

Chinese haze versus Western smog: lessons learned

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Abstract: Air pollution in many Chinese cities has been so severe in recent years that a special terminology, the “Chinese haze”, was created to describe China’s air quality problem. Historically, the problem of Chinese haze has developed several decades after Western high-income countries have significantly improved their air quality from the smog-laden days in the early- and mid-20th century. Hence it is important to provide a global and historical perspective to help China combat the current air pollution problems. In this regard, this article addresses the followings specific questions: (I) What is the Chinese haze in comparison with the sulfurous (London-type) smog and the photochemical (Los Angeles-type) smog? (II) How does Chinese haze fit into the current trend of global air pollution transition? (III) What are the major mitigation measures that have improved air quality in Western countries? and (IV) What specific recommendations for China can be derived from lessons and experiences from Western countries?

Keywords: Air pollution; emissions; health effects; clean air legislation

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History of air pollution and its health consequences

While air pollution in cities has only recently become an alarming concern in China, it has long been recognized as a threat to public health through both its acute and long-term adverse effects. Outdoor or ambient air has always been contaminated with pollutants from natural sources, including, for example, pollens, smoke from fires and volcanoes, and emissions of organic compounds from plants. The current problems and patterns of air pollution date to industrialization and the rise of cities. Together, fossil fuel combustion for heating and cooking and eventually for electric power generation and emissions from factories led to worsening pollution during the Industrial Revolution. The 20th century added mobile sources, including cars, trucks, and other vehicles, as major contributors to urban air pollution.

Urban air pollution was recognized centuries ago as a

threat to health. Well-chronicled disasters during the 20th century motivated the actions that have led to marked improvements in air quality in North America and Western Europe. Most notably, the London Fog or the great London smog of 1952, an extreme air pollution event during a week-long episode of atmospheric stagnation, resulted in 10,000 or more excess deaths before the weekly mortality rate returned to the baseline (*Figure 1*) (1). It followed the 1930 episode in the Meuse Valley of Germany (2) and the 1948 episode in Donora, Pennsylvania, in the United States (3); both of these episodes were also accompanied by readily detected excess deaths and were well-documented in the scientific literature. Levels of air pollution during the great London smog were extreme by contemporary standards; “black smoke”, a surrogate for airborne particulate matter (PM), reached approximately 4 mg/m³, orders of magnitude above typical levels in high-income countries of the West. The clear and dramatic loss of lives that was caused by the London smog

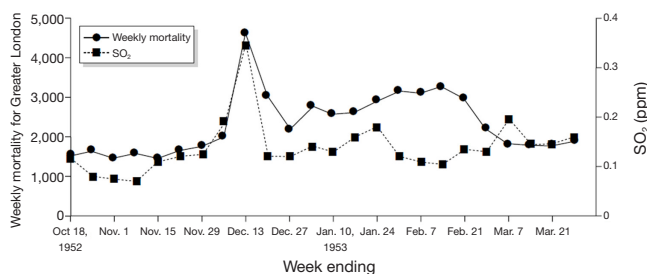


Figure 1 Weekly mortality and SO_2 -concentrations for Greater London during the 1952 smog episode. Adapted from Bell and Davis 2001 (1).

of 1952 motivated action: research to better understand the risks of air pollution and regulations to reduce emissions. This research quickly showed that fossil fuel combustion, particularly coal combustion for power generation as well as household space heating, and industrial sources, were resulting in high levels of airborne PM and sulfur oxides.

There were also episodes of serious air pollution with increments in day-to-day mortality counts in the United States. In the 1940s, a new air pollution problem emerged in California—the type of air pollution that was originally referred to as “smog” but more specifically is termed photochemical pollution. The first well-documented episode of such pollution occurred in Los Angeles in 1943. About 10 years later, Dr. Arie Haagen-Smit reported on the nature and causes of photochemical smog, finding that the ultraviolet radiation of sunlight caused photochemical reactions involving nitrogen oxides and hydrocarbons that resulted in an oxidant-rich pollution mixture (4). Ozone is a key component of this mixture and it is used as a general indicator of photochemical smog. Secondary aerosols (e.g., sulfate and nitrate salts), formed through photochemical conversions of organics, sulfur oxides, and nitrogen oxide, are also key components of the complex mixture.

Thus, by the 1960s and 1970s, two broad types of air pollution had been recognized: the mixture of particles and sulfates (acid aerosols) arising from fossil fuel combustion (also called London-type smog) and the photochemical pollution occurring in areas with high vehicle traffic and sunlight (also called Los-Angeles-type smog). The latter type of pollution was initially thought to be a problem localized to California, but with growth of urban regions such pollution was soon present throughout the United States and is now present in many cities around the world. Beyond these two widely occurring air pollution mixtures, other, more specific air pollution problems were identified: carbon monoxide from

combustion sources, lead from lead-containing gasoline and industrial emissions, various metals, carcinogens, and large numbers of air toxics (e.g., benzene and formaldehyde) emitted from industrial and other sources.

