the world to charge cars for driving into the city center in 1975. The Electronic Road Pricing (ERP) system was subsequently introduced in 1998, in which motorists pay each time they drive into a congestion-prone area. The ERP charge depends on traffic conditions. The Vehicle Quota System (VQS), introduced in 1990, regulates the increase in the number of vehicles and also helps to regulate traffic congestion. The VQS is facilitated through the auction of car ownership permits called Certificate of Entitlements (CEOs) for 10 yr, for which the actual cost triples the price of a small sedan (e.g., 1600 cc). Through these and other schemes (Off-Peak Car, and Park and Ride schemes) Singapore has recently reduced the annual growth rate of private vehicles to 1.5% (Ministry of the Environment and Water Resources, 2009). However, the number of vehicles has nevertheless increased by 36% during the last decade (Singapore Department of Statistics, 2010).

Although the various control measures have been effective in maintaining the ambient concentrations of criteria pollutants below international air quality standards, it is not clear if this is also the case for $PM_{2.5}$. Controlling exposure to single criteria pollutants also manages exposure to other primary emitted pollutants. At the same time, however, exposure to secondary pollutants, such as O_3, SOAs, and oxygenated VOCs, which are distinguished by the fact that they form in the atmosphere, is not controlled. The effectiveness of moving heavy industry a few kilometers away from the residential areas needs to be assessed by considering the regional synoptic conditions and the local meteorology. For example, during NE monsoon conditions, industrial emissions may not directly affect the city, which will be located upwind. During the SW monsoon season, however, potentially air toxics emitted from the extensive industrial area or formed as secondary pollutants within the emitted plumes will be advected across Singapore, in particular over the residential areas that are increasingly planned to be located in the western part of the island.

During the last few decades, Singapore has tightened its emission regulations and decreased its carbon intensity. As mentioned previously, Singapore has reduced its CO_2 emissions in recent years despite a significant increase in population and in economic, transportation, and industrial activities. However, it is not clear if emissions of other air pollutants have also decreased. Stronger regulations and new technologies do not always solve environmental problems unless the entire urban ecosystem is considered. For example, in the mid-1980s, municipal authorities in Atlanta implemented strong regulations to reduce the anthropogenic emissions of VOCs to control the photochemical production of O_3. The program turned out to be unsuccessful because the regulatory measures did not consider vegetation, which was found to be the most important source of reactive VOCs in the region (Chameides et al., 1988). In the context of Singapore, the mix of anthropogenic pollutants, including those emitted by ships crossing Singapore Strait and natural emissions from the remaining tropical rainforest in the region, local urban vegetation (biogenic VOCs) and ocean (aerosols) may enhance the aerosol formation/growth in the region and contribute to the $PM_{2.5}$ loading in the atmosphere.

The information compiled in the present article indicates that the scientific knowledge about Singapore's air quality is likely to be insufficient to completely and comprehensively understand the origin, formation, fate, and impact of the local atmospheric pollution. With the exception of PM studies conducted by Balasubramanian et al. (Balasubramanian et al., 2003; Balasubramanian and Qian, 2004; He and Balasubramanian, 2009; He et al., 2010; Kalaiarasan et al., 2009; See and Balasubramanian, 2008; See et al., 2006a, 2006b) and the research on human exposure and health effects due to aerosol pollution described above, no other research is reported on topics relevant to air pollution. International experience indicates that actions taken as a result of comprehensive and inclusive air quality assessments are successful in improving air quality with subsequent net economic benefits (Molina and Molina, 2002). In May 2008, a workshop on "Meteorology, Air Quality and Health Impacts in Singapore and other Asian Cities" organized by the NUS Environmental Research Institute (NERI) and attended by local and international experts was held to review the currents state of the knowledge, identify scientific gaps, and gauge interest for international collaboration in key areas related to air quality research in tropical cities. Three scientific topics of strategic interest for Singapore's air quality management were identified during the workshop, to better understand (i) physical characteristics of the tropical urban atmosphere; (ii) emission, formation, and transformation of air pollutants; and (iii) health impacts and air quality. Table 2 presents a list of the specific scientific topics identified for each component. A condensed list is as follows:

- Dynamics and structure of a tropical urban atmosphere, as well as transport of air pollutants.
- Continuous monitoring of a comprehensive number of criteria pollutants, air toxics, and meteorological variables.
- Comprehensive inventory of local and regional emissions from natural and anthropogenic sources.
- Development of predictive air quality models (including forecasting of transboundary smoke-haze episodes).
- Formation and evolution of air pollutants (including SOAs).
- Greenhouse gases and global climate change (including aerosol-cloud interactions).
- Exposure and health impacts of air pollution.
- Cost-benefit analysis and policy implications of reducing pollutants.

