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**REVIEW**

# Chinese Anthropogenic Emissions and Air Quality Control: From the Perspective of Environment and Earth Sciences

***Chunxiao Li, Jihong Xiao, Xiaojie Mo*** *

*Shandong Academy of Environmental Sciences Co., Ltd., Jinan 250109, China*

## ABSTRACT

The fast industrialization and urbanization in China have created intricate man-made emissions that have led to gross air degradation with immense environmental, climatic, and health consequences. This is a synthesis of the existing knowledge on Chinese emissions, considering the lenses of environmental and Earth science and incorporating the knowledge on the origins of emissions, atmospheric change, transportation of the pollutants, and environmental effects. It also takes a critical look at ground and satellite-based monitoring, emission inventories, and chemical transport modeling and their importance in assessing the dynamics of pollutants and the effectiveness of control measures. The air quality management policies of China are also examined in the article, such as policy frameworks, technological interventions, and socio-economic measures, and their effectiveness in reducing $PM_{2.5}$ and $SO_2$, as well as the current challenges of $NO_x$, ozone, and secondary aerosols. The main new challenges, including aerosol-climate interactions, formation of secondary pollutants, and transboundary transport, are outlined, with the importance of integrated, adaptive, multi-sectoral responses. The review determines knowledge gaps in quantification of emissions, chemical transformation, and policy review, providing guidelines on future research and management policies that can maximize environmental, climatic, and public health co- benefits. This work offers an integrated approach to the science of emission, atmospheric processes, and environmental management that can be used to help us understand and control air pollution in China.

***Keywords:*** Anthropogenic Emissions; Air Quality Control; Atmospheric Chemistry; Environmental Management

*CORRESPONDING AUTHOR:

Xiaojie Mo, Shandong Academy of Environmental Sciences Co., Ltd., Jinan 250109, China; Email: 13678829812@163.com

ARTICLE INFO

Received: 8 April 2026 | Revised: 4 June 2026 | Accepted: 11 June 2026 | Published Online: 5 August 2026

DOI: https://doi.org/10.30564/jees.v8i8.13429

CITATION

Li, C., Xiao, J., Mo, X., 2026. Chinese Anthropogenic Emissions and Air Quality Control: From the Perspective of Environment and Earth Sciences. Journal of Environmental & Earth Sciences. 8(8): 27–48. DOI: https://doi.org/10.30564/jees.v8i8.13429

# 1. Introduction

One of the most acute issues of environmental concern in the world is air pollution, and its consequences on human health, ecosystems, and climate are far-reaching [1]. China has received a special focus among the countries, because of its fast industrialization, urbanization and energy consumption in the last few decades [2]. A complex trend of anthropogenic emissions, such as particulate matter ($PM_{2.5}$ and $PM_{10}$), nitrogen oxides (NOx), sulfur dioxide ($SO_2$), carbon monoxide (CO), volatile organic compounds (VOCs), and heavy metals, is a result of these socioeconomic developments [3]. A combination of these emissions has resulted in extreme air quality degradation, intermittent smog outbreaks, and hazy effects in the regions, especially in the North China Plain, Yangtze River Delta and Pearl River Delta, which are densely populated. The air quality problems are not in isolation; they are interconnected with other Earth system processes, such as local climates, atmospheric chemistry and hydrology [4]. This leads to the need to have an integrative approach to understand Chinese anthropogenic emissions that spans across the environmental sciences, atmospheric physics, and earth system studies.

In spite of decades of studying, there are still major gaps in our overall knowledge of the processes involved in the association of emissions, quality of the air, and environmental effects. Traditional research has concentrated on industry-specific emission inventories or locally-based air quality indicators, which have provided a piece-meal view of national pollutant dynamics. Additionally, numerous studies have focused on air quality management and environmental effects independently, restricting information on the responses between policy actions, emission reductions and Earth system response. The current progress of observational technologies, including high-resolution satellite remote sensing, dense ground-based monitoring networks, and real-time chemical analysis, together with advanced modeling tools, allows researchers to now capture multi-scale interactions and long-term trends as never before [5,6]. These technological innovations offer unprecedented chances to evaluate not only the existing level of air pollution in China but also its dynamic interactions with climate, life worlds, and human health.

Existing review papers on Chinese air pollution have mainly focused on compiling emission inventories [7], policy implementation [8], or health effects [9], treating these themes as independent areas. Very few have attempted a truly integrated synthesis that encompasses emission characteristics, atmospheric transformation processes, climate feedbacks, ecosystem responses, and policy evaluation within a common environmental/earth science framework. The review provides three unique contributions: (1) a systematic cross-scale analysis of emission sources (energy, industry, transport, agriculture, residential) through regional atmospheric chemistry processes and transboundary impacts; (2) an in-depth evaluation of secondary pollutant formation (ozone and secondary aerosols) focusing on the non-linear relationship between precursors and secondary pollutant formation, and their implications for the implementation of policy measures; and (3) an integrated analysis of the effectiveness of policy measures, including a critical evaluation of the co-benefits of policies for climate, ecosystems, and public health. The review is comprehensive, offering a reference document that is different from previous sector-based or discipline-specific reviews, which tend to be narrowly focused, by connecting emission science and atmospheric processes to environmental management [7–9].

The temporal and spatial heterogeneity of Chinese emissions is also discussed in this review. Anthropogenic sources show high seasonality, which is the heating needs during the winter months, agricultural fire, and energy usage patterns [10]. In terms of space, industrial complexes, cities and transport corridors are the hot spots of pollutant emissions and can be transported by aerosol to influence areas distant from emission sources [11]. These dynamics are essential to understand in order to design effective air quality management strategies that are both regionally oriented, and temporally adaptive. In addition, the review also addresses the efficacy of the existing control measures, such as emission standards, industrial restructuring, fuel switching, and clean energy adoption, providing insight into which policies have already brought tangible progress and where there are gaps.

Scientifically, this review can be seen as a contribution to the new research area of integrated environmental-earth systems since it highlights the feedback mechanisms between anthropogenic emissions, atmospheric chemistry, climate interactions, and ecosystem responses. It emphasizes the importance of coordinated studies that integrate high-resolution observational data, process-based modelling and policy analysis. This is a critical approach that will not only help in the development of basic knowledge but also help in the development of practical air quality management strategies that are in line with the Sustainable Development Goals (SDGs). By doing so, this review attempts to offer a framework of how the air quality issues in China are not only a national, but a global issue, which associates local emission control initiatives with the larger environmental and climate goals[12,13].

Overall, the article provides a synthesis of both Chinese anthropogenic emissions, their impact on the environment, and the measures of air quality management with a particular focus on the integrated environmental and Earth sciences outlook[14]. This review seeks to contribute to scientific knowledge and policy implications by tackling the temporal, spatial, and sectoral aspects of emissions and their interactions with the Earth system. Its uniqueness is that it fills in the gaps between emission science, atmospheric processes and environment management, providing a comprehensive viewpoint which is crucial in addressing the multi-faceted and changing challenges of air pollution in China.

# 2. Literature Selection Methodology

The review was performed using a systematic literature search strategy for complete and reproducible coverage. Searches were performed in the following databases: Web of Science Core Collection, Scopus, China National Knowledge Infrastructure (CNKI), and PubMed. The time frame examined was from January 2000 to December 2025, and some earlier landmark references (e.g., basic papers on atmospheric chemistry or early emission inventories) were added when necessary for context.

The following terms and phrases were searched for: “China” OR “Chinese” AND “anthropogenic emissions” OR “air pollution” OR “air quality” AND “$PM_{2.5}$” OR “NOx” OR “$SO_2$” OR “ozone” OR “VOCs” AND “control” OR “policy” OR “management”. Further specific searches were conducted on the topics: aerosol-climate interaction, secondary aerosol formation, emission inventory, satellite monitoring, chemical transport model and health co-benefits.

The inclusion criteria are: (i) peer-reviewed journal articles, (ii) official government reports and policy documents (such as from the Chinese Ministry of Ecology and Environment), (iii) reputable review articles and book chapters, and (iv) studies that provide original observation or modeling results useful for the study of anthropogenic emissions or air quality control in China. Exclusion criteria: (i) Non-English or non-Chinese publications that were not available in full-text translation, (ii) conference abstracts only (without full paper), (iii) studies that only focused on indoor air quality or occupational exposures but were not relevant to ambient outdoor air pollution, and (iv) studies without a clear methodological description.