These same air pollution problems now affect many of the world’s large cities and mega-cities, including those of China. China has rapidly industrialized in the past few decades and added millions of vehicles to its highways, leading to severe decreases in air quality associated with industrial processes, urbanization, and population growth. As such, appropriately, there has been mounting concern on the part of the government and the population of China generally as to the consequences of such high levels of air pollution, which are so high as to greatly limit visibility. Such concerns are warranted as monitoring data and research studies show that much of China now has air pollution sufficiently severe to threaten public health. Indeed, the term ‘*wu mai*’, or ‘Chinese haze’, is now well known to the general public in China; and $\text{PM}_{2.5}$ (particles less than 2.5 micrometers in diameter) is part of everyday conversation among average Chinese people.

This paper provides a snap-shot of China’s air pollution problems and describes some key characteristics of the Chinese haze. Furthermore, we offer a perspective on “lessons learned” from research and air quality management in western countries, as, in general, local and regional air pollution has greatly diminished in such countries.

$\text{PM}_{2.5}$ in Beijing: a snap shot

Outdoor air pollution was responsible for an estimated 3.3 million premature deaths worldwide in 2010 (5), but the majority of this disease burden occurs in low- and middle-income countries with China contributing 1.2 million deaths to the total. These estimates for the Global Burden of Disease 2010 were based on estimated population-weighted $\text{PM}_{2.5}$ concentrations as shown in *Figure 2*.

We now ‘zoom in’ from this global picture of $\text{PM}_{2.5}$ to Beijing’s $\text{PM}_{2.5}$ levels. While a systematic assessment, considering spatial variations and multiple pollutants, would offer a more complete picture of Beijing’s air quality, $\text{PM}_{2.5}$ data measured at one site are readily available and provide a clear understanding of PM pollution in Beijing. Consequently, we present data from the “StateAir” website of the U.S. Department of State Air Quality Monitoring.

Data from the program (<http://stateair.net/web/mission/1/>) which tracks daily $\text{PM}_{2.5}$ concentrations on the grounds of the U.S. Embassy in Beijing in the winter

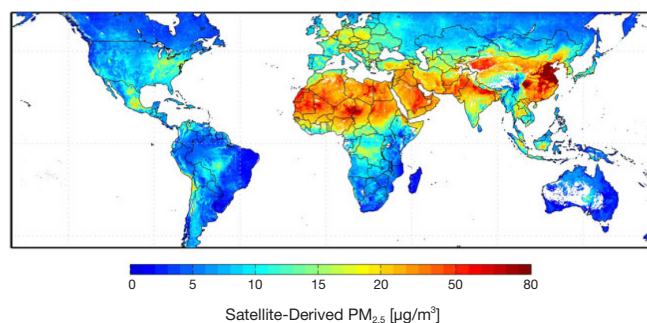


Figure 2 Global distribution of population-weighted $PM_{2.5}$ concentrations. Adapted from van Donkelaar *et al.* (6).

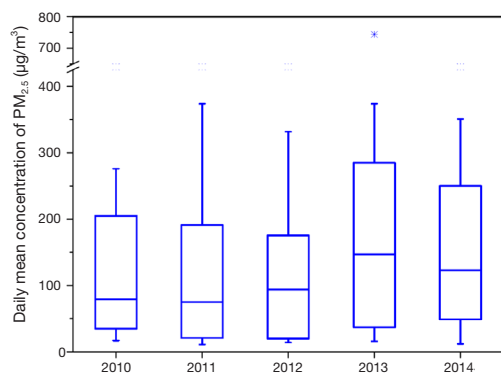


Figure 3 Winter-month $PM_{2.5}$ concentrations measured at the U.S. Embassy in Beijing 2010-2014. Winter months are months of December, January, and February. In these boxplots, the top whisker line corresponds with the 90th percentile, the top line of the box corresponds with the 75th percentile, the middle box line is the median, the bottom box line is the 25th percentile, and the bottom whisker line is the 10th percentile. The star sign is the highest daily concentration. Data were retrieved from the Beijing U.S. Embassy air monitoring Twitter feed at <https://twitter.com/BeijingAir>.

months from 2010 to 2014 are shown in *Figure 3*. Daily $PM_{2.5}$ concentrations exceeded $100 \mu\text{g}/\text{m}^3$ for more than half of the days and reached as high as $744 \mu\text{g}/\text{m}^3$, more than 20 times the US Environmental Protection Agency's (EPA) 24-hour standard for $PM_{2.5}$ of $35 \mu\text{g}/\text{m}^3$. From 2011 to 2013, median levels appeared to be rising in the same winter months, although the 2014 median level was slightly lower than the 2013 level. Concentrations across all five winters were high, indicating that the severe $PM_{2.5}$ pollution in Beijing was not just associated with one 'bad winter' with unfavorable meteorological conditions for atmospheric dispersion of air pollutants. In

