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Major Factors Influencing the Health Impacts from Controlling Air Pollutants with Nonlinear Chemistry: An Application to China

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Predicting the human-health effects of reducing atmospheric emissions of nitrogen oxide (NO_x) emissions from power plants, motor vehicles, and other sources is complex because of nonlinearity in the relevant atmospheric processes. We estimate the health impacts of changes in fine particulate matter ($PM_{2.5}$) and ozone concentrations that result from control of NO_x emissions alone and in conjunction with other pollutants in and outside the megacity of Shanghai, China. The Community Multiscale Air Quality (CMAQ) Modeling System is applied to model the effects on atmospheric concentrations of emissions from different economic sectors and geographic locations. Health impacts are quantified by combining concentration-response functions from the epidemiological literature with pollutant concentration and population distributions. We find that the health benefits per ton of emission reduction are more sensitive to the location (i.e., inside vs. outside of Shanghai) than to the sectors that are controlled. For eastern China, we predict between 1 and 20 fewer premature deaths per year per 1,000 tons of NO_x emission reductions, valued at \$300–\$6,000 per ton. Health benefits are sensitive to seasonal variation in emission controls. Policies to control NO_x emissions need to consider emission location, season, and simultaneous control of other pollutants to avoid unintended consequences.

KEY WORDS: Air pollution; China; CMAQ; health risk; ozone; NO_x; $PM_{2.5}$

1. BACKGROUND

Epidemiologic studies have shown that exposure to elevated concentrations of fine particles and ozone is associated with increases in mortality, cardiovascular, and respiratory diseases.[(1–4)] Air pollution levels in many parts of China far exceed Chinese and international air quality standards and pose a serious threat to public health. In particular, emissions of nitrogen oxides (NO_x) in China have been increasing more rapidly in recent years than other pollutants, e.g., sulfur dioxide (SO_2), volatile organic compounds (VOC), and fine particulate matter ($PM_{2.5}$),[(5)] likely as a result of growing fossil fuel consumption and a dramatic rise in the number of vehicles. NO_x is listed in the 12th Five-Year Plan (years 2011–2015) of the Chinese government as a key pollutant for emission control. However, among the different pollutants, such as SO_2, NO_x, $PM_{2.5}$, and VOC, the health impacts of NO_x emission

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reductions are the most complex, as NO_x emissions can significantly influence the concentrations of both $PM_{2.5}$ and ozone, and there are substantial nonlinearities in the relevant atmospheric processes.(6) For example, reductions in NO_x emissions can increase ozone concentrations in some locations, such as the urban core.(7) Secondary $PM_{2.5}$ and ozone require some time to form, and they have long atmospheric lifetimes. In addition, controlling NO_x and VOC simultaneously could be much more effective in reducing ozone concentration than controlling only NO_x in some cases.(7) As a result, government policies that target NO_x emission reductions alone in certain cities or locations may not be globally optimal.

We found two studies in the literature that calculated the health impacts due to the change in multipollutant concentrations corresponding to NO_x emission reductions using a state-of-the-art air quality model in China.(8,9) Although both studies show that there are nonlinear responses of ozone concentration to NO_x emission reductions, neither study analyzed the impact of geographic locations on the effectiveness of air pollution control from different sectors. In this study, we estimate the joint health impacts from the change in $PM_{2.5}$ and ozone concentrations corresponding to NO_x control alone and in conjunction with other pollutants in different sectors and geographical locations. Our analysis would allow us to determine whether a narrow geographic orientation for practical reasons, such as the economic resources available or ease in implementation, is the optimal control strategy locally or globally and how the results vary by sector and other pollutants under control jointly.

We designed control strategies in and around a large mega-city—Shanghai, China. We chose to focus on Shanghai in our analysis mainly for two reasons. First, it is one of the world's largest cities with over 18 million long-term residents and is located in the heavily populated region of Yangtze River Delta with fast economic development. As a result, for any emission reduction measures, there could be significant positive or negative health impacts, depending on how they influence the air pollution concentration levels. Second, as Shanghai has been hosting large international events, such as the World Expo in 2010, it is plausible that the local government may occasionally aim at reducing its air pollution levels further than its neighboring provinces temporarily. Although we focus on Shanghai in our analysis, the findings could provide relevant scientific evidence when similar decisions need to be made regarding NO_x control in other parts of China or elsewhere. In this study, we focus our analysis on the power, mobile, and industry sectors, which have high NO_x and VOC emissions. To determine their effectiveness in reducing population exposure, we compare the hypothetical emission control strategies implemented inside Shanghai with those outside Shanghai.

2. METHODS

We begin by estimating baseline emissions in the year 2006 from sources in the study area and calculate the corresponding pollutant concentration and population exposure. Next, we design hypothetical scenarios, which represent emission reductions from the base case. An advanced air quality model is used to characterize concentration distributions. Health impacts (mortality) are quantified by combining coefficients from concentration-response (C-R) functions from the epidemiological literature with the pollutant concentration and population distributions. Finally, the economic values of the health improvements are calculated. More details of the health-impact assessment methods are presented elsewhere.(10,11) Below, we describe the components involved in this study.

2.1. Study Domain and Air Quality Modeling

A state-of-the-science Eulerian grid model (Community Multiscale Air Quality model—CMAQ (v4.6))(12,13) is applied to an emission inventory we developed for the year 2006(9) to estimate the baseline concentrations and incremental changes associated with hypothetical control strategies. We apply a one-way nested grid in the CMAQ simulations with 27 km (covering most of China) and 9 km (covering eastern China including Shanghai) grid resolutions (Fig. S1). Output from the domain with 27 km resolution is used as boundary conditions for the 9-km resolution "study domain." Meteorological inputs are generated using the PSU/NCAR Mesoscale Model (MM5), version 3.7.(14) All the simulations are for calendar year 2006. Annual averages of $PM_{2.5}$ and eight-hour maximum ozone concentrations, most relevant to health-impact assessment given the state of the epidemiological evidence, are calculated based on hourly $PM_{2.5}$ and ozone concentration output from CMAQ. For more detailed information on the CMAQ and MM5 configurations, refer to Table S1.

$PM_{2.5}$ is not currently a criteria air pollutant in China, so it is not monitored routinely. Also, there are no publicly available ozone-monitoring data. These factors limit our ability to conduct a comprehensive model performance evaluation over the entire study domain. We performed model evaluation based on monitoring data available from a research monitoring site located in the downtown of Shanghai. For both $PM_{2.5}$ and ozone, the model performs reasonably well, with mean fractional bias (MFB) and mean fractional error (MFE) below or close to the benchmark values.[(15)] More detailed information on the model evaluation can be found in the Supporting Information.

