Review Article

Chemistry, Air Quality, and Climate Change: Uniting the Pieces of the Puzzle

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Abstract | Chemistry plays a major role in learning the underlying mechanisms responsible for changes in air quality, which subsequently exert substantial effects on climate patterns. Various chemical processes, including the production of greenhouse gases and photochemical reactions, have an impact on the composition of the atmosphere and the rise in air pollution. The release of pollutants resulting from human activities, including transportation and industrial processes, worsens air quality issues, thereby causing detrimental impacts on both ecosystems and human health. Moreover, there is a strong interconnection between air quality and climate change. Numerous atmospheric pollutants, such as black carbon and methane, exhibit substantial warming characteristics, thereby intensifying the greenhouse effect and expediting the process of global warming. The presence of aerosols and their chemical interactions can exert a significant influence on the formation and characteristics of clouds, thereby affecting climate patterns at both regional and global scales. Understanding the complex relationships between various factors are of the utmost priority in formulating productive policies and strategies for mitigating air pollution and the detrimental impacts of climate change. The objective of this review is to examine the complex interplay between chemistry, air quality, and climate change. In this discussion, we aim to demonstrate the key connections among these three components and underscore their wide-ranging consequences for environmental concerns.

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Introduction

Climate change and air pollution are deeply interconnected environmental concerns, exhibiting a wide range of interdependencies (Alahmad *et al.*, 2023). These issues have a strong connection with the complex interactions of atmospheric properties, emissions, dynamic processes, and complicated chemistry, along with the potential avenues for mitigation (Iriti *et al.*, 2020; Viana *et al.*, 2020). Prominent contributors to emissions include a variety of air pollutants and greenhouse gases, such as ozone, nitrogen oxides, sulphur dioxide (SO_2), carbon monoxide, particulate matter (PM), and carbon

dioxide (CO_2). The atmospheric properties of these pollutants play a crucial role in shaping their impact on atmospheric chemistry processes, atmospheric lifetime, radiative forcing, ecosystems, and human health. Particulate matter has the potential to exert a direct influence on radiative forcing through its ability to absorb or scatter incoming radiation, thereby leading to detrimental impacts on human health. Moreover, it is worth noting that particulate matter has the potential to serve as cloud condensation nuclei, thereby exerting an influence on radiative forcing and the complicated mechanics of weather patterns (Ramanathan *et al*., 2005).

Generally, energy efficiency improvements and switching to solar or wind power reduce greenhouse gases across the board, mitigating climate change and improving air quality (Williams, 2012). However, some mitigation strategies may assist one area while harming another. For example, biomass consuming for residential heating reduces CO_2 emissions (such actions frequently referred to as "carbon-neutral"), but it also decreases air quality by emitting particulate matter (Haluza *et al*., 2012). In the context of climate science, trade-offs encompass choices that do not result in mutual benefits for all parties involved, but rather create a situation where one-party gains while another loses. The potential advantages of implementing coordinated measures that consider these interconnections are increasingly being recognized, particularly in light of prominent political initiatives like the Climate and Clean Air Coalition (CCAC). These initiatives strive to stimulate action in this the field, facilitating swifter and more effective advancements in maintaining human well-being and ecosystems, and simultaneously mitigating the impacts of climate change.