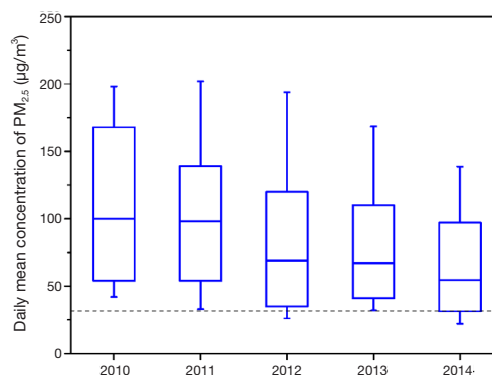


Figure 4 Summer-month $PM_{2.5}$ concentrations measured at the U.S. Embassy in Beijing 2010-2014. Summer months are months of June, July, and August. In these boxplots, the top whisker line corresponds with the 90th percentile, the top line of the box corresponds with the 75th percentile, the middle box line is the median, the bottom box line is the 25th percentile, and the bottom whisker line is the 10th percentile. The dash horizontal line indicates the US Environmental Protection Agency's (EPA) 24-hour standard for $PM_{2.5}$ of $35 \mu\text{g}/\text{m}^3$. Data were retrieved from the Beijing U.S. Embassy air monitoring Twitter feed at <https://twitter.com/BeijingAir>.

general, Beijing's cold months are prone to atmospheric inversions, limiting the dispersion and resulting dilution of pollutants emitted at the ground level. In addition, fuel combustion for space heating adds additional $PM_{2.5}$ emissions in the winter months.

In contrast, $PM_{2.5}$ concentrations were generally lower in summer months (see *Figure 4*). But, in 2010 and 2011, approximately half of the days had $PM_{2.5}$ concentrations above $100 \mu\text{g}/\text{m}^3$ and even the 10th percentile exceeded the US EPA daily standard of $35 \mu\text{g}/\text{m}^3$.

Chinese haze in the context of global air pollution transition

Over the last four decades, the high-income countries in the West have implemented policies to curtail the severe air pollution events that had plagued them during the early- and mid-20th century. One of the consequences of the increased stringency of pollution control regulations in these countries is the outsourcing of more polluting manufacturing jobs into the low- and middle-income countries by multi-national corporations. In fact, China has been recognized as "the world's factory" in the last few decades. Meanwhile, China has undergone very rapid

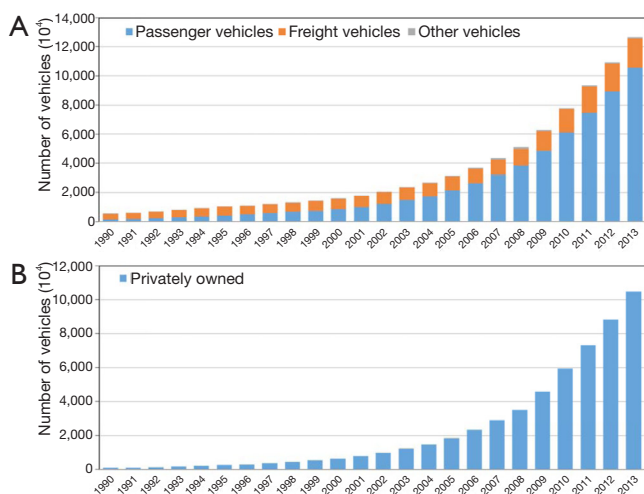


Figure 5 China national number of vehicles from 1990 to 2013, unit: 10,000 vehicles. (A) Blue, orange, and grey bars represent passenger vehicles, freight vehicles and other vehicles, respectively; (B) privately owned vehicles. National Bureau of Statistics of China (<http://www.stats.gov.cn/tjsj/>).

urbanization and substantial economic growth, as reflected in a double-digit annual increase in GDP for more than a decade until the recent slowing. Increased national wealth has brought higher living standards among the population. For example, the use of cars as a means of personal transportation rose rapidly in China, contributing to growing health concerns related to traffic-related pollution (see *Figure 5*). Consequently, increased vehicle traffic, increased energy use by households, rising factory emissions, and ever-greater numbers of power plants have created high concentrations of air pollutants in the tightly packed population centers. Experience in recent years shows that extremely high concentrations can extend beyond the urban centers in winter months, creating regional pollution problems.

Thus, the Chinese haze is a complex mixture of air pollutants that are present at high concentrations in a city or a region, reflecting a dynamic and growing set of sources. This mixture includes such major components as PM (e.g., PM₁₀ and PM_{2.5}) and gaseous pollutants (e.g., ozone, nitrogen dioxide, carbon monoxide, and sulfur dioxide). These pollutants are commonly present at elevated concentrations in all polluted atmospheres around the globe. However, the Chinese haze may have particular characteristics compared to outdoor pollution mixtures in Western high-income countries, in addition to the substantially higher PM_{2.5} concentrations in Chinese haze.

