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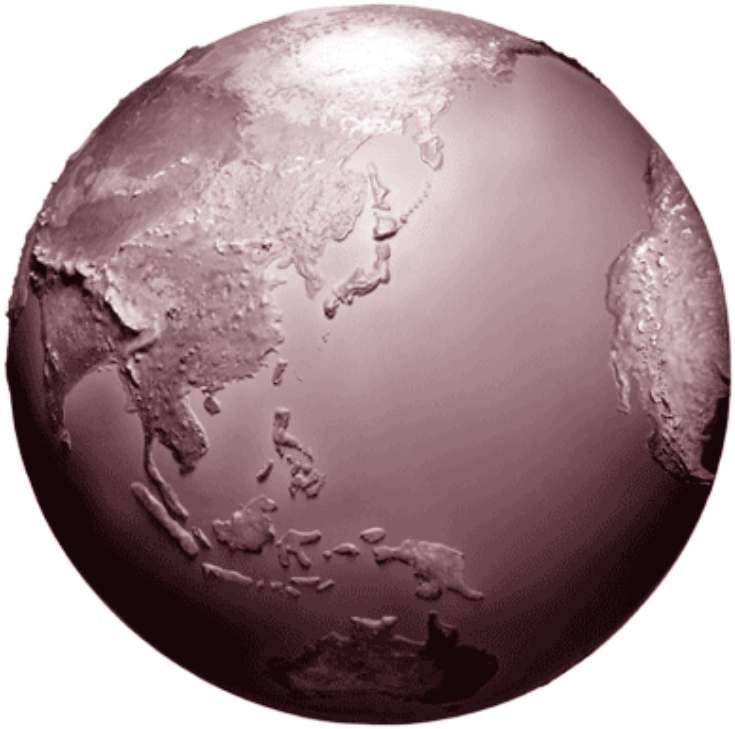

Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review

HEI International Scientific Oversight Committee

EXECUTIVE SUMMARY

ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI receives half of its core funds from the U.S. Environmental Protection Agency and half from the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or certain research programs. The Public Health and Air Pollution in Asia (PAPA) Program was initiated by the Health Effects Institute in part to support the Clean Air Initiative for Asian Cities (CAI-Asia), a partnership of the Asian Development Bank and the World Bank to inform regional decisions about improving air quality in Asia. Additional funding was obtained from the U.S. Agency for International Development and the William and Flora Hewlett Foundation.

HEI has funded more than 280 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in the peer-reviewed literature and in more than 200 comprehensive reports published by HEI.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Health Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Health Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Health Review Committee are widely disseminated through HEI's Web site (*www.healtheffects.org*), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

EXECUTIVE SUMMARY

Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review

EXECUTIVE SUMMARY

Asia is undergoing economic development at a rapid rate, resulting in levels of urban air pollution in many cities that rival the levels that existed in Europe and North America in the first decades of the 20th century. This development is also transforming the demographic and epidemiologic characteristics of the population in ways that are likely to affect its vulnerability to air pollution. Nearly two thirds of the estimated 800,000 deaths and 4.6 million lost years of healthy life worldwide caused by exposure to urban air pollution in 2000 occurred in the developing countries of Asia (also referred to as "developing Asia"; World Health Organization [WHO*] 2002). In rural areas and urban slums, indoor air pollution from the burning of solid fuels confers its own large burden of disease and contributes to increased outdoor concentrations of pollutants in some locales. Developing Asia's poorest populations are also susceptible to the unexpected effects of climate change, including possibly substantial health effects.

Effective public policy responses to the public health challenges posed by air pollution in developing Asia require high-quality scientific evidence on the health effects of air pollution in the region. Epidemiologic studies are among the most important and critical components of the required evidence; together with toxicologic and clinical studies, they provide estimates of the quantitative relation between exposure and disease. These estimates both demonstrate the existence of a public health hazard and allow its magnitude to be estimated. Owing to limitations of the available epidemiologic studies in Asia, estimates from assessments of the health impact of air pollution in Asian populations (e.g., the estimate from the WHO cited above), rely in large part on extrapolation, with considerable uncertainty, of the results of Western studies to Asian populations (Cohen et al. 2004; HEI International Scientific Oversight Committee [ISOC] 2004).

HEI initiated the Public Health and Air Pollution in Asia (PAPA) program in 2002 to reduce uncertainties about the health effects of exposure to air pollution in the cities of developing Asia. The first major publication of the PAPA program was Special Report 15, *Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review* (HEI ISOC 2004). That report was also the first comprehensive review of the peer-reviewed Asian literature on the health effects of air pollution, a literature that at that time (2004) comprised over 100 studies in nine countries. On the basis of Special Report 15, the PAPA program initiated a coordinated set of analyses of air pollution and daily mortality in four selected Asian cities (Hong Kong, Bangkok, Wuhan, and Shanghai). These studies have now been completed (HEI Public Health and Air Pollution in Asia Program 2010), as have additional studies in India and Vietnam (Balakrishnan et al. 2010; Rajarathnam et al. 2010; Collaborative Working Group on Air Pollution, Poverty, and Health in Ho Chi Minh City 2009).

The current report is the second PAPA literature review, *Outdoor Air Pollution and Health in Developing Countries of Asia: A Comprehensive Review.* It begins with a broad overview of the status of and trends in air pollution sources, emissions, concentrations, and exposures in the developing countries of Asia, as well as factors related to urban development, population health, and public policy that set the context for the health effects of air pollution. Next, the review describes the current scope of the Asian literature on the health effects of outdoor air pollution, enumerating and classifying more than 400 studies identified through 2007 via HEI's Web-based Public Health and Air Pollution in Asia — Science Access on the Net (PAPA–SAN) literature survey (HEI 2006). In addition, a systematic and quantitative assessment (conducted using St, George's Air Pollution Epidemiology Database [APED]) of 82 time-series studies that estimate the effect of short-term exposure to air pollution on daily mortality and hospital admissions for cardiovascular and respiratory disease — four times the number of studies analyzed for Special Report 15. The studies covered in the current review include the coordinated studies of air pollution and daily mortality in four Asian cities conducted as part of HEI's PAPA research program, as well as a first-ever critical and qualitative analysis of Asian studies of long-term exposure to air pollution and chronic respiratory disease, lung cancer, and adverse reproductive outcomes. The review concludes with a discussion that places the Asian health effects studies in the context of the worldwide literature, identifies gaps in knowledge, and recommends approaches by which to address them.

THE ASIAN LITERATURE IN CONTEXT

Development, Air Pollution, and Population Health

This review evaluates the evidence of health effects of outdoor air pollution in developing Asia in the context of ongoing changes in both air quality and population health. The nature of the health risks associated with the natural

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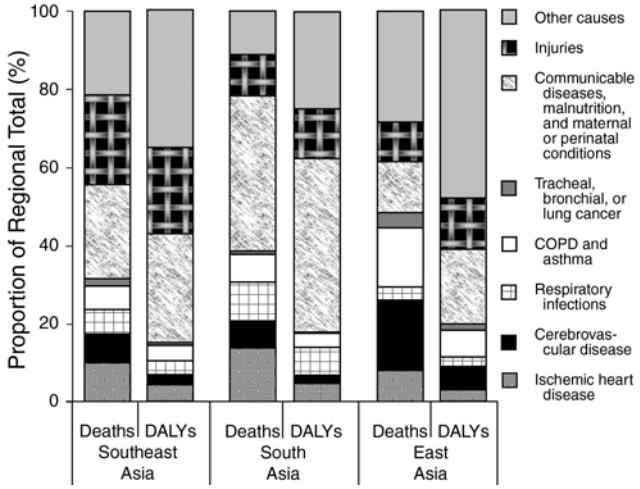
* A list of abbreviations and other terms appears at the end of the summary.