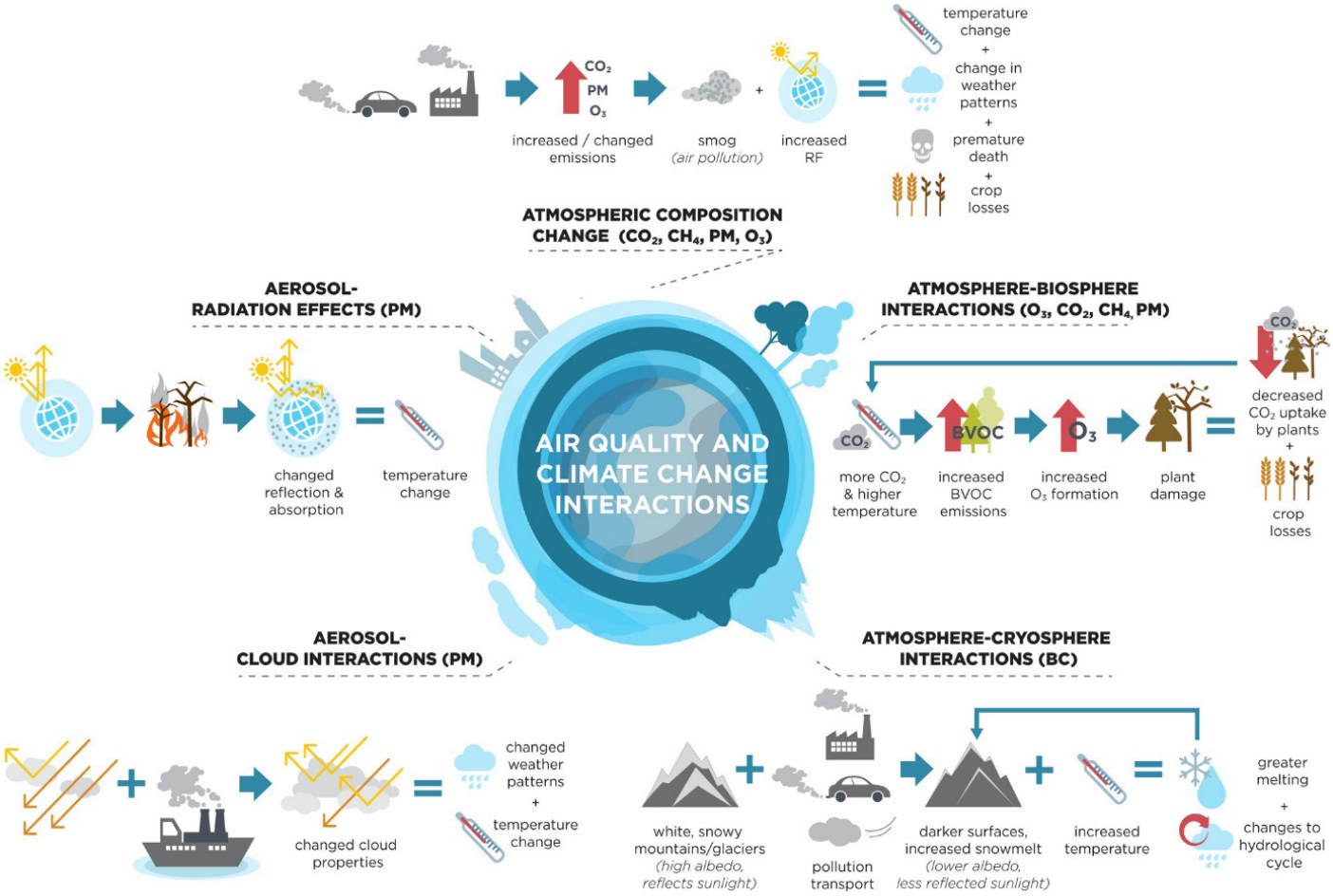

Figure 1: *A thorough review of the primary classes of climate change and air quality interactions, along with an illustration of a representative connection or feedback within each class. The emission sources depicted in the illustration serve as illustrative examples of potential sources, but they do not encompass the entirety of emission sources that are essential to the interaction shown. The components that hold the utmost relevance are indicated within the brackets subsequent to the respective class. Particulate matter (PM) serves as a comprehensive indicator for various sulphur dioxide (SO_2), black carbon (BC), and aerosol sources (encompassing organic aerosol (OA)). On the other hand, ozone (O_3) encompasses both O_3 itself and its precursor compounds, namely nitrogen oxides (NOx), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) (Figure is reprinted under Creative Commons Attribution License (CC BY) from Von Schneidemesser et al., 2015).*

Links Researchers

This review examines the chemistry, processes, and properties of the atmosphere, emphasis on the sources of emissions and their connections to climate change. It addresses pollutants' role in air quality, climate, ecosystems, and human health, as well as their impact on radiative forcing.

- Air pollutants
- Gaseous pollutants

Nitrogen oxides

Fossil fuel combustion accounts for two-thirds of all anthropogenic and natural NOx (NO and NO_2) emissions to the atmosphere, with the remaining one-third coming from lightning, soils, and biomass burning (Turnock *et al*., 2020). An estimated 57 Tg of anthropogenic NOx (NO_2) were released into the atmosphere in 2000 (Lamarque *et al*., 2010). Combustion in diesel and gasoline cars, industry, transportation, and residential heating are all examples of uses for fossil fuels. The mixing ratios of NOx in atmospheric vary from below 1 ppb in forest environments or pristine marine to above 10 ppb in urban and agricultural areas. Combustion processes release NOx, primarily NO (95%) and some primary NO_2. When NO is oxidized, primary NO_2 is produced. There has been a reported 30-50% increase in primary NO_2 emitted in the transportation sector due to the rise in use of diesel cars (Carslaw *et al*., 2006). The seasonal nature of biomass burning causes a spike in these emissions in the early spring and late winter (Cooper *et al*., 2014).

The emissions of NO_2 have been found to have significant implications for human health, leading to various adverse effects such as asthma exacerbation, airway inflammation, cardiovascular diseases, heightened hospitalization rates, and even premature mortality (Zhang *et al*., 2022). The impacts of these phenomena are notably amplified in the vicinity of vehicles and in close proximity to road networks, exhibiting concentrations that surpass those observed in adjacent regions by 30-100%. Furthermore, it is important to note that NOx emissions play a significant role in worsening detrimental impacts on ecosystems, particularly through the process of acidification.

Ammonia

Nitrogen, an essential component for sustaining life, plays a crucial role in the nutritional requirements of most organisms, as they heavily rely on fixed nitrogen. Bacterial play a crucial role in the process of nitrogen fixation within the soil, establishing a symbiotic relationship with vegetation (Vitousek *et al*., 2013). It is abundantly found within the composition of amino acids and the NH_4^+ ions present in cellular fluids. The exchange of NH_4^+ in plant tissues with the atmosphere occurs primarily through stomata and is influenced by various factors such as pH levels, NH_4^+, and atmospheric NH_3 concentrations (Jiang *et al*., 2021). The balancing point refers to the concentration at which NH_3 is either emitted or deposited near external surfaces. NH_3, an atmospheric constituent, is primarily derived from natural emissions originating from various sources such as animal excreta, soil, and vegetation. The contribution to the nitrogen cycle from industrial nitrogen fixation via the Haber Bosch process and the utilization of legume crops is significant. It is estimated that the annual nitrogen fixation resulting from these activities amounts to approximately 120 Tg N (Erisman *et al*., 2008). The anthropogenic contributions observed can be likened to the natural process of nitrogen fixation occurring in unmanaged oceans and ecosystems.

