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CURRENT STATUS OF NEAR-SURFACE OZONE POLLUTION RESEARCH IN CHINA

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Abstract: In recent years, with the effective control of fine particulate matter (PM2.5) pollution in China, the problem of near-surface ozone (O3) pollution has become increasingly prominent, becoming one of the important factors restricting the continuous improvement and attainment of ambient air quality standards. This article systematically reviews the latest progress in research on near-surface ozone pollution in China. Studies show that since the 13th Five-Year Plan, the overall O3 concentration in China has shown a trend of first rising and then plateauing, exhibiting significant regional differences and seasonal high incidence in key urban clusters such as the Beijing-Tianjin-Hebei region and the Yangtze River Delta. In terms of formation mechanism, the nonlinear relationship between ozone formation and its precursors, nitrogen oxides (NOx) and volatile organic compounds (VOCs), has always been the core of research: most urban central areas are in VOCs control zones, while regional background areas and some suburban areas are mostly NOx control zones or transition zones, and their control sensitivity dynamically evolves with the progress of pollution reduction . Meteorological conditions, especially extreme high temperatures and strong solar radiation, have a significant promoting effect on ozone formation and accumulation, and the "heat wave-ozone" compound pollution is gradually becoming a new prominent problem. In terms of prevention and control strategies, the synergistic control of ozone and PM2.5 has risen to an important strategic direction. It is urgent to implement differentiated NOx and VOCs emission reduction measures based on precise sensitivity analysis, and to strengthen regional joint prevention and control mechanisms. Future research should focus on the synergistic governance of compound pollution, refined source spectrum analysis and efficient control of VOCs, the microscopic processes of ozone formation, and the systematic upgrading of forecasting and early warning technologies.
Keywords: Ozone pollution; Research review; PM2.5 synergistic control; VOCs; NOx; Control sensitivity; Regional transport

1 INTRODUCTION

In recent years, with the continuous deepening of China's air pollution prevention and control work, the concentration of traditional pollutants represented by fine particulate matter (PM2.5) has decreased significantly, and the overall ambient air quality has shown an improving trend. However, while the PM2.5 level has continued to decrease, the problem of near-ground ozone (O3) pollution has become increasingly prominent and has gradually evolved into one of the primary pollutants affecting China's air quality standards[1]. This change indicates that China's air pollution prevention and control is moving from a single pollution control stage dominated by PM2.5 to a new stage of coordinated prevention and control of PM2.5 and O3, which puts forward higher requirements for scientific research and policy formulation.

Ground-level ozone is a typical secondary pollutant. It is not emitted directly, but is generated under strong solar radiation conditions by a series of complex photochemical reactions of precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) [2]. Ozone has extremely strong oxidizing properties and is significantly harmful to human health, ecosystems and crop production. Long-term exposure to high concentrations of ozone can induce or aggravate respiratory diseases, reduce lung function, and even cause irreversible damage [3]. At the same time, ozone can also inhibit plant photosynthesis, leading to reduced crop yields and damage to the structure and function of ecosystems [4].

Given the complex causes and widespread impact of ozone pollution, a systematic review of research progress on near-surface ozone pollution in my country is of significant theoretical and practical value for deepening scientific understanding and supporting precise prevention and control. This paper systematically reviews research findings on the spatiotemporal distribution characteristics, formation mechanisms, and influencing factors of ozone pollution in my country, as well as collaborative control and prevention strategies. It also provides an outlook on future research priorities, aiming to offer scientific references for ozone pollution prevention and control in my country.

2 STATUS AND SPATIOTEMPORAL CHARACTERISTICS OF OZONE POLLUTION IN CHINA

2.1 Overall Trend

Since the implementation of the Action Plan for Air Pollution Prevention and Control in 2013, my country's ambient air quality monitoring network has been continuously improved, laying a solid data foundation for ozone pollution research.

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Numerous studies have shown that during the 13th Five-Year Plan period (2016-2020), my country's ozone pollution showed an overall change characteristic of "first rising and then stabilizing" [5].

During the period from 2015 to 2018, ozone concentrations in most cities across the country generally increased. This is partly due to the significant decrease in PM2.5, which weakened the extinction effect of aerosols and enhanced near-surface solar radiation, thereby promoting the photochemical generation of ozone[6]. On the other hand, in VOCs control areas, the initial stage of NOx emission reduction may trigger a "seesaw effect", that is, the decrease in NOx concentration leads to an increase in ozone levels[7].