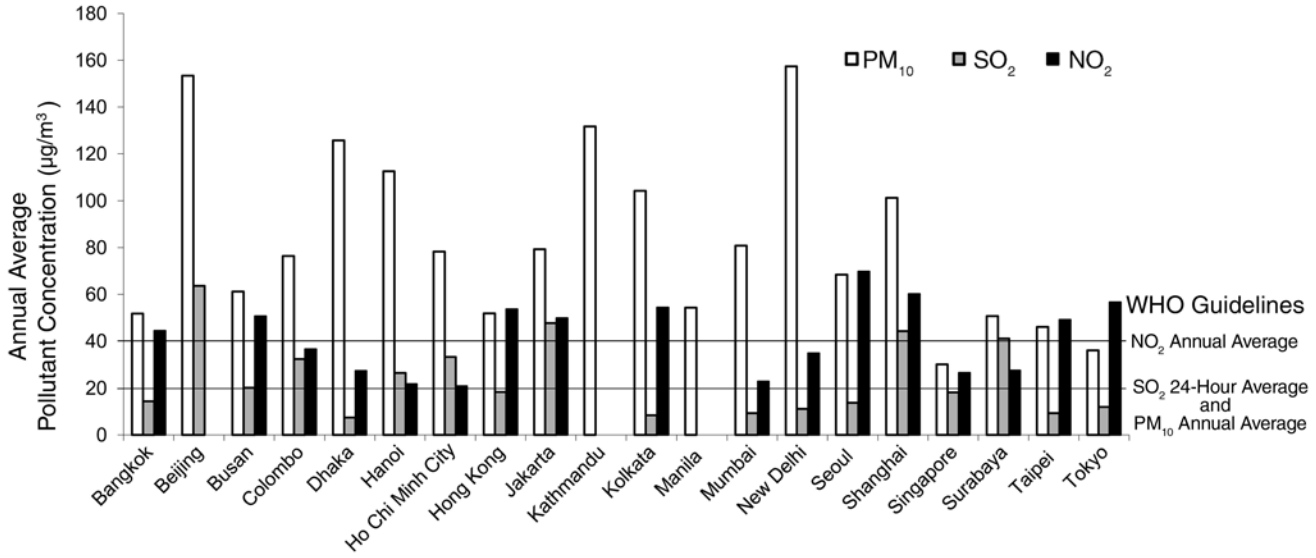
and built environments changes as economic development occurs. Economic development and attendant urbanization has been, and continues to be, based in large part on the increased combustion of fossil fuels. This pattern of development has led, in some countries, to impressive reductions in poverty levels and increased life expectancy. Economic development and poverty reduction have also led to gradual decreases in environmental risks at the household level, such as indoor air pollution from the burning of solid fuels and poor water quality, although the burden of disease associated with these exposures in young children and women remains substantial. There have also been commendable improvements in urban air quality in many parts of Asia. At the same time, the size of the exposed population that may be vulnerable to air pollution is increasing, as is evidenced by a large and growing burden of disease from chronic noncommunicable diseases — such as ischemic heart disease (IHD), cerebrovascular disease, chronic obstructive pulmonary disease (COPD), and cancer. The increased population size is, in part, owing to larger numbers of people living to older ages and to the increased prevalence of tobacco smoking, higher rates of obesity, and changes in dietary patterns (Figure 1).

Air pollution has become a major policy issue in many parts of Asia and has prompted actions to improve air quality. As a result, there have been improvements in air quality across the region, even in the face of increasing fossil-fuel consumption. These improvements, however, have not occurred in all highly populated areas, and some areas have in fact been experiencing deteriorating air quality. In general, air pollution concentrations in Asian cities

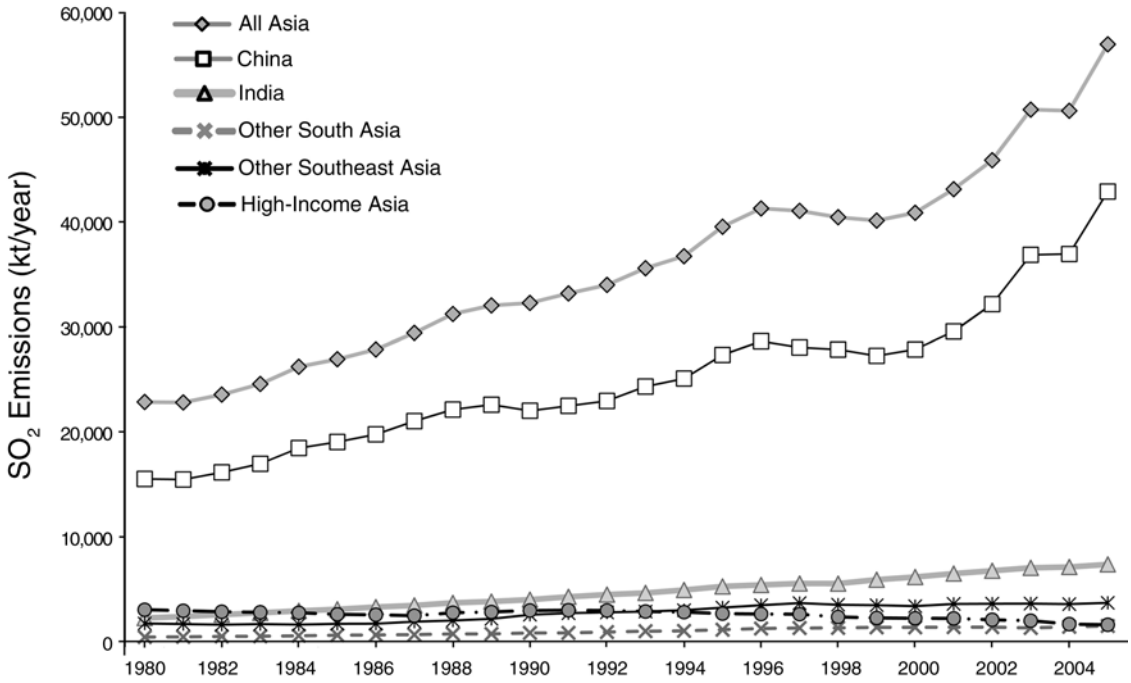


Executive Summary Figure 1. Deaths and disability-adjusted life-years (DALYs) in Asia in 2004, by region and cause. "Southeast Asia" corresponds to WHO Southeast Asian Region B; "South Asia" to WHO Southeast Asian Region D; and "East Asia" to WHO Western Pacific Region B. [Data compiled from WHO 2008.]

