



Review Article

Photochemical Dynamics of Surface Ozone (O₃), Carbon Monoxide (CO), and Nitrogen Oxides (NO_x): Implications for Air Pollution, Health and Climate

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Abstract

Atmospheric trace gases such as ozone (O₃), carbon monoxide (CO), and nitrogen oxides (NO and NO₂, collectively termed NO_x) play a central role in tropospheric photochemistry and strongly influence air quality, climate forcing, and ecosystem health. This manuscript explores the current understanding of the sources, chemical transformation pathways, and environmental impacts of these trace gases by integrating from observational studies and atmospheric modeling research. The literature was compiled through a structured review of peer-reviewed research published in science journals, with emphasis on recent advances in photochemical mechanisms, boundary layer dynamics and regional air pollution processes. Particular attention is given to nonlinear O₃ formation regimes, radical chemistry involving volatile organic compounds (VOCs), and the interactions between trace gases and climate processes. This manuscript highlights how the balance between NO_x and VOC emissions determines O₃ production efficiency in different atmospheric environments, ranging from NO_x limited rural regions to VOC limited urban areas. Regional perspectives from South Asia illustrate how rapid urbanization, biomass burning, and meteorological variability influence trace gas distributions. The analysis identifies major knowledge gaps related to radical chemistry uncertainties, climate–chemistry feedback mechanisms, and the integration of observational networks with chemical transport models. Improved monitoring strategies and advanced modeling approaches are essential for developing effective air quality management policies and understanding the evolving role of trace gases in the Earth’s climate system.

Keywords

Air Pollution, Surface Ozone, Nitrogen Oxides, Carbon Monoxide, Atmospheric Oxidative Capacity

1. Introduction

Air pollution is widely recognized as one of the most critical environmental challenges of the twenty-first century due to its profound impacts on climate systems, ecological balance, and human health [1, 2]. Rapid industrialization, urban expansion, and increas-

ing energy demand have intensified atmospheric emissions, leading to significant degradation of air quality across many regions of the world. Although particulate matter (PM) often receives greater attention in air-quality discussions, gaseous pollutants particularly

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atmospheric trace gases play an equally important role in atmospheric chemistry and secondary pollutant formation [3]. Trace gases are present in the atmosphere at very low concentrations, typically in the parts-per-billion (ppb) to parts-per-million (ppm) range, yet they exert substantial influence on atmospheric processes due to their chemical reactivity and radiative properties [7]. Key atmospheric trace gases include ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO and NO_2), volatile organic compounds (VOCs), methane (CH_4), and sulfur dioxide (SO_2), all of which participate in complex atmospheric chemical cycles that regulate air quality and climate interactions [2, 4].

Air pollution generally results from a complex interplay between primary emissions and secondary chemical formation processes in the atmosphere. Primary pollutants are directly emitted from sources such as vehicular exhaust, industrial activities, power generation, and biomass burning. In contrast, secondary pollutants are produced through chemical reactions involving precursor gases under favorable atmospheric conditions [3]. Surface O_3 is not emitted directly but forms through photochemical reactions involving NO_x , VOCs, and solar radiation. Similarly, nitrate aerosols, an important component of fine particulate matter ($PM_{2.5}$) are produced through the oxidation of nitrogen oxides in the atmosphere [5]. The behavior and distribution of trace gases in the lower atmosphere are largely governed by photochemical processes driven by solar radiation, meteorological conditions, and interactions with aerosols and other atmospheric constituents [6]. These reactions influence the formation, transformation, and removal of atmospheric pollutants, thereby determining the chemical composition of the troposphere.

Among atmospheric trace gases, surface O_3 , CO, and NO_x are particularly important because of their strong influence on atmospheric chemistry and regional air quality. Surface O_3 is a secondary pollutant formed through complex photochemical reactions involving precursor emissions from fossil fuel combustion, solvent usage, and biomass burning, as well as natural emissions such as biogenic volatile organic compounds from vegetation [8]. While stratospheric O_3 protects life on Earth by absorbing harmful ultraviolet radiation, tropospheric O_3 acts as a harmful pollutant that adversely affects human respiratory health, agricultural productivity, and ecosystems, and also contributes to climate forcing as a greenhouse gas [9].

Carbon monoxide (CO) is a colorless and odorless gas primarily produced through incomplete combustion of carbon-containing fuels. Major anthropogenic sources include motor vehicles, industrial combustion processes, residential fuel use, and open biomass burning, while natural sources include the oxidation of CH_4 and other hydrocarbons in the atmosphere [10]. Due to its relatively long atmospheric lifetime, ranging from several weeks to months, CO can be transported over large regional and continental scales, thereby influencing air quality far from its original emission sources [11].