During the period from 2018 to 2020, as ozone pollution prevention and control measures were gradually strengthened, especially in the spring and summer of 2020, ozone concentrations across the country showed a general downward trend for the first time [8], indicating that the emission reduction measures for precursors began to show results. However, overall, ozone concentrations remained relatively high, and some key areas continued to exceed the standards.

Since 2021, ozone pollution in my country has remained severe against the backdrop of frequent extreme weather conditions. For example, in the summer of 2022, southern China experienced an unprecedented extreme high-temperature process, which led to a significant rebound in ozone concentrations across the country[9]. High temperatures and strong radiation significantly enhance the intensity of photochemical reactions, causing the risk of "heat wave-ozone" compound pollution to continue to rise[10]. The latest ecological and environmental status bulletin shows that ozone remains one of the main pollutants causing air quality to exceed standards in many places[11].

2.2 Regional Distribution Characteristics

Near-ground ozone pollution in China has significant spatial heterogeneity, with high-value areas mainly concentrated in economically developed, densely populated, and high-emission-intensity urban clusters [12].

The Beijing-Tianjin-Hebei region and surrounding areas have long been in the high ozone pollution zone in the country, with ozone concentrations in most cities in the region exceeding the national secondary standard limit for many consecutive years [13]. Ozone pollution in this region is not only significantly affected by local emissions, but also by the superimposed effect of regional transport.

The Yangtze River Delta region also faces a prominent ozone pollution problem. Although ozone levels in some cities have improved in recent years (e.g., ozone concentration in Shanghai has dropped to a low level in recent years[14]), ozone is still an important factor restricting the achievement of regional air quality standards. Regional transport plays an important role in ozone pollution in the Yangtze River Delta, and the transport of precursors from upstream areas has a significant impact on ozone levels in downstream cities[15].

The Pearl River Delta region is one of the earliest regions in my country to carry out research and control of ozone pollution, and its ozone pollution has obvious seasonal characteristics. Related studies have shown that most areas in this region are in NOx control areas, which is significantly different from the characteristics of the core urban areas of Beijing-Tianjin-Hebei and Yangtze River Delta, which are mainly controlled by VOCs[16].

In addition, ozone pollution problems in areas such as the Fenwei Plain, the Chengdu-Chongqing urban agglomeration and the middle reaches of the Yangtze River have become increasingly prominent, and their formation mechanism and control pathways have gradually become new research hotspots[17].

2.3 Seasonal and Diurnal Variation Characteristics

The near-surface ozone concentration in my country exhibits a significant seasonal variation, typically reaching its highest value in late spring and early summer (April to September), while it is at its lowest point during winter [18]. This pattern is mainly controlled by seasonal variations in solar radiation intensity, air temperature, and atmospheric chemical reaction conditions.

On a diurnal scale, ozone exhibits typical photochemical characteristics, with its concentration typically peaking in the afternoon (13:00–16:00) and gradually decreasing at night [19]. At night, ozone is mainly consumed through titration with NO and dry deposition. In urban centers, where NO emissions are higher, the ozone concentration decreases more significantly at night, while in suburban areas and background stations, it tends to maintain a higher background level.

3 THE FORMATION MECHANISM AND INFLUENCING FACTORS OF OZONE POLLUTION

3.1 Precursor Control Sensitivity Analysis

The formation of near-ground ozone (O3) is a highly nonlinear photochemical process, and its formation efficiency mainly depends on the relative abundance of precursors nitrogen oxides (NOx) and volatile organic compounds (VOCs) and the reaction environment. Clarifying the response characteristics of ozone formation to different precursors, i.e., the ozone formation control sensitivity, is the key foundation for formulating scientific and effective emission reduction strategies [20].

Theoretically, the relationship between ozone formation and precursor concentration can usually be characterized by empirical kinetic model curves (EKMA curves), and the study area can be divided into VOCs control area, NOx control area and transition area [21]. In the VOCs control area, ozone formation is limited by the VOCs level, and prioritizing the reduction of VOCs emissions can effectively reduce ozone concentration; in the NOx control area, ozone formation is more sensitive to NOx, and NOx emission reduction has a significant inhibitory effect; while in the transition area, ozone formation is affected by both NOx and VOCs. In recent years, indicators based on satellite remote sensing observations (such as the HCHO/NO2 ratio) have been widely used in the rapid identification and regional comparison studies of ozone formation sensitivity[22].