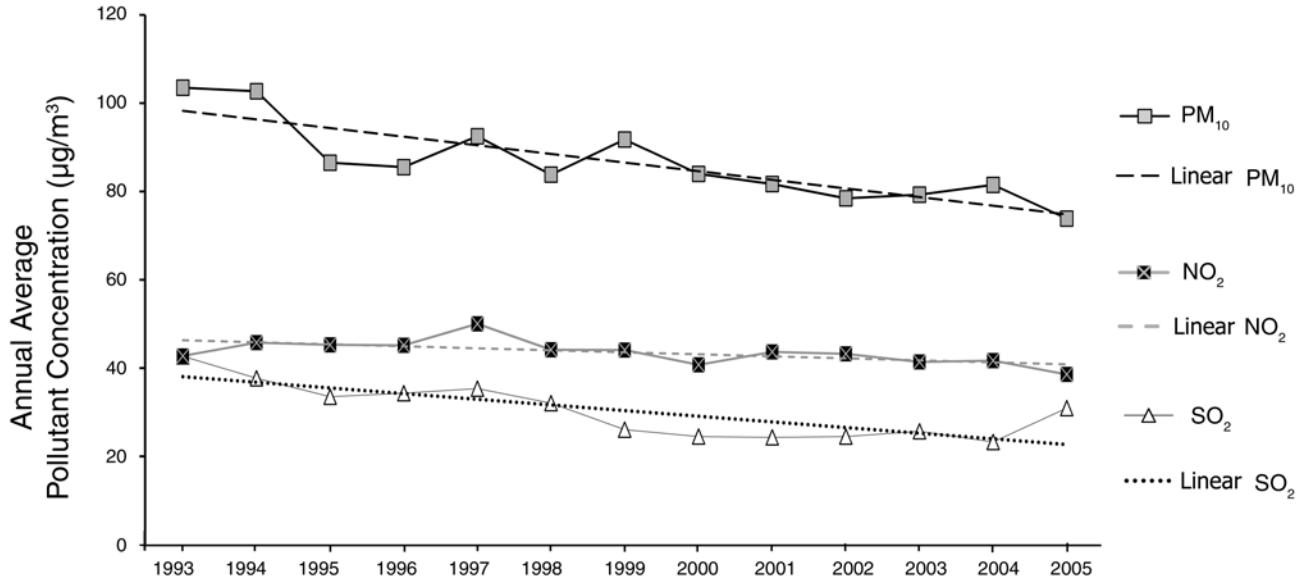
greatly exceed current WHO health-based air quality guidelines and many current national standards (Figure 2). In a large number of studies worldwide, air pollution has been found to adversely affect people with chronic cardiovascular and respiratory diseases, and it may also contribute to the development of those diseases in otherwise healthy people. Thus, even as air quality has improved in some locations, there remains an important adverse impact on public health, which may grow as populations age and rates of chronic disease and urbanization increase.



Executive Summary Figure 2. Five-year (2000–2004) average PM_{10}, SO_2, and NO_2 concentrations in selected Asian cities. Standards are from WHO Air Quality Guidelines, 2005 Global Update (WHO 2006a): PM_{10} annual average 20 µg/m³; SO_2 24-hr average 20 µg/m³; NO_2 annual average 40 µg/m³. PM_{10} is particulate matter 10 µg/m³ or smaller in aerodynamic diameter; SO_2 is sulfur dioxide; NO_2 is nitrogen dioxide. [Reprinted with permission from Clean Air Initiative for Asian Cities [CAI-Asia] Center (*www.cleanairnet.org/caiasia*; accessed January 2008).]



Executive Summary Figure 3. SO_2 emissions in Asia, 1980–2005. Data are given in kilotons per year. *China* comprises mainland China, Hong Kong, and Taipei,China. *Other South Asia* comprises Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, and Sri Lanka. *Other Southeast Asia* comprises Cambodia, Indonesia, Laos, Malaysia, Myanmar (Burma), Philippines, Thailand, Timor-Leste, and Vietnam. *High-Income Asia* comprises Brunei, Japan, South Korea, and Singapore. Values for *All Asia* are weighted averages of the regions. [Adapted from the Frontier Research Center for Global Change 2007 with additional material from T. Ohara (personal communication, May 26, 2008).]



Executive Summary Figure 4. Annual averages of PM_{10}, SO_2, and NO_2 aggregated among selected Asian cities, 1993–2005. The cities used for this figure are shown in Figure 2. The straight lines are smoothed estimates of trends in air pollution levels. [Reprinted with permission from CAI-Asia (*www.cleanairnet.org/caiasia*; accessed January 2008).]

Air quality in Asia reflects complex and evolving relations between increased energy consumption for transport and power generation and measures being taken to improve air quality. Overall, estimates of pollution emissions as well as measured and estimated ambient concentrations indicate that air quality is improving throughout much of urban Asia (Figures 3 and 4). Trends in air quality have largely shown improvement during periods of dramatically increased energy use in Asia, a testament to the impact of effective air quality management as well as improved energy efficiency and reduced intensity of energy use.

Executive Summary Figure 5. Number of studies identified in the PAPA–SAN Asian literature review, according to country of study.

From past experience in Western countries, it seems clear that substantial increases in the combustion of fossil fuels for power generation and transportation can improve economic conditions but can also, if not controlled, have important negative consequences for human health and environmental quality in Asia and elsewhere, through transboundary transport of pollutants. It is also clear that effective approaches to controlling and reducing pollution exist. Investment in these approaches need not necessarily impede economic growth and, on the basis of documented experience in developed countries and emerging evidence in Asia, the developing countries of Asia may be able to avert increased environmental degradation and associated adverse health impacts while reducing poverty and providing economic security for their populations (Clean Air Initiative for Asian Cities [CAI-Asia] Center 2008, U.S. Environmental Protection Agency [U.S. EPA] 2008).