To facilitate studies in areas (i) and (ii) and provide the necessary data for (iii), it is essential to conduct continuous and long-term measurements of meteorological variables and air pollutants. Similar to other large, interdisciplinary air quality programs conducted in metropolitan areas, installation of a "supersite" equipped with state-of-the-art instrumentation along with expert staff for operation and maintenance is necessary (e.g., Wittig et al., 2004; Solomon et al., 2008; Järvi et al., 2009). Air quality supersites provide continuous measurements with better time-resolution ($\sim$seconds), lower detection limits, and a larger number of chemical species and physical parameters than those from typical monitoring stations for air quality compliance. During the last decades, a number of large, international, multiagency collaborative programs, based on intensive field campaigns during short periods of time (from one to a few months) and featuring instrumentation at fixed ground sites, mobile platforms, and aircrafts, have proven to be effective means to better understand the chemical and physical processes of air pollution, as well as their impacts on human health and ecosystems. Results of these studies, together with data collected from permanent supersites, have been fundamental for the design of new environmental policies in many metropolitan regions. Examples of such programs include the Megacity Initiative Local and Global Research Observation (MILAGRO) Campaign carried out in Mexico City in 2006 (Molina et al., 2010), the Program of Regional Integrated Experiments of Air Quality over the Pearl River Delta (PRIDE-PRD) conducted in 2004 (Zhang et al., 2008), and the Texas Air Quality Study phase II (TexAQS II) carried out in Houston in 2004 (Parrish et al., 2009), among others.

Table 2. Specific scientific topics of strategic interest for Singapore's air quality management identified during a workshop on "Meteorology, Air Quality and Health Impacts in Singapore and other Asian Cities" organized by NERI (May 5–6, 2008)

(i) Physical Characteristics of the Tropical Urban Atmosphere	(ii) Emission, Formation, and Transformation of Air Pollutants	(iii) Health Impacts and Air Quality
Air-sea fluxes.	Quantification, characterization, and impacts of emissions of pollutant and greenhouse gases (emissions of shipping, container ports, petrochemical industries, vehicles, etc.).	Exposure to key pollutants or pollutant mixtures in outdoor and indoor microenvironments.
Mixing layer height.	Quantification of natural emission sources (wildfires, vegetation, ocean, etc.).	Health impacts during smoke-haze episodes triggered by wildfires in neighboring countries.
Mean and turbulence structure of the atmospheric boundary layer.	Monitoring of primary, secondary and intermediate species (e.g., VOCs, NO_x, OH, etc.).	Estimation of economic costs due to health effects produced by atmospheric pollution.
Surface-layer energy balance.	Monitoring of toxic compunds (e.g., mercury and polyaromatic hydrocarbons).	Personal exposure monitoring system; new sensors.
Urban heat island.	Monitoring of bioaerosols (e.g., bacteria, fungi) in hot and humid environments.	Health impacts of nanoparticles.
Land/sea breeze dynamics.	Characterization of chemical and physical properties of aerosols.	Mechanistic studies in vitro and in vivo with animals and humans.
Influence of monsoon on air quality.	Formation of secondary air pollutants.	Epidemiological surveys together with molecular epidemiological studies using biomarkers in urine, blood, and breathe condensate.
Importance of convection in tropical urban atmosphere.	Aerosol formation and evolution (heterogeneous nucleation, condensation).	
Sub-grid parameterizations for urban climate/ dispersion models.	Sea salt interactions with anthropogenic emissions.	
Urban canyon large eddy simulation (LES) modeling.	Cloud condensation nuclei (CCN) formation and optical radiative properties of aerosols.	
Urban climate modeling using numerical weather prediction systems such as the Weather Research and Forecasting (WRF) model.	Sinks of gaseous pollutants (sea salts and particulates).	
Aerosol optical thickness.	Wet and dry deposition processes.	
Direct sun measurements, scattering albedo, and refractive indexes.	Chemical characteristics of biomass burning. Plume evolution and transport (pollutants aging).	
Satellite meteorology and air pollution monitoring (e.g., National Aeronautics and Space Administration [NASA] A-Train).	Background pollution characterization.	
Impact of climate change on urban climatology and air quality.	Biogenic SOAs formation.	
	Prediction of transboundary smoke-haze.	
	Development of predictive air pollution and air quality models.	