Duplicated records were eliminated. Titles and abstracts were screened, followed by full-text assessment. Additional relevant studies found by conducting a hand search of reference lists of included articles were considered (snowballing). The final reference set (n = 101) is a balance of basic knowledge and more recent advances (2015–2025).

# 3. Characteristics and Sources of Chinese Anthropogenic Emissions

The fast industrialization and urbanization of China in the last few decades have created a distinctive emission profile, which is both time- and space-complex. The nature of anthropogenic emissions in China is that they are of high intensity, heterogeneous in chemical composition, and highly heterogeneous in regions[15]. These emissions are related to various sectors such as the production of energy, industry, transport, agriculture and residential areas. It is important to know the nature and origin of these emissions to assess their effects on the air, climate, and ecosystems and to develop effective mitigation measures.

## 3.1. Energy and Industrial Sectors

Production of energy has been the leading contributor to anthropogenic emissions in China, mainly because of a heavy dependence on coal and fossil fuels[12]. The power plants that use coal release huge amounts of sulfur dioxide ($SO_2$), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM), which are the major contributors to episodes of haze in the region[16]. Industrial operations, such as cement manufacturing, iron and steel production, and chemical processing, also contribute to the worsening of particulate matter, volatile organic compounds (VOCs) and heavy metal contamination (lead, mercury, and cadmium) [17]. These industrial sources tend to be concentrated in certain areas, including the Bohai Bay industrial belt, the Yangtze River Delta, and the Pearl River Delta, forming hotspots of emissions.

The policies of energy efficiency and emission cuts in the industrial and power sectors have changed the environmental emissions in the last ten years. $SO_2$ and NOx emissions in power plants have been reduced successfully by use of flue-gas desulfurization (FGD) and selective catalytic reduction (SCR); the elimination of small, inefficient industrial boilers has lowered particulate emissions [18,19]. In spite of these achievements, there are still problems, such as the increasing electricity demand, the lack of uniformity in the use of modern technologies in different areas and the fact that part of the north is still using high-sulfur coal. As a result, energy and industrial emissions are still a major factor in the air pollution problems in China, as the control of emissions and their interactions with economic growth and the structure of energy in the region are complex.

## 3.2. Transportation Emissions

The transportation sector has become a more prominent contributor of air pollution in Chinese cities [20]. The rapid increase in the number of vehicles, especially in large cities, has contributed to a higher level of emissions of NOx, CO, VOCs and fine PM [21]. Motor vehicles do not only cause primary pollutants, but also precursors to secondary pollutants like ozone and secondary aerosols, which are formed as a result of chemical reactions in the atmosphere. **Table 1** summarizes the relative contributions of various sectors to the total anthropogenic emissions in China, which have spatial and temporal variability between regions. Transportation emissions are concentrated in cities and along major highways to the point of causing serious local air quality issues.

**Table 1.** Sectoral contributions to Chinese anthropogenic emissions, including key pollutants, estimated percentage contribution, spatial distribution, and temporal variability.

| Sector | Pollutants | Estimated Contribution (%) | Spatial Characteristics | Temporal Variability |
|---|---|---|---|---|
| Energy (coal-fired power) | $SO_2$, NOx, $PM_{2.5}$, CO | 40–50 | Northern and Eastern China, industrial clusters | Winter peak due to heating demand |
| Industry (steel, cement, chemical) | PM, $SO_2$, VOCs, heavy metals | 25–30 | Bohai Bay, Yangtze River Delta, Pearl River Delta | Year-round, industrial cycle dependent |
| Transportation | NOx, VOCs, $PM_{2.5}$, CO | 15–20 | Urban centers, highway corridors | Summer ozone peaks, morning/evening traffic peaks |
| Agriculture | $NH_3$, $CH_4$, $N_2O$ | 10–15 | North China Plain, central China | Fertilizer application and post-harvest burning |
| Residential | PM, VOCs, CO | 5–10 | Rural and peri-urban northern regions | Winter heating peak |

The quantity of transportation emissions depends on the fuel type, the age of the vehicle, and the emission control technologies. Older vehicles and diesel engines produce more $PM_{2.5}$ and nitrogen oxides, whereas newer vehicles with catalytic converters and diesel particulate filters display a better emission profile. Urban NOx emissions and particulate emissions are minimized by policy interventions such as vehicle emission standards, high-emitting vehicle bans, and electric mobility encouragement [22]. Nevertheless, there are still issues with the transportation demand-reduction balance, especially in rapidly expanding megacities, where traffic jams and large volumes of traffic still fuel air pollution events.

## 3.3. Agricultural and Residential Emissions

The agricultural activity is a significant source of ammonia ($NH_3$), methane ($CH_4$), and nitrous oxide ($N_2O$), which are precursors to the formation of secondary inorganic aerosols and contribute to the formation of $PM_{2.5}$ [23]. The major sources of these emissions are fertilizer application, livestock husbandry, and biomass burning. Although the agricultural sector has long been the least regulated sector compared to industrial or energy sectors, its role in the production of secondary particulate matter qualifies it as an important aspect of the management of air quality. The spatial distribution of agricultural emissions is directly linked to areas of high crop production and animal husbandry, especially in the North China Plain and in some areas of central China.

Residential sources, which are heating and cooking, have traditionally been sources of high levels of PM and VOCs, especially in the northern regions during the winter months [24]. Domestic heating with coal and biomass caused the intensive period of air pollution during the seasons, which in many cases contributed to the increase in winter smog. Policy interventions that have encouraged the use of cleaner heating technology, such as the replacement of coal stoves with natural gas or even electricity, have made some quantifiable decrease in the level of particulate emissions. However, the rural and peri-urban regions still might have high levels of pollution due to the lack of full implementation of clean energy solutions and the transportation of pollutants in the region.

## 3.4. Temporal and Seasonal Variations

In China, anthropogenic emissions are highly variable both in terms of time and season. During winter, the energy needs of residential heating and industrial production are higher, and the emissions of particulate matter and sulfur dioxide are higher. The burning of biomass as part of some agricultural processes, including the burning of residual materials after harvest, further contributes to peak episodes of pollution. Summer months, on the other hand, are found to be characterized by heightened photochemical activity, which contributes to the formation of ozone because of the high concentrations of VOCs and NOx that are produced by industries, transportation, and biogenic sources. Such seasonal heterogeneity highlights the significance of emission inventories that are temporally resolved and adaptive air quality management plans that consider seasonal peaks in pollutant concentrations [10,25].

The effects of national emission control policies can also be seen in long-term temporal trends. After the adoption of the $SO_2$ and particulate matter reduction plan, namely the Air Pollution Prevention and Control Action Plan, in 2013, the country experienced a significant drop in the emissions of these substances [26]. Although the emission of NOx has decreased in certain urban areas, it is still a major problem with the rising vehicle population. The dynamics of emissions over time underscores the dynamic nature of policy, technology, economic activity and demand for energy and underscore the importance of incorporating time dynamics in the assessment of air quality. The evolution of carbon emissions over the past two decades in key regions is shown in **Figure 1**, highlighting yearly and policy-driven trends.