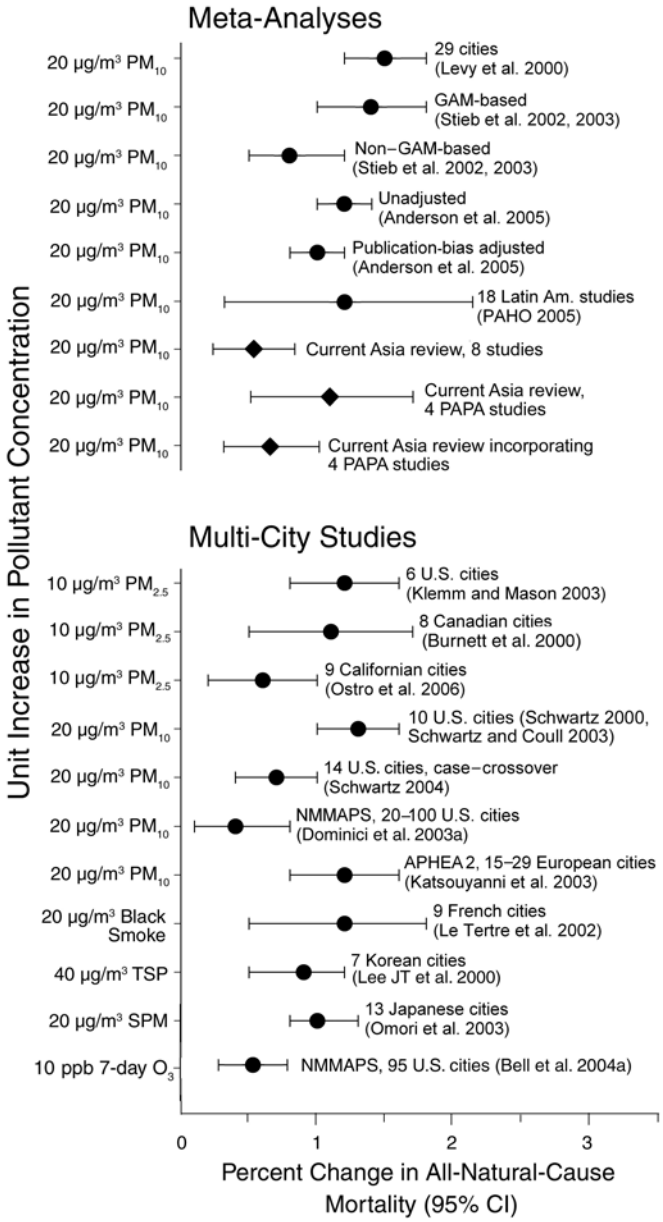
Climate change and emissions of climate-forcing pollutants present a considerable challenge for Asia but are offer an additional rationale for continued improvement in air quality, with near-term benefits for public health from reductions of short-lived greenhouse gases (GHGs). Strategies for reducing GHG emissions, though directed toward climate change, may also have direct impacts on local and regional air quality, resulting in faster and larger improvements than would otherwise occur in the region.

Review of Epidemiologic Studies of Air Pollution

As a result of these developments, the need for high-quality research on the health effects of air pollution in Asia has never been greater, and the scientific community is responding with an increasing number of studies of the effects of exposure to air pollution on morbidity and mortality due to cardiovascular or respiratory diseases, adverse reproductive outcomes, and other health effects. Systematic searches of the peer-reviewed literature in HEI's PAPA–SAN database have identified over 400 studies of the health effects of air pollution in Asia published from 1980 through 2007 (Figure 5). The studies have been conducted in 13 countries, and the rate of publication has increased over the past 20 years. The spectrum of adverse health effects associated with air pollution exposure ranges from acute and chronic respiratory symptoms and changes in pulmonary function to increased mortality from cardiovascular or respiratory diseases or lung cancer — the same spectrum of adverse health outcomes associated with air pollution in the West.

Meta-Analyses of Daily Time-Series Studies

Time-series studies of the effects of short-term exposure on morbidity and mortality from cardiovascular or respiratory diseases continue to provide some of the most current and consistent evidence of serious adverse health effects of air pollution in Asia, with over 100 studies published since 1980. This literature now includes the results of the coordinated studies in four Asian cities funded under the PAPA program (HEI Public Health and Air Pollution in Asia Program 2010), consisting of the type of evidence that has contributed most importantly to international guidelines and science-based regulatory policies in Europe and North America (Samoli et al. 2008; WHO 2005). Meta-analyses of time-series studies and coordinated multi-center studies of the effect on mortality of an increase in the concentration of a given air pollutant (called "effect estimates",



Executive Summary Figure 6. Estimates of percent change in daily mortality from all natural causes for selected meta-analyses and multi-city studies of daily changes in air pollution exposure, by study type and unit change in pollutant concentration. TSP is total suspended particles; SPM is suspended particulate matter; O_3 is ozone; GAM is generalized additive models; PAHO is Pan American Health Organization; NMMAPS is National Morbidity, Mortality, and Air Pollution Study; APHEA2 is Air Pollution and Health: A European Approach. [Adapted from Pope and Dockery 2006 with estimates added from the meta-analysis in this Asian Literature Review (diamond data points; see Table 15 in the main report).]

shown here as the percent change in daily all-natural-cause mortality), including those from the four PAPA studies, are presented in Figure 6.

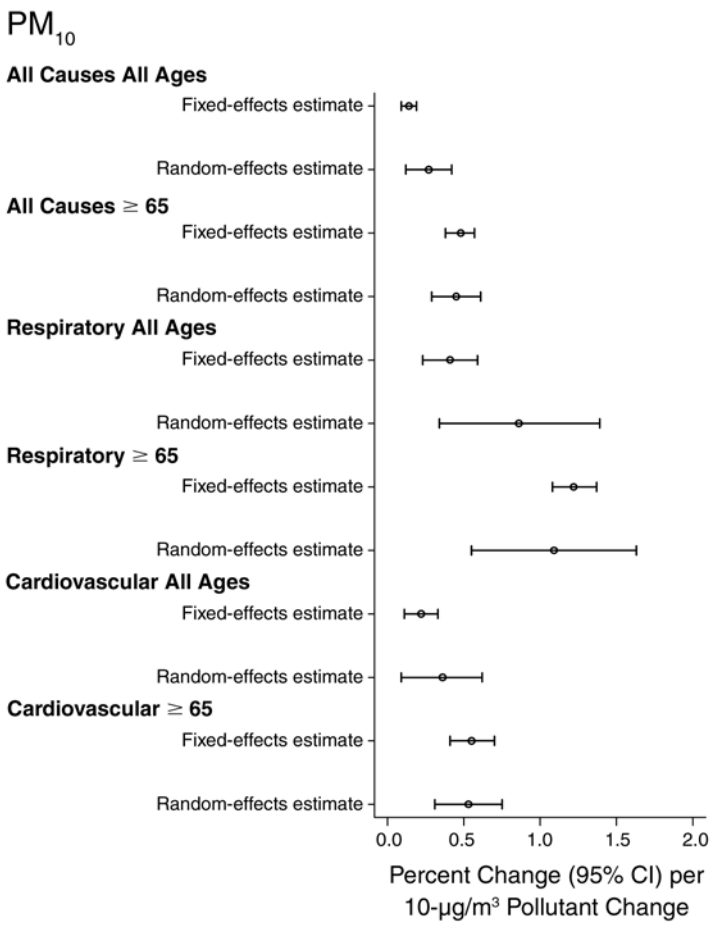
The updated meta-analyses of Asian time-series studies presented in this review summarizes results from 82 reports published through August 2007, more than three times the number in the 2004 review (HEI ISOC 2004), providing more reliable and detailed estimates of the magnitude of the effect of exposure on daily mortality and hospital admissions in Asian populations and allowing for more definitive comparisons of Asian evidence with results from other regions. Short-term exposure to particulate matter (PM) with an aerodynamic diameter ≤ 10 µm (PM_{10}) is estimated to increase daily mortality from all natural causes by 0.27% (95% confidence interval [CI], 0.12–0.42) per 10-µg/m³ increase in pollutant concentration, an effect similar to that reported in meta-analyses and multi-city studies in Europe, North America, and Latin America. Underlying this estimate is the increased daily mortality

from cardiovascular disease (chiefly IHD and stroke), the major current and future cause of death of adults in the region (Figure 7). Consistently larger exposure-related increases in all-natural-cause, cardiovascular, and respiratory mortality were also observed among older people, who represent an increasingly large proportion of Asian populations.