2.2. Hypothetical Scenarios for Emission Reductions

We construct a set of scenarios to estimate the incremental effects of controlling key pollutants by emission source and region. We focus on NO_x, which influences $PM_{2.5}$ and ozone concentrations nonlinearly. We include VOC, which may influence ozone concentration significantly, depending on the ratios of VOC and NO_x. In addition, for comparison purpose, we include primary $PM_{2.5}$, which can also provide significant co-benefits for control strategies that address both NO_x and primary $PM_{2.5}$ emission reductions. We focus on economic sectors that are major emission sources: power, industry, and mobile. These sectors have very different source characteristics; e.g., power plants are point sources with tall stacks, whereas mobile produces line sources close to the ground. By comparing NO_x controls in the mobile and power sectors, we gain an insight into the importance of source characteristics in reducing ozone and $PM_{2.5}$ concentrations. For the region under study, we model the effects of emission controls inside and outside Shanghai on the health of Shanghai residents and of those in the entire study domain.

The emission scenarios are shown in Table I. In addition to the baseline scenario (reflecting emissions in the year of 2006), there are five scenarios with emission reductions in Shanghai alone and five with emission reductions outside Shanghai. One scenario includes emission reductions both inside and outside Shanghai to test for nonlinear effects of simultaneous control in both regions. In addition, we have one scenario with zero emissions from all sources in Shanghai to determine the contribution of outside sources to Shanghai residents' exposure. For the pollutants under study, we include scenarios for reducing NO_x alone, supplemented with VOC and with VOC and primary $PM_{2.5}$ control. The magnitudes of the emission reductions approximate the effects of specific control technologies for the power sector and plausible emission reductions in other sectors.

For each scenario, we estimate total exposure and health effects but focus on the incremental effects per ton of emissions to facilitate comparisons among emission sectors, regions, and pollutants. To estimate pollutant-specific benefits, we use changes in population exposure between scenarios.

2.3. Population Exposure

Changes in population exposure are calculated by combining population in each location with the corresponding concentration change. Population distribution is estimated using LandScan 2007 population data.[(16,17)] Additional demographic information such as baseline mortality rates is obtained from China Census 2000.[(18)] The study includes a total population of 1.1 billion of whom 16 million are in Shanghai. Fig. 1 shows the population distribution in the study domain.

Comparison of the incremental benefits per ton of emission reduction is facilitated by using the concept of intake fraction (iF), the fraction of a material, or its precursor, released from a source that is inhaled or ingested by the population.[(19)] We calculate iF as $\Sigma(C_i \times P_i) \times \mathrm{BR}/Q$, where C_i is the incremental concentration of the pollutant in grid cell i (μg/m^3) associated with source emission rate Q (μg/day, noting that the emitted material can be pollutant j or a precursor), P_i is the population in the grid cell, and BR is a nominal breathing rate of 20 m^3/day. Note that iFs become a unit-free metric when breathing rate is incorporated. This term cancels out in the health-impact calculations and hence does not influence their values. A simple linear adjustment is needed when comparing our iF values with other studies where different breathing rates are used. We calculate iFs for primary $PM_{2.5}$, secondary $PM_{2.5}$, and ozone. Note that for secondary pollutants, i.e., secondary $PM_{2.5}$ and ozone, iFs are not technically unit less, representing the change in the mass of $PM_{2.5}$ or ozone inhaled per unit mass of NO_x or VOC emission change. The iFs for $PM_{2.5}$ are based on annual average concentrations and those for ozone are based on the annual average of the daily eight-hour maximum ozone concentrations, reflecting the structure of the epidemiological evidence for these pollutants.

Table I. CMAQ Simulation Scenarios Targeting Emission Reductions of NO_x, VOC, and Primary $PM_{2.5}$ in Different Sectors

Scenario	Sector	Location	Description	Reduction Percentage
0	All	Inside Shanghai	All pollutants	100%
1	Power	Inside Shanghai	NO_x	85%
2	Power	Outside Shanghai	NO_x	85%
3	Power and industry	Inside Shanghai	NO_x + VOC	85% for NO_x from power; 20% for VOC from industry
4	Power and industry	Outside Shanghai	NO_x + VOC	85% for NO_x from power; 20% for VOC from industry
5	Power and industry	Entire 9 km domain	NO_x + VOC	85% for NO_x from power; 20% for VOC from industry
6	Power and industry	Inside Shanghai	NO_x + VOC + $PM_{2.5}$	85% for NO_x from power; 20% for VOC and $PM_{2.5}$, from industry
7	Power and industry	Outside Shanghai	NO_x + VOC + $PM_{2.5}$	85% for NO_x from power; 20% for VOC and $PM_{2.5}$, from industry
8	Mobile	Inside Shanghai	NO_x	50%
9	Mobile	Outside Shanghai	NO_x	50%
10	Mobile	Inside Shanghai	NO_x + VOC + $PM_{2.5}$	50% for NO_x, VOC and $PM_{2.5}$
11	Mobile	Outside Shanghai	NO_x + VOC + $PM_{2.5}$	50% for NO_x, VOC and $PM_{2.5}$

Notes: In addition to the scenarios listed above, CMAQ simulation was performed for the base case, reflecting the actual status of year 2006. Though arbitrary, the percentages of emission reductions in the simulation scenarios listed are considered reasonable given existing technologies. For example, reduction of NO_x emissions can be achieved using the SCR technology. Primary $PM_{2.5}$ emission reductions in the industry sector can be achieved using fabric filter. VOC emission reduction technology varies for different types of industries. Mobile sector emission controls also include engine upgrade.

2.4. C-R Functions

We restrict attention to mortality effects, as prior studies have found that these dominate the total economic value of $PM_{2.5}$ and ozone-related health effects. As described elsewhere,[9] we previously developed C-R function coefficients for $PM_{2.5}$ and ozone mortality based on epidemiological studies conducted in the United States and China. To summarize, for ozone, we use a 0.3% reduction in all-cause mortality per 10 μg/m^3 reduction in annual average of eight-hour daily maximum ozone as a central estimate, with 0.15% and 0.45% as lower and upper bounds, respectively. For $PM_{2.5}$, we use a 1% increase in all-cause mortality per 1 μg/m^3 increase in annual $PM_{2.5}$ concentrations as our central estimate, with 0.3% and 2.0% as lower and upper bounds, respectively. Note that although NO_x may influence different components of $PM_{2.5}$ (e.g., sulfate, nitrate, and ammonium[20]), C-R functions usually do not account for $PM_{2.5}$ composition. Therefore, we use the total $PM_{2.5}$ concentration output from the CMAQ simulations when applying the coefficients of C-R functions summarized here. We consider the potential sensitivity of our findings to this assumption as well as the assumption of a linear C-R function throughout the range of ambient concentrations in China.