Nitrogen oxides (NO_x) are produced predominantly during

high-temperature combustion processes associated with transportation, power generation, and industrial activities [6]. In addition to anthropogenic emissions, natural processes such as lightning and microbial activity in soils also contribute to atmospheric NO_x levels, though these sources exhibit strong spatial and seasonal variability [2]. NO_x play a crucial role in atmospheric chemistry as key precursors for tropospheric O_3 formation and as regulators of the oxidative capacity of the atmosphere through their participation in radical-mediated photochemical reactions [4]. Consequently, comprehensive understanding of the distribution, sources, and chemical interactions of these trace gases is essential for assessing air-quality variability and for formulating effective mitigation strategies aimed at reducing atmospheric pollution and its associated environmental and health impacts.

Understanding the sources, atmospheric lifetimes, chemical transformation pathways, and removal mechanisms of trace gases is therefore essential for improving our knowledge of atmospheric pollution dynamics and for developing effective air-quality management strategies [12]. This manuscript describes the current knowledge on the sources, chemical transformation pathways, and environmental implications of O_3 , CO, and NO_x , with particular emphasis on their contributions to urban and regional air pollution dynamics. It further highlights the complex interactions among emissions, atmospheric chemistry, and meteorological processes that govern the formation, transport, and removal of these trace gases in the troposphere.

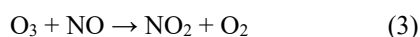
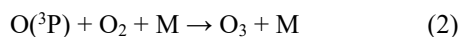
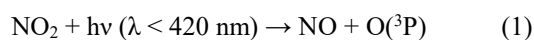
2. Photochemical Production of Trace Gases

The photochemical production and destruction of major atmospheric trace gases such as O_3 , NO, NO_2 , CO, and CH_4 are governed by a complex network of radiation-driven reactions and radical chain mechanisms that determine the oxidative capacity of the troposphere. Atmospheric photochemistry is strongly influenced by free radicals—highly reactive atomic or molecular species possessing unpaired electrons such as hydroxyl radicals (OH), peroxy radicals (RO_2), and nitrate radicals (NO_3). Among these, the hydroxyl radical is often referred to as the “detergent” of the atmosphere because it initiates the oxidation of numerous trace gases, including CO and VOCs. Meteorological conditions exert a dominant influence on trace gas concentrations and atmospheric chemical transformation rates [3]. While emissions determine the availability of precursor species, meteorological parameters regulate pollutant dispersion, dilution, vertical mixing, chemical reactivity, and removal processes. Consequently, the concentrations of O_3 , CO, and NO_x exhibit strong sensitivity to boundary layer dynamics, temperature, solar radiation, humidity, cloud cover, wind patterns, and large-scale synoptic circulation. Surface O_3 formation is governed by nonlinear photochemical interactions between nitrogen NO_x and VOCs. The

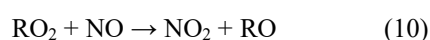
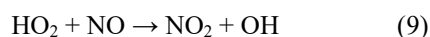
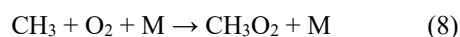
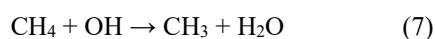
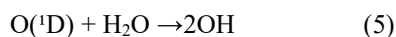
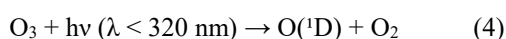
efficiency of O_3 production depends strongly on the relative abundance of these precursors, leading to two principal chemical regimes: NO_x limited and VOC limited conditions. In NO_x limited environments, typically found in rural or remote regions, O_3 formation increases with increasing NO_x concentrations because the availability of NO_x restricts radical propagation cycles. In contrast, VOC limited conditions commonly occur in polluted urban environments where high NO_x emissions suppress O_3 production through radical termination reactions. Understanding these regimes is essential for effective air quality management, since emission reduction strategies must target the appropriate precursor species to achieve meaningful O_3 reductions.

2.1. Photochemistry of Surface O_3

Surface O_3 forms through a series of reactions in the presence of solar radiation. It begins with the photolysis of NO_2 to produce NO and an oxygen atom. The free oxygen atom then combines with molecular oxygen (O_2) to form O_3 . However, for net O_3 accumulation, VOCs or CO must participate to oxidize NO back to NO_2 without consuming O_3 . Specifically, oxidation of CO or VOCs yields peroxy radicals (RO_2 or HO_2), which convert NO to NO_2 , sustaining O_3 production under sunlight. The fundamental photochemical reactions are written separately as follows:

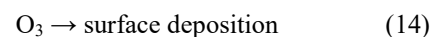
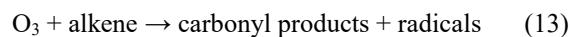
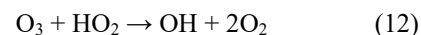
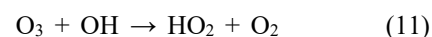