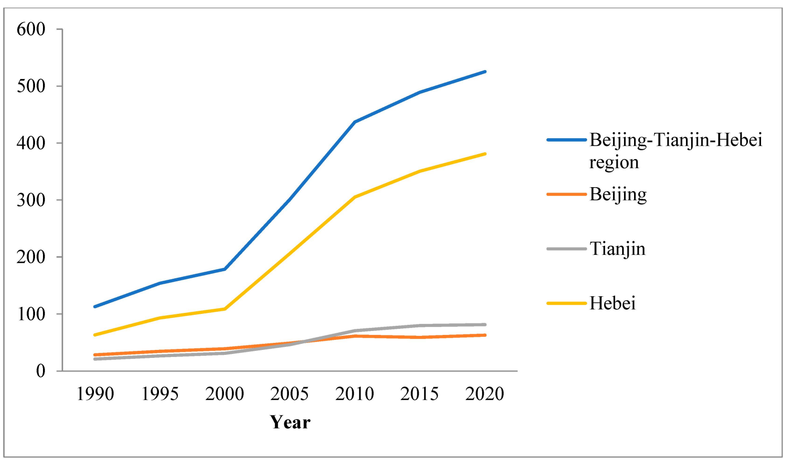
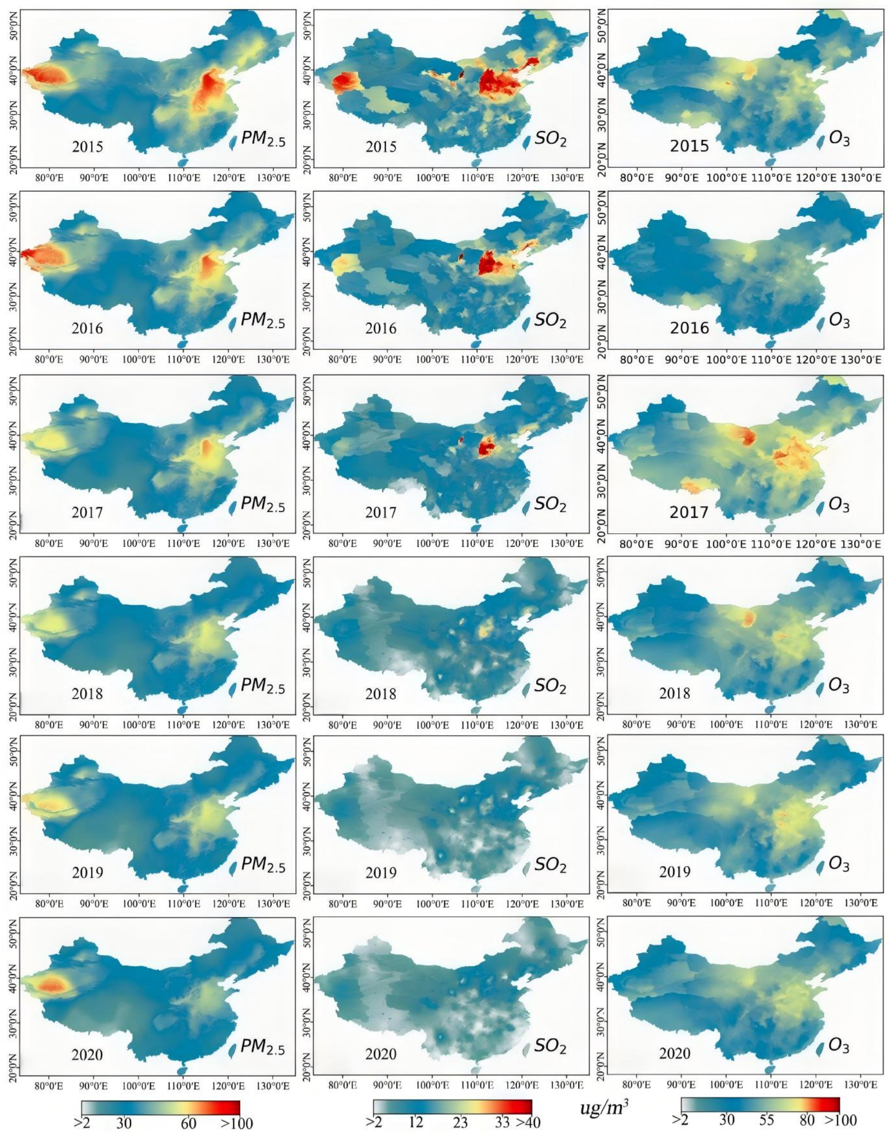



**Figure 1.** Temporal trends of net carbon emissions in the Beijing–Tianjin–Hebei region from 1990–2020 (million tons) [27].

## 3.5. Spatial Heterogeneity and Regional Hotspots

The anthropogenic emissions of China are extremely heterogeneous as they depend on the regional differences in the industrial structure, energy consumption, the degree of population density, and the degree of climatic conditions. Northern China has the largest emissions of $SO_2$, NOx, and particulate matter, with coal-based energy systems and heavy industry being the leading ones [28]. On the other hand, the high population and high transport systems are present in the southeastern coastal regions and thus high concentration of VOC and NOx emissions form ozone in the urban areas [29]. Even though the western and southwestern states are less industrialized, coal mining, cement production, and burning biomass are becoming more and more significant to the areas, causing local pollution and cross-border transportation of aerosols [30].

Cities and industrial belts are areas of high-density emissions. The regions of Beijing–Tianjin–Hebei, Yangtze River Delta and Pearl River Delta are collectively contributing a disproportionate number of national emissions based on their geographic size [31]. Not only do these hotspots impact local air quality, but they also have an impact on regional atmospheric chemistry and climate due to the transport of pollutants long distances, the formation of secondary aerosols, and aerosol-radiation interactions [32]. Knowledge of spatial heterogeneity is thus vital in the development of region-based mitigation measures that consider the local sources, transport processes, and meteorological factors. **Figure 2** presents the simulated average annual distributions of $PM_{2.5}$, $SO_2$, and ozone across China from 2015 to 2020 using the proposed method.




(**a**) The annual mean $PM_{2.5}$ concentrations for 2015–2020. (**b**) The annual mean $SO_2$ concentrations for the same period. (**c**) The annual mean ozone levels.

**Figure 2.** Spatial maps of the annual average distributions of $PM_{2.5}$, $SO_2$, and ozone across China from 2015 to 2020.

Note: The colour bars at the bottom indicate the pollutant concentration ranges within the study area [33].

It indicates that the concentrations of high risk of $PM_{2.5}$ and $SO_2$ are mostly concentrated in north and north-west China[34]. Ozone also presents higher values in these areas, and there are other high values in the Qinghai-Tibet plateau[35]. These trends are in line with the site observations and past research that validates the stability and reliability of the MuAP approach towards simulation of ozone. Clearly distinct spatial boundary differences are further emphasized with the introduction of meteorological factors and regional ranking.

### 3.6. Chemical Characteristics and Pollution Formation Mechanisms

The Chinese anthropogenic emissions are of various chemical compositions that include both primary and secondary pollutants. The main forms of pollutants are particulate matter, $SO_2$, NOx, CO, and VOCs, whereas secondary pollutants like ozone and secondary inorganic aerosols are produced by the multifaceted photochemical and heterogeneous reactions in the atmosphere[36]. The presence of high densities of reactive precursors, especially in industrialized and urbanized areas, enhances the quick development of fine PM and secondary pollutants that may have extensive effects on human health, visibility, and climate.

The critical evaluation of the pollutant formation processes has suggested that the formation of secondary aerosols, especially sulfate, nitrate, and ammonium compounds, is a significant source of $PM_{2.5}$ mass in China[37]. The mutual interaction between agricultural ammonia emissions and acidic emissions of the industrial and energy sectors leads to the production of secondary aerosols, which demonstrates the interdependence of emissions by the industries. The ozone formation process is also complicated and depends on the VOC–NOx photochemistry and is affected by meteorological factors like solar radiation, temperature, and stagnation of the atmosphere. These processes demonstrate the need to develop multi-sectoral strategies for controlling emissions, including the fact that the decrease in one pollutant can be offset by further progress in air quality without the need to decrease the chemical precursors to form secondary pollutants.

### 3.7. Critical Insights and Knowledge Gaps

Although significant advances have been made in defining Chinese anthropogenic emissions, there are still a number of gaps in knowledge. To begin with, there are uncertainties in emission inventories, especially of small-scale industrial emission sources, rural energy consumption, and agricultural activities, which restrict the accuracy of air quality models[38]. Second, emission, weather, and atmospheric chemistry interactions are not fully characterized, making it challenging to predict pollution events and trends[39]. Third, there are regional differences in the effectiveness of emission control policies and the evaluation of co-benefits of climate and ecosystem health is not complete[40]. These gaps must be filled with the concerted action of high-resolution observations, sophisticated modeling frameworks, and combined assessment or policy interventions.

## 4. Environmental and Earth Science Impacts

The anthropogenic emissions of the Chinese environment and Earth system have intricate impacts, such as atmospheric chemistry, climate interactions, hydrology, ecosystem responses and human health[41]. Most of the effects are indirect and result in complicated interactions between emissions, meteorology, and processes within the Earth system as opposed to primary pollutants. This section is a synthesis of existing knowledge of these effects and focuses on how emissions change the composition of the atmosphere, climate at the regional scale and ecological integrity, as well as outlining the important lessons that must be learned to implement successful air quality management and mitigation policies.