In most areas of high-income countries, concentrations of sulfur dioxide (SO₂) and nitrogen dioxide (NO₂), for example, are now quite low; and PM, which has numerous sources, is most intensively investigated and also used as an index for considering the risk posed to public health by air pollution. In contrast, the gaseous pollutants in China are still at concentrations high enough to cause significant health problems, and they remain as useful surrogates for certain air pollution sources (e.g., SO₂ for coal and high-sulfur oil combustion). For example, ambient SO₂ and NO₂ concentrations in Chinese cities have been associated with various adverse health effects, such as pathophysiological biomarkers of adverse cardiopulmonary events (7,8), respiratory symptoms and reduced lung function (9,10), and low birth weight (11). The associations were stronger with SO₂ than PM_{2.5} or PM₁₀ in some of these studies.

Sulfur dioxide and main sources

SO₂ has been dramatically reduced in high-income countries by regulations concerning industrial emission controls and other important sources, and reduction of sulfur in fuels. On the whole, global SO₂ emissions have declined from 1990 to 2010 (from 121 to 103 Tg SO₂), led mostly by declines in the developed world (12). However, China alone contributed 29% of global SO₂ emissions in 2011. Emissions of SO₂ peaked in China in 2005, after which the control measures in the 11th Five Year Plan [2006–2010] resulted in a 14% reduction in SO₂ emissions and concomitant 13–15% and 8–10% reductions in ambient SO₂ and particulate sulfate concentrations, respectively, over eastern China (13). Nevertheless, China is still the largest contributor to global SO₂ emissions of any country, largely due to its extensive use of coal for industrial processes and power generation.

In comparison, coal use in the U.S. contributed 6.2% of the global total SO₂ in 2011; and over 70% of total SO₂ emissions in the U.S. came from coal-fired power plants in 2008 (14). However, cleaner coal processing and increased removal of gaseous byproducts from flue gas in the U.S. have reduced SO₂ ambient levels in 2012 and nearly all monitors are below the US EPA one-hour maximum standard of 75 ppb (196 µg/m³) (15).

Nitrogen dioxide and main sources

In many areas of high-income countries, the greatest

source of NO_x (NO_x is the sum of NO_2 and NO but usually dominated by NO_2) is traffic-related pollution. Overall, mobile sources (57.5%), fuel combustion from stationary sources (24.2%), and industrial processes (8.4%) account for the majority of the 14.1 Tg of NO_x emissions in the U.S. (16). In comparison, China is the largest producer of NO_x , emitting 23.4 Tg in 2012. However, 71% was from industrial sources, with motor vehicles only accounting for 27% (17). Beijing has a high concentration of vehicle traffic, but about 50% of the NO_x in its air comes from regional and not local sources (18). The high industrial contribution to Beijing NO_x levels is likely due to sources in the greater Beijing/Tianjin/Hebei area, which accounts for 43% of national coal consumption, 30% of national thermal power consumption, and 50% of national steel and coke production (18).

Because motor vehicles are the major NO_x source in the US and many other countries, the cities with the greatest concentrations of NO_2 in the U.S. often have the worst traffic problems, such as downtown Los Angeles, California (19). As such, great effort has been made to reduce vehicular emissions of NO_x . For example, the State of California has the most stringent vehicular emission standards for NO_2 and other pollutants. The Japanese government enacted the Automobile NO_x Law in 1992 to ban vehicles in certain areas not conforming to emission standards and strengthened it to include PM considerations and stricter standards in 2001. Areas in which the law was enforced had half the average annual NO_2 concentration of unenforced areas (20). Given that regional industrial emissions are the largest NO_x sources in Beijing and likely other Chinese cities, controlling vehicular emissions alone will not be effective in substantially reducing ambient concentrations of NO_2 (and other pollutants).

Clean air legislation in Western countries

Air pollution control strategies have largely reflected a pollution framework that acknowledges PM pollution and photochemical oxidant pollution as the two major threats to public health, while also considering the specific threats outside of this framework that also need to be addressed, such as lead and carbon monoxide. In the U.S., the Clean Air Act, initially passed in 1970, mandated that specific major pollutants, including PM and photochemical oxidant pollution, should be regulated based on the scientific evidence on their harmful effects in humans primarily and to the environment (e.g., crops and atmospheric visibility) secondarily. Six pollutants are currently regulated as so-

called “criteria pollutants” (“criteria” referring to the scientific evidence) and National Ambient Air Quality Standards (NAAQS) for these pollutants are to be set that protect public health with an “adequate margin of safety”. For each of the six pollutants, an indicator (e.g., ozone for photochemical oxidant pollution), averaging time (e.g., 24 hours), statistical form (e.g., the 99th percentile), and a level (e.g., 35 $\mu\text{g}/\text{m}^3$) are specified; these four elements of the standard are reviewed every five years as evidence accumulates. In the United States, the combination of increasingly strict NAAQS along with components of the Clean Air Act that are directed at particular source categories has proven effective and air pollution has diminished greatly in most places. The regulations have forced new technologies such as emission controls on motor vehicles and scrubbers for sulfur oxides on power plants.