These reactions establish the photo-stationary equilibrium. Net O_3 production occurs only when NO is oxidized to NO_2 by peroxy radicals without consuming O_3 . The key radical propagation steps are:

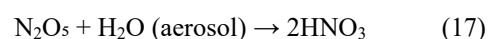
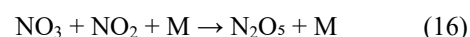
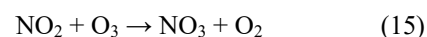


Because HO_2 and RO_2 convert NO to NO_2 without destroying O_3 , additional NO_2 photolysis results in net O_3 accumulation. Methane oxidation proceeds through a sequence of intermediates: The destruction of O_3 in the troposphere occurs via

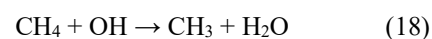
several pathways:



At night, additional chemistry occurs:



These heterogeneous reactions permanently remove reactive nitrogen and suppress O_3 production. Carbon monoxide and methane play crucial roles in regulating the atmospheric oxidizing capacity. Increased CH_4 reduces OH availability:



Lower OH concentrations prolong CH_4 lifetime (~9–12 years) and enhance background O_3 . Carbon monoxide, with a lifetime of weeks to months, competes for OH and indirectly modifies tropospheric O_3 and CH_4 lifetimes. The overall photochemical system is highly nonlinear and depends strongly on NO_x levels. In low NO_x regimes, radical termination processes limit O_3 formation, whereas in high- NO_x conditions O_3 production is enhanced; however, at very high NO concentrations, O_3 is reduced through titration. Thus, the coupled photochemistry of O_3 , NO, NO_2 , CO, and CH_4 links atmospheric composition, air pollution, and climate forcing through radical chain reactions, catalytic cycles, and feedback mechanisms that regulate the oxidative capacity of the atmosphere.

2.2. Impact of CO and VOCs on Atmospheric Oxidative Capacity and O_3 Formation

Carbon monoxide (CO) and Volatile Organic Compounds (VOCs) plays an important role in regulating the oxidative capacity of the troposphere through their interactions with hydroxyl radicals (OH), the primary atmospheric oxidant responsible for the removal of many trace gases. CO reacts with OH ($CO + OH \rightarrow CO_2 + H$), thereby reducing the availability of OH for the oxidation of other species such as methane (CH_4) and VOCs. As a result, elevated CO concentrations can decrease the atmosphere's oxidizing capacity, extend the lifetime of CH_4 , and alter radical propagation pathways. The oxidation of CO also produces hydroperoxyl radicals (HO_2), which convert NO to NO_2 , indirectly promoting O_3 formation under NO_x rich conditions. VOC's further enhance tropospheric photochemistry by generating peroxy radicals (RO_2)

during their oxidation by OH. These radicals react with NO to form NO₂, which subsequently undergoes photolysis to produce atomic oxygen that combines with molecular oxygen to form O₃. VOCs originate from both anthropogenic sources, such as transportation emissions and industrial activities, and natural sources including vegetation and soil microbial processes, with biogenic VOCs like isoprene and monoterpenes being particularly significant in tropical regions. Through these interactions, CO and VOCs strongly influence atmospheric radical cycling, ozone production, and the overall chemical balance of the troposphere. Schematic representation of the photochemical and destruction of trace gases in the troposphere is shown in the [Figure 1](#).

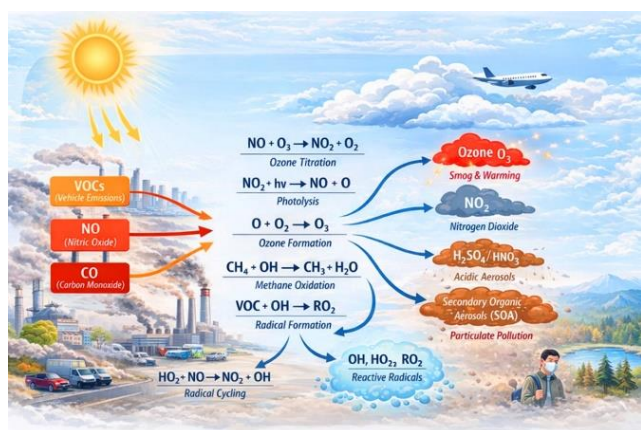


Figure 1. Photochemical and destruction of trace gases in the troposphere.