### 4.1. Atmospheric Chemistry and Aerosol Formation

Anthropogenic emissions in China modify the atmospheric chemistry greatly, resulting in increased secondary aerosol production and changing the oxidative capacity of the atmosphere[42]. Photochemical and heterogeneous reactions of primary emissions, such as sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds, produce fine particulate matter ($PM_{2.5}$) and ozone, which are leading air pollution events in cities and industrial regions. In the North China Plain and other industrial hotspots, a large fraction of $PM_{2.5}$ mass also consists of sulfate, nitrate, and ammonium, which are called secondary inorganic aerosols[43]. The impact of such aerosols on air quality includes increasing the level of particulate matter and reducing visibility, acting as a reaction surface for other chemical reactions, which contribute to more pollution events. A conceptual schematic illustrating the pathways of primary and secondary pollutant formation, atmospheric transport, and climate interactions is provided in **Figure 3.**

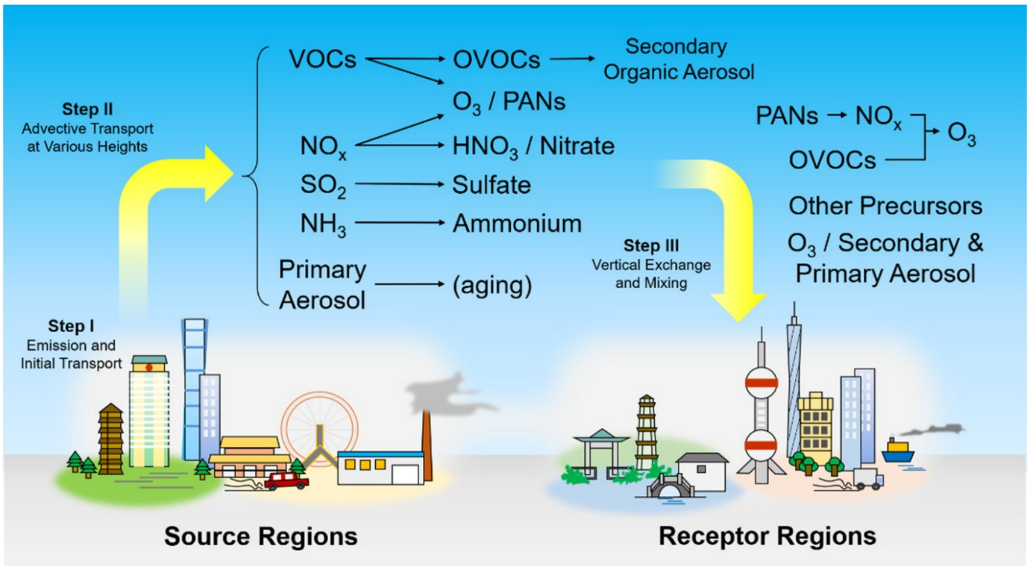



**Figure 3.** Schematic representation of atmospheric pollutant formation and transport in China.

Note: **Figure 3** shows primary emissions, secondary aerosol and ozone formation, transport, deposition, and climate feedbacks [44].

The other significant atmospheric impact is photochemical production of ozone. Ozone formation is also dependent on the ratio of VOCs and NOx, solar radiation and ambient temperature. The regimes with limited VOCs are dominant in the majority of Chinese megacities, and, to be more precise, in the given conditions, a reduction in the NOx will only be able to offset unintuitive ozone levels [45]. This nonlinear chemistry makes the management of air quality more complicated and emphasizes the necessity to use integrated approaches to address a number of precursors. Moreover, the aerial concentration of the photolysis rates of significant atmospheric species is also modified by the high aerosol concentration, which further modifies the oxidative capacity and the feedback of the atmosphere.

The Chinese emissions are also a contributing factor in the long-range transportation of pollutants. Fine particulate matter and ozone precursors have lengths of hundreds and thousands of kilometers, which means that the areas affected are far away [46]. Transboundary transport impacts the development of regional haze, modifies cloud microphysics and can enhance the production of secondary aerosols in downwind areas. High intensity of emissions, multifaceted chemical interactions, and dynamic transport with a complex transport system are three elements that emphasize the unique atmospheric challenges in China and the need to have multi-scale observation and modeling frameworks.

## 4.2. Aerosol-Climate Interactions

The radiative effects of the aerosol produced by man are very strong, and these influence climate, both locally and globally [47]. The scattering and absorption of solar radiation by aerosols change the surface energy balance and redistribute temperatures. The excessive levels of black carbon, organic carbon, sulfate and nitrate in eastern China have been found to create the cooling effect of the regions on the surface and heating of the atmosphere through absorption, resulting in temperature inversion exacerbation of the pollution events. These aerosol-radiation interactions stabilize the dynamics of atmospheric stability and boundary layers and influence local meteorology and dispersal of pollutants [32].

In addition, cloud condensation nuclei are aerosols, and have an impact on cloud microphysics, cloud life, and precipitation [48]. Increased aerosol concentrations in polluted areas have the capability of inhibiting precipitation by the so-called aerosol indirect effect, reducing the coalescence of droplets and altering cloud albedo. The observational study and modeling analysis in China have also revealed that aerosol-cloud interaction leads to the formation of spatially heterogeneous patterns of precipitation with implications towards the regional water availability and hydrological processes. This feedback shows how intricate the relationship is between emissions and climate processes, and that direct and indirect aerosol impacts should be taken into account in air quality and climate mitigation strategies.

### 4.3. Impacts on Hydrological and Biogeochemical Cycles

The anthropogenic emissions in China also influence the hydrological and biogeochemical processes, which can be largely attributed to acid deposition and unbalanced nutrients. Acidic substances, such as sulfuric acid and nitric acid are formed due to $SO_2$ and NOx emissions and are deposited on the soil and water ecosystems, leading to the acidification of soil, leaching of nutrients, and alteration of the productivity of the ecosystem [49]. It has been shown that low soil pH and base cation loss in forested areas of northern and central China influences tree growth, microbial activity, as well as carbon sequestration. In line with this, the deposition of acid in freshwater habitats in turn results in reductions in alkalinity that affect aquatic species richness and the resilience of ecosystems.

The next pathway through which air pollution is connected to the functioning of the ecosystem is nitrogen deposition due to the emissions of NOx and ammonia [50]. Nutrient enrichment can stimulate primary productivity in nutrient-limited ecologies, but high deposition can lead to nutrient imbalances in soil and species shifts, and can cause eutrophication of the downstream waters. Agricultural lands are particularly vulnerable because the deposits of nitrogen can react with the application of fertilizers and create hotspots of the over-enrichment of nutrients that impact the terrestrial and aquatic biogeochemical processes.

### 4.4. Ecosystem and Biodiversity Responses

The impacts of the Chinese anthropogenic emissions are not simply restricted to the alterations in chemicals but also have direct impacts on ecosystems and biodiversity. A large concentration of particulate matter decreases the light penetration when the concentration is high and this influences the photosynthesis in plants and phytoplankton. Contact with ozone kills the tissue of the leaf, decreases the harvest and deforms the plant physiology. High ozone has been reported to reduce the productivity of wheat and rice in the research conducted in eastern China, and has an implication on food security. The type of species, rate of growth, resistance to pests and diseases altering in the long-term to air and pollutants are some of the characteristics used to define forest ecosystems [51,52].

It also has an impact on biodiversity in water and on land. Nitrogen enrichment and acidic deposition can lead to this loss of diversity through encouraging fast-growing and pollution-resistant species at the cost of sensitive native species. Acidification and nutrient enrichment in freshwater disrupt species balance, disrupting trophic interactions, and exposing them to algal plankton [53]. These environmental impacts demonstrate the domino effect of the anthropogenic pollutants, relating the quality of air with the health, stability and functionality of the ecosystems.