Final Remarks

Air quality has become one of the most important environmental and health concerns of large cities. Los Angeles, New York, and Mexico City, for example, have significantly reduced ambient levels of criteria pollutants without compromising their economic growth (Parrish et al., 2011), even though their strategic environmental plans recognize that large efforts are necessary to achieve "clean" air. Links between air pollution and health effects are observable even where pollutant levels are seemingly low (Anderson, 2009; Craig et al., 2008). It is known that poor air quality can cause short- and long-term impacts on public health, resulting in increased health costs, loss in manpower hours, and ultimately reduction in quality of life. In a first analysis carried out for Singapore, Quah and Boon (2003) estimated that costs associated with health impacts caused by PM_{10} pollution amounted to 4.3% of Singapore's GDP in 1999, a year not impacted by transboundary smoke-haze events. Similarly, Sultan (2007) estimated savings of 17.1% of the nation's GDP in 2002 from reduced health risk by improving building design, ventilation, and filtration. Besides detrimental health effects, economic losses due to air pollution are becoming an increasing concern either because of direct financial losses or diminished attractiveness of a place (Hidy and Pennell, 2010).

Unlike many industrialized metropolitan areas, Singapore is far from being a hazy and highly polluted city. Although substantial environmental monitoring data are available in some areas, several aspects of local air quality are difficult to assess due to the lack of publicly available data. For example, similar to many other large cities, fine aerosols are potentially a significant air pollution problem and health concern, but corresponding data are not published (with the exception of annual averages). Information about other pollutants such as VOCs, some of which are known to be toxic (e.g., benzene, toluene, and 1,3-butadiene) or highly efficient in the formation of SOAs and other secondary pollutants (aromatics, olefins, terpenes, etc.), is also not available or reported, but would be valuable for a more holistic assessment of the local air quality as mentioned above.

As of 2008, Singapore's contribution to global CO_2 emissions is only ~0.11% (United Nations, 2011a) and as a "Non-Annex 1" country it has no obligation to reduce emissions, similar to most developing countries. However, Singapore is a wealthy nation with a very high per-capita carbon footprint. As a model of a green city, Singapore has an opportunity to reduce its emissions of greenhouse gases through innovative policies integrated into the current air quality management. Policies to mitigate climate change can have important implications for air quality and vice versa. Many anthropogenic sources simultaneously emit greenhouse gases and air pollutants. Furthermore, some of these pollutants, besides being toxic, contribute directly to climate forcing or react in the atmosphere to form new climate-forcing pollutants. Singapore's position on carbon emissions has been critically analyzed by Hamilton (2009) and Weida (2009).

In response to air pollution and climate change concerns, environmental authorities in Singapore (and other cities) could strengthen their air quality and climate change mitigation programs by actions that lead to the better evaluation of air quality policies, tracking the chain of events from regulatory actions to human health benefits (Brook et al., 2009; Hidy and Pennell, 2010). Changes in emissions, ambient concentrations, and exposure need to be constantly monitored. To achieve this, air quality management systems need to improve the spatial and temporal resolution of ambient monitoring networks and emission inventories. New and existing monitoring programs as well as new sensors need to be (re)designed to address more pollutants, including species emitted from existing or emerging technologies that could pose future risks while unregulated. More consideration should be given to the use of continuous emissions measurement systems, such as eddy covariance flux systems, to track emission changes of pollutants and greenhouse gases (Velasco and Roth, 2010; Velasco et al., 2009). Attention must be given to the development of mathematical models that integrate the most recent photochemical reactions and meteorological modules to better simulate the local atmospheric conditions and impacts at the regional, if not global, scale.

Science-based air quality management systems based on a multipollutant approach (Craig et al., 2008; Hidy and Pennell, 2010; Hidy et al., 2011) can assist Singapore's efforts to continue to improve its air quality and by extension promote financial investment, local economic growth and increase international competitiveness. At the same time Singapore will reinforce its position as a livable and sustainable city, with the unique opportunity of leading air quality and greenhouse gas management in Southeast Asia. A comprehensive characterization of emission sources, transport, and fate of pollutants and greenhouse gases will build a strong knowledge base applicable to other fast-growing cities in Southeast Asia and tropical places in general. This will require an important investment in theoretical and applied research, as well as international collaborations. The atmosphere over tropical cities is not well researched and represents an opportunity for Singapore to expand its agenda in environmental research and development.

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