3. Boundary Layer Dynamics and Its Impact on Atmospheric Pollutants

The planetary boundary layer (PBL) represents the lowest portion of the troposphere that is directly influenced by surface forcing through turbulent fluxes of heat, momentum, and moisture. Its depth exhibits pronounced diurnal variability driven by radiative heating and surface energy balance processes, typically ranging from less than 500–800 m under stable nocturnal conditions to more than 1500–3000 m during daytime convective periods [13, 14]. The evolution of the PBL strongly regulates the dispersion, chemical transformation, and vertical redistribution of atmospheric pollutants. Under shallow PBL conditions, particularly during night-time and early morning hours, suppressed turbulence and reduced mixing heights limit vertical dilution, leading to the accumulation of primary pollutants such as NO_x, CO, and particulate matter near the surface [3, 4]). Simultaneously, stable atmospheric stratification and weak ventilation favour the build-up of VOCs and oxidants, promoting secondary aerosol formation through gas-to-particle conversion pathways involving oxidation of VOCs by OH, O₃, and NO₃ radicals [3, 15]. During daytime, solar heating destabilizes the lower atmosphere and

leads to the development of a convective mixed layer, which enhances turbulent transport and promotes efficient vertical mixing of surface emissions. A deep convective PBL significantly increases the dilution volume available for pollutants, thereby reducing near-surface concentrations of primary species while redistributing O₃ precursors throughout the mixed layer [13, 16]. This vertical transport can elevate reactive nitrogen species (NO_y) and VOCs to higher altitudes, altering regional photochemical regimes and potentially enhancing in situ ozone production aloft through photolysis-driven radical chemistry.

Another critical process influencing surface air quality is entrainment at the PBL top. As the daytime boundary layer grows, it can entrain air from the residual layer or lower free troposphere, which often contains O₃ rich air formed during the previous day's photochemical activity. This entrainment process can significantly enhance late-morning and afternoon surface O₃ concentrations, particularly under clear-sky conditions with strong convective mixing [17]. Furthermore, mesoscale meteorological processes such as land–sea breezes, low-level jets, and synoptic-scale subsidence can modify PBL structure and influence pollutant transport over regional scales [14, 16].

Model sensitivity experiments have demonstrated the critical role of boundary layer dynamics in regulating surface air quality. Numerical simulations indicate that a 30% reduction in PBL height can lead to a 20–35% increase in near-surface NO_x and CO concentrations due to reduced dilution capacity, while also intensifying subsequent O₃ production rates during photochemically active periods owing to elevated precursor densities [18, 19]. These interactions highlight the strong coupling between boundary layer structure, turbulent transport, and atmospheric chemical processes. Consequently, accurate representation of PBL dynamics including turbulence parameterization, entrainment fluxes, and mixing heights is essential for improving the reliability of regional air quality and atmospheric chemistry models such as WRF-Chem and CMAQ [18, 20].

4. Long-range Transport and Regional Effects of Air Pollutants

Long-range atmospheric transport plays a critical role in shaping regional air quality by redistributing trace gases and their photochemical precursors far beyond their original emission sources [3]. Carbon monoxide (CO), having a lifetime ranging from several weeks to a few months, serves as an effective tracer for intercontinental pollution transport due to its relative chemical stability in the troposphere [4]. Once emitted from anthropogenic combustion sources, CO can be advected across continents through large-scale circulation systems such as mid-latitude westerlies and tropical Hadley circulation, thereby elevating background pollutant concentrations in downwind regions [7]. Although NO_x are comparatively

short-lived near the surface, they can be transported over long distances in the form of thermally stable reservoir species such as peroxyacetyl nitrate (PAN), particularly within the colder upper troposphere. During transport to warmer environments, PAN undergoes thermal decomposition, releasing NO₂, which subsequently enhances regional O₃ production far from the original emission sources [6]. Surface O₃ itself possesses a lifetime of several days to weeks, enabling its accumulation and hemispheric-scale transport under favorable meteorological conditions [2]. Synoptic scale systems, including high pressure ridges, frontal boundaries, and jet streams, facilitate both vertical lifting and horizontal advection of polluted air masses across regions [21]. In addition, deep convective processes can inject boundary layer pollutants into the free troposphere, where reduced removal rates allow for widespread dispersion.

Regional topography further modulates transport pathways through mountain valley circulations that either trap pollutants locally or channel them across adjacent regions [22]. Consequently, elevated O₃ or CO concentrations observed in rural or remote environments may reflect transported pollution rather than local emissions alone. This transboundary movement of atmospheric pollutants complicates air quality management strategies, as local emission control measures may be offset by imported pollution loads. Effective mitigation therefore necessitates coordinated regional and international emission reduction frameworks supported by satellite observations and chemical transport modelling to distinguish between locally generated and transported pollutant contributions.