In the United Kingdom, there have also been great improvements in air quality. A somewhat different overall strategy has been followed in comparison with the pollutant-specific approach taken in the United States. Emphasis has been placed on controlling sources and reducing emissions to the extent possible with available technology. The Clean Air Act of 1956 addressed the problem of smoke pollution (London-type smog) and created smoke-free zones to address burning of coal for heating, a potent source of pollution in the densely-settled cities of the United Kingdom. Later Acts addressed industrial sources. Other European nations also had steady improvement in air quality, although there is substantial variation of key indicators across the current European Union. Only now is the European Commission addressing the establishment of uniform air quality standards across its members.

The World Health Organization has developed guidelines for air quality (*Table 1*) (21). These guidelines have no legal basis for implementation by nations, but stand as global guidelines. The guidelines acknowledge the heterogeneity of air pollution across the globe, by not only offering guidelines, but providing targets for those nations, such as China, that cannot feasibly achieve the guidelines at present.

Clean air legislation in China

Ambient air quality has been regulated in China since 1982. In 1996, the standards were strengthened for initially regulated pollutants from the 1982 levels and expanded to include more pollutants under National

Table 1 Sources, health effects, and World Health Organization guidelines on major ambient air pollutants

Pollutant	Source types and major sources	Health effects	WHO guidelines
Particulate matter	Primary and secondary- Anthropogenic: burning of fossil fuel, wood burning, natural sources (e.g., pollen), conversion of precursors (NO _x , SO _x , VOCs) Biogenic: dust storms, forest fires, dirt roads	Respiratory symptoms, decline in lung function, exacerbation of respiratory and cardiovascular disease (e.g., asthma), mortality	PM ₁₀ Annual mean: 20 µg/m ³ 24-hour mean: 50 µg/m ³ PM _{2.5} Annual mean: 10 µg/m ³ 24-hour mean: 25 µg/m ³
	Ozone	Secondary- Formed through chemical reactions of anthropogenic and biogenic precursors (VOCs and NO _x) in the presence of sunlight	Decreased lung function, increased respiratory symptoms, eye irritation, bronchoconstriction
Nitrogen dioxide	Primary and secondary- Anthropogenic: fossil fuel combustion (vehicles, electric utilities, industry), kerosene heaters Biogenic: biological processes in soil, lightning	Decreased lung function, increased respiratory infection Precursor to ozone. Contributes to PM and acid precipitation	Annual mean: 40 µg/m ³ 1-hour mean: 200 µg/m ³
Sulfur dioxide	Primary Anthropogenic: combustion of fossil fuel (power plants), industrial boilers, household coal use, oil refineries Biogenic: decomposition of organic matter, sea spray, volcanic eruptions	Lung impairment, respiratory symptoms. Precursor to PM. Contributes to acid precipitation	Annual mean: 20 µg/m ³ ; 10-minute mean: 500 µg/m ³

Adapted from World Health Organization 2006 (21).

Table 2 Chinese national ambient air quality standards updated in 2012: GB 3095-2012. Grade I standards apply to special areas such as national parks and Grade II standards apply to all other areas

Pollutant (unit)	Averaging time	Standard	
		Grade I	Grade II
SO ₂ (µg/m ³)	Annual	20	60
	24 hours	50	150
	Hourly	150	500
NO ₂ (µg/m ³)	Annual	40	40
	24 hours	80	80
	Hourly	200	200
CO (µg/m ³)	24 hours	4	4
	Hourly	10	10
O ₃ (µg/m ³)	Daily, 8-hour maximum	100	160
	Hourly	160	200
PM ₁₀ (µg/m ³)	Annual	40	70
	24 hours	50	150
PM _{2.5} (µg/m ³)	Annual	15	35
	24 hours	35	75

Standard GB 3095-1996. However, the standards were revised with less stringent limits for NO₂ and O₃ in 2000. In February 2012, China released a new set of ambient air quality standards, GB 3095-2012. This was the first time that a standard was set for PM_{2.5} in China. The new standards, shown in *Table 2*, will take effect nationwide in 2016, but many cities and regions in China are required to implement the standards earlier than the national timeline (<http://datacenter.mep.gov.cn/airdesc.jsp>).