The analysis of the potential impact of a shifting climate on NH_3 emissions has been studied by (Fowler *et al*., 2015; Sutton *et al*., 2013). In the recent examination of NH_3 emission and deposition conducted by Sutton *et al*. (2011). It is contended that the methodology for estimating emissions should incorporate climate considerations, instead of relying solely on predetermined emission levels for agricultural sectors. This is due to the significant influence of temperature on the separating between both the gas and liquid forms of NH_3. The observed outcome of a 5°C alteration in global surface temperature is demonstrated to result in a 42% amplification in global NH_3 emissions. Taking into account the complex relationship between global temperature fluctuations and human-induced activities, it is probable that there would be a discernible rise in NH_3 emissions, reaching an estimated value of 132 Tg of nitrogen in the form of NH_3 per year. The primary sources of uncertainty in projecting future atmospheric NH_3 emissions are predominantly linked to the various factors influencing NH_3 consumption (Fowler *et al*., 2015).

Methane

In terms of radiative forcing, methane is undoubtedly the most important greenhouse gas, with values 28%

higher than those of non-CO_2 atmospheric elements (Hofmann *et al*., 2006). The infrared absorption capacity of CH_4 is 28 times that of CO_2 (Myhre *et al*., 2014). Destroying it in the presence of hydroxyl radicals sets off a chain reaction that has far-reaching consequences for ozone generation and air quality, therefore affecting the chemical equilibrium of atmosphere. The potential upper limit of ozone production resulting from the oxidation of a single CH_4 molecule to water and CO_2 is estimated to be five molecules of ozone. But the potential yield mentioned is not typically achieved in real-world atmospheric conditions due to the presence of various competing reactions (Seinfeld and Pandis, 2016). CH_4 has a lifetime in the atmosphere that typically ranges from 9 to 11 years, during which it undergoes various chemical reactions. One of the primary outcomes of these reactions is the formation of CO_2 (Holmes *et al*., 2013).

Key determinants of wetland CH_4 emissions include substrate availability, soil temperature, and water table depth, making these emissions particularly vulnerable to climate change (O'Connor *et al*., 2010). Parameterizing and modelling basic mechanisms at a high level of complexity is required to assess potential climate changes and simulate wetland ecosystems. The low number of studies shows discrepancies in results due to the fact that several wetland ecosystem activities have not been examined in depth (O'Connor *et al*., 2010). Large uncertainties exist in estimated emission and loss due to the lack of a precise quantification of methane source and sink processes. The uncertainty has been reduced via connecting regional sources and sinks through inverse modelling (Bousquet *et al*., 2006). Bergamaschi *et al*. (2013) discovered that there has been a notable rise in worldwide methane emissions since 2006, with emissions peaking between 2007 and 2010 in comparison to the mean emission rate seen between 2003 and 2005 (Bergamaschi *et al*., 2013). Biomass burning and wetlands were shown to have significant year-to-year fluctuation in their CH_4 emissions. The capacity of atmospheric inversions to identify CH_4 sources relies on the maintenance of lengthy meteorological time series, and expanding the spatial range of observations helps in detecting trends (Bruhwiler *et al*., 2014).

Ozone (O3)

Ozone is classified as a secondary air pollutant that arises from the photochemical processes involving CH_4, NOx, carbon monoxide (CO), and volatile organic compounds (VOCs) (Monks *et al*., 2015). Ozone plays a pivotal function in atmospheric chemistry through its process of oxidizing biogenic VOCs. When the double bond in VOC carbon chains is targeted by ozone, it leads to the formation of a Criegee intermediate. This intermediate subsequently generates hydroxyl radicals, which play a crucial role as oxidizers for VOCs and SO_2 (Mauldin *et al*., 2012; Taatjes *et al*., 2014). The aforementioned procedure plays a substantial role in the generation of sulfuric acid within rural areas (Boy *et al*., 2013). Furthermore, it is worth noting that the process of ozone oxidation can result in the production of highly oxidized organic molecules known as extremely low VOCs. These extremely low VOCs have the ability to condense onto air particles, even when they are as small as nano sized (Ehn *et al*., 2014).

Ozone, a well-known air pollutant, exhibits detrimental impacts on human health, such as diminished pulmonary function, exacerbation of asthma, respiratory afflictions, and premature deaths (Popescu and Ionel, 2010). The World Health Organization (WHO) has established a recommended limit value of 100 μg m^{-3} for this particular parameter. However, it is important to note that individual responses to this level may exhibit variability. The concentrations of ozone exhibit a wide range, spanning from 26 to 62 μg m^{-3} in the marine boundary layer of the southern hemisphere, while exceeding 240 μg m^{-3} in heavily polluted urban areas of China (Han *et al*., 2013). Prolonged exposure to certain environmental factors has been found to potentially result in chronic consequences, as indicated by recent scientific investigations that have linked such exposure to an estimated 0.2 million premature deaths related to respiratory ailments on a global scale each year (Silva *et al*., 2013).

