Postprint: Research Advances in Atmospheric Haze Source Apportionment and Control by the Chinese Academy of Sciences

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Date: 2017-03-22T00:00:00+00:00

Abstract

The Chinese Academy of Sciences has conducted systematic investigations into the formation mechanisms of atmospheric haze through the implementation of the "Atmospheric Haze Tracing and Control" Category B Pioneer Program, employing research methods including experimental simulation, field observation, and model simulation. Air pollution in China originates from combined emissions from multiple sources, characterized by diverse emission sources, complex pollutant composition, and high concentrations, with mutual influence and synergistic promotion relationships existing among different pollutants. According to the characteristics of haze formation, the fundamental strategy for current-stage governance should, while continuing to prioritize source emission reduction, concentrate efforts on addressing heavy pollution issues during the winter half-year, and further enhance the targeting of control measures.

Full Text

Formation Mechanism and Control Strategies of Haze in China

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Abstract

The Chinese Academy of Sciences (CAS) has conducted systematic research on the formation mechanism of atmospheric haze through the Strategic Priority Research Program (Category B) "Formation Mechanism and Control Strategies of Haze in China," employing experimental simulations, field observations, and modeling studies. China's air pollution results from the compounding of multiple emission sources, characterized by diverse pollution sources, complex

pollutant composition, and high concentrations, with different pollutants exhibiting mutual influence and promotion. Based on the characteristics of haze formation, the fundamental approach to current control efforts should continue to emphasize emission reduction at the source while focusing resources on addressing heavy pollution episodes during the winter half-year, with enhanced specificity in control measures.

Keywords: Chinese Academy of Sciences (CAS); formation mechanism and control strategies of haze; strategic priority research program
DOI: 10.16418/j.issn.1000-3045.2017.03.001

Scientific understanding of haze formation mechanisms provides a crucial foundation for developing effective control measures. Based on research advances from the CAS Strategic Priority Program on haze, we conclude that haze formation results from the combined effects of internal and external factors, with the superposition effect of compound pollution being the key process in haze formation in China.

1. Overall Haze Pollution Has Declined in Recent Years, but Wintertime Improvement Remains Limited

Atmospheric environmental monitoring data indicate that since 2013, national air quality has generally improved, with the proportion of days experiencing heavy or worse pollution gradually decreasing and the proportion of good air quality days significantly increasing. In 2016, the annual average PM2.5 concentration across 31 provinces, municipalities, and autonomous regions was 47 g/m^3, with an average of 78.8% good air quality days. Compared with 2015, the annual average PM2.5 concentration decreased by 6%, while the proportion of good air quality days increased by 2.1%. Taking Beijing as an example, the number of days meeting air quality standards from 2013 to 2016 was 176, 172, 186, and 198 days, respectively, while heavy pollution days were 58, 47, 46, and 39 days, respectively.

Beijing' s annual average PM2.5 concentration in 2016 was 73 g/m^3, representing a cumulative reduction of 19% since 2013, but still exceeding the national standard (35 g/m^3) by more than twofold. The fact that particulate concentrations have not yet reached the inflection point for significant environmental improvement explains why the public has not yet perceived obvious air quality improvements. Furthermore, the air pollution prevention and control situation remains severe in parts of central and eastern China during autumn and winter. Observations show that Beijing' s winter PM2.5 concentrations in 2016 did not decrease significantly compared with the previous three years, with limited improvement in the Beijing-Tianjin-Hebei region and surrounding areas, indicating that emission reduction efforts during winter have been far from adequate.

2. Major Pollution Sources Vary by Region

China' s PM2.5 and its various components originate from complex and diverse sources, including industry, transportation, construction, agriculture, livestock farming, biomass burning, and dust. According to CAS source apportionment research, coal combustion, motor vehicles, and industry are the main sources of atmospheric particulates in typical cities of the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and Guanzhong regions. In northern China, the contribution follows the order: coal combustion > motor vehicles > industry, while in southern China, coal combustion and motor vehicles contribute similarly and both exceed industrial contributions.

For Beijing specifically, although the relative contributions of various emission sources differ across pollution events or different stages of a single event, motor vehicles and coal combustion have the largest impacts. During 2014–2015, the contribution rates in Beijing were 29% from motor vehicles, 16% from coal combustion, 14% from industry, and 8% from dust, with the remainder from regional transport (24%) and uncertain sources. Compared with 2012–2013, the proportion of emissions from motor vehicles in Beijing has increased significantly in recent years (by approximately 7%).