The PAPA Studies

The PAPA studies constitute the first designed and coordinated multi-city set of studies of the health effects of air pollution in Asia. As such, they provide a unique, if limited, picture of the short-term impact of current ambient concentrations of particulate air pollution on mortality in four large metropolitan areas in East and Southeast Asia: Bangkok, Hong Kong, Shanghai, and Wuhan. In the combined analysis of the city-specific results (Wong CM et al. 2008; Wong CM and the PAPA Teams 2010a), a 10-μg/m^3 increase in PM_{10} concentration was associated with an increase of 0.6% (95% CI, 0.3–0.9) in the daily rate of death from all natural causes, estimates similar to or greater than those reported in multi-city studies in the United States and Europe. This proportional increase in daily mortality is seen at levels of exposure (mean PM_{10} concentration, 51.6–141.8 μg/m^3) several times higher than those in most large Western cities, and in each of the four Asian cities, daily mortality continues to increase over a fairly large range of daily average ambient PM_{10} concentrations, up to several hundred micrograms per cubic meter.

The summary estimate for PM_{10} from the four cities of the PAPA studies exceeds the overall meta-analytic summary estimate for the Asian studies for all pollutants and outcomes (with the exception of respiratory mortality, for which the PAPA estimates are lower) (Figure 6). The reasons for these differences are unclear but may be due to the higher estimates in Bangkok (for unknown reasons) or the systematic selection and quality control of air quality data according to rigorous and explicit protocols in the PAPA studies. Stochastic variation, or the play of chance, is another possible explanation. When the PAPA city-specific estimates are added to the meta-analyses, the summary estimate for all-natural-cause mortality per 10-μg/m^3 increase in PM_{10} becomes 0.33% (95% CI, 0.16–0.51), versus 0.27% (95% CI, 0.12–0.42). Preliminary data from the PAPA-funded studies in two Indian cities, Delhi (Rajarathnam et al. 2010) and Chennai (Balakrishnan et al. 2010), also show increased rates of all-natural-cause mortality in association with short-term exposure to PM_{10},



Executive Summary Figure 7. Summary effect estimates for all-natural-cause, respiratory, and cardiovascular mortality per 10-μg/m^3 change in PM_{10} concentration. Y-axis labels in bold type specify the cause of death and the age group.

though the point estimate for Delhi, 0.15% (95% CI, 0.07–0.23) per 10-μg/m^3 increase in PM_{10} concentration, is roughly half the meta-analytic summary estimate.

The studies in Hong Kong, Wuhan, Shanghai and Bangkok were designed to provide a combined picture of the effects of short-term exposure to pollution on daily mortality across the four cities, but each study also explored more detailed aspects of the epidemiology of exposure to air pollution in each location, providing additional insight into how factors such as weather and social class might modify the estimated relative risk of health effects of air pollution. The study in Wuhan, one of China's "oven cities" (cities that experience very high temperatures and humidity), found that the estimated relative risk may increase by a factor of 5 at extremely high temperatures, as compared with temperatures typical of temperate zones (Qian Z et al. 2008, 2010). The studies in Hong Kong (Wong CM et al. 2008, 2010b) and Shanghai (Kan H et al. 2008, 2010) found evidence of higher relative risks among the economically disadvantaged and those with the least education, respectively, corroborating the results of some earlier studies in Western cities (O'Neill et al. 2003).

Critical, Quantitative Review of Chronic-Effects Studies

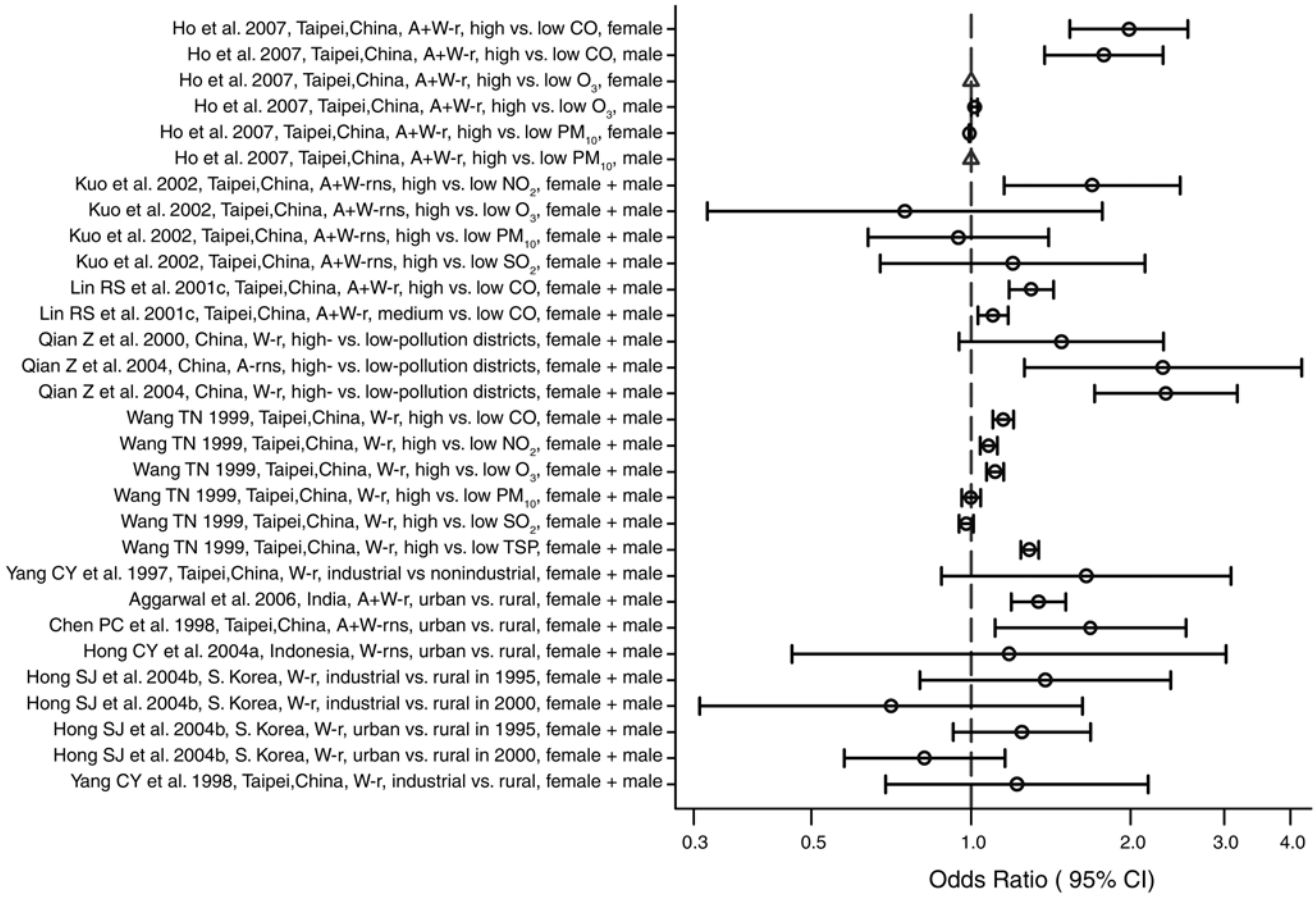
The Asian literature on the chronic effects of long-term exposure to air pollution is more limited than the literature from Europe and North America, especially with regard to chronic cardiovascular disease. The design and quality of the studies also vary widely. Nonetheless, the results of this review suggest that long-term exposure to air pollution from combustion sources is contributing to chronic respiratory disease in both children and adults, to lung cancer, and to adverse reproductive outcomes in Asian populations.

