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I interned as a visiting researcher at The Energy and Resources Institute (TERI), an environmental research institute based in New Delhi, to help assess the health impacts of widespread exposure to polluted air in India. This work directly advanced my dissertation research on air pollution epidemiology in the Nelson Institute for Environmental Studies (Environment and Resources program) and the Department of Population Health Sciences (Epidemiology) at UW-Madison.

Air pollution is a major environmental and public health challenge in India, where a recent assessment led by the World Health Organization estimated that ambient particulate matter air pollution ($PM_{2.5}$) in 2010 contributed to 620,000 annual excess deaths from respiratory disease, cardiovascular disease, and lung cancer on the Subcontinent, a sharp increase from the year 2000 estimate of 100,000 excess deaths. Exposure to ambient concentrations of fine particulate matter is the sixth leading risk factor for disease and early death in South Asia and the ninth worldwide. My analysis of pollution estimates at TERI suggests that half of India's urban population currently experiences particulate matter pollution levels exceeding national air quality standards and WHO air quality guidelines.

While the current air quality situation in India is dire, research that I completed at TERI indicates that this environmental and public health challenge will grow in coming years. First of all, the rapid pace of economic growth on the Indian subcontinent suggests that air quality issues and their public health impacts will remain central over the next 20-50 years due to overall increases in emissions. The Indian government has championed a goal of maintaining annual economic growth above 8% for the next two decades, which would increase per-capita income by a factor of five and stimulate an increasing demand for energy. With regards to emission trends in India, the electricity and road transportation sectors are of primary concern. India's electricity sector is highly reliant on coal and domestic deposits contain relatively high levels of sulfur, exacerbating particulate emissions and requiring more solid fuel to be burned to return the same amount of usable energy. Coal will account for about half of the national energy mix through at least the next two decades, with about 70% dedicated to the power sector. Economic growth in India is also expected to increase the share of two-wheelers and automobiles on already congested roadways: between 1951-1991, the population of Delhi expanded fourfold while vehicle registrations skyrocketed by a factor of more than fifty. Although fleet emission standards are steadily being lowered, the number of new vehicle owners may overwhelm these gains and contribute to increasing polluting emissions from the transportation sector and exacerbate the smog of ozone (O_3) pollution.

In addition to the effects of economic growth on demand for electricity and road transportation, research that I completed at TERI shows that climate change is expected to exacerbate surface concentrations of $PM_{2.5}$ and O_3 in India. The chemical formation of O_3 in the atmosphere is temperature dependent, and as a result climate change and higher surface temperatures are expected to worsen O_3 pollution in India. This direct effect will be a particularly important policy concern in cities such as Delhi, one of the most polluted urban areas in India, which is expected to experience a relatively large increase in annual mean temperature over the coming decades compared to historic climate patterns. Global climate models suggest that O_3 concentrations may rise 1–10 parts per billion (up to 10% of the Indian standard) as a result of surface warming.

What do these anticipated effects mean for estimates of future air quality and health impacts in India? I worked with air pollution modelers at TERI and collaborators at the International Institute for Applied Systems Analysis on a computer model for simulating air pollution scenarios and calculating impacts on public health. This model, the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) program, is the best available tool for predicting future air pollution levels for India on a national scale. Our modeling of air quality suggests that by 2030, $PM_{2.5}$ levels will increase by 30%.

My work at TERI focused on improving the methodology in GAINS for health impact assessment of $PM_{2.5}$ exposure at high levels. Large studies of chronic exposure to $PM_{2.5}$ and mortality risk are largely confined to areas with low to moderate ambient $PM_{2.5}$ concentrations and posit linear dose-response mortality risk estimates. I applied new mathematical risk functions from WHO to improve our estimates of how exposures to air pollution affect life expectancy in India. I used air pollution projections assembled at TERI and health data (mortality estimates for specific causes of disease) from the Indian Ministry of Health to calculate changes in life expectancy for those exposed to high $PM_{2.5}$ levels over many years. For the first time, health impact estimates for India were shaped by national age- and cause-specific mortality rates.

In my work, modeled year 2030 $PM_{2.5}$ pollution in India reached an annual mean of 74$\mu g/m^3$, nearly eight times the corresponding WHO air quality guideline. Nationally, I calculated an average per capita loss in life expectancy due to air pollution of 32.5 months. The dramatic shortening of life expectancy peaked in Delhi, the most polluted region (108 months, or 9 years), and nationally 1.1 billion years of life lost were attributed to chronic $PM_{2.5}$ exposure. My work likely underestimates the total health burden caused by air pollution exposure due to model assumptions on minimum age thresholds of pollution effects, and suggests that the most polluted Indian cities will reap major health benefits only with ambitious efforts to improve air quality.

While working at TERI, I was struck by the degree to which environmental threats to public health are increasingly issues which span national borders and disciplinary boundaries. While my work focused on air pollution in India, I had to consider pollution sources from neighboring China and Pakistan, which complicate the policy implications of air pollution control in India. My research relied on the challenging integration of data from energy, air pollution, and health research efforts. Moreover, the air pollution problems which I modeled at TERI were plainly visible during my daily commute, and I became increasingly cognizant of risks to particularly vulnerable populations in the country, including rickshaw drivers, expecting mothers, and the urban poor. Environmental exposure and epidemiologic studies of these groups are just getting off the ground in Asian cities. My hope is that future collaborations between TERI and public health institutions can help to identify and mitigate the mounting environmental threats to well-being in India and beyond. I believe that health impact assessments of the current and future air pollution-related burden of disease can help motivate policies to achieve sustainable development and a cleaner energy future, resulting in healthier air quality for the Indian population, and reductions in rates of air pollution-related disease and early death.