During heavy pollution episodes, the local emission contribution from motor vehicles in Beijing becomes even more pronounced. In surrounding areas such as Tianjin and Shijiazhuang, however, coal combustion remains the largest pollution source during heavy pollution events.

3. Haze Pollution Involves Both Internal and External Factors

PM2.5 particulate matter originates from two sources: direct emissions (primary sources) and secondary formation (secondary sources). Various pollution sources directly emit particulate matter to varying degrees, creating some light extinction (light blocking). Secondary formation refers to the process by which gaseous pollutants emitted into the atmosphere are transformed into solid particulate matter. Although this process may not immediately cause light extinction (i.e., haze may not be visible at the time of emission), after several days under appropriate meteorological conditions, these gases are converted through various chemical and physical processes into solid fine particles such as sulfates, nitrates, ammonium salts, and secondary organic aerosols, which then produce visible light extinction (i.e., haze). This explains why the sky can be clear one day and moderately to heavily polluted the next—it is not merely caused by primary emissions. For some pollution sources such as gasoline vehicles, although primary particulate concentrations in exhaust are not high, the nitrogen oxides and other gaseous substances emitted react with other atmospheric gases such as sulfur dioxide to produce large quantities of solid particulate matter, forming haze and becoming a significant source of urban PM2.5.

Globally, secondary particulate matter contributes 20–80% to PM2.5 concentrations. CAS research indicates that in central and eastern China, the proportion of secondary particulates often reaches as high as 60%, becoming even higher during stagnant weather conditions. This is the reason we frequently observe "explosive" haze formation episodes.

Unfavorable meteorological conditions characterized by low wind speeds and temperature inversions constitute the external factors for haze formation. Temporally, air quality in China is generally better from March to October, largely because the summer atmospheric boundary layer is higher with stronger horizontal wind speeds that facilitate pollutant dispersion and provide greater environmental capacity, whereas winter conditions are the opposite. During autumn and winter 2016, the North China region experienced anomalous southerly winds, with winter northwesterly winds significantly weaker than the multi-year average, fewer cold air activities, and relatively stable atmospheric conditions that were unfavorable for pollutant dispersion. Meteorological data show that the annual average wind speed in the Beijing-Tianjin-Hebei region has decreased year by year over the past 40 years, with a reduction of 37%, particularly in the frequency and speed of northerly winds that are favorable for pollutant dispersion. However, such stagnant weather conditions also occurred in the 1950s and 1960s.

Furthermore, positive feedback processes can occur between internal and external factors. PM2.5 particles emitted into the atmosphere reduce the intensity of sunlight reaching the surface, causing surface temperatures to decrease, while particles in the upper atmosphere increase temperatures in that layer through light absorption, creating a stable atmospheric structure that is cold at the bottom and warm at the top. This further reduces air convection, causes the atmospheric boundary layer height to decrease, reduces environmental capacity, and thereby exacerbates pollution levels.

4. China' s Air Pollution Results from Complex Emission Compounding

Over recent decades, China' s rapid economic development has led to simultaneous emissions of multiple pollutants, creating the characteristic of compound pollution. This manifests as diverse emission sources, complex pollutant composition, and high concentrations. CAS research demonstrates that different pollutants interact and promote each other, accelerating the transformation of gaseous pollutants into particulate matter and amplifying pollution effects. For example, under conditions of high atmospheric concentrations of nitrogen oxides and mineral particles (dust), the rapid conversion of sulfur dioxide to sulfates is promoted (through oxidation and catalysis), representing a typical example of compound pollution.

Compared with the London smog event, sulfur dioxide concentrations during heavy haze episodes in China' s Beijing-Tianjin-Hebei region are 1–2 orders of magnitude lower, yet the resulting fine particulate concentrations are comparable. A key reason is that large emissions of nitrogen oxides (primarily from motor vehicles and coal combustion) and ammonia non-linearly reduce the atmospheric environmental capacity for sulfur dioxide, promoting haze outbreaks. In other words, while London' s air pollution mainly originated from coal combustion emissions, China' s pollution results from the combined effects of coal combustion, motor vehicles, and other emission sources.