The prevalence of chronic phlegm, a major symptom of chronic respiratory disease indicating long-term exposure to inhaled irritants, was found to be associated with exposure to combustion-source air pollution both in qualitative comparisons among areas with differing concentrations of pollution and in quantitative comparisons of measured concentrations of air pollution. Studies that controlled for major potential confounding factors, including tobacco smoking and indoor air pollution from the burning of solid fuels, reported relative risk estimates generally between 1.1 and 5.0, regardless of how pollution was characterized. Associations were observed with both PM, measured as PM_{10}, and gaseous combustion-source pollutants such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). Similar associations with pollution, after controlling for smoking, have been reported in many surveys in North America and Europe, including some in which the sources and concentrations of pollutants were similar to those in some Asian cities in this review. The increased prevalence of chronic phlegm was seen in both adults and children. In children, although it is not an indicator of chronic bronchitis or COPD (which are diseases of later life), chronic phlegm may be correlated with repeated respiratory infections, which in turn may result in reduced pulmonary function. Reduced lung function in childhood and early adulthood is associated with an increased risk of developing COPD later in life (Fletcher and Peto 1977; Rennard and Vestbo 2008).

Evidence from Asia regarding air pollution effects on ventilatory lung function is limited, and few studies of adults have used acceptable methods with regard to testing protocols or control for the effects of tobacco smoking. The studies of children and non-smoker adults that have been conducted suggest adverse effects of ambient exposures, but because these studies are cross-sectional and because the air pollution exposures were estimated for whole geographic areas rather than for individuals, it is difficult to reach firm conclusions as to the impact of ambient pollution on pulmonary function. Such cross-sectional studies suggest detrimental effects of exposure to air pollution on children's lung function, providing snapshots of events that are part of a dynamic process that affects lung growth and development. Longitudinal studies are needed to determine whether the cross-sectional associations with air pollution represent a slower-than-normal growth of lung function that results in permanent deficits (and might subsequently lead to an accelerated decline in lung function in adulthood) or, as some studies in Western countries suggest, a transient worsening of pulmonary function with recovery as pollution concentrations improve. There is also the potential for residual confounding, such as confounding due to differences among factors related to socioeconomic status. These problems are encountered in cross-sectional studies in Western counties as well as in Asia.

A similarly diverse and overlapping collection of studies also provides some evidence for an increased prevalence of asthma and asthma-related symptoms in association with exposure to air pollution from a variety of sources. Most studies show an elevated prevalence in association with air pollution exposure, with estimated relative risks generally greater than 1.0 but less than 2 (Figure 8). Studies of long-term exposure to ambient air pollutants and asthma symptoms and diagnoses vary considerably in design. Differences in exposure have been estimated at between- and within-city levels, with the within-city comparisons including roadside exposures. The studies also vary widely in terms of statistical power, quality of exposure assessment, and degree of control of confounding factors. Overall, however, the design and conduct of the studies are similar to those from Western countries. Although the results of the studies reviewed in this Special Report are not entirely consistent, there is some evidence for a modest effect of air pollution on asthma prevalence — and possibly more evidence than in current Western studies. We still know little about the reasons for this effect or for the observed heterogeneity among the findings. Asthma prevalence ranges widely among children in Asia, but this variation seems unlikely, on the basis of the current evidence, to be explained by the corresponding range of ambient air pollution concentrations (Anderson et al. 2010).

There is limited evidence regarding air pollution and lung cancer in Asian populations. The two studies that have addressed potential confounding by strong risk factors, such as tobacco smoking and indoor air pollution from the burning of



Executive Summary Figure 8. Odds ratios (and 95% CIs) for asthma or wheeze from qualitative comparisons between areas with differing pollutant concentrations in studies of urban and rural locations, or between or within cities. Y-axis labels give study information in the following sequence: reference citation; location, outcome, pollutant levels or areas that were compared; and sex of subjects (female; male; or combined). Possible outcomes were A-r (doctor-diagnosed or self-reported asthma within the last 3 years), A-rns (doctor-diagnosed or self-reported asthma, whose time of diagnosis or self-reporting was unspecified or not recent), W-r (wheeze symptoms reported within the last 3 years), W-rns (wheeze symptoms whose time of reporting is unspecified or not recent) or a combination of asthma and wheeze (A+W-r and A+W-rns). CO is carbon monoxide; TSP is total suspended particles. A log scale is used on the x axis to accommodate the range of estimates. Two studies reported "no significant association" with no odds ratio; data points are shown here as triangles without CIs. For study details, see Table 19 of the main report.

solid fuels, report relative risks for lung cancer in the range of 1.5 to 3.0, consistent with those from studies in Europe and North America; but more definitive evidence will require larger studies that directly assess the effects of exposure using measured, rather than estimated, concentrations of air pollutants (at the higher concentrations) and that adequately control for potential confounders.

The Asian literature suggests that the risks of adverse reproductive outcomes, such as low birth weight and preterm delivery, in association with exposure to air pollution are relatively small. Overall, the estimated relative risks are between 1.04 and 2.0. Exposure in early pregnancy appears to be most strongly associated with risk. These results are generally consistent with those from the larger global literature on air pollution and adverse pregnancy outcomes. However, the Asian studies, like those conducted elsewhere, are limited by incomplete control for potential confounders, such as maternal smoking, and are subject to exposure measurement error owing to the use of routinely collected health and air quality data. Some studies have reported the risk per quantitative increases in pollutant concentrations, but most have instead characterized exposure in terms of residential proximity to sources of pollution, mainly industrial sources, thus limiting comparisons of these studies with the larger international body of studies that use ambient air pollution measurements to characterize exposure.

IMPLICATIONS FOR ASSESSMENT OF HEALTH IMPACTS

Very large populations are exposed to high concentrations of air pollution in developing Asia. Indeed, 30 million people currently reside in just the first four cities studied in the PAPA research project. Thus, the estimated effects of both short- and longer-term exposures reviewed in this report, though small in relative terms, probably translate to large numbers of illnesses and deaths attributable to air pollution. The WHO estimated that over 500,000 deaths in Asia in 2000 were due to outdoor air pollution exposure, accounting for approximately two thirds of the total global burden of deaths attributed to air pollution (WHO 2002). Indoor air pollution from use of solid fuel contributed an

additional 1.1 million deaths. Other impact assessments have reported similar estimates (World Bank and the Chinese State Environmental Protection Administration [SEPA] 2007). That said, air pollution is but one of many factors that affect the health of people in developing Asia (Ezzati et al. 2002). Nonetheless, the substantial health impacts of exposure to air pollution are clearly a factor that should be considered in transportation and energy policy in the region.