2.5. Valuation of Health Impacts

Following standard practice, we calculate the monetary value of the change in mortality risk by multiplying the expected change in annual deaths by the "value per statistical life" (VSL), which represents the population average rate at which people would exchange money for small changes in mortality risk. VSL depends on income and other population characteristics. Because the number and quality of direct VSL estimates for China are limited, we adopt estimates from Hammitt and Robinson[21] that are derived by extrapolating values from the United States and adjusting for the difference in income, yielding a base estimate of \$250,000 with lower and upper values of \$86,000 and \$740,000, respectively (2007 dollars adjusted for purchasing-power parity, PPP). Direct estimates for urban populations in China are smaller than our base estimate and comparable to our lower value; however, those estimates were obtained for populations with smaller average incomes than the value of \$5,370

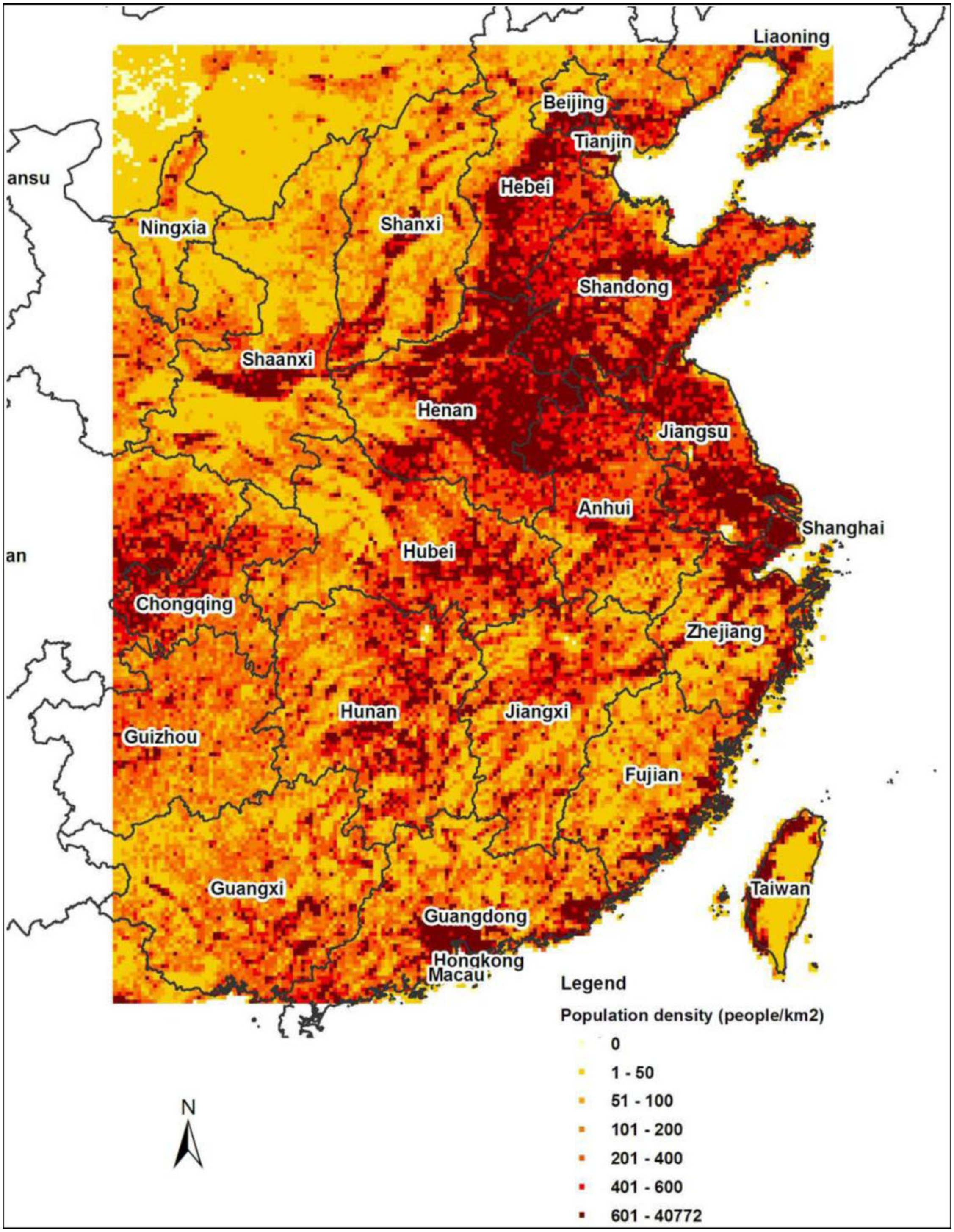

Fig. 1. Population distribution (number of people per square kilometer).

used by Hammitt and Robinson.[21] Adjusting from exchange rates to PPP, direct estimates of VSL include: \$80,000[22] with mean income of \$1,400 for urban workers; \$110,000 and \$50,000[23] with mean incomes of \$4,800 and \$3,000 for Beijing and Anqing city, respectively; and \$60,000 for Chonqing city[24] with mean income of \$900. Although we report the central estimates, we also conduct a Monte Carlo simulation to estimate the possible ranges of the health-benefit estimates due to uncertainty in the inputs.

Although comprehensive benefit-cost analyses would be useful for prioritizing control strategies, data on control costs for China are limited and deriving appropriate estimates is beyond the scope of our study. To illustrate the interpretation of our results, we compare the monetary value of health impacts in one control scenario with rough estimates of control cost. Based on the limited information available,[25] we estimate the cost for NO_x emission reductions from power plants using selective catalytic reduction (SCR). For a reduction of 2.4 million tons of NO_x, the initial investment is about 32.9 billion RMB and the annual operating cost is about 20.3 billion RMB. If we assume 15 years in operation and an exchange rate of 6.45 RMB for \$1, the cost is about \$1,500 per ton of NO_x removal, neglecting discounting and adjustment for inflation for this first-order approximation. This estimate is comparable to annualized cost estimates for the United States. For example, in the regulatory impact analysis of the Clean Air Interstate Rule, the U.S. EPA estimated that the marginal cost of this cap-and-trade program would be approximately \$1,300 per ton for NO_x in 2010.[26] EPA's AirControlNET estimate of the annual operating cost is about \$1,000 for NO_x control in the power sector using SCR with 85% removal efficiency.[27] Our cost estimates are used only for demonstration as they are based on very limited data.

3. RESULTS AND DISCUSSION

3.1. Base Case Emissions and Ambient Concentrations

Table II reports emissions by sector and pollutant for the study domain. The power sector emits the largest quantity of NO_x, though its emissions of VOC and primary $PM_{2.5}$ are less than 25% of those from the industry sector. The industrial sector has the highest emissions of VOC and $PM_{2.5}$ and is a major contributor of NO_x. Mobile sector contributes significantly to the emissions of both VOC and NO_x. Sources in Shanghai contribute a small fraction of the total emissions in the study domain, 3% of NO_x and VOC, respectively, and 1% of $PM_{2.5}$.