Ozone exerts both direct and indirect influences on the dynamics of climate change. The degradation of chlorophyll and subsequent reduction in photosynthesis rates have been observed to slow down the uptake of CO_2 in vegetation, thereby impacting plant growth (Templer *et al*., 2012). The estimated radiative forcing resulting from ozone due to plant feedbacks by the year 2100, compared to the year 1900, ranges from +0.62 to +1.09 Wm^{-2} (Sitch *et al*., 2007). According to the study conducted by Collins *et al*. (2010) it has been determined that the indirect

effects of ozone precursors play a substantial role in influencing the climate over a 20-year period. These effects have been observed to have a notable impact on the ability of the terrestrial biosphere to absorb CO_2. Unger and Pan posit that the intricate interplay among biogeochemical cycles, aerosols, and ozone could potentially exert the most significant influence on the climate as a result of short-lived air pollutants (Unger and Pan, 2012).

Anthropogenic NMVOCs and CO

In the year 2000, the total estimated emissions of anthropogenic NMVOCs amounted to 129 Tg. Various sources, including biomass burning, solvent utilization, industrial activities, and road transportation made substantial contributions to these emissions (Janssens-Maenhout *et al.*, 2013; Lamarque *et al.*, 2010). NMVOCs are known to have detrimental impacts on human health as a result of their involvement in the formation of ozone and the toxicity associated with specific chemicals such as styrene, benzene, and formaldehyde which have carcinogenic or mutagenic properties (Popescu and Ionel, 2010). The primary causes of toxicity are attributed to a specific number of NMVOCs, namely furan acrolein, and formaldehyde. These NMVOCs originate from residential and transportation activities, and it is worth noting that their emission patterns do not necessarily overlap with those of the major ozone-forming compounds (Laurent and Hauschild, 2014). Granier *et al.* (2011) observed that worldwide CO emissions exhibit comparable trends, with a 28% variation in the dispersion across all estimated values (Granier *et al.*, 2011). Combustion, including both anthropogenic and natural origins such as fossil fuel and biomass burning constitutes the predominant contributor to CO emissions. The primary causes to environmental pollution are biomass burning and transportation, with additional contributions stemming from the atmospheric oxidation of NMVOCs and CH_4. Elevated levels of CO have the potential to be fatal, although lesser levels of exposure can lead to detrimental health outcomes such as headaches, vomiting, nausea, and lethargy (Popescu and Ionel, 2010).

Biogenic NMVOCs

Biogenic NMVOCs are released into the Earth's atmosphere through a combination of human activities and natural processes. The emission of biogenic NMVOCs from terrestrial vegetation is estimated to be approximately 1000 Tg annually, which is significantly higher compared to anthropogenic sources, with a ratio of 8 (Guenther *et al.*, 2012; Sindelarova *et al.*, 2014). The primary constituents released into the atmosphere encompass a range of organic compounds, including terpenes as well as oxygenated VOCs such as acetaldehyde, acetone, ethanol, and methanol (Haluza *et al.*, 2012). Peroxy radicals engage in a chemical reaction with NO resulting in the formation of organic nitrates, particularly peroxyacetyl nitrate (PAN). The presence of PAN in the atmosphere serves as a reservoir for radicals and NOx, thereby mitigating the production of surface ozone (Atkinson, 2000). Due to its inherent chemical stability, this substance exhibits a remarkable capacity for transportation to fresh and isolated ecosystems. The thermal or chemical decomposition of PAN result in the production of N_2, which subsequently triggers the formation of ozone in the respective environments (Heald *et al.*, 2003; Val Martin *et al.*, 2006).

In an atmosphere free of pollution and characterized by a low concentration of NOx, yet with a sufficient presence of VOCs, the troposphere operates within an environment where NOx serves as the limiting factor (Seinfeld and Pandis, 2016). The process of VOC oxidation leads to the generation of peroxy radicals, which play a significant role in atmospheric chemistry. However, it is important to note that the presence of NOx may block the formation of ozone in the atmosphere. Biogenic VOCs have the capacity to reduce ozone levels by means of direct chemical reactions. The depletion of atmospheric oxidants, primarily hydroxyl radicals, leads to a decrease in the atmosphere's capacity for oxidation, thereby exerting an influence on the climate (Atkinson and Arey, 2003). The hydroxyl radical plays a crucial role in mitigating the levels of methane, a potent greenhouse gas, by acting as a significant sink. The reduction in hydroxyl radicals' levels lead to an increase in the chemical lifetime of methane, thereby exacerbating its impact on the environment (Poisson *et al.*, 2000).

Aerosols

Aerosols are small liquid or solid components that remain floating in a gas. They can come from both natural and man-made sources (Seinfeld and Pandis, 2016). They can be released directly or made in the air from gases that were already there. Their affects are mostly a regional or local and last from a few days

to a few weeks. Particulate matter (PM) is typically monitored using PM10, PM2.5, and even PM1. The number of particles in the air affects health and the climate. Aerosols and PM can get into the air as main particulates or through indirect means by the formation of secondary aerosols (Jiang *et al*., 2022; Lee *et al*., 2019). PM are the pollutants that can cause health problems, such as early death, asthma, lung disease, and other breathing illnesses. Continuous interaction with PM is the biggest health problem for most people (Heal *et al*., 2012). It's clear that high particle mass concentrations lead to bad health effects, and there's more and more proof that ultrafine particles can hurt your heart, lungs, and the brain (Goldstone, 2015).