5. Comprehensive Haze Control Requires Long-term Efforts

Analysis of the London smog event, Los Angeles photochemical smog event, and Yokkaichi asthma event in Japan shows that through a "combination punch" of strict legislation and enforcement, upgraded pollution control technologies, and industrial and energy structure adjustments, air quality was improved after 20-40 years of effort. The haze problem facing China is more complex. With a large base of total pollutant emissions, emission intensities from motor vehicles, industry, agriculture, and domestic sources have increased significantly in recent years, resulting in high concentrations of various pollutants in the atmosphere. China's industrial layout is relatively concentrated, giving distinct regional characteristics to North China, Northeast China, Chengdu-Chongqing, Guanzhong, Pearl River Delta, and Yangtze River Delta regions, particularly North China, which has the highest energy consumption and pollutant emissions per unit area globally. Gradual emission reductions will require considerable time. While the overall trend shows national air quality improving, fundamentally solving the haze pollution problem involves numerous issues including industrial structure, energy structure, control technologies, and socioeconomic costs, requiring a continuous process of optimization and adjustment.

6. Current Haze Control Requires Enhanced Specificity

Based on the characteristics of haze formation, the fundamental approach to current control efforts should continue to emphasize emission reduction at the source while concentrating resources on addressing heavy pollution during the winter half-year. In terms of specific measures, five key areas should be prioritized:

(1) Local governments must maintain firm commitment to both economic growth and emission reduction throughout the year, avoiding a pattern of "strict early, lax later," and ensuring production capacity reductions are fully implemented during the winter half-year.

(2) For winter heating in North China, multiple measures tailored to local conditions should be implemented to increase clean energy substitution. CAS has developed efficient and practical medium- and small-scale coal combustion technologies such as novel co-firing and decoupled combustion for residential coal burning in rural North China, which can effectively

reduce pollutant emissions while saving energy (see images on inside front cover).

(3) Control emissions from heavy-duty trucks. Although heavy-duty trucks account for only 5% of motor vehicle ownership, they contribute 90% of primary particulate emissions and over 50% of nitrogen oxide emissions from motor vehicles. Structural adjustments, capacity reductions, and improved logistics networks should be used to reduce transportation demand and improve efficiency, while actively promoting upgrades in fuel quality and retrofitting of emission control devices. CAS-developed catalysts for controlling harmful gas emissions from diesel vehicles have been widely applied, capturing 60% of the new vehicle market. Recently, CAS has developed a novel purifier based on original triboelectric nanogenerator technology specifically for removing particulate matter from vehicle exhaust, which can reduce PM2.5 content from 800–2,000 g/m^3 to below 10 g/m^3 (removal efficiency >98%) without affecting engine performance. If all of the city' s more than 5 million vehicles were equipped with such purifiers, the overall atmospheric particulate concentration could potentially decrease by 30% (see images on inside front cover).

(4) Conduct comprehensive straw management. Straw pollution covers large areas and volumes, with approximately 85 million tons generated annually nationwide. Administrative, legal, and market mechanisms should be comprehensively applied to explore large-scale, specialized, and industrialized operation models for straw utilization. CAS has developed technologies for accelerating straw degradation and bioenergy conversion.

(5) Strengthen supervision of illegal enterprise emissions. CAS has developed high spatiotemporal resolution monitoring systems that can significantly improve regulatory efficiency (see images on inside front cover).

Author Biography

Bai Chunli is a renowned chemist and leading scientist in nanoscience. As President of the Chinese Academy of Sciences (CAS), President of the Presidium of the Academic Divisions of CAS, and President of the World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), he has authored numerous scientific publications and received over twenty prestigious awards for his academic achievements, including the UNESCO Medal for Contributions to the Development of Nanoscience and Nanotechnology. He has been elected as a member or foreign member of more than ten national academies of science or engineering worldwide, including the CAS, TWAS, US National Academy of Sciences, the Royal Society, American Academy of Arts and Sciences, Academia Europaea, the Russian Academy of Sciences, the Australian Academy of Science, the Indian Academy of Sciences, the German Academy of Science and Engineering, and the Royal Danish Academy of Sciences and Letters. He serves as Chief Scientist for the National Steering Committee for Nanoscience

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Bulletin of Chinese Academy of Sciences, 2017, Vol. 32, No. 3, pp. 215–218

Note: Figure translations are in progress. See original paper for figures.