Fig. 2 shows the base case annual average $PM_{2.5}$ concentration in 2006. Based on the newly published Ambient Air Quality Standard of China, $PM_{2.5}$ will become a criteria pollutant starting 2016.[28] The annual average concentration limit is 15 $\mu g/m^3$ for class I areas, which include national parks and areas under special environmental protection; 35 $\mu g/m^3$ for class II areas, which include residential, business, cultural, agricultural, and industrial areas. As a comparison, the limit for annual average primary $PM_{2.5}$ concentration is 12 $\mu g/m^3$ in National Ambient Air Quality Standard (NAAQS) in the United States, whereas that for secondary $PM_{2.5}$ is 15 $\mu g/m^3$. Fig. 2 shows that most of the study domain has annual average $PM_{2.5}$ concentration greater than 15 $\mu g/m^3$ and a significant portion of the domain has $PM_{2.5}$ concentration greater than 35 $\mu g/m^3$. The concentrations in some highly industrialized areas in Hebei, Shandong, and Jiangsu provinces are well above 75 $\mu g/m^3$. Fig. 2 also shows the annual average of the daily eight-hour maximum ozone concentration in the base case, which ranges from 9 to 65 ppb. This metric is widely used in epidemiological studies though it is not directly comparable with the ozone NAAQS (which limits the three-year average of the fourth highest daily maximum eight-hour average ozone concentrations to 75 ppb). In the new Ambient Air Quality Standard of China, the limits for hourly ozone concentration range from 0.16 to 0.2 mg/m^3 (approximately 75–90 ppb assuming standard temperature and pressure) depending on the region classification, whereas there is no annual average ozone concentration limit.

Eliminating all the emissions from the three sectors under study (i.e., power, industry, and mobile) in Shanghai decreases Shanghai residents' $PM_{2.5}$ population exposure by 55%. In contrast, this action increases Shanghai residents' ozone exposure by nearly 90%.

3.2. Population Exposure

Table III shows the impact of emission-control measures on iF by sector, pollutant, location of control, and location of residents. Positive iF values mean that emission control reduces population exposure, with larger values corresponding to larger reductions. Negative values imply that emission reductions increase exposure.

Table II. Estimated Emission Rates by Sector, Pollutant, and Location in the Base Case (in 1,000 Tons per Year) for the Sectors Under Study

Pollutant	Location	Power Plant	Mobile	Industry	Total
NO_x	Entire domain	8,488	5,199	4,990	18,677
	Shanghai	295	174	153	622
	Percent from Shanghai	3.5%	3.4%	3.1%	3.3%
VOC	Entire domain	1,009	6,063	7,803	14,875
	Shanghai	41	120	278	439
	Percent from Shanghai	4.1%	2.0%	3.6%	3.0%
Primary $PM_{2.5}$	Entire domain	1,441	425	6,081	7,947
	Shanghai	38	5	49	92
	Percent from Shanghai	2.6%	1.1%	0.8%	1.2%

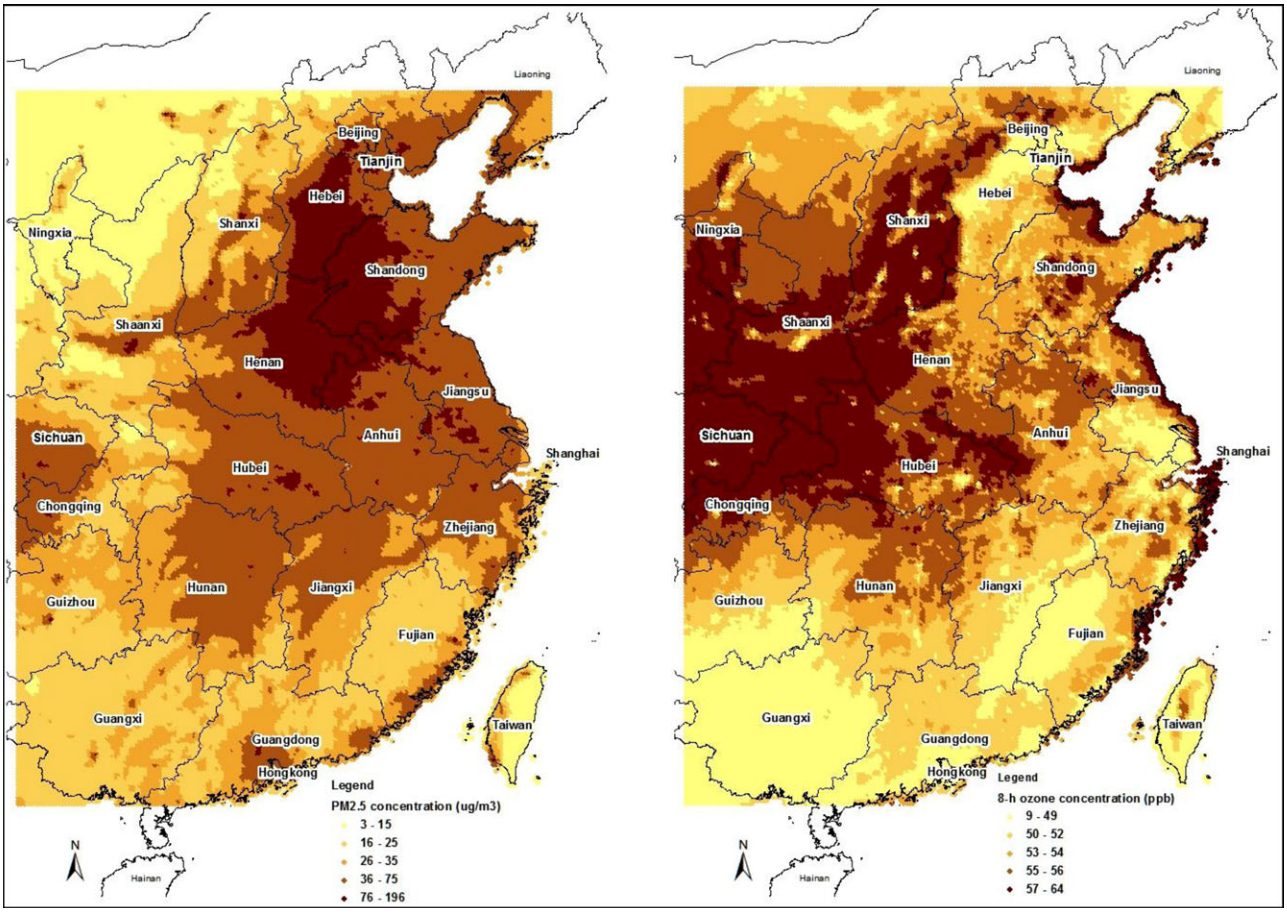

Fig. 2. Estimated annual average of $PM_{2.5}$ concentration and of daily maximum 8-hour ozone concentration in the base case.