Compared to the WHO guidelines (*Table 1*), the Chinese standards (*Table 2*) are substantially less stringent. For example, the 24-hour limits for both PM_{2.5} and PM₁₀ in China (Grade II) are three times those recommended by WHO. However, considering the current ambient levels of air pollutants, achieving these relatively non-stringent new standards is still very challenging. Recognizing this challenge, the State Council issued the “Air Pollution Prevention and Control Action Plan” in September 2013, which mandates 25%, 20%, 15%, and 10% PM_{2.5} reductions in the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, the Pearl River Delta region, and all other cities, respectively, by 2017 from their 2012 baseline

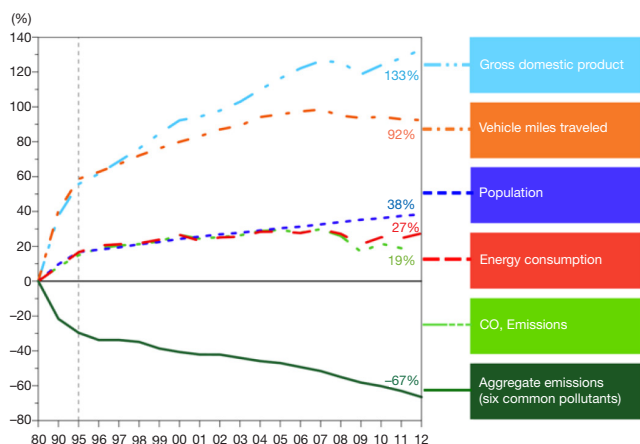


Figure 6 The 1970 Clean Air Act lowered emissions of key air pollutants even as energy consumption, GDP, vehicle miles, and population increased. This graph was adapted directly from the US EPA website (22).

annual average concentrations. Similarly targets have been or will be set for reducing concentrations of PM_{10} and other pollutants.

On September 9, 2014, the Legislative Affairs Office of China's State Council released the first draft of the highly-anticipated revisions to the national *Air Pollution Prevention and Control Law* and accepted comments on revisions of the law until October 8, 2014. Releasing the draft law for public comment at such an early stage of the process is unusual in China and is a major step forward for both governmental transparency and public participation. This revised draft has been passed by the State Council on November 26, 2014. Upon further revisions, the draft will be submitted to the People's Congress of China that has the ultimate legislative authority.

China's *Air Pollution Prevention and Control Law* was originally enacted in 1987, first revised in 1995, and further strengthened in 2000. However, the earlier versions lacked specific details and mechanisms for enforcement. The most recently revised law incorporates several critical advancements to help address today's severe air pollution problems – the Chinese haze, with the following key points among a list of specific action items. (http://transportpolicy.net/index.php?title=China:_Air_Quality_Standards).

- ❖ The responsibility of governments for environmental protection is clarified, especially with regards to the role of local governments in managing regional air quality. Local officials will be assessed on compliance with air quality targets and the results

will be released to the public.

- ❖ The air pollutant emissions control system will be improved by increasing the scope of emissions caps, establishing new targets for key emissions controls, and suspending approval for new projects in areas that exceed emissions targets.
- ❖ Key areas for air pollution prevention and control are identified including strengthening measures to confront pollution from coal, motor vehicles, industries, dust, and other specific sources.
- ❖ Environmental air quality and pollution source monitoring will be strengthened by organizing a national monitoring network.
- ❖ A heavy pollution weather monitoring forecast system will be established whereby provincial governments' environmental and meteorological departments will cooperate to forecast heavy pollution days.

Historical lessons and recommendations

Clean air legislation in some western countries, as described above, has proven effective not only in preventing severe air pollution problems, as seen in the early- and mid-20th century, from recurring but also leading to decreased emissions and general and progressive trends of improving air quality, accompanied with apparently substantial health benefits. For example, although gross domestic product (GDP) and vehicle miles traveled increased by 133% and 92%, respectively, from 1980 (ten years after the US Clean Air Act was passed) to 2012 in the U.S., the aggregate emissions of the six criteria pollutants (PM_{10} , SO_2 , NO_2 , CO, O_3 , and lead) decreased by 67% in the same period (see *Figure 6*) (22). The reduction in SO_2 emissions in this period resulted in a 78% reduction in national SO_2 levels (23). An analysis of the relationship between reductions in ambient $PM_{2.5}$ concentrations and increases in life expectancy in U.S. cities suggests that the 1970 Clean Air Act alone may have extended life expectancy by a half-year to a year (24). The additional health impact of the 1990 Clean Air Act Amendments is shown in *Table 3*.

By contrast, air quality in China has actually worsened long after the establishment of national air quality standards. A key issue for China is not a lack of laws or regulations, but the effectiveness of enforcement of the laws (partly due to inadequacies of the law which lacks key details and mechanisms for enforcement). By contrast, the US Clean Air Act contains an extensive series of requirements

Table 3 The 1990 Clean Air Act Amendment improved a number of health outcomes associated with PM_{2.5} and ozone. Numbers are presented as number of cases avoided

Health effect reductions (PM _{2.5} & ozone only)	Pollutant(s)	Year 2010	Year 2020
PM _{2.5} adult mortality	PM	160,000	230,000
PM _{2.5} infant mortality	PM	230	280
Ozone mortality	Ozone	4,300	7,100
Chronic bronchitis	PM	54,000	75,000
Acute bronchitis	PM	130,000	180,000
Acute myocardial infarction	PM	130,000	200,000
Asthma exacerbation	PM	1,700,000	2,400,000
Hospital admissions	PM, ozone	86,000	135,000
Emergency room visits	PM, ozone	86,000	120,000
Restricted activity days	PM, ozone	84,000,000	110,000,000
School loss days	Ozone	3,200,000	5,400,000
Lost work days	PM	13,000,000	17,000,000

This table was adapted directly from (25).

related to implementation and penalties for not attaining the NAAQS. Today, the Chinese haze is often so severe and widespread that schools are closed, people are advised to stay indoors, and they use air filters or purifiers and wear dust masks during heavy episodes. Some are leaving the cities and even the country in search of clean air for their families, particularly for their children.