Aerosols, acting as climate influencers, have the potential to impact radiation in both direct and indirect ways via aerosol-radiation effects. Aerosol-radiation effects include the capturing interactions between radiation and aerosol particles, which results in the scattering or absorption of radiation. These phenomena play a crucial role in both cooling the surface of the planet and warming the atmosphere. Aerosol-cloud effects consist of the interaction between aerosol particles, typically ranging in size from 50-100 nm, and their role as cloud condensation nuclei (CCN). These CCN play a crucial role in the formation of cloud droplets within ascending air masses (McCoy *et al*., 2020; Moch *et al*., 2022). The presence of a greater amount of CCN particulates leads to enhanced cooling mechanisms, as these particles contribute to the formation of clouds that provide shade from solar radiation. The hygroscopicity of particles serving as CCN is a crucial attribute, exhibiting a spectrum of values ranging 0.1 to 0.9 for PM, 0.01 to 0.5 for organic species, and 0 to 1.4 for inorganic salts (Petters and Kreidenweis, 2007).

Black carbon

Black carbon (BC) plays a significant role in the composition of fine particulate matter (PM2.5) and is released into the atmosphere as a result of partial combustion of carbon-based fuels and carbonaceous substances (Pani *et al*., 2020; Seinfeld, 2008). Prominent contributors encompass the combustion of forests and grasslands, the utilization of biofuels for residential purposes, the burning of fossil fuels, various industrial processes, and the generation of power. In the year 2000, the global annual aggregate of BC emissions amounted to 7.5 Tg. BC particles exhibit a size distribution spanning from 0.01 to 0.1 μg m^{-3}, reaching higher concentrations of 10 to 15 μg m−3 in certain heavily polluted areas of Asia (Becker *et al*., 2021; Wu *et al*., 2009). Black carbon, also known as soot, has been extensively linked to detrimental impacts on human health. These impacts manifest in various ways, such as breathing and heart disease, raised rates of hospital admissions, and increased mortality rates attributed to lung cancer and heart disease. Prolonged exposure to elevated levels of BC fraction in fine PM2.5 has been observed to potentially exert more significant impacts on mortality rates compared to other mixtures of PM2.5 (Smith *et al*., 2009).

BC is a very important light-absorbing gas in the environment. When it settles on high-albedo objects like snow, it absorbs solar radiation and reduces the amount of light that is reflected back into space. It is believed that, after CO_2, it is the 2nd most important factor in the current radiative force that is causing global warming (Ramanathan and Carmichael, 2008). But the exact effect of BC on the climate is still up for question because of unknowns in human emissions, long-distance transport, and processes that affect the length of time BC stays in the air. From petroleum and biofuels, the IPCC's AR5 says that BC has a radiative force of +0.4 W m2 (Samset *et al*., 2014). Biomass-burning sources release both BC and organic aerosol (OA), but the amount of BC vs. OC varies a lot from source to source. Because of the strong insolation, the RF from BC on snow is maximum on boreal ground snow and from March to May (Flanner *et al*., 2007). BC particulates can also mix with clouds, which could change the cloud's reflectivity, cover or emissivity. BC can act as CCNs when clouds form. This changes the amount of liquid droplet size and ice fragments in the cloud, which affects how well clouds produce precipitation and how long they last (Nabat *et al*., 2022).

Sulfate

Sulfate aerosol plays a vital role in the composition of fine particulate matter (PM2.5), predominantly originating from the combustion of fossil fuels, biomass, and natural phenomena such as volcanic and oceanic emissions (Fung *et al*., 2022; Junkermann and Hacker, 2022). The formation of this phenomenon takes place via the process of sulfuric acid oxidation, wherein it undergoes interaction with solar radiation, leading to its growth through the mechanism of

coagulation (Karlsson *et al*., 2022). Sulfate aerosols possess the capacity to exert detrimental impacts on both human health and ecological systems, primarily through the process of acid deposition. The mitigation of sulfate concentrations yields positive outcomes for both air quality and human health. However, it is important to admit that such reductions can also have implications for the Earth's climate system, specifically by modifying its radiative balance. The potential consequences of decreasing sulfate aerosols include the possibility of experiencing accelerated warming in the immediate future. However, this warming may be partially counteracted by the presence of short-lived warming species (D'Amato and Akdis, 2020).

Sulfate emissions, which are a constituent of PM, exhibit health impacts that are similar to those caused by aerosols. The emission of SO_2 from industrial activities, as well as its subsequent accumulation through rainfall into water and soils, has been found to have detrimental impacts on vegetation, forests, and aquatic ecosystems (Steinfeld *et al*., 2009). Air pollution mitigation strategies have been effectively deployed in North America and Europe since the 1970s with the primary objective of curbing sulfur emissions and enhancing the overall air quality. It is believed that there will be a notable decline in emissions within developed nations over the coming decades and throughout the entirety of the 21st century. But rapidly developing countries in Southeast Asia still have a lot of SO_2 emissions, which will rise between 2010 and 2040 and then start to go down (Van Vuuren *et al*., 2011). Alternative plans, like Shared Socioeconomic Pathways (SSPs), are being made to figure out how the air quality will change in the future (Van Vuuren *et al*., 2014). Because they have a lot of sulfur, power plants powered by coal are a big source of Sulfur emission. If innovations like post combustion scrubbing were used all over the world, they could cut human-made SO_2 pollution by 80%. China is now using scrubbers more and more. Starting in 2005, SO_2 emissions from the energy sector are projected to drop by a lot (Xu, 2011).