Existing research shows that there are significant spatial differences in the sensitivity of ozone generation control among different urban agglomerations and regions in China, and these differences exhibit dynamic evolution characteristics as pollution prevention and control progresses [23] . The core urban areas of the Beijing-Tianjin-Hebei urban agglomeration are mostly VOCs-controlled, while the suburbs and regional scales gradually shift to transition zones or NOx control zones; the Yangtze River Delta urban agglomeration is mainly VOCs-controlled, but there are significant local differences; the Pearl River Delta region is mostly in NOx control zones, which may be closely related to the higher background concentration of ozone and the earlier implementation of NOx emission reduction measures [24–27].

Based on this, the study further focused on the reactivity analysis of key VOC species. Different types of VOCs (such as olefins, aromatic hydrocarbons and aldehydes and ketones) have significantly different contributions to ozone formation [28]. Through methods such as maximum incremental reactivity (MIR), the study identified some highly reactive VOC components in industrial solvent use and traffic emissions as important factors driving ozone formation , providing a scientific basis for implementing differentiated and precise VOC emission reduction.

3.2 Impact of Meteorological Conditions

Meteorological conditions play a crucial regulatory role in the generation, accumulation and transport of ozone, and their influence is mainly reflected in two aspects: photochemical reaction rate and pollutant diffusion conditions[29].

Solar radiation is the direct energy source for photochemical reactions, and the intensity of ultraviolet radiation is usually significantly positively correlated with the concentration of ozone near the ground. Rising temperatures can not only accelerate the photochemical reaction kinetics, but also significantly enhance the emission of biogenic VOCs (such as isoprene), thereby promoting ozone formation [30]. The mechanism of relative humidity affecting ozone is more complex: low humidity conditions are usually conducive to ozone accumulation, while high humidity conditions may inhibit ozone formation by affecting free radical chemical processes. At the same time, stable weather conditions (low wind speed, high air pressure) are not conducive to the diffusion of pollutants, which can easily cause ozone and its precursors to accumulate in the near-surface layer and induce regional ozone pollution events [31].

Against the backdrop of climate change, the frequency and intensity of extreme high-temperature events continue to increase, making the "heat wave-ozone" compound pollution problem increasingly prominent [32]. Studies have found that under high-temperature heat wave conditions, enhanced vertical mixing processes and increased emissions of biogenic VOCs will change the relative ratio of NOx to VOCs, thereby affecting ozone formation sensitivity [33]. Related results indicate that conventional emission reduction measures alone are insufficient to effectively suppress the rising trend of ozone under high-temperature conditions, suggesting that future ozone control strategies urgently need to incorporate climate change adaptability and forward-looking considerations .

3.3 Regional Transmission and Source Analysis

Ozone pollution has significant regional and transport characteristics. The ozone level in a single city or local area is not only controlled by local emissions, but also by the transport of ozone and its precursors from upwind areas [34].

Previous studies have used backward trajectory analysis, source-sink apportionment, and adjoint models to quantitatively assess the role of regional transport in ozone pollution formation. The results show that ozone pollution in the Yangtze River Delta region is affected to some extent by transport from northern Jiangsu and Anhui and surrounding areas, while the Beijing-Tianjin-Hebei region exhibits obvious zonal transport characteristics, with emissions from upwind cities making a significant contribution to the ozone peak in downstream cities [35,36].

In terms of source apportionment technology, advanced numerical simulation tools such as adjoint models can efficiently quantify the sensitivity of ozone to different precursor species, emitting industries and geographical sources, providing strong support for regional joint prevention and control and emission reduction priority ranking[37]. In addition, observation-based models (OBM) and receptor models are also widely used in qualitative and quantitative research on ozone sources.

4 RESEARCH PROGRESS ON OZONE POLLUTION PREVENTION AND CONTROL STRATEGIES AND SYNERGISTIC CONTROL

4.1 The Necessity and Challenges of Synergistic Control of Ozone and PM2.5

Ozone and PM2.5 are two core issues facing my country’s current air pollution prevention and control. The two have a complex coupling relationship in terms of generation mechanism and control path, mainly reflected in the shared precursors (NOx and VOCs) and the regulatory role of atmospheric oxidation capacity on the generation of secondary pollutants [38].