In Asia and elsewhere, an increased life expectancy is a major social benefit of economic growth and its attendant, if often variable, reductions in poverty. Exposure to air pollution acts to reduce healthy life expectancy, shortening lives by months and even years, on average, in some populations (Brunekreef et al. 2007). Although the time-series studies reviewed here document the occurrence of excess mortality related to short-term exposure, the study results cannot currently be used directly to estimate reductions in life expectancy due to extended exposure (Rabl 2006; Burnett et al. 2003). Such estimates are provided by cohort studies, in which large numbers of individuals exposed to various concentrations of air pollution are observed for years and the mortality rates in each exposure group are compared. Such studies have been conducted in the United States and Western Europe, but to date, no cohort studies of long-term exposure to air pollution and mortality from chronic cardiovascular or respiratory disease appear to have been reported in Asia. As a result, recent estimates of the health impacts of air pollution in Asia (WHO 2002; World Bank and SEPA 2007) are based on the results of a single U.S. study (Pope et al. 2002).

The broad consistency of the results of Asian time-series studies of mortality with those in Europe and North America, including the evidence of greater rates of cardiovascular morbidity and mortality among older people than among younger people, supports the continued use of data from Western cohort studies to estimate the Asian burden of disease attributable to air pollution. However, developing Asia currently differs from the United States and Europe with regard to energy use, air quality, and population health, which are also dynamically changing. Thus, estimates of the impact of air pollution that are based on even the most carefully executed U.S. studies must be used with caution. One key area of uncertainty is the shape of the concentration–response function relating long-term exposure to air pollution and mortality from chronic disease. The concentrations of PM with an aerodynamic diameter $\leq$ 2.5 μm ($PM_{2.5}$) studied in the American Cancer Society (ACS) study (Pope et al. 2002) were much lower than the concentrations in major cities in China and India, requiring that analysts extrapolating the ACS data to Asia make projections regarding the shape of the concentration–response function at much higher concentrations. The uncertainty in the resulting estimates, when quantified in sensitivity analyses, was substantial (Cohen et al. 2004).

KNOWLEDGE GAPS AND RESEARCH NEEDS

The acute toxicity of short-term exposure to high air pollution concentrations has been appreciated since the early 20th century, and recent multi-city studies in Europe and North America have identified toxic effects at even lower concentrations. Therefore, the results of meta-analyses of Asian time-series studies of daily mortality and hospital admissions are not unexpected and can serve as an important part of the scientific basis and rationale for interventions to improve air quality. Nevertheless, there is much we still need to learn in order to fully understand the substantial air pollution challenges in Asia, and high-quality, credible science from locally relevant studies will be critical to helping decision makers choose which policies are most likely to result in public health benefits.

How Does the Nature of the Air Pollution Mixture Affect Air Quality, Exposure, and Health Effects?

Health impacts in cities in developing countries of Asia result from exposure to a mixture of pollutants, both particles and gases, which are derived in large part from combustion sources (Harrison 2006). This is true in Europe and North America as well, but the specific sources and their proportional contributions in Asia are different. Time–activity patterns, building characteristics, and proximity of susceptible populations to pollution sources in the region also differ from those in Western countries in ways that may affect human exposure and health effects. Our current knowledge of these issues is rudimentary, based largely on studies of individual pollutants, and additional research is needed to inform effective and sustainable control strategies. Without such studies, epidemiologists will have a difficult time assessing the relative effects of various pollution mixtures or specific pollution sources or even interpreting patterns of variation.

What Are the Effects of Long-Term Exposure to Air Pollution?

Although time-series studies will continue to be important potential drivers of environmental and public policy, additional study designs, such as recent U.S. and European cohort studies, are needed in Asia to estimate the effects of long-term exposure on annual average rates of mortality from chronic cardiovascular or respiratory diseases and impacts on life expectancy, the metrics that may be the most meaningful and relevant to policy.

Conducting such studies will be challenging, not least because of rapidly changing air pollution concentrations and exposures in developing Asia, although as some U.S. studies suggest, if chronic effects are due to recent exposure, this problem may not be severe. Recent exposure will also be most relevant in studies of adverse reproductive outcomes and effects on the health of young children. A detailed quantitative review of the larger Asian literature (including cross-sectional studies of chronic respiratory disease and studies of lung cancer and adverse reproductive outcomes) may better inform extrapolations of the results from the Western studies; the same may be true of the concentration–response functions describing short-term exposure and daily mortality recently reported for three Chinese cities (Wong CM et al. 2008; Wong CM and the PAPA Teams 2010a), but long-term Asian studies will provide the most direct evidence. It may be possible to "retrofit" existing Asian cohort studies, originally designed to address issues other than air

pollution, with estimates of air pollution exposure, the approach used in the ACS study. Retrofitting studies requires the building of multidisciplinary teams of investigators, with commitment of adequate, long-term resources, to work in collaboration with government officials, their industrial counterparts, and local stakeholders. In order to assess the current potential for such studies, HEI's PAPA program issued a Request for Information and Qualifications (Health Effects Institute 2009) for teams of investigators to conduct such studies in developing countries of Asia. Based on the responses, they concluded that the potential exists in several locations.

What Do Results of Current Time-Series Studies in a Subset of Asian Cities Tell Us About Health Effects of Air Pollution Exposure in Other, As Yet Unstudied, Asian Locales?

The numbers of time-series studies being reported from across Asia is growing; the first Indian studies of short-term exposure to respirable suspended particles (RSP) and daily mortality, part of the PAPA research program, will soon be published (Balakrishnan et al. 2010; Rajarathnam et al. 2010). Even so, almost all current studies have been conducted in mainland China, Taipei,China, and South Korea. Major population centers in South and Southeast Asia (India, Pakistan, Vietnam, Philippines, Indonesia, and Malaysia) are still largely understudied (with the exception of Bangkok). Differences in the relative prevalence of urban air pollution sources (such as open burning) and urban poverty may modify the effects of exposure. Expanded coordinated multicity studies, designed and analyzed consistently and conducted across the region, could provide more definitive answers. In some cases, outcomes other than mortality, such as hospital admissions, may also be studied, enabling policy makers to better quantify the health impacts of air pollution.

What Role Does Indoor Air Pollution Play in the Health Effects of Outdoor Air Pollution?

The magnitude and prevalence of exposure to indoor air pollution are high in Asian cities, especially among people living in poverty. We need a better understanding of how air pollution from indoor sources contributes to concentrations of outdoor air pollution and how indoor exposure to air pollution from indoor sources affects risk estimates for outdoor air pollution. Coordinated measurements of exposure and coordinated epidemiologic studies will be needed to address these questions.

What Role Does Poverty Play in the Health Effects of Air Pollution?