Organic aerosol

Organic aerosol (OA) constitutes a substantial proportion of PM in both contaminated and unspoiled environments, exhibiting variable contributions based on geographical context. OA frequently exhibit a prominent presence in contaminated ecosystems, exhibiting mass concentrations that can be likened to those of sulfate. In undisturbed tropical and boreal environments, OA prevail, constituting a significant portion of the fine-mode aerosol mass burden, reaching up to 90% (Brito *et al*., 2014). OA are generated through the release of primary OA (POA) emissions and subsequent chemical transformations, wherein VOCs in the gas phase undergo oxidation reactions and subsequently combine to generate secondary OA (SOA) (Andreae and Merlet, 2001). POA predominantly arise from the combustion of biomass, such as vegetation or wood. On the other hand, secondary OA is produced when gaseous organic compounds undergo condensation or nucleation processes, leading to the formation of PM. The abundance of secondary organic aerosols (SOA) has been observed to surpass that of POA in various field studies. Furthermore, this phenomenon exhibits an upward trend as the distance from significant emission sources increases. However, the numerical models yield varying outcomes in terms of the dominance of SOA owing to limitations in comprehending their origins, mechanisms of formation, and atmospheric transformations (Heald *et al*., 2011).

Models often underestimate the worldwide burden of biomass burning OA (BBOA), which is demonstrated by the demand for factors ranging from 2 to 5 in order to align with measurements of aerosol optical depth. According to a recent modeling study conducted in South East Asia, the inclusion of minor fires detected by satellites in emission inventories resulted in enhanced comparability with observational data (Reddington *et al*., 2014). Various measurement experiments have been conducted to assess biomass burning, both in controlled laboratory settings and in real-world field conditions. These investigations have demonstrated the significant variability in emission factors of BBOA at the source (May *et al*., 2014). The investigation of the semi-volatile component of SOA has garnered considerable attention due to its ability to bridge the disparity observed between empirical measurements and theoretical models. The methodology known as the volatility basis set (VBS) is employed to classify organic compounds based on their volatility, while also considering particulate organic matter emissions as being of a semi-volatile nature. As a consequence, the production of intermediate VOCs occurs in the gaseous state, and subsequent chemical processing can lead to their redistribution into the particle phase. The volatility-based sensitivity (VBS) technique exhibits a high

degree of sensitivity to initial assumptions pertaining to the volatility of OA, hence posing challenges in its quantitative measurement. Emerging findings indicate that the expeditious atmospheric auto-oxidation mechanism of volatile organic compounds, leading to the formation of very low volatility organic compounds, could potentially account for the observed disparities between quantified and simulated levels of SOA (Jokinen *et al*., 2014). OA has the ability to simultaneously reflect and absorb solar radiation, which introduces complexity in evaluating its comprehensive climate impact.

Climate effects on air quality

Meteorology and ozone: Climate change has the potential to impact the ozone layer through multiple mechanisms, encompassing alterations in temperature, meteorological patterns (such as clouds, humidity, stagnation events, precipitation, etc.), natural emissions, and the interchange of gases between the troposphere and stratosphere. Several modeling studies have been conducted to examine the anticipated shifts in future ozone levels. These studies have often focused on isolating and analyzing various conditions in order to comprehend the factors that contribute to fluctuations in ozone levels (Doherty *et al*., 2013; Wang *et al*., 2013).

Research conducted on China from 2000 to 2050 revealed that the impact of climate change on ozone levels was particularly significant during the summer season (Wang *et al*., 2013). The study showed both positive and negative increases in ozone concentrations. The observed phenomenon can be attributed to a combination of variables, including elevated natural emissions of substances that contribute to the formation of ozone, as well as meteorological conditions such as increased water vapor content, elevated temperatures, and decreased rates of air movement. Ozone has a role in the generation of hydroxyl radicals, while water vapor serves as a mechanism for ozone depletion:

$$O_3 + h\nu \rightarrow O(^1D) + O_2$$
$$O(^1D) + H_2O \rightarrow 2OH$$

It is anticipated that in a future climate, there would be a rise in water vapor levels, which is projected to result in a reduction in the lifespan of ozone and a decrease in surface ozone concentrations in regions with lower pollution levels, particularly in oceanic areas (Doherty *et al*., 2013). Nevertheless, OH plays a pivotal role in atmospheric processes, which has the potential to result in increased formation of ozone. Elevated levels of humidity have been observed to lead to overall reductions in ozone level in warmer geographical locations, while simultaneously causing localized pockets of heightened ozone levels in cooler regions (Thambiran and Diab, 2010).

The effect of climate change on air travel patterns has shown inconsistent large-scale spatial responses. This suggests that changing travel patterns is unlikely to have a big effect on how ozone is distributed in different regions (Doherty *et al*., 2013). Barnes and Polvani (2013) have provided evidence of a strong reaction of eddy-driven jets to climate change within the CMIP5 multi-model mean ensemble. Gaining insight into forthcoming changes in the positioning of jet streams could facilitate the analysis of modifications in the variability of surface ozone during the summer season, as well as the examination of the links between ozone and temperature. The role of climate-induced alterations in transportation patterns may exert a more significant influence on the occurrence of peak ozone levels. Previous research has indicated that the utilization of domain average sensitivity alone was inadequate for accurately predicting fluctuations in ozone levels, mostly due to the heterogeneous nature of their response. Horton *et al*. (2014) conducted a study to examine the frequency and duration of future air standstill events and projected that there will be an increase in stagnation occurrences that will impact around 55% of the current global population. These disparities highlight the indeterminacy linked to alterations in the circulation patterns within a prospective climate and the height of the boundary layer.