From the perspective of coordinated control, NOx and VOCs are not only key precursors to ozone formation, but also important sources of nitrates and secondary organic aerosols in PM2.5. Implementing coordinated emission reduction strategies can help achieve simultaneous reduction of multiple pollutants and maximize environmental and health benefits [39]. In addition, as an important indicator of atmospheric oxidation capacity, changes in ozone concentration will affect the efficiency of SO2, NOx and other pollutants in their conversion to particulate matter, thereby further affecting PM2.5 levels.

However, due to the strong nonlinearity of ozone formation, coordinated control also faces practical challenges such as the "seesaw effect" [40]. In VOCs control areas, simply reducing NOx emissions may weaken the titration effect of NO on ozone, leading to a short-term increase in ozone concentration. Therefore, coordinated control strategies must be based on refined sensitivity analysis, and the emission reduction ratios of NOx and VOCs should be determined according to local conditions to avoid neglecting one aspect for the other.

4.2 VOCs Emission Control Research

Given that ozone generation in the central areas of most cities in China is mainly controlled by VOCs, the refined management of VOCs has become one of the core links in ozone pollution prevention and control[41].

Existing research has continuously improved the VOCs emission inventory system, focusing on enhancing the characterization accuracy of various types of emissions, including industrial sources, mobile sources, solvent use, and biological sources [42]. In recent years, atypical emission sources and fugitive emissions have gradually attracted attention, providing new research directions for improving the reliability of emission inventories.

In terms of control technology and management, the focus of industrial source control is on the optimized application of end technologies such as adsorption, catalytic combustion and regenerative thermal oxidation (RTO), as well as the source substitution of low VOCs raw and auxiliary materials[43]. In terms of mobile sources, emission intensity is continuously reduced by raising emission standards, promoting new energy vehicles and strengthening the supervision of oil and gas recovery. For bio-source VOCs, research mainly focuses on the emission change characteristics under the background of climate change and their parameterized expression in models.

4.3 Regional joint prevention and control mechanism

Given the significant regional transport characteristics of ozone pollution, its prevention and control work urgently needs to break through administrative boundary restrictions and implement regional joint prevention and control[44].

At present, key regions such as Beijing-Tianjin-Hebei and the Yangtze River Delta have established relatively mature collaborative prevention and control mechanisms. Model simulation and scenario analysis results show that cross-regional collaborative reduction of NOx and VOCs emissions is an effective way to reduce regional ozone peaks and pollution frequency[45].

Future research will focus more on scientific zoning based on pollution characteristics and transport paths, identify key source areas that contribute the most to ozone in downstream cities through high-resolution simulation, and formulate differentiated emission reduction plans accordingly to achieve precise and coordinated governance of multiple cities and industries in the region [46].

5 CONCLUSION AND OUTLOOK

5.1 Research Summary

Over the past decade, my country has made significant progress in research on near-surface ozone pollution. Overall, the research findings are mainly reflected in the following aspects: First, the spatiotemporal evolution characteristics of ozone pollution nationwide and in key regions have been systematically clarified, identifying ozone as a key pollutant affecting air quality standards. Second, through extensive sensitivity analysis studies, the understanding of ozone formation mechanisms has been deepened, revealing significant differences in control sensitivity between urban centers and regional background areas. Third, a theoretical framework for the synergistic control of ozone and PM2.5 has been gradually established, providing scientific support for addressing the complex problems of multiple pollutants. Fourth, the application of new technologies such as accompanying models and satellite remote sensing has significantly improved the scientific rigor of ozone source analysis and control decisions.

5.2 Future Research Directions

Despite significant research progress, ozone pollution control in China still faces long-term and complex challenges. Future research urgently needs to deepen in the following areas: First, strengthen research on the coordinated governance of ozone, PM2.5, and climate change, enhancing the systematicness and resilience of emission reduction strategies; second, further refine VOCs source profile analysis and develop efficient and economical emission reduction and substitution technologies; third, explore the role of atmospheric oxidation capacity and atypical ozone formation pathways under China's environmental conditions at the microscopic level; fourth, promote the development of high-resolution forecasting, early warning, and intelligent source tracing technologies to provide technical support for precise prevention and control and emergency response; and fifth, strengthen the quantitative assessment of ozone's health and ecological effects to provide a scientific basis for evaluating pollution control effectiveness and optimizing standards.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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