### 4.5. Human Health Implications

This review emphasises an environmental and Earth science viewpoint, but a relationship between emissions and human health provides a wide integrative view of the effects [54]. Fine particulate matter, ozone, and secondary aerosols are only associated with respiratory and cardiovascular diseases, increased hospitalization and preterm deaths. The high cost to public health due to air pollution has been estimated through epidemiological studies in China, and thus, there is an urgent need to find ways of controlling the emissions. In addition, health effects can have feedback effects on environmental management by affecting the policy priorities, energy planning and urban development strategies.

Scientifically, to comprehend the pathways in which the emissions can be converted to health outcomes requires a combination of atmospheric chemistry, exposure modeling, and epidemiology [55]. The non-homogeneity of the emissions of space and time, the density of the population and the meteorological variations make it hard to carry out the exposure assessment and risk evaluation. These issues highlight the importance of interdisciplinary methods that are able to bridge the gap between emissions characterization, the transformation of pollutants, and exposure assessment to make evidence-based mitigation decisions.

## 4.6. Interactions with Climate Change

The Chinese emissions, which are anthropogenic, interact with climate change in a number of ways. The short-lived climate pollutants are black carbon and ozone that create radiative forcing and regional warming and sulfate aerosols that create cooling effects that temporarily offset greenhouse gas-induced warming [56,57]. Temperatures, precipitation and atmospheric circulation changes associated with climate change further modify the distribution of the dispersion of pollutants, chemical transformation, and deposition. As an example, the increase of temperature increases photochemical activity, which boosts the formation of ozone in the summer seasons, and the changing monsoon patterns can affect aerosol transportation and removal. Such a two-way relationship has shown that there exists a strong interdependence between air pollution and climate and that concerted efforts should be made in tackling the air quality and climate mitigation efforts.

Climate–air quality interaction policy implications also exist. Pollution control actions that reduce greenhouse gas emissions, such as the replacement of clean energy, will reduce co-emitted air pollutants and create co-benefits to health and ecosystems [58]. Conversely, part of the adaptation strategies, such as using more energy during heatwaves so as to cool down, can also contribute to the occurrence and emission of pollution. The importance of understanding these complex interactions is in coming up with combined environmental management strategies that are maximizing in terms of air quality as well as climate.

## 4.7. Transboundary and Regional-Scale Impacts

The Chinese emissions have global ramifications. The fine particulate matter, ozone precursors, and acidic compounds are transported to the neighboring countries and regions such as Korea, Japan, and some parts of Southeast Asia by atmospheric transport [59]. Regional haze events are usually linked to the eastern parts of China that have emission hotspots where the transported pollutants may result in serious issues with air quality in the downwind areas. The transboundary effects put an accent on the need to cooperate regionally in monitoring, modelling and policy realisation and the importance of considering long-range transport to emission control policies.

Moreover, the impacts, at the regional scale, are transferred to oceanic systems and coastal systems [60]. Nitrogen and sulfur transport within the atmosphere have the potential to alter coastal nutrient dynamics, lead to coastal eutrophication, and affect marine biodiversity [61]. Biogeochemical cycles, like the supply of micronutrients, including iron, to marine ecosystems due to the deposition of aerosols on oceans, also have an impact [62]. These interactions illustrate the applicability across the board of the Chinese emission profile and the way national control of emissions has externalities on the land as well as the marine environment at greater spatial levels.

## 4.8. Critical Analysis and Emerging Challenges

Although there have been major breakthroughs on the environmental and Earth science implications of the Chinese emissions, there are still a number of challenges. Firstly, the role of the different sectors in the formation of the secondary aerosol and the production of ozone remains unclear. The absence of linearity in chemical interactions and changeability in meteorology complicates modeling and requires resolution of observational networks and process-oriented models. Second, not all emissions, climate, and ecosystem feedbacks are fully comprehended, particularly on the aerosol-cloud interactions, the impacts of nitrogen deposition, and the local hydrological feedbacks. Third, assessment of the effectiveness of emission control policies in changing the environmental effects needs to be done using integrated assessment frameworks that integrate the emissions data, model atmospheric and ecological monitoring data [63].

The re-arranging energy scenario, the birth of urban megacities, and the appearance of secondary pollutants are also emerging issues. The shift from coal to cleaner energy sources alters the emission composition and may even alter the major and minor pollutant balance [64]. The fast urban growth alters the meteorology of the area, the spread of pollutants, and exposure. It is also possible that the interaction of climate variability and pollutant chemistry will escalate and will require adaptive approaches that can adapt to the changing environmental conditions [65]. **Table 2** compiles the environmental and Earth science impacts of Chinese emissions, such as atmospheric, climatic, ecosystem and health impacts.

**Table 2.** Summary of environmental and Earth science impacts of Chinese anthropogenic emissions, including pollutants, mechanisms, spatial/temporal patterns, and implications.

| Impact Category | Pollutants/Drivers | Mechanisms | Spatial/Temporal Patterns | Critical Implications |
|---|---|---|---|---|
| Atmospheric Chemistry | $SO_2$, NOx, VOCs, $NH_3$ | Secondary aerosol formation, ozone photochemistry | Urban and industrial regions, seasonal variation | Complex non-linear chemistry, challenges for control of secondary pollutants |
| Climate Interactions | Aerosols (Black Carbon (BC), sulfate), ozone | Radiative forcing, aerosol-cloud interactions | Regional cooling/warming, monsoon modulation | Affects surface temperature, boundary layer, precipitation patterns |
| Hydrological/Biogeo-chemical | Acidic compounds, nitrogen | Acid deposition, nutrient loading | Forests, croplands, freshwater systems | Soil acidification, eutrophication, altered ecosystem productivity |
| Ecosystem & Biodiversity | PM, $O_3$, acid deposition | Photosynthesis inhibition, species shifts | Forests, croplands, freshwater systems | Reduced productivity, biodiversity loss, ecosystem imbalance |
| Human Health | $PM_{2.5}$, $O_3$, CO | Respiratory/cardiovascular stress | Urban centers, high-exposure populations | Premature mortality, hospital admissions, public health burden |
| Transboundary Impacts | $PM_{2.5}$, NOx, $SO_2$ | Long-range transport, deposition | Downwind regions in Asia | Regional haze, ecosystem deposition, coastal nutrient input |

# 5. Air Quality Monitoring and Modeling Approaches

Proper characterization of the concentrations of pollutants, sources, and transport processes is the key to success in air quality management in China. Monitoring and modeling would be the heart of air quality assessment that would be capable of providing both empirical and predictive data needed to assess the policy and design mitigation strategies [66]. The enhancement of observational technology, satellite remote sensing, and computational modeling has transformed the understanding of anthropogenic emissions, their spatial and temporal distribution, and their impact on the environment in China. This section is an overview of the most important air quality monitoring and modeling techniques in China, their strengths and shortcomings, and their contribution to overall environmental management.

## 5.1. Ground-Based Monitoring Networks

The most straightforward way of measuring the level of air pollutants is ground-based monitoring. In China, nationwide and regional-scale monitoring networks have been established that provide virtually real-time measurements of $PM_{2.5}$ ($PM_{10}$), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide, among other significant pollutants [67,68]. The Chinese National Environmental Monitoring Center (CNEMC) has established a network of over 1,500 stations in urban, suburban, and rural regions that have yielded high-resolution datasets that capture spatial and temporal variations.

The surveillance networks have revealed some crucial trends in air quality. The $PM_{2.5}$ and ozone levels are always high in cities, and the levels of sulfur dioxide and NOx are high in industrial districts [69]. Seasonal variations such as high $PM_{2.5}$ in winter heating seasons and high ozone in summer seasons have been well-documented [70]. Furthermore, the networks permit the identification of episodic pollution events because they allow the researchers to investigate the meteorological and chemical conditions that can lead to severe haze and smog events. As much as ground-based networks are significant, they have shortcomings. The stations are also unevenly distributed; the rural and remote areas are underrepresented, which may lead to biases in the national assessment. Moreover, the majority of the stations do not sample at different heights and positions, and this limits the ability to sample vertical profiles, urban canopy, and micro-scale variability. Integration of ground-based observation with other observational systems, such as mobile sensors, low-cost monitoring networks, etc., is also becoming a possibility to fill these spatial gaps and provide a more comprehensive air quality measurement.