A comparative analysis conducted between the conditions of the 1990s and projected scenarios for the 2090s revealed a notable escalation in the net transport of ozone into the troposphere within the anticipated future climate (Collins *et al*., 2003). Certain confounding factors, such as photochemical ozone loss and humidity, have the potential to mitigate or offset some of the observed increases. A comparative analysis conducted through a worldwide model research, spanning from 2000 to 2100, revealed that an enhanced Brewer-Dobson circulation would result in a 35% enhancement of stratospheric ozone influx. Additionally, higher convective activity would

lead to a 50% rise in lightning NOx emissions, thereby amplifying ozone generation in the upper troposphere (Hauglustaine *et al*., 2005). The competition resulting from the presence of wetter and warmer climates has been found to contribute to an intensified process of ozone breakdown. It has been projected that the overall load of tropospheric ozone, as influenced by climate change, is expected to exhibit a modest decline. In a recent study conducted by Young *et al*. (2013) it was discovered that an addition in stratospheric influx can cover up more pronounced adverse alterations in the overall ozone burden, resulting from reductions in emissions of ozone precursor substances (Young *et al*., 2013). According to many models, it is indicated that there is a rise in upper tropospheric ozone due to an increase in the transfer of ozone from the stratosphere to the troposphere, as well as an increase in lightning production (Kawase *et al*., 2011). The alteration of ozone depleting compounds and stratospheric ozone can lead to significant modifications in the composition of the troposphere, resulting in a noteworthy impact on radiative forcing. These effects should be taken into account when examining the relationships between composition and climate (Voulgarakis *et al*., 2013).

BVOCs

The BVOCs' emissions from plants are greatly affected by various environmental conditions, including leaf area, vegetation type, air chemical composition, light intensity, and temperature. It is expected that BVOC emissions will be influenced as these components experience fluctuations in a future climate. The integration of energy balance, carbon and hydrological cycles, and biochemical processes with spatial and temporal variations in plant covering enables dynamic vegetation models to effectively examine prospective variations in BVOC emissions (Arneth *et al*., 2007). According to scientific projections, there is an expected increase in global isoprene emission ranging from 30% to 80% by the year 2100, primarily attributed to climate changes occurring in the 21st century (Guenther *et al*., 2006). The changing of land cover has the potential to result in varying emissions levels, reliant on the specific geographical context. It is thought that forthcoming climate circumstances could perhaps facilitate the proliferation of temperate and boreal forests in the Northern Hemisphere. Conversely, the region of South America, including Amazonia, is projected to experience a decline in biomass as a result of increased temperatures and aridity (Gomez *et al*., 2023). Anthropogenic activities, such as the deliberate clearing of forests and their subsequent replacement with agricultural fields, have the potential to cause a reduction in the emission of isoprene. In general, variations in land cover exert a more pronounced influence on isoprene emissions, contingent upon the specific situations under examination.

The specific effect of CO_2 on future estimations of BVOC emissions remains uncertain. High concentrations of CO_2 have been found to have a beneficial effect on vegetation fertilization, primary production, and leaf growth. This, in turn, has a favorable impact on the emissions of BVOCs by increasing the biomass that emits these compounds (Zanis *et al*., 2022). However, empirical investigations have demonstrated that the suppression of isoprene production in certain plant species cultivated in conditions with increased levels of carbon dioxide can potentially lead to a decrease in future emissions of isoprene (Sun *et al*., 2013). The changing of land cover resulting from anthropogenic activity can potentially have consequences on the emissions of biogenic VOCs in the future. The emission of isoprene can be reduced by tropical deforestation and the conversion of land into crop fields, whereas the replacement of oil palm plantations or agricultural land with woody biofuel species results in increased isoprene emissions (Ashworth *et al*., 2013). Potential future shifts BVOC emissions have the potential to induce feedback mechanisms on the Earth's climate by affecting the generation of surface ozone and organic aerosols (Young *et al*., 2009). The complicated connection between the biosphere and atmosphere exhibits a level of complexity that remains insufficiently elucidated by current scientific understanding. Further comprehension is required in order to more effectively assess the correlation between BVOC emissions and the prospective climate of the Earth.

Particulate matter (PM)

Climate change has a significant impact on PM, which shares similarities with ozone, through its effects on meteorological patterns, natural emissions, and temperature. Wildfires have the potential to exert a substantial influence on PM concentrations as well (Spracklen *et al*., 2009). Nevertheless, there is a limited body of research that has examined the impact of climate change on particulate matter (PM). According to a multi-model analysis, an observed correlation was identified between higher precipitation