3.2.1. *Impact of Control Location on Population Exposure to $PM_{2.5}$ in the Study Domain*

When population in the entire study domain is considered, all the emission reduction scenarios under study (both inside and outside Shanghai) reduce total population exposure. The $PM_{2.5}$ iFs corresponding to NO_x controls are on the order of 10^{-6} for emission reductions outside Shanghai and 10^{-7} for reductions in Shanghai (Table III). This means that population exposure to $PM_{2.5}$ in the study domain falls, on average, 1 g for each ton by which NO_x emissions are reduced outside Shanghai and 0.1 g per ton for

Table III. Intake Fractions by Industry, Pollutant, Control Location, and Exposed Population Location

			iF[a] ($PM_{2.5}$)		iF[a] (Ozone)	
Pollutant	Sector	Control Location	Population Inside Shanghai	Population in Entire Domain	Population Inside Shanghai	Population in Entire Domain
NO_x	Power	Inside	-1.1×10^{-7}	3.1×10^{-7}	-4.2×10^{-6}	-5.4×10^{-6}
		Outside	2.4×10^{-8}	2.9×10^{-6}	-1.3×10^{-8}	-2.2×10^{-6}
	Mobile	Inside	-8.5×10^{-8}	7.3×10^{-7}	-7.4×10^{-6}	-2.0×10^{-6}
		Outside	1.8×10^{-8}	1.9×10^{-6}	2.7×10^{-9}	-3.9×10^{-6}
VOC	Industry	Inside	4.3×10^{-8}	7.9×10^{-7}	4.7×10^{-7}	4.1×10^{-6}
		Outside	8.1×10^{-10}	7.3×10^{-9}	1.1×10^{-8}	1.9×10^{-6}
	Mobile[b]	Inside	n/a	n/a	5.2×10^{-7}	4.9×10^{-6}
		Outside	n/a	n/a	2.3×10^{-8}	4.9×10^{-6}
Primary $PM_{2.5}$	Industry[c]	Inside	4.1×10^{-5}	5.3×10^{-5}	2.5×10^{-9}	-1.6×10^{-7}
		Outside	1.1×10^{-7}	1.9×10^{-5}	-6.1×10^{-10}	-9.7×10^{-8}
	Mobile[d]	Inside	6.9×10^{-5}	1.2×10^{-4}	n/a	n/a
		Outside	1.9×10^{-7}	3.7×10^{-5}	n/a	n/a

[a]Positive values mean there is exposure reduction associated with emission reduction; negative values mean there is an increase in exposure associated with emission reduction. For details regarding which scenarios are compared in calculating the intake fractions in the table, refer to Table S2.
[b]Calculated as (ozone exposure change)/(VOC emission reductions), which includes small contribution from PM-related exposure reduction in this scenario.
[c]There is a small but nonzero ozone intake fraction for primary $PM_{2.5}$ emission reductions. This could be because primary $PM_{2.5}$ emissions from the industry sector include primary nitrate emissions. Reducing primary nitrate emissions can impact the equilibrium of nitrate, NO_2, and NO, which can lead to small changes in ozone concentration.
[d]Calculated as ($PM_{2.5}$ exposure change)/(primary $PM_{2.5}$ emission reduction), which includes small contribution from VOC-related exposure reduction in this scenario.

emission reductions inside Shanghai. For VOC emission reductions, the iFs for $PM_{2.5}$ population exposure in the entire study domain are on the order of 10^{-7}–10^{-9}. The effects per ton of emission reduction are two orders of magnitude larger for controls inside Shanghai than outside Shanghai, likely due to higher population density near the Shanghai VOC sources. The spatial patterns associated with these iF values are illustrated in Fig. S3, which shows the influence on annual average $PM_{2.5}$ concentration for controls inside Shanghai, including an 85% reduction in NO_x emissions from the power sector and 20% reductions in VOC and primary $PM_{2.5}$ emissions from the industry sector, and Fig. S4, which shows the change in $PM_{2.5}$ concentration when these emission controls are applied outside Shanghai.

3.2.2. *Impact of Control Location on $PM_{2.5}$ Exposure of Shanghai Residents*

When only the population in Shanghai is considered, NO_x emission reductions in the mobile and power sectors inside Shanghai result in an increase in $PM_{2.5}$ exposure as shown by the negative iF values. Interestingly, reducing regional rather than local NO_x emissions is more effective in reducing Shanghai residents' exposure to $PM_{2.5}$. As a comparison, when primary $PM_{2.5}$ emissions from the industry and mobile sectors inside Shanghai are reduced, the corresponding $PM_{2.5}$ iFs for Shanghai residents are positive and on the order of 10^{-5}. In this case, exposure reduction among Shanghai residents dominates the total exposure reduction, contributing about 60–80% of the exposure reduction for the entire domain. For primary $PM_{2.5}$ emission reductions outside Shanghai, the iF for residents in the study domain is also on the order of 10^{-5}, but the iF for Shanghai residents is two orders of magnitude smaller. This implies that for primary $PM_{2.5}$, unlike for NO_x, it is more effective to reduce emissions in Shanghai than outside to reduce Shanghai residents' exposure.

3.2.3. *Impact of Control Location on Ozone Exposure*

For ozone, half of the iF values are negative, showing that emission controls can increase ozone concentrations in many instances. With one exception (mobile sector outside Shanghai for populations inside Shanghai), all of the iFs for ozone exposure from NO_x emission reductions are negative. In contrast, all the ozone iFs for VOC emissions are positive, presumably because ozone formation is likely VOC-limited in many areas of the study domain. Ozone iFs for population in the entire study domain related to VOC reductions are on the order of 10^{-6}, regardless of the location and sector of control. For Shanghai residents, reducing VOC emissions inside Shanghai is an order of magnitude more effective than reducing VOC emissions outside Shanghai, for both industry and mobile sectors.