5. Review Methodology

The following section is based on a systematic evaluation of peer-reviewed literature addressing the photochemical behavior, sources, and environmental impacts of major atmospheric trace gases in the troposphere. Foundational studies together with recent advances published over the past two decades were examined in order to capture the progression of scientific understanding in atmospheric chemistry and air-quality research. Particular emphasis was placed on studies investigating the formation and transformation of key trace gases such as O₃, NO_x, CO, and VOCs, which play critical roles in tropospheric photochemistry and secondary pollutant formation. Research encompassing global atmospheric chemistry assessments, regional air-pollution dynamics, long-term monitoring observations, and numerical modeling frameworks was included in the review. The selected literature was systematically analyzed to identify dominant scientific themes, advances in observational and modeling techniques, and emerging research directions. In addition, the review highlights persisting uncertainties associated with chemical reaction mechanisms, emission inventories, and meteorological influences that continue to challenge accurate representation of tropospheric trace gas chemistry in atmospheric models.

The study of air pollution across the globe is essential due

to its profound impacts on human health, climate systems, ecosystems, and sustainable development. Air pollutants contribute to millions of premature deaths annually by causing respiratory illnesses, cardiovascular diseases, and other chronic health conditions [1]. Beyond health implications, air pollution significantly influences atmospheric chemistry and the Earth's radiative balance, thereby accelerating climate change and altering regional and global weather patterns [23]. Since pollutants can travel long distances across national boundaries through atmospheric transport processes, air quality is not merely a local issue but a global concern requiring coordinated international research and policy responses [24]. Comprehensive global studies help in identifying emission sources, understanding chemical transformation mechanisms, assessing meteorological influences, and evaluating long-term trends in air pollutant concentrations [3]. Such scientific investigations are crucial for developing accurate atmospheric models, designing effective mitigation strategies, implementing emission control regulations, and achieving global climate and sustainability goals [25]. In the context of rapid urbanization, industrial growth, and increasing energy demand worldwide, systematic and continuous research on air pollution is indispensable to safeguard public health, protect ecosystems, and ensure a sustainable and resilient future for the planet.

5.1. Global and Regional Perspectives on Trace Gas Air Pollution

Air pollution research over the past several decades has demonstrated significant progress in understanding the sources, chemistry, and impacts of atmospheric trace gases. In North America, regulatory policies have led to substantial reductions in key pollutants. Analyses by the United States Environmental Protection Agency indicate that sulphur dioxide (SO₂) and NO_x emissions declined dramatically following the implementation of the Clean Air Act and its amendments. Long-term monitoring data reveal reductions exceeding 80% in SO₂ emissions since the 1980s, largely attributed to flue gas desulfurization technologies and fuel switching in power plants [26]. O₃ transported from Asia and influenced by climate variability contributes to exceedances in western North America [27]. Similar emission reduction trends have been observed across Europe following the adoption of stringent environmental policies. Reports from the European Environment Agency indicate that SO₂ emissions across the European Union have decreased by more than 90% since 1990 due to emission standards and the National Emission Ceilings Directive [28]. However, NO₂ levels remain elevated along traffic corridors in major cities such as London and Paris. Epidemiological studies across multiple European cohorts have demonstrated strong associations between long-term NO₂ exposure and respiratory morbidity [29]. In response to growing evidence of health impacts, the World Health Organization updated its Global Air Quality Guidelines in 2021, recommending stricter limits for pollutants including NO₂ and O₃.

East Asia has also received considerable scientific attention due to rapid industrialization and urban expansion. Satellite observations from instruments such as OMI and TROPOMI revealed sharp increases in tropospheric NO₂ concentrations over eastern China during the early 2000s [30]. Ground-based measurements similarly reported elevated SO₂ levels associated with coal combustion [31]. Following the implementation of China's Air Pollution Prevention and Control Action Plan in 2013, significant reductions in SO₂ and particulate matter were observed. Nevertheless, surface O₃ concentrations have continued to increase in several Chinese cities, largely due to VOC limited photochemical regimes and changing emission ratios [32]. Transboundary transport of O₃ precursors across East Asia has also been documented, particularly affecting regions such as South Korea and Japan [33].

In many developing regions, biomass burning represents a major source of trace gases. Satellite observations reveal strong seasonal peaks in CO and O₃ over central Africa during dry seasons associated with savanna fires [34]. Field campaigns in West Africa demonstrate that biomass burning emissions significantly alter regional atmospheric oxidative capacity by releasing large quantities of NO_x and VOCs [35]. However, the lack of long-term ground-based monitoring networks in many African countries creates substantial uncertainties in pollution exposure assessments.

Research in the Middle East highlights the role of hydrocarbon extraction and petrochemical activities in regional air pollution. Satellite inversion studies have identified methane emission hotspots over major oil and gas production regions in countries such as Saudi Arabia and Iran [36]. Urban centres including Riyadh and Tehran exhibit elevated NO₂ levels due to traffic emissions and intense photochemistry driven by strong solar radiation [12]. CH₄ plays an important role in atmospheric chemistry because it acts both as a greenhouse gas and as a precursor for surface O₃ formation. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change emphasizes methane's strong radiative forcing and the potential climate benefits of rapid emission reductions [2].