## 5.2. Satellite Observations

Satellite remote sensing, which is a new type of remote sensing, has proved to be an effective tool to complement ground-based monitoring, offering coverage over large regions and the possibility of monitoring those regions that lack in situ measures. The equipment, such as the Ozone Monitoring Instrument (OMI), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Tropospheric Monitoring Instrument (TROPOMI), is used to get information on the composition of the atmosphere, which contains $NO_2$, $SO_2$, ozone, aerosols, and formaldehyde. In China, satellite observations have been applied to identify the location of the pollution in the country, monitor the movement of pollution over a long distance, and track the change in emissions over time[71].

One of the advantages of satellite data is that they are able to monitor spatial gradients and transboundary pollution episodes[72]. To illustrate this, the post-policy intervention emissions, such as the adoption of the action plan of Air Pollution Prevention and Control in 2013, have been determined through the assistance of satellite-based $NO_2$ columns. The aerosol optical depth (AOD), with the addition of ground-based $PM_{2.5}$ measurements, can help to estimate concentrations of particulate matter in areas without a monitoring station. Also, satellite measurements can be an essential input to chemical transport models to enhance simulations of pollutant dispersions and chemical reactions.

Nevertheless, there are many difficulties with satellite observations. Vertical column measurements are not always dependent on the pollutant concentrations on the surface, and special algorithms of retrieval and comparison to ground-based measurements are required. Cloud cover, aerosol scattering, and instrument resolution hamper the accuracy of the data and its ability to cover time[73]. Moreover, satellite measurements tend to be snapshots at very specific overpass times, and thus, diurnal variability is hard to measure. Despite these weaknesses, a combination of satellite and ground-based data has played a significant role in the full evaluation of air quality in China, which enhances the coverage of the observation and also the validation of the model. **Table 3** illuminates the significant air quality monitoring systems and observation platforms in China, their strengths, and limitations.

**Table 3.** Overview of China's key air quality monitoring networks and observational platforms, including measured pollutants, coverage, temporal resolution, strengths, and limitations.

| Network/Platform | Pollutants Measured | Coverage | Temporal Resolution | Main Strengths | Limitations |
|---|---|---|---|---|---|
| CNEMC Ground Stations | $PM_{2.5}$, $PM_{10}$, $SO_2$, NOx, CO, $O_3$ | >1,500 stations nationwide | Hourly | High temporal resolution, real-time data | Sparse in rural areas, limited vertical profile |
| MODIS/AOD | Aerosols | Nationwide, regional, global | Daily | Large spatial coverage, long-term trends | Surface concentration not directly measured, cloud interference |
| OMI/TROPOMI | $NO_2$, $SO_2$, $O_3$ | Nationwide, regional, global | Daily | Chemical composition, hotspot detection | Limited diurnal info, vertical integration uncertainties |
| Mobile/Low-cost Sensors | PM, CO, NOx | Localized urban areas | Continuous | Flexible deployment, urban-scale resolution | Calibration and accuracy issues |

## 5.3. Emission Inventories

One of the keys to the knowledge of the sources of the pollutants and to the creation of the modelling schemes is the inventory of emissions. In China, the bottom-up inventories are constructed based on the data of activities, emission factors, and outputs of the sectors to estimate the overall emissions of industry, energy, transportation, agriculture, and residential[74]. There are such well-known inventories as the Multi-resolution Emission Inventory of China (MEIC) that provide high-resolution data on a sector-by-sector basis of diverse pollutants through time.

A list of emissions has shed some light on key aspects of emissions in China. The sectoral contributions indicate that coal burning is the biggest contributor to $SO_2$ and primary PM, transportation and industrial sectors are the biggest contributors to NOx and VOCs[28]. Spatial distribution maps of the hotspots of emissions in the North China Plain, Yangtze River Delta, and Pearl River Delta are developed using inventories. The time-temporal patterns show that the flue-gas desulfurization and industrial restructuring have reduced some of the pollutants, such as $SO_2$, but in other regions, such as NOx in urban traffic, they have increased.

Although emission inventories are handy, they are susceptible to uncertainties. The discrepancies between the estimates of the inventory and the observed concentrations are also brought about by the change in the emission factors, underreporting of small-scale or informal industries, as well as regional differences in the quality of fuels. Top-down methods, which apply atmospheric measurements and inversion modeling to deduce emissions, are increasingly used to verify and refine bottom-up inventories [75]. The two methods, when combined, can also provide more accurate estimates of emissions, which are necessary to model pollutant transport, formation, and deposition.

## 5.4. Chemical Transport Modeling

Chemical Transport Models (CTM) are needed to model the dynamics and are used to study the movement, transformation, and fate of pollutants in the atmosphere [76]. These models also include information on emissions and meteorological fields and chemistry reaction mechanisms to model the concentration of pollutants at various times and space. Some of the most popular models used in China are Community Multiscale Air Quality (CMAQ) model, Weather Research and Forecasting with Chemistry (WRF-Chem) model and Model of Ozone and Related Chemical Tracers (MOZART) [77]. These models have been employed to understand the processes of haze formation, ozone events, the production of secondary aerosols and the usefulness of emission control measures.

CTMs have provided valuable information on the mechanisms that lead to serious cases of pollution. Indicatively, winter conditions with stagnant meteorological conditions and elevated emissions have been simulated to enhance the production of secondary aerosols, leading to the occurrence of dense haze. The non-linear chemistry of ozone formation is also modeled and emphasizes the VOC-limited regime, the NOx-limited regime, and the information on the desired emission reductions [78]. Additionally, it is possible to perform scenario analysis and assess the potential impacts of policy interventions, technological advances, and energy transitions on future air quality with the help of the CTMs.

Modeling challenges remain. Computation is expensive and a high spatial resolution of simulations might not be adequate in urban-scale analysis [79]. The chemical processes and aerosol processes are complex and contain numerous feedbacks that make it difficult to make predictions. Meteorological conditions, especially the dynamics of the boundary layer, are also of great concern in the correct simulation of the dispersion and accumulation of the pollutants. Nevertheless, CTM is still a valuable instrument to comprehend the dynamics of air quality and assess mitigation measures in China.

## 5.5. Data Assimilation and Integrated Approaches

Recent advancements in data assimilation are a combination of observational data on the ground stations, satellites and airborne data on the ground using the CTMs to improve the accuracy of the models and reduce uncertainty [80]. The model outputs are then modified by methods (such as 3D-Var, Ensemble Kalman Filter and hybrid inversion methods) that react to the measured concentrations so that the predictions of the pollutant distribution can be more precise. Applications of data assimilation in China have been used to enhance the emission estimates, haze prediction and to quantify the effectiveness of emission control policies at high time and space scales.

Integrated methods go beyond observation-model coupling to encompass the socio-economic and policy aspects. By linking emission inventories, atmospheric models, and measurements of health or ecosystem impacts, researchers are able to examine co-benefits of air quality management, priority areas, and create adaptive mitigation strategies [81]. This viewpoint on systems level is critical due to the multidimensional challenges underlying the complex emission landscape in China. **Figure 4** illustrates the integrated monitoring and modeling framework for assessing air quality, combining ground-based and satellite observations, emission inventories, and chemical transport models.