3.2.4. Impact of Sector on Population Exposure

Reducing VOC emissions in the mobile sector could be twice as effective as that in the industry sector in reducing ozone concentrations. Similarly, reducing primary $PM_{2.5}$ emissions in the mobile sector could be twice as efficient as the reduction in the industry sector in lowering $PM_{2.5}$ concentration. This finding is consistent with another study of iF for primary $PM_{2.5}$,[29] in which outdoor primary $PM_{2.5}$ reductions from ground-level sources in urban areas are about twice that for elevated sources (44×10^{-6} vs. 26×10^{-6}). For iFs relating NO_x emissions and $PM_{2.5}$ and ozone exposure, this relationship is less clear. Overall, iFs are on the same order of magnitude for the same control location and target population combinations across sectors. For both $PM_{2.5}$ and ozone, the variance of iFs for the sector of emission control is smaller than the variance for the pollutants under control (i.e., NO_x, VOC, primary $PM_{2.5}$), control location (inside vs. outside Shanghai), and target population (in Shanghai vs. entire domain).

3.2.5. Impact of Control Timing on Population Exposure

Although there is an increase in the annual average ozone exposure for most NO_x controls, exposure reductions could be achieved if control measures are implemented only during certain months of the year. Fig. 3 shows monthly percentage changes in ozone exposure for Shanghai residents corresponding to NO_x emission reductions in the power sector. Although there is little seasonal variation for NO_x emission reductions inside Shanghai, reducing NO_x emissions outside Shanghai reduces Shanghai residents' ozone exposure from May through September. This could result from the warmer temperatures that yield more biogenic VOCs in the summer, along with faster photolysis rates that favor OH formation and NO_x-limited conditions. $PM_{2.5}$ exposure does not demonstrate strong seasonal patterns for the different emission controls modeled.

3.3. Health Impacts

3.3.1. Health Impacts for Shanghai Residents

Table IV reports calculated changes in annual fatalities resulting from changes in $PM_{2.5}$ and ozone concentrations, applying our central estimates for the sake of comparisons across scenarios and noting that ratios among scenarios by pollutant are not sensitive to the C-R function. For Shanghai residents, the net annual mortality change per 1,000 tons of NO_x emission reductions ranges from an increase of 2 to a reduction of 0.2. The mortality reduction per 1,000 tons of VOC emission reduction in the industry sector (on the order of 0.4 to 0.008) is smaller than the increase in mortality due to NO_x reduction in the power sector in the same control location. For comparison, annual mortality reductions per 1,000 tons of primary $PM_{2.5}$ emission reductions range from 1 to 400, meaning that reducing primary $PM_{2.5}$ could be several orders of magnitude more effective than controlling NO_x emissions alone in the same location (all else being equal).

3.3.2. Health Impacts for Residents in the Entire Study Domain

For the entire study domain, PM-related mortality falls in all control scenarios and ozone-related mortality rises in six scenarios, but the net effect is always beneficial for our central estimate C-R functions. The values for annual NO_x-related mortality reduction per 1,000 tons of emission reduction are between 10 and 20 for controls outside Shanghai, while that for controls inside Shanghai is less than 10. Similar to the case for Shanghai residents, for the entire domain, the largest gains per ton of emission reduction are from reducing VOC and primary $PM_{2.5}$ emissions simultaneously from the mobile sector inside Shanghai, partly explained by the large health benefit among Shanghai residents and that associated with primary $PM_{2.5}$ control alone as seen from the industry sector. The lowest benefits per ton are from controlling VOC from industry sectors outside Shanghai. This is likely due mainly to the relatively small impacts of VOC on $PM_{2.5}$ concentration.

Regardless of the location of residents, the overall health benefits per ton of emission reductions are

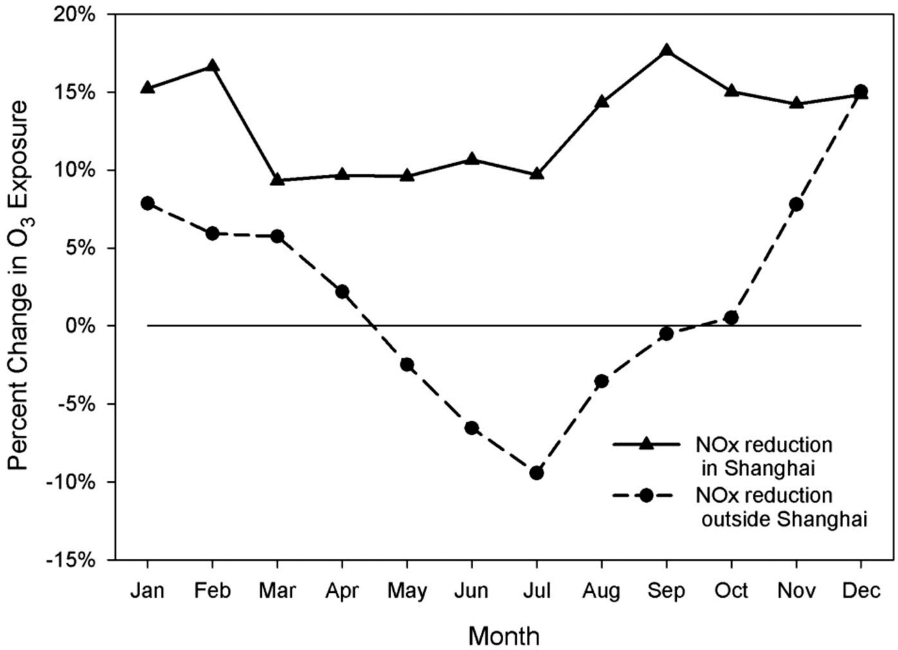

Fig. 3. Change in ozone exposure of Shanghai residents by month corresponding to NO_x emission reductions from power plants inside versus outside Shanghai.

dominated by $PM_{2.5}$, partially due to the larger C-R function coefficient used in calculating health impacts for $PM_{2.5}$ than for ozone.

3.3.3. Control Harmonization

Although not shown in Table IV, we find that when identical control measures on NO_x, VOC, and primary $PM_{2.5}$ are implemented simultaneously both inside and outside Shanghai, the total mortality reduction is only a few percent higher than the sum of controlling emissions separately at the two locations. Considering the uncertainties in air quality modeling, this suggests that effects of controls in the two regions are nearly additive with no additional benefits from harmonization.

3.4. Valuation of Health Impacts

The monetary values for mortality change are calculated by multiplying the net annual mortality changes per ton of emission reductions by our central VSL estimate of $250,000. These range across pollutants and sectors from about −$500 to $100,000 per ton of emission reductions when only Shanghai residents are considered, and from about $100 to $200,000 per ton of emission reductions for the entire study domain. The rankings of the monetary values of health impacts for the different emission reductions remain the same as that for the unit mortality change in Table IV.

For our illustrative benefit-cost comparison, the monetized health benefits of reducing NO_x can be compared with the cost of reducing NO_x in the power sector of roughly $1,500 per ton. When only the benefits to Shanghai residents are considered, the net benefits are negative for reducing NO_x alone from the power sector inside Shanghai and about $40 per ton for the same control outside Shanghai. For the entire domain, the net benefits are $300 and $6,000 per ton of reductions in NO_x emissions inside and outside Shanghai, respectively. Recognizing substantial uncertainties in these calculations and in the control cost estimate, the results suggest that applying NO_x controls to the power sector outside Shanghai is likely to be cost beneficial overall.