Health impact assessments consistently demonstrate the global burden of trace gas pollution. Long-term cohort studies in the United States have shown that chronic exposure to ozone significantly increases mortality risk [37]. Similar investigations in Europe and Asia have linked NO₂ exposure to asthma incidence and respiratory illness in children [29]. According to the Global Burden of Disease study, millions of premature deaths each year are attributable to ambient air pollution, with O₃ contributing substantially to respiratory mortality [38].

The chemical mechanisms underlying trace gas pollution have been extensively studied. Foundational work by [3] established the framework for photochemical smog formation, demonstrating how VOCs and NO_x interact under solar radiation to produce secondary pollutants such as O₃. Advances in satellite remote sensing and chemical transport modelling have further enhanced the ability to monitor global pollution

patterns and quantify emission sources [39]. Overall, global research demonstrates that stringent emission controls can significantly reduce pollutants such as SO₂ and NO_x. However, the persistence of O₃ pollution illustrates the complexity of atmospheric chemistry and the need for integrated emission reduction strategies addressing multiple precursors.

5.2. Trace Gas Air Pollution in South Asia and India

South Asia has emerged as one of the most polluted regions globally due to rapid urbanization, industrial growth, population density, and extensive biomass burning. The Indo-Gangetic Plain (IGP) is widely recognized as a major hotspot of atmospheric pollution, influenced by emissions from transportation, coal based power generation, agricultural burning, and household biomass combustion [40, 41]. Long-term monitoring data from the Central Pollution Control Board indicate that NO₂ concentrations in major Indian cities such as Delhi, Mumbai, and Kolkata frequently exceed national air quality standards. While SO₂ levels have declined in several cities due to cleaner fuels and emission regulations, NO_x emissions continue to increase with expanding transportation demand [42]. Satellite observations from instruments such as OMI and TROPOMI confirm persistent NO₂ hotspots across northern India and around major thermal power plants [43].

Studies indicate that surface O₃ levels in India have increased over the past two decades, with frequent exceedances during pre-monsoon and summer periods characterized by high solar radiation and stagnant atmospheric conditions [41]. Chemical transport modelling suggests that surface O₃ formation in several Indian cities occurs under VOC limited regimes, implying that reductions in VOC may be more effective for controlling O₃ than NO_x reductions alone [44]. Biomass burning contributes substantially to trace gas emissions in South Asia. Post-monsoon agricultural residue burning in Punjab and Haryana generates large amounts of CO, NO_x, and VOCs that are transported across northern India and Pakistan, often causing severe pollution episodes in Delhi [45]. Household biomass combustion in rural regions also remains a significant source of carbon monoxide and hydrocarbons [46]. CH₄ emissions from agriculture, particularly rice paddies and livestock, are another important component of South Asian atmospheric chemistry. Global CH₄ budget analyses identify South Asia as a rapidly growing CH₄ emission region [47]. Because CH₄ contributes to background O₃ formation, mitigation strategies targeting CH₄ emissions provide co-benefits for both climate stabilization and regional air quality improvement.

5.3. Case Study: Trace Gas Air Pollution in Kerala

Although Kerala is generally perceived as less industrialized compared with many other Indian states, recent studies

indicate that trace gas pollution is increasing due to urbanization, vehicular growth, and industrial activities. Monitoring programs conducted by the Central Pollution Control Board and the Kerala State Pollution Control Board under the National Air Quality Monitoring Programme have reported elevated nitrogen dioxide and ozone levels in major urban centres including Thiruvananthapuram, Kochi, and Kozhikode [42]. Research conducted by the SPL, VSSC Thiruvananthapuram has demonstrated that coastal meteorology plays a crucial role in pollutant dispersion across Kerala. Land–sea breeze circulations strongly influence trace gas transport, with marine air masses during monsoon seasons helping dilute urban pollution, while stable atmospheric conditions during summer promote photochemical O₃ formation [48, 49]. VOC characterization studies in the Kochi industrial region indicate substantial contributions from petrochemical industries and vehicular emissions [50].

High-altitude observations from Munnar further reveal the influence of long-range transport on regional atmospheric composition. Observations conducted by [51], indicate that background O₃ levels are affected by pollutant transport from the Indo-Gangetic Plain and Arabian Sea shipping corridors. Satellite analyses using instruments such as OMI and TROPOMI also reveal localized SO₂ and NO₂ enhancements near industrial clusters such as the Kochi refinery region [52].