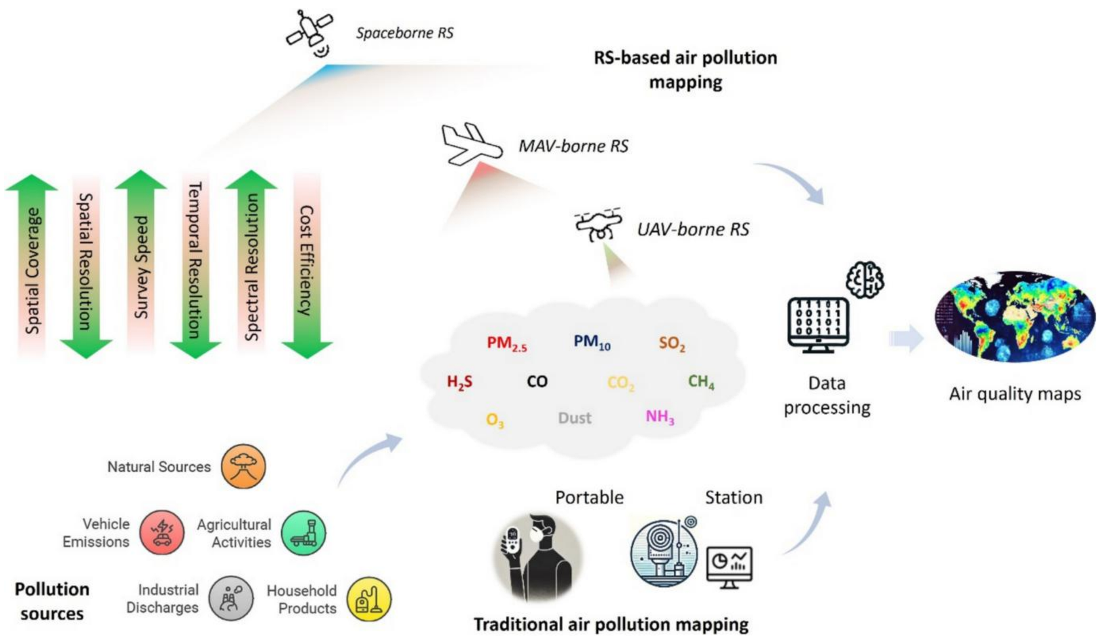



**Figure 4.** Integrated framework for air quality assessment in China.

Note: **Figure 4** shows the flow of observational data, emission inventories, modeling, data assimilation, and policy evaluation [82]. RS, remote sensing; MAV, micro aerial vehicle; UAV, unmanned aerial vehicle.

## 5.6. Uncertainties and Knowledge Gaps

Although there are significant advancements in monitoring and modeling, there are a few uncertainties that constrain the accuracy of air quality measurements in China. Rural regions may be biased in ground-based networks, satellites have low vertical and temporal resolution, and inventories of emissions have been constrained by the quality of the data and scope of sectors. Although complex, chemical transport models are based on the correct meteorological input and chemical processes, which can be locally different [80]. Additionally, the interaction between aerosol-cloud and aerosol-radiation is not completely understood, which restricts the predictability of the models concerning extreme pollution events and climate interactions.

New challenges include integrating high-resolution measurements with urban, regional, and national models, measuring the creation and transportation of secondary pollutants, and the implications of climate variability on the dynamics of pollutants. Such gaps will need to be bridged by a mix of dense observational systems, long-term observation, sophisticated modeling systems, and interdisciplinary collaborations among atmospheric chemists, climatologists, and policy analysts [80].

## 5.7. Critical Insights and Implications for Air Quality Management

It has incorporated monitoring and modeling techniques that have revolutionized the knowledge on the dynamics of Chinese air quality. Ground-based and satellite observations are very empirical data and emission inventories and CTMs can be subject to a mechanistic and predictive analysis. The tools can be applied together to detect the sources of pollutants and calculate the routes of chemical conversions and assess mitigation efforts [83]. The recognitions of ozone formation non-linear chemistry, the importance of the formation of secondary aerosols and the spatial heterogeneity of pollutant distribution caused by industrial and urban hotspots played a crucial role.

These results highlight the need to implement region-based interventions in various sectors for policymakers. A single pollutant reduction can be counterproductive because of the intricate chemical interactions; thus, concerted control measures that address various precursors are needed. Likewise, to successfully improve air quality, adaptive management that takes into account seasonal and meteorological variability is important [84]. These adaptive, evidence-based policies have a scientific basis by incorporating observational and modeling models.

# 6. Strategies for Air Quality Control

One of the most ambitious and complicated challenges to environmental management in the world is air quality control in China due to the size of anthropogenic emissions, the rate of urbanization, and economic development [12]. The mitigation of these impacts should be done at a multi-level scale and interventions at the policy level, technological level, and socio-economic mechanism. The section will generalize the main approaches to air quality management in China, critically analyze their design and implementation, performance, and problems, and analyze them in the context of environmental and Earth science.

## 6.1. Policy and Regulatory Frameworks

A powerful developing policy framework guides the air quality management in China. The legal and regulatory framework is comprised of the Environmental Protection Law, the Air Pollution Prevention and Control Law, and a series of specific action plans addressing the major pollutants [85]. The 2013 Air Pollution Prevention and Control Action Plan (APPCAP) is a historic policy intervention that requires the reduction of $PM_{2.5}$, $SO_2$, and NOx in major areas. The strategy provided legally binding levels of emission reduction, restructuring of industry was a priority, and strong monitoring and enforcement mechanisms were put in place.

The latter policies, such as the Blue-Sky Défense Battle (2018–2020) and the Three-Year Action Plan to Win the Blue-Sky Defence Battle, further strengthened the control of the regions' measures and were even more oriented to the coordination and integration of the energy, industrial, and transportation planning [86]. As a result of these policies, an observable positive change in air quality, particularly the reduction in the concentration of $SO_2$ and $PM_{2.5}$ in the eastern and northern states, has been achieved. The growing role of transportation and residential energy consumption has been challenging to control NOx and ozone; however, due to the non-linear chemistry of secondary pollutants and growing contributions by non-point sources. **Table 4** provides an overview of the air quality policies, the measures of their implementation, and results, and indicates both achievements and challenges persisting.

**Table 4.** Summary of major air quality control policies in China, including target pollutants, implementation measures, observed outcomes, and limitations.

| Policy/Action Plan | Implementation Year | Target Pollutants | Measures | Observed Outcomes (2013–2023) | Challenges/Limitations |
|---|---|---|---|---|---|
| Air Pollution Prevention and Control Action Plan (APPCAP) | 2013 | $PM_{2.5}$, $SO_2$, NOx | Industrial restructuring, emission limits, monitoring | $PM_{2.5}$ decreased by ~30–40% in key regions, $SO_2$ decreased by >60% | NOx and secondary pollutants still problematic |
| Blue Sky Defense Battle | 2018 | $PM_{2.5}$, $SO_2$, VOCs | Regional coordination, coal reduction, traffic control | Further $PM_{2.5}$ reduction in northern China; ozone still rising | Enforcement in small-scale industry remains uneven |
| Clean Energy Transition | 2015–present | $SO_2$, PM, $CO_2$ | Renewable energy expansion, coal-to-gas | Substantial $SO_2$ and PM reduction, co-benefits for climate | Regional energy disparities, intermittent renewable supply |
| Vehicle Emission Standards (China VI) | 2019 | NOx, VOCs, PM | Diesel particulate filters, electric mobility promotion | Urban NOx and $PM_{2.5}$ reduction, improved urban air quality | Fleet turnover and compliance monitoring remain challenges |

One such important lesson of Chinese policy is the need to have regionally differentiated strategies. The sources of emissions, the mechanisms of the formation of pollutants and the meteorological environment all differ greatly in the provinces and urban agglomerations. The general direction is provided on a national level, but more localized interventions must be provided at the regional level, e.g., specific reductions of emissions of industrial activities in the North China Plain or of traffic emissions in megacities along the coast [87]. The policy formulation must also take into account any trade-offs, such as relocation of the industry to less-regulated regions or modifications to the source of energy that may affect other pollutants or climatic effects.

## 6.2. Technological Measures

One of the pillars of the air quality control strategies in China lies in technological interventions. The $SO_2$ emissions in the energy industry have been reduced by the installed flue-gas desulfurization (FGD) units in the coal-fired power stations and the installed selective catalytic reduction (SCR) technology [18]. The emissions of particulate matter have been reduced using electrostatic precipitators, fabric filters, and desulfurization byproducts [88]. Modernization of boilers, introduction of low-emission production processes, and stricter emissions standards of the industry have led to significant decreases in primary pollutants.

Increased technology in transportation is also present. China VI vehicle emissions standards, which are equivalent to Euro VI emission standards, have led to a decrease in NOx, VOCs, and PM emissions. Diesel particulate filters, selective catalytic reduction devices, and streamlined engine technologies have been introduced in the case of heavy-duty automobiles. Also, the electric mobility and public transportation system has been promoted, offering an alternative to transport based on fossil fuels, and a decrease in urban concentrations of NOx and $PM_{2.5}$ was measured [89].