3.5. Uncertainty Analysis

Clearly, the health damage and other estimates are quite uncertain, but it is challenging to quantify and propagate uncertainty across all model components. To approximate the uncertainty in the valuation of the mortality change or damage costs, we

Table IV. Mortality Reduction Estimates by Industry, Pollutant, Control Location, and Exposed Population Location

Scenario	Sector	Control Location	Pollutant Controlled	Emission Reductions from Base Case (1,000 ton/yr)	PM-Related Mortality Change per Year		Ozone-Related Mortality Change per Year		Net Mortality Change (PM and Ozone) per Year		Net Mortality Change per Year per 1,000 Tons of Emission Reductions	
					Shanghai Residents	All Residents	Shanghai Residents	All Residents	Shanghai Residents	All Residents	Shanghai Residents	All Residents
1	Power	Inside Shanghai	NO_x	250	−190	580	−220	−290	−410	290	−1.7	1.2
2	Power	Outside Shanghai	NO_x	7,000	1,100	160,000	−19	−2,700	1,100	160,000	0.16	23
3	Industry	Inside Shanghai	VOC	56	16	360	5.4	54	22	410	0.39	7.4
4	Industry	Outside Shanghai	VOC	1,500	8.2	26	3.4	630	12	660	0.0077	0.44
6	Industry	Inside Shanghai	Primary $PM_{2.5}$	10	2,600	3,500	0.0043	−0.27	2,600	3,500	260	360
7	Industry	Outside Shanghai	Primary $PM_{2.5}$	1,200	880	170,000	−0.16	−28	880	170,000	0.73	140
8	Mobile	Inside Shanghai	NO_x	87	−51	530	−130	−14	−180	520	−2.1	6.0
9	Mobile	Outside Shanghai	NO_x	2,500	300	38,000	1.4	−1,400	300	36,000	0.12	14
10	Mobile	Inside Shanghai	VOC & Primary $PM_{2.5}$	VOC: 60 Primary $PM_{2.5}$: 2	1,000	1,900	6.3	69	1,000	1,900	440	840
11	Mobile	Outside Shanghai	VOC & Primary $PM_{2.5}$	VOC: 3,000 Primary $PM_{2.5}$: 210	270	56,000	15	3,400	280	60,000	1.3	290

Notes: Positive number in the column means there is reduction, e.g., in emission, mortality cases. All values are provided to two significant figures, and sums may not add due to rounding. The net mortality change per year per 1,000 tons of emission reductions in the last two rows is approximated by that of primary $PM_{2.5}$ emissions reduction, as health impacts related to $PM_{2.5}$ account for more than 94% in the overall health benefits for the corresponding scenarios. There is some small change in "ozone-related mortality change" when primary $PM_{2.5}$ emission from industry sector is reduced in scenario 7. This could be because primary $PM_{2.5}$ emissions from the industry sector include primary nitrate emissions. Reducing primary nitrate emissions can impact the equilibrium of nitrate, NO_2, and NO, which can lead to small changes in ozone concentration. The health impact due to the change in ozone concentration in this scenario is less than 0.1% of that of $PM_{2.5}$. Scenario 5 is not shown in the table as it is meant for studying control harmonization.

conducted a simple uncertainty analysis, taking into consideration uncertainty in the different components, including pollutant concentration, slopes of C-R functions, and VSL. We assume that the slopes of the C-R functions for $PM_{2.5}$ and ozone both follow a triangular distribution with central estimate as the mode (i.e., 1% increase in all-cause mortality per 1 μg/m^3 increase in annual $PM_{2.5}$ concentrations, 0.3% increase in all-cause mortality per 10 μg/m^3 increase in annual average of eight-hour daily maximum ozone) and the lower and upper bounds as the minimum (i.e., 0.3% for $PM_{2.5}$, 0.15% for ozone) and maximum (i.e., 2% for $PM_{2.5}$, 0.45% for ozone) values for the distribution. For VSL, we use the base value of \$250,000 as the mode with upper and lower values of \$740,000 and \$86,000, respectively, as previously reported. For pollutant concentrations, our comparison of modeled versus observed concentrations in one monitoring site in Shanghai yields a normalized mean error (NME) of about 45% for $PM_{2.5}$ and 30% for ozone. Therefore, for both pollutants, we assume a lognormal distribution with concentration output from CMAQ as the median. The standard deviation of $PM_{2.5}$ is 1.45 times the modeled concentration, whereas that for ozone is 1.3 times the modeled ozone concentration with the assumption that the CMAQ model performance is the same in the entire domain. We ignore the uncertainty in background mortality and population distribution, as these are negligible in comparison. We performed Monte Carlo analysis using SAS 9.3 (SAS Institute Inc., Cary, NC, USA) to combine the distributions. Thus, we find that the 5th and 95th percentile in the damage costs estimate for $PM_{2.5}$ is a factor of about 5 from the central values, whereas that for ozone is slightly lower. The total monetized mortality change per ton (sum of the $PM_{2.5}$ and ozone damage cost) is accurate within a factor of approximately 3.5 to 5.7 across the scenarios modeled. For example, when controlling NO_x outside Shanghai, the 95% confidence interval for the damage cost per ton of NO_x for the entire domain could range from \$1,200 to \$30,000, with a central estimate of \$6,000.

3.6. Discussion

Our study illustrates a number of implications of the complex relationship between NO_x control, $PM_{2.5}$ and ozone formation, and population health effects. First, controlling NO_x can result in an increase in ozone concentrations both in Shanghai and in the entire study domain, as shown by the negative iFs (on the order of -10^{-6}). A previous study measured air pollutant concentrations (including NO_x, VOC, and ozone) in the Yangtze River Delta area and found that O_3 chemical formation is under the "VOC-limited" regime in both the rural and urban areas in the region.(30) Our previous study in YRD(9) also reported negative ozone iFs ranging from -10^{-7} to -10^{-5}. In contrast, VOC-related ozone iFs are positive (on the order of 10^{-6} for the study domain), suggesting that VOC emission reductions can be effective in reducing ozone concentrations in this region. For the other pollutant affected by NO_x emissions, secondary $PM_{2.5}$ iFs are on the order of 10^{-6}–10^{-7} when residents in the entire domain are considered. This estimate is similar to what we found in previous studies in China(9,31,32) and is one to two orders of magnitude higher than those reported for the United States.(33,34) The larger iF in China than the United States is attributable in part to the larger at-risk population. When coupled with large simulated emission reductions (with a domain that includes most of China), it explains the large estimated mortality reductions for many control scenarios addressing sources outside Shanghai. For example, controlling NO_x from power plants outside Shanghai reduces emissions by 7 million tons per year, approximately five times the NO_x emission reduction in the Clean Air Interstate Rule.(35) Coupled with the higher iF in China, health benefits two to three orders of magnitude higher than those modeled in the United States would be predicted. On the other hand, iFs for the Shanghai population are not only smaller than for the entire domain (as expected), but can also differ in sign, implying that the same control measure can be beneficial over the entire study domain yet detrimental to Shanghai residents.