Recent investigations in northern Kerala have focused on trace gas variability in Kannur district. Observational studies conducted at Kannur University report clear diurnal and seasonal variations in O₃ and NO₂ concentrations, with higher levels during winter months and morning traffic periods [53]. The coastal setting of Kannur introduces strong land–sea breeze circulations that influence the dispersion and chemical transformation of reactive nitrogen species [54]. Simultaneous CO measurements indicate elevated concentrations during peak traffic hours, suggesting vehicular emissions as a dominant local source. These findings demonstrate that air quality in Kerala results from a combination of local emissions, coastal meteorology, and long-range transport processes. Continued integration of ground-based monitoring, satellite observations, and chemical transport modelling is essential for improving emission inventories and developing effective air quality management strategies in the region.

6. Biological and Ecological Effects of Air Quality Degradation

Trace gases exert substantial adverse effects on both human health and ecological systems, even at relatively low ambient concentrations [1]. Surface O₃, penetrates deep into the pulmonary system where it induces airway inflammation, impairs lung function, exacerbates asthma, and increases susceptibility to respiratory infections through oxidative damage to epithelial tissues [37]. Prolonged exposure to elevated O₃ levels has been associated with chronic obstructive pulmonary disease (COPD), reduced life expectancy, and increased rates of

premature mortality due to cardiopulmonary complications [55]. CO, although chemically non-reactive in biological systems, poses serious toxicological risks by binding competitively with haemoglobin to form carboxyhaemoglobin (COHb), thereby impairing oxygen transport and delivery to critical organs such as the brain and heart [56]. Elevated CO exposure can result in neurological impairment, cardiovascular stress, headaches, dizziness, and in extreme cases, fatal hypoxic conditions. NO₂ emissions, contributes to respiratory tract irritation and increases vulnerability to pulmonary infections, particularly among children, the elderly, and individuals with pre-existing respiratory conditions [57]. Beyond their direct health impacts, these trace gases participate in atmospheric photochemical reactions leading to the formation of secondary pollutants such as O₃ and nitrate-containing fine particulate matter (PM_{2.5}), which are strongly linked to cardiovascular diseases, systemic inflammation, ischemic stroke, and adverse birth outcomes [5]. From an ecological perspective, elevated O₃ concentrations impair plant physiological processes by diffusing through stomatal openings and generating reactive oxygen species within leaf tissues, thereby reducing photosynthetic efficiency, crop productivity, and forest biomass accumulation [58]. Furthermore, atmospheric oxidation of NO_x results in nitrogen deposition that alters soil nutrient composition, promotes eutrophication in aquatic ecosystems, and disrupts nitrogen cycling processes in sensitive terrestrial habitats [59]. Collectively, the multifaceted health and ecological consequences associated with trace gas pollution underscore the urgent need for integrated emission control strategies targeting both primary emissions and secondary pollutant formation pathways.

7. Climatic Impacts of Trace Gases in the Troposphere

Trace gases exert significant influence on the Earth's climate system through a combination of direct radiative forcing and indirect chemical feedback mechanisms that alter the atmospheric oxidation capacity and the lifetime of greenhouse gases [2]. Tropospheric O₃ is recognized as a short-lived climate pollutant and an important anthropogenically driven greenhouse gas that absorbs outgoing longwave infrared radiation, thereby contributing positively to radiative forcing and enhancing global warming [9]. Unlike long-lived greenhouse gases such CO₂, tropospheric ozone exhibits strong spatial and temporal variability because it is not emitted directly into the atmosphere but is formed through photochemical reactions involving precursor gases such as NO_x, CO, and VOCs under the influence of solar radiation [3]. As a result, regional emissions of O₃ precursors from industrial activities, biomass burning, vehicular exhaust, and fossil fuel combustion can substantially influence regional climate forcing by altering O₃ production rates. In addition to its radiative effects, O₃ affects climate indirectly by influencing plant physiological processes;

elevated O_3 levels reduce stomatal conductance and photosynthetic efficiency, thereby diminishing carbon uptake by terrestrial vegetation and weakening the land carbon sink, which in turn amplifies atmospheric CO_2 accumulation [60].

Carbon monoxide, although not an effective greenhouse gas in terms of infrared absorption, plays a crucial indirect role in climate regulation by reacting with hydroxyl radicals (OH), the primary atmospheric oxidant responsible for CH_4 removal [4]. The oxidation of CO reduces OH availability, thereby prolonging the atmospheric lifetime of CH_4 and enhancing its radiative forcing potential. Since CH_4 itself contributes to surface O_3 formation through oxidation pathways, elevated CO concentrations can indirectly intensify both CH_4 driven warming and secondary O_3 production, creating a feedback loop that further amplifies climate forcing [61]. NO_x promotes photochemical O_3 formation in the troposphere, thereby exerting a warming effect through increased greenhouse gas concentrations [62]. On the other hand, NO_x enhances hydroxyl radical production through catalytic reaction cycles, which accelerates CH_3 oxidation and shortens its atmospheric lifetime, thereby exerting a cooling influence on climate [63]. Furthermore, atmospheric oxidation of NO_x leads to the formation of nitrate aerosols, which scatter incoming solar radiation and contribute to negative radiative forcing, partially offsetting greenhouse warming [64].