Limited evidence, largely from studies in Europe and North America, suggests that economic deprivation increases the rates of morbidity and mortality related to air pollution. One reason may be the higher air pollution exposures that people of lower socioeconomic status experience. The degree of vulnerability can also be affected by factors related to socioeconomic status, such as health, nutritional status, and access to medical services. Studies of these issues are relatively rare in Asia, where extreme poverty is more prevalent than in the West, so that results of the Western studies cannot be simply extrapolated, though the recent results of the PAPA studies in Shanghai and Hong Kong are welcome and much-needed additions (Kan H et al. 2008, 2010; Wong CM et al. 2008, 2010b). Some analyses of U.S. cohort studies suggest that low levels of attained education were associated with larger estimated relative risks of air pollution–related mortality (Krewski et al. 2000), but more recent analyses based on extended follow-up of the largest cohort have not upheld this pattern (Krewski et al. 2009). Studies in Asia that examine the effect of exposure on morbidity and mortality from diseases associated with poverty (such as acute lower respiratory infection in children, and tuberculosis) and studies that estimate effects of exposure across socioeconomic strata are needed. HEI's recently completed study of hospital admissions for acute lower respiratory infection in children in Ho Chi Minh City is, to our knowledge, the only example of such a study (Collaborative Working Group on Air Pollution, Poverty, and Health in Ho Chi Minh City 2009).

What Are the Health Consequences of Changes in Air Pollution Resulting from Climate Change and Efforts to Reduce Emissions of Climate-Forcing Agents?

Changes in air pollution resulting from climate change and from efforts to reduce emissions of climate-forcing agents may have important consequences for health in the region, especially in low- and middle-income countries. However, major unknowns remain, including (1) the quantitative association between reductions in the concentrations of GHGs (such as carbon dioxide) and toxic air pollutants such as ($PM_{2.5}$), (2) the relative toxicity of short-lived greenhouse pollutants with opposite climate-forcing potentials (such as sulfate and black carbon), and (3) the impact of policy choices. There is also a need to understand more fully how concentration–response functions for air pollution may vary with regard to global and within-region differences in climate, demographics, and pollutant mixes.

Finally, although the ability to conduct research on the health effects of air pollution in developing Asia is improving, it is still constrained by limitations in environmental and public health infrastructures. Air quality monitoring has increased in the region, but there is a need for more extensive monitoring of urban air quality designed to support health effects studies and impact assessments and a corresponding need for more highly trained professionals in air quality monitoring, exposure assessment, and environmental epidemiology. Equally important, there remain considerable deficiencies in registration of vital statistics in Asia, especially regarding accurate and comprehensive assignment of causes of death. There is also a need to encourage cooperation and collaboration in health effects research between health and environmental scientists and public agencies. These deficiencies constitute a major impediment to environmental health research and, more broadly, to the development of appropriate, evidence-based public health policy.

SUMMARY AND CONCLUSIONS: ENHANCED EVIDENCE OF EFFECTS OF AIR POLLUTION IN ASIA

Based on findings from more than 80 Asian time-series studies, including coordinated multi-city time-series studies, the meta-analytic estimates appear consistent in both direction and magnitude with those from other regions. In broad terms, the effects of short-term exposure in Asian cities are on a par with those observed in hundreds of studies worldwide. The same pollutants — RSP and gaseous pollutants such as ozone (O_3), SO_2, and NO_2 — affect older people with chronic cardiovascular or respiratory disease. The adverse effects in some locales, reported in studies published in the 1980s and 1990s, may reflect the effects of air pollution concentrations that have subsequently decreased. However, more recent studies continue to report adverse effects at lower levels in cities in Thailand and Japan, where air quality has improved, as well as in heavily polluted Chinese and Indian cities.

The results of our meta-analyses of time-series studies should serve to reduce concerns regarding the generalizability of the results of the substantial, but largely Western, literature on the effects of short-term exposure to air pollution. They suggest that neither genetic factors nor longer-term exposure to highly polluted air substantially modifies the effect of short-term exposure on daily mortality rates in major cities in developing Asia. This provides support for the notion, implicit in the approach taken in setting the WHO world air quality guidelines (Krzyzanowski and Cohen 2008), that incremental improvements in air quality are expected to improve health, even in areas with relatively high ambient concentrations. The results also suggest that health benefits would result from further reductions in exposure to pollution concentrations below those specified in the WHO guidelines.

The results of the chronic-effects studies reviewed in this report appear to be broadly consistent with those of studies in other regions, suggesting that long-term exposure to air pollution promotes chronic pulmonary disease and other adverse effects that result in reduced life expectancy. Nevertheless, these studies are more susceptible than the time-series studies to uncontrolled confounding by strong risk factors, such as tobacco smoking, indoor air pollution from the burning of solid fuels, and factors related to socioeconomic status, such as diet. These risk factors may also modulate the effect of air pollution, leading to larger effects in some population groups and smaller effects in others. Some of these factors, such as those related to the level of economic development, may be particularly important in developing Asia. If they are ignored or poorly measured, an inaccurate estimate of the effects of air pollution may result, and real differences among study results in various regions may be obscured.

This literature review documents a number of promising improvements in air quality in Asian cities, even in the context of economic growth. However, future assessments may yield larger estimates of the health impacts of air pollution in the region because of increasing rates of chronic cardiovascular and respiratory disease as populations age, risk factors increase in prevalence, and as exposure to combustion-source air pollution becomes more widespread, owing to urbanization, vehicularization, and industrialization. The effect of these changes could be counterbalanced by improved access to medical care and other improvements in the standard of living. Higher estimates of the magnitude of air pollution effects may also contribute to larger impact estimates. For example, the most recent publication from the ACS study (Krewski et al. 2009) reports larger estimates of the risks of cardiovascular mortality and lung cancer than previously reported.

This review demonstrates that the information on the health effects of air pollution in developing Asia is substantial and continues to grow in both size and quality. As such, it provides an increasingly confident base of scientific evidence to inform critical decisions in the region regarding policies to protect public health while furthering economic development. Important gaps still remain in the range of Asian settings studied and in the types of studies that need to be conducted in order to fully inform public policy decisions. This need will only grow as the attention of policy makers and the public increasingly focuses on issues of regional importance, such as climate change and transboundary air pollution. HEI intends that the publication of this Special Report, and continued funding of a targeted program of research in Asia under the PAPA program, will improve understanding of the problems posed by air pollution in Asia and will further develop the capacity of Asian scientists to conduct additional scientific research toward solutions.

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ABBREVIATIONS AND OTHER TERMS

ACS	American Cancer Society
APHEA	Air Pollution and Health: A European Approach
CAI-Asia	Clean Air Initiative for Asian Cities
CI	confidence interval
CO	carbon monoxide
COPD	chronic obstructive pulmonary disease
DALYs	disability-adjusted life-years
GAM	generalized additive model
GHG	greenhouse gas
IHD	ischemic heart disease
ISOC	International Scientific Oversight Committee
NMMAPS	National Morbidity, Mortality, and Air Pollution Study
NO_2	nitrogen dioxide
O_3	ozone
OR	odds ratio
PAHO	Pan American Health Organization
PAPA	Public Health and Air Pollution in Asia
PAPA–SAN	Public Health and Air Pollution in Asia — Science Access on the Net
PM	particulate matter
$PM_{2.5}$	PM with an aerodynamic diameter ≤ 2.5 μm
PM_{10}	PM with an aerodynamic diameter ≤ 10 μm
RSP	respirable suspended particles
SEPA	Chinese State Environmental Protection Administration
SO_2	sulfur dioxide
TSP	total suspended particles
U.S. EPA	U.S. Environmental Protection Agency
WHO	World Health Organization

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