The general urgency for action is clear, much as with the London smog of 1952 and other air pollution disasters. In fact, given the extremely high levels of air pollution measured at times, there is risk for such dramatic public health disasters in China. As occurred in the United Kingdom and the United States decades ago, urgent and effective action is needed. The growing concerns of the public as pollution becomes an ongoing and daily health risk need to be matched by a strong governmental response. Strong political will is needed and is apparent at China's national leadership level, along with a willingness to pay for the costs of air pollution control. During the Beijing Olympics in 2008 and the most recent APEC meeting (November 2-11, 2014) in Beijing, aggressive control measures implemented to cut industrial and vehicular

emissions resulted in substantial temporary reductions in pollutant levels in Beijing. After weeks of haze episodes in Beijing in October 2014, a new term was invented, namely "the APEC blue", referring to the blue sky air quality during the APEC meeting in early November. While the public enjoyed the temporary relief from breathing highly-polluted air, President Xi hoped and believed the APEC blue would continue through tireless efforts to control air pollution. With much industry state-operated, China is in a position to take quick action. Given the urgency of the situation, China will need to "leapfrog". It can draw on more than a half-century of research and action in the high-income countries and use strategies and control technologies that have proven effective elsewhere. Most importantly, China has opportunities to utilize the most advanced emission control technologies that were nonexistent at mid-20th century when the current high-income countries experienced their worst air pollution problems. Based on the history of Western smog, we specifically recommend the following.

Control industrial emissions especially from coal combustion

Western countries have had a long history of controlling industrial emissions. The core of the success is the implementation of stringent emission standards. For example, the European Union has experienced significant reductions in emissions of industrial air pollutants as a result of its Large Combustion Plant (LCP) Directive, implemented in 2001, which required that new plants follow strict standards and that old plants exhibit significant reductions in criteria pollutants by 2008 (26). From 2007-2009, LCPs reduced emissions of SO₂ by 44%, NO_x by 27%, and dust by 44% (27). In contrast, China's higher contribution of industrial sources to the total pollutant emissions reflects a lack of enforcement of emission standard laws.

Flue gas scrubbers and other technologies have been instrumental in reducing industrial sources of air pollution. The common technologies used to clean flue gases include electrostatic precipitators and fabric filters for reducing PM, flue-gas desulfurization (FGD) for reducing SO₂; flue-gas denitrification for reducing NO_x through selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), and wet and dry scrubbing, absorbers, flue gas recirculation, for a variety of air pollutants. China has adopted most of these technologies to varying extents, including circulating fluidized beds (CFB), in which a gas or fluid is passed through a high kinetic energy solid-fluid

mixture to increase gas/fluid-solid contact, to increase coal combustion efficiency and reduce emissions (28). The extensive use of FGD systems in coal-fired plants during the 11th Five Year Plan has helped to reduce SO₂ emissions from the 2005 peak. However, the relatively high operating costs of NO_x removal systems, such as SNCR/SCR, have impeded their large-scale installation in China until the 12th Five Year Plan [2011-2015] (28,29). Although China has issued laws requiring the use of these technologies, enforcement appears to be too relaxed, given the numbers of plants and factories above emission standards.

Air pollutant monitoring results ordered by the Ministry of Environmental Protection (MEP) in July 2013 revealed that several large-scale steel factories and thermal power plants were consistently breaching discharge standards. From October to December 2013, a comparison of eight major pollution sources each in Hebei and Shandong showed that NO_x emissions were 30 and 37 times greater, respectively, than eight major sources in Beijing (18). Data show that pollutant emissions are largely from coal combustion that is used to power industrial and power plants. Coal use is extremely high in most industrialized regions such as the Yangtze River Delta region (Jiangsu/Zhejiang/Shanghai). This region consumes more coal than the entire U.S. (30), and consequently, it is the area of China with the greatest discharge intensity (tons per km² land area) for SO₂ and NO_x (18). Although China has adopted some technologies to clean flue gas on a case-by-case basis, it needs more stringent legislation and, more importantly, enforcement measures to ensure that these technologies are used across the country.