Second, the location of control has a greater impact on iF and health impacts per ton of emission control than the sector under control, in particular for secondary $PM_{2.5}$. This is likely because secondary pollutants (e.g., nitrate particles and ozone) travel some distance while forming and their relatively long near-surface atmospheric lifetimes allow complete mixing in the boundary layer. By contrast, health benefits of controlling primary $PM_{2.5}$ emissions can be observed closer to the source.

Third, our results show that timing of pollution control can be important for determining health impacts. For example, controlling NO_x emissions outside Shanghai throughout the year increases Shanghai residents' ozone exposure, but implementing the same control only during ozone season reduces their exposure. Although our modeling results show limited variation in $PM_{2.5}$ exposure change during the year, the seasonality in ozone exposure change could have significant practical implications for designing optimal NO_x control strategies.

Fourth, the annual monetary values of the health benefits range from \$300 to \$6,000 per ton of NO_x depending on control location, when the exposure in the entire domain is considered. This range is comparable to the damage cost ranging from \$500 to \$15,000 per ton of NO_x for various power plants in the United States reported by Levy *et al.*,(33) albeit with significant differences in inputs such as VSL and population density. As we illustrated, the health benefits or damage costs can be compared with control cost in designing NO_x control strategies. Furthermore, the benefits related to different $PM_{2.5}$ and ozone precursors can be used to roughly estimate the co-benefits when a control technology reduces several pollutants simultaneously and may be worth giving higher priority.

3.7. Limitations

There are some additional uncertainties not embedded in our uncertainty calculations. First, for pollutants with nonlinear chemistry (i.e., NO_x and VOC), iF depends on both initial conditions and the magnitude of change in emissions. Because of these, the iF values reported in this study are valid only for the particular emissions scenarios modeled here. Similarly, when more than one pollutant is involved, we calculate the pollutant-specific change in exposure based on the difference between two scenarios. Due to the nonlinear chemistry in secondary pollutant formation, particularly for ozone, the pollutant-specific exposure and the corresponding health impacts may vary for a different combination of pollutants or percentage reductions. Note that we partially tested this in one scenario of our previous analysis(9) and the health impacts are approximately proportional to the magnitude of emission reductions of the same pollutants in this case. Second, when moving from NO_x-only controls in the mobile sector to those involving primary $PM_{2.5}$ and VOC controls, we did not separately add each pollutant (to limit computation). This could introduce some error to the estimate of primary $PM_{2.5}$ and VOC-related health impacts, though the error is likely to be small. For $PM_{2.5}$ concentration, the influence of VOC is negligible compared with primary $PM_{2.5}$, as shown by the results for the power sector in this study as well as results for the mobile sector in our previous study.(9) Similarly, ozone concentration is minimally influenced by primary $PM_{2.5}$ emissions, which allows us to quantify the impact of VOC on ozone concentrations reasonably well.

Third, when calculating health impacts, we assumed a causal relationship with a linear C-R function for both $PM_{2.5}$ and ozone. Regarding causality, while uncertainty exists and ongoing research continues to explore mechanisms, the evidence base is strong and our assumptions are similar to those conventionally made in the scientific literature, by the World Health Organization, the U.S. EPA, the European Union, and all other major regulatory bodies for air pollution. For $PM_{2.5}$, for example, the persistence of a mortality effect across multiple studies in multiple settings using different statistical designs made it difficult to believe that it could be caused solely by confounding.(36) There are also fewer questions about causal linkages at the high levels of exposure observed in China. A more challenging question relates to the assumption of linearity. Although concentrations in our domain are clearly above any putative thresholds, the slope at high concentrations may differ from the slope at low concentrations. Modeling work incorporated into global burden of disease analyses(37) provides some evidence that the $PM_{2.5}$-mortality association flattens at high concentrations, which would indicate potential overestimation of PM-related health effects in our study. However, the departures from linearity are relatively modest for key outcomes such as lung cancer and at the ambient levels observed in our study. Broadly, although many of these issues would influence the magnitude of our mortality estimates, they would not materially influence our conclusions regarding the importance of considering nonlinear atmospheric chemistry.

Fourth, when we calculate the monetary values of health impacts, we use the same VSL for Shanghai residents and those outside Shanghai. As people in large metropolitan areas such as Shanghai are usually wealthier, this approach potentially underestimates the monetary value of health impacts for Shanghai residents, although applying differential VSL by income is not likely palatable to decisionmakers and is rarely done in analyses of this sort. Finally, we compare the simplified emission control costs with health benefits for the purpose of demonstration, and the costs do not reflect adjustment for inflation or other intricacies. Future benefit-cost analysis should be based on more detailed and up-to-date cost estimates.

4. CONCLUSION

In conclusion, our results show that secondarily formed air pollutant concentrations in Shanghai are substantially influenced by transport from outside Shanghai. To effectively reduce adverse health effects of $PM_{2.5}$ and ozone in Shanghai, the governments of Shanghai and the neighboring provinces need to coordinate their efforts. Due to the nonlinear chemistry in ozone formation, NO_x control needs to be deployed strategically to avoid unintended consequences. Location, season, and pollutants to control simultaneously as well as possible co-benefits of various control strategies need to be taken into consideration. When secondary pollutants such as $PM_{2.5}$ and ozone are involved, the benefits of emission control may not be in the vicinity of the control, highlighting the importance of control coordination among different regions. Otherwise, control may have suboptimal or even detrimental effects on the target location or in aggregate.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Table S1. CMAQ and MM5 Model Configurations

Table S2. Scenarios Compared for Calculating Intake Fractions in Table III and Health Impacts in Table IV

Figure S1. Study domains.

Figure S2. Statistical evaluations of hourly O_3 and daily $PM_{2.5}$.

Figure S3. CMAQ-simulated annual average $PM_{2.5}$ concentration change when NO_x, VOC, and primary $PM_{2.5}$ emissions are reduced inside Shanghai ($\mu g/m^3$).

Figure S4. CMAQ-simulated annual average $PM_{2.5}$ concentration reduction when NO_x, VOC, and primary $PM_{2.5}$ emissions are reduced outside Shanghai (μg/m).