The overall climatic impact of NO_x emissions is therefore determined by the balance between these warming and cooling processes, which vary depending on regional chemical regimes and background atmospheric composition. In addition, trace gases influence cloud microphysical properties by modifying aerosol concentrations that act as cloud condensation nuclei (CCN), thereby altering cloud reflectivity, lifetime, and precipitation patterns through aerosol cloud interactions [65]. These indirect effects further complicate the assessment of net radiative forcing associated with trace gas emissions. Long-range transport of O_3 and its precursors can extend their climatic influence across continents and oceans, enabling regional emissions to exert hemispheric-scale impacts on atmospheric composition and radiative balance [7]. Moreover, changes in atmospheric circulation patterns, temperature, and humidity driven by climate change can in turn affect the chemical transformation and removal rates of trace gases, establishing feedback interactions between atmospheric chemistry and climate dynamics. Consequently, the net climatic impact of trace gases is highly dependent on emission patterns, atmospheric transport processes, chemical reaction pathways, and interactions with clouds and aerosols [66].

8. Knowledge Gaps and Future Research Directions

Despite decades of research, significant uncertainties remain in the understanding of surface trace gas chemistry. One

major challenge involves accurately quantifying radical reaction pathways that control the atmospheric oxidative capacity. Laboratory experiments and field measurements have revealed discrepancies between modeled and observed radical concentrations, indicating gaps in current chemical mechanisms. Another important research priority is the characterization of nonlinear O_3 production regimes across different environments, particularly in rapidly developing regions where emission patterns are changing rapidly. Improved integration of ground-based monitoring networks, satellite observations, and high-resolution chemical transport models is essential for capturing spatial and temporal variability in trace gas concentrations. Additionally, interactions between atmospheric chemistry and climate processes remain poorly constrained. Changes in temperature, humidity, and atmospheric circulation patterns can significantly alter O_3 production efficiency and the global distribution of reactive gases. Future research should therefore focus on developing coupled climate–chemistry modeling frameworks capable of resolving these feedback mechanisms.

9. Conclusion

This study highlights the complex and interdependent roles of key atmospheric trace gases O_3 , CO, and NO_x in shaping tropospheric air pollution, atmospheric chemistry, human health risks, ecological impacts, and climate interactions. Despite their relatively low concentrations, these gases exert significant influence due to their high reactivity and involvement in radical-driven photochemical processes. The results emphasize that air pollution is governed not only by emission strengths but also by nonlinear chemical transformations strongly modulated by meteorological and environmental conditions. Surface O_3 is a secondary pollutant whose formation depends on the interaction of NO_x and VOCs under sunlight. The efficiency of O_3 production varies between NO_x limited and VOC limited regimes, making the identification of chemical environments essential for designing effective emission control strategies. CO also plays an important atmospheric role by reacting with OH radicals, thereby influencing the oxidative capacity of the atmosphere and altering the lifetime of other trace gases such as CH_4 . NO_x further regulate O_3 formation through rapid NO- NO_2 cycling and contribute to the formation of nitric acid and nitrate aerosols, linking gaseous pollution to secondary PM formation. Meteorological factors such as boundary layer dynamics, solar radiation, temperature, and atmospheric circulation significantly influence pollutant dispersion, chemical reaction rates, and removal processes. In addition, long-range transport of O_3 precursors and reservoir species such as PAN demonstrates that air pollution often transcends regional boundaries, requiring coordinated mitigation strategies. The combined health and ecological impacts of these trace gases including respiratory illnesses, oxidative plant damage, and reduced agricultural productivity underscore the importance of integrated air quality management.

Overall, the findings demonstrate that effective air pollution control must consider the nonlinear chemistry of trace gases, their interactions with meteorology, and their broader climate implications. Continued advances in observational networks, satellite monitoring, and atmospheric modelling will be essential for improving our understanding of these processes and for developing sustainable strategies to protect air quality, public health, and climate stability.

Abbreviations

O ₃	Ozone
CO	Carbon Monoxide
NO _x	Nitrogen Oxides
VOCs	Volatile Organic Compounds
CH ₄	Methane
SO ₂	Sulfur Dioxide
O ₃	Ozone
CO	Carbon Monoxide
NO _x	Nitrogen Oxides

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflicts of interest.

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