Intensive residential energy interventions have also decreased emissions of particulate matter during winter seasons in northern China, especially by substituting coal or biomass-fired stoves with natural gas or electricity or district heating [90]. Interventions also reduce the secondary aerosol precursors and this fact points towards the inter-sectoral interrelationship of technological interventions. Having such achievements, there are issues. The adoption of new technologies cannot be regarded as homogeneous, particularly in small-scale industries and rural areas, where the usage of combustion systems that are no longer current still takes place. Maintenance, operational efficiency, and compliance monitoring is important in long-term emission reductions. Secondly, technology alone can never be sufficient to deal with the secondary pollutants, i.e., ozone or secondary organic aerosol, which need a concerted control of a myriad of precursors at both sector and regional levels.

## 6.3. Socio-Economic and Behavioral Measures

Policy and technology are not the only areas of air quality control, as it is also addressed in socio-economic indicators and involvement of the people. Emission intensity and patterns of exposure are affected by urban planning, land use management, and transportation policies [91]. As an example, compact city planning, building of mass transit, and limitations on the use of vehicles in megacities assist in mitigating urban NOx and PM emissions. Likewise, economic stimuli, including subsidies on the adoption of clean energy, high-emission fuel taxation, and compensation for industrial retrofits, promote compliance and speed up the adoption of technology. Behavioral interventions also influence residential emissions and sustainable practices, such as engaging communities in emission reduction programmes and awareness creation through publicity. Monetary incentives, training and technical assistance will most probably encourage rural families to use clean cooking and heating technologies. The socio-economic measures can particularly be applied in the handling of diffuse and small-scale emissions, which are difficult to regulate within the normal enforcement measures.

As per the critical analysis, integrated socio-economic indicators are most appropriate and ought to be included according to technological interventions and regulations. Other incentives to promote cleaner fuels, energy efficiency, and transport with low emissions are supplementary to direct technological improvements and increase compliance. In addition, multi-stakeholders, including the government, industry, and the people, must be engaged to achieve sustainable air quality improvement [92].

## 6.4. Evaluation of Control Effectiveness

Assessment of the effectiveness of the air quality control strategies employed by China has been conducted both based on observational data and modeling [93]. An amalgamation of satellite remote sensing, ground-based monitoring, and chemical transport models all demonstrate that there has been a significant reduction of $PM_{2.5}$, $SO_2$, and CO over the last 10 years in northern and eastern China. The concentrations of $PM_{2.5}$ in Beijing, Tianjin, and Hebei, among others, have decreased by 30–40% since 2013, and this shows the effectiveness of the joint measures of emission reduction. Similarly, the countrywide release of $SO_2$ is cut down by over 60%, in part due to the application of flue-gas desulfurization in electrical power plants as well as to the reorganization of the industry.

However, certain pollutants are more challenging to manage, including NOx and ozone. Non-linear atmospheric chemistry means that in the urban areas where VOC limits ozone increases, the reduction of NOx emissions can lead to ozone increases. Megacities in the southern part of China note that the levels of ozone are increasing, although the rates of NOx are declining, indicating the value of joint control of precursors. The development of secondary aerosols is also an issue, and primary PM emissions reductions do not necessarily correlate with the accompanying decreases in $PM_{2.5}$ concentrations in extreme haze events [94].

Evaluation also brings about regional discrepancies in control effectiveness. Northern industrial regions have been very successful in gaining a lot through being aggressively dominated in coal and industrial emissions, but the south and southwest continue to be exposed to localized pollution problems related to transportation, biomass burning, and industrial emissions. These results indicate the applicability of regionally specific strategies and adaptive policy frameworks, which view the local origins of emissions, atmospheric chemistry, and meteorology [95].

## 6.5. Emerging and Innovative Strategies

New methods of air quality control have been innovated to complement the traditional methods in recent years. Integrated energy transition programs, i.e., coal consumption reduction, renewable energy increases and electrification of transportation, have co-benefits in air quality and climate control [96]. The urban-scale interventions, such as low-emission zones, congestion pricing, and real-time alerts on pollution, bring about localized and responsive air quality management.

Digital technologies to monitor emissions, traffic flows, and forecast cases of pollution are increasingly being used, including the Internet of Things (IoT), big data analytics, and artificial intelligence [97]. Such practices enhance the capabilities to perform a particular intervention and real-time enforcement and enhance the overall effectiveness. In addition, ecosystem-based strategies that result in the deposition of particulate matter and mitigation of urban heat islands are also urban greening strategies and wetland restoration, which have complementary environmental benefits. The critical analysis of the implemented innovative strategies and traditional measures in the combination will be able to contribute to the overall improvement of performance, particularly in complex secondary pollutants and problems in urban air quality. However, these interventions require institutional adjustment, technical capacity and long-term investment, and the interaction of technological innovation, governance, and socio-economic viability.

## 6.6. Challenges and Knowledge Gaps

However, the air quality control measures in China have a few problems that restrict their effectiveness. First, secondary (i.e., ozone and secondary aerosol) pollutants are difficult to control as they are not produced in linear reactions, and may be carried over long distances [98]. Second, the absence of standardization and application in different regions and sectors inhibits improvements at the national level [12]. The micro-industrial factories, the untamed sources of power and the rural industries are typically un-regulated and they contribute proportionately more to the localised cases of pollution.

Third, it is even less certain regarding the relationship between air quality and climate change [99]. The higher temperatures, the variation of precipitation patterns, and the more frequent appearance of stagnant weather conditions can increase the spurts of pollution and alter the output of the efforts on the reduction of emissions. Fourth, the socio-economic and behavioral determinants of energy demand rise, transportation rise and population awareness influence the emissions and demand adaptive management in the paths [100].

There are gaps in knowledge in various areas. The integrated assessment models will require the combination of the emissions and atmospheric chemistry with socio-economic variables to measure the co-benefits of climate, ecosystems and human health benefits of reducing emissions. The viability over the long term of technological interventions which might be implemented in rural and industrial environments is challenging to consider. Finally, to have coordinated air quality management across provinces and neighboring countries, it is vital to comprehend the transboundary transport and regional scales feedbacks [101].

## 6.7. Critical Insights for Integrated Management

The experience of China shows that to have an effective air quality control, it is necessary to have a systems level approach, which includes policy, technology and socio-economic measures [2]. Single sector interventions cannot be effective in combating complex secondary pollutants and regional transport. Good policies are a combination of regulatory and technological adherence, economic incentives and participation of citizens, with the emphasis made on multi-level alignment and reactive management.

Atmospheric chemistry, climate interactions, and ecosystem reactions have to be included in the air quality management from an Earth science perspective [102]. The policies with the emission reduction but without considering the secondary pollutant formation and meteorological variability may yield marginal or even opposite outcomes. Integrated techniques, like scenario modeling and predictive assessment, provide a paradigm of how to give priority to interventions, maximize co-benefits, and change strategies to evolving environmental conditions.

## 7. Conclusions

The anthropogenic emissions in China form a complex environmental problem that traverses atmospheric chemistry, local climate, processes in the ecosystem, and human health. Over the decades, quick industrialization, urbanization, and energy use have produced varied pollutants, such as particulate matter, nitrogen oxides, sulfur dioxide, ozone precursors, and heavy metals. These emissions are very spatially heterogeneous, seasonal, and very chemically reactive, as a result of which the air quality significantly decreases, haze occurs, and transportation across borders.

The discussion in this review reveals that good air quality management should be done through an integrated process that involves the detailed characterization of emissions, good monitoring, sophisticated modeling, and multi-level policy and technological interventions. Ground-based and satellite monitoring networks, coupled with chemical transport models, provide valuable data on the origins of the pollutants, how they form, and how they are transported across regions to enable the evaluation of mitigation strategies. The air quality control in China through strict emission standards, industrial and energy restructuring, the use of clean technology, and social-economic incentives has shown quantifiable gains in $PM_{2.5}$ and $SO_2$ cuts. Non-linear chemistry, regional variations, and new sources of emissions continue to present challenges to NOx, ozone, and secondary aerosols, though.

Adaptive management must inform future strategies as it takes into account the atmospheric feedbacks, climate variability, and socio-economic dynamics. Combining earth system science, technological innovation, and cross-sectoral coordination should be integrated to further enhance air quality, maximize climate and ecosystem co-benefits, and direct global air pollution management. This review underscores the need to have holistic measures to address both the direct and indirect effects of anthropogenic emissions in China.

## Funding

This work received no external funding.

## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

All the data is presented in the article.

## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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