and a marginal reduction in PM2.5 concentrations in Europe (Colette *et al*., 2013). A comparative analysis was conducted to examine the differences between present-day and future climates, focusing on the levels of PM10. The findings of this study revealed minimal alterations in PM10 concentrations, however there were conflicting opinions regarding the direction of these changes (Manders *et al*., 2012). According to the study conducted by Hedegaard *et al*. (2013) there was an observed decline in PM2.5 levels in regions with high latitudes, specifically in the Arctic (Hedegaard *et al*., 2013). Conversely, there was a slight elevation in PM2.5 concentrations in certain portions of the Atlantic Ocean, as well as in subtropical and tropical regions. The impact of climate change and anticipated emissions intensify the declines in PM. According to the study conducted by Tai *et al*., it was observed that between the years 2000 and 2050, the general circulation models, when weighted, indicated a slight rise in PM2.5 levels in the eastern region of the United States (Tai *et al*., 2012). This increase was attributed to a decrease in the occurrence of frontal ventilation events. However, it is believed that there would be a slight decline in the Pacific Northwest region of the United States as a result of increased occurrences of maritime imports. According to Liao *et al*., their study revealed that climate change induced by increased levels of CO2 would lead to a reduction in the loads of all aerosol components, with the exception of SOA, which would see an increase of 9% (Liao *et al*., 2006). These changes mostly arise from alterations in wet deposition, the thermodynamic equilibrium of aerosols, and emissions sensitive to climate conditions. Numerous studies consistently indicate that the primary drivers of modelled changes in PM concentrations are alterations in emissions resulting from air pollution and/or climate policy. According to Spracken *et al*. (2009), it was projected that average midsummer concentrations of organic carbon (OC) and elemental carbon (EC) would experience a 40% and 18% rise, respectively, in the western region of the United States (Spracklen *et al*., 2009). The researchers attributed the majority of this increase to emissions resulting from wildfires. The further rise in OC levels was attributed to shifts in meteorological conditions and emissions of monoterpene, hence impacting the observed changes.

Wildfires arise from a multifaceted interplay of several factors, encompassing meteorological conditions, combustible materials, geographical features, and anthropogenic activities (Ghorbanzadeh *et al*., 2019). The influence of a dynamic climate on many components is believed to have a substantial impact on fire risk, with climate change being a key driver of increased occurrences of extreme events. Research findings indicate that an escalation in the frequency or magnitude of fires would lead to a corresponding increase in PM emissions. This is attributed to the raised PM or aerosol loadings that accompany a greater incidence of forest fires (Athanasopoulou *et al*., 2014; Slezakova *et al*., 2013). Numerous studies indicate an elevated likelihood of forest fires due to the direct effects of rising temperatures, diminished precipitation, and reduced relative humidity. These factors contribute to the extension of fire seasons, characterized by prolonged periods of dryness. Additionally, the reduced or earlier melting of snowpacks further exacerbates the situation (Westerling and Bryant, 2008). It is anticipated that there will be a rise in the frequency of ignitions caused by lightning in the future as a result of climate change. This can be attributed to the projected increase in the occurrence of thunderstorms and the increased vulnerability of fuels to ignition. Wetter conditions characterized by relatively modest temperature increases may potentially yield a higher incidence of fires in general. The spatial distribution of changes in fire danger or predicted area burned exhibits notable variability, which is contingent upon alterations in weather patterns, the position and density of forest cover, land use practices, fire suppression efforts, and fuel management operations (Clark *et al*., 2014; Flannigan *et al*., 2005). The challenge of forecasting fluctuations in PM levels within a future climate comes from the significant association between PM concentrations and meteorological factors. The most recent IPCC acknowledges the challenge in assessing the overall influence of climate change on PM2.5 distributions, as it does not assign a confidence level to this relationship (Masson-Delmotte *et al*., 2021). The relationship between changes in ozone and changes in temperature is highly correlated, as evidenced by the steady increase in temperature observed in the 21st century across several general circulation models, including regional scales (Liao *et al*., 2006).

Metrics for assessing impact

Air quality metrics: Air quality metrics serve as valuable tools for quantifying the efficacy, advancement, or effectiveness of air quality policies. In the field of environmental science, a comprehensive evaluation

encompasses a multitude of factors that include but are not limited to cost, health implications, vegetation dynamics, material composition, and aesthetic considerations. These factors collectively contribute to the development of diverse metrics, which are tailored to meet the specific requirements of the assessment at the moment (No, 2010). Hourly concentrations of primary air pollutants exhibit a notable skewness, indicating a significant deviation from a symmetrical distribution. In contrast, ozone, which is categorized as a secondary pollutant and typically has a higher background concentration, displays frequency distributions that diverge from those observed for primary pollutants (McDonald-Buller *et al.*, 2011). In order to obtain precise measurements of ozone levels, a variety of metrics are employed, which capture distinct characteristics of the frequency distribution of hourly ozone concentrations. The observed metrics exhibit spatial variability, which is a sign of the impacts of regional, national, and global factors that govern the concentration levels (Lefohn *et al.*, 2010; Lin *et al.*, 2013).

Table 1: *Air quality metrics: These metrics provide valuable insights into the composition and condition of the air, allowing us to evaluate its impact on human health and the environment.*

Air Quality Problem	Metric
Ozone	➢ Maximum hourly concentration ➢ Maximum 8 h concentration ➢ Running 8 h mean ➢ Annual average concentration ➢ Accumulated ozone exposure over 40 ppb threshold (AOT40)
Particulate matter	➢ Maximum daily PM_{10} ➢ Annual average PM_{10} ➢ Maximum daily $PM_{2.5}$ ➢ Annual average $PM_{2.5}$ ➢ Maximum daily PM_{coarse} ➢ Annual average PM_{coarse} ➢ Ultrafine particle mass or number
Deposition	➢ Nitrogen total ➢ Nitrogen in excess of critical loads ➢ Acid total ➢ Acid in excess of critical load
Air toxics health	➢ Acid in excess of critical load ➢ Concentration or technology-based measures ➢ Premature mortality ➢