Improve quality of gasoline and diesel fuels

As China continues to add motor vehicles onto its roads, having a cleaner fleet is essential for controlling mobile source emissions. Achieving this goal requires more efficient engines, emission control devices, and/or higher quality fuels (mainly gasoline and diesel). Since 2000, China has adopted increasingly more stringent vehicle emission standards on an incremental basis. The adoption of each set of the standards (e.g., China I, II, and III) generally began in the large metropolitan areas, such as Beijing, Shanghai, and Guangzhou, before proliferating to the rest of country. For example, Beijing implemented Euro 4 standards for light-duty vehicles in 2008 (the year of the Beijing Olympics) and Euro 5-based standards from 2013. This change in requirements resulted in a fast

turnover of the vehicle fleet (as vehicles that cannot meet the standards are removed from the roads). Given that the vehicle fleet in China, especially in metropolitan areas, has already and will likely continue to use the most advanced engine technologies, we think improving fuel quality to further reduce pollutant emissions should be given emphasis at present.

Worldwide, various regulations have phased out harmful additives (e.g., lead) and reduced levels of certain components (e.g., sulfur) in gasoline and diesel. One of the first initiatives to improve gasoline quality was the international effort to phase out tetraethyl lead (TEL) as an anti-knocking agent in gasoline, not only because lead is toxic to humans but also because lead in gasoline can inactivate catalytic converters. Catalytic converters have been used starting in 1975 in the U.S. to catalyze redox reactions that decrease hydrocarbon, CO, and NO_x emissions. Japan enacted the first ban on leaded gasoline in 1986, and most countries including China have officially phased out TEL use by the early 2000s. However, there is evidence of illegal leaded gasoline production in some nations, such as China, despite national regulations (31).

High sulfur content of gasoline and diesel leads to high emissions of sulfur oxides (SO_x, mainly SO₂) and PM. When sulfur in fuels is converted to SO_x during combustion, SO₂ can adsorb onto palladium, platinum, or rhodium catalytic converters (32). This adsorbed sulfur both physically and electrically blocks the binding of other emission chemicals to the catalytic surface, thereby reducing the efficiency of catalytic converters.

The most stringent sulfur standards for gasoline and diesel (below 15 ppm for diesel) are mostly in the wealthier nations, particularly those in Europe, North America, and Australia (33). Moderate to high diesel sulfur standards (between 50 and 500 ppm) exist in Mexico, many parts of Africa, Russia, South Asia, East Asia, and Southeast Asia. The least stringent standards (greater than 500 ppm) predominate in South America, Central Asia, the Middle East, and most of Africa. By the end of 2014, China will have implemented the China IV sulfur content standard of 50 ppm in both gasoline (GB 17930-2011) and automobile diesel (GB 19147-2013) (http://transportpolicy.net/index.php?title=China:_Fuels:_Diesel_and_Gasoline). Off-road or “general” diesel currently has a standard of 350 ppm (GB 252-2011). By December 31, 2017, implementation of the China V gasoline and diesel standard of 10 ppm sulfur content is planned. However, enforcement remains the key issue for these policy mandates.

Conduct scientific research to support evidence-based policies

Scientific research has been the backbone for evidence-based policies that are designed and implemented to control air pollution in western high-income countries. For example, credible and impartial findings from air pollution health effects studies have helped governments to establish air quality standards; and source apportionment studies have helped to prioritize control targets. In addition to providing research funding, the western governments have made air pollution data (and health data) available to the public, so that the data can be readily used in numerous studies. Until recently, air quality data measured by the government were not available to the public, even though a comprehensive air quality monitoring network across the country has been in place for decades. The government should make further efforts to ensure the transparency and credibility of the monitoring network and to generate data with sufficient quality for scientific research (e.g., not just a gross air quality index or blue sky day count but actual pollutant concentrations). Having such data would not only support research but also enforcement.

At the present time when air pollutant concentrations are so high in China, studies on adverse health consequences may not be necessary to support setting air quality standards (as opposed to such research needs in western high-income countries). However, we recommend planning a national research agenda on air pollution that will address gaps in knowledge that are particular to China and relevant to decision-making. For example, what additional types of studies are needed to characterize the air pollution mixtures in major Chinese cities? What are the long-term and short-term policy options to improve air quality? What kind of interventions at the personal, community, city, and national level can be used to reduce the harmful effects of air pollution? Which subgroups of the general population (e.g., children, people with chronic disease) are most susceptible to air pollution and hence need to be specially protected? How effective is the newly revised Air Pollution Prevention and Control law in reducing ambient concentrations of regulated pollutants and in improving public health?

In summary, we believe China can learn important lessons from the history of air pollution in western high-income countries. The lessons span across science, technology, and policy. A key factor leading to improved air quality is the effective implementation of evidence-based policies. Today's China faces severe air pollution problems similar to the problems that the western countries faced in early and mid-20th century. However, today's China does

not need to rediscover all the scientific knowledge and reinvent all the technologies to resolve its problems. We acknowledge that there are unique characteristics and new challenges about the Chinese haze that need to be addressed in terms of both scientific research and policies; but there is a strong and useful body of evidence from research in other countries. With the top Chinese officials showing a strong political will and the general public calling loudly for better air quality, it is the time to use strong science, technology, and law enforcement to win the war against air pollution. (Premier Keqiang Li eloquently declared a war against air pollution in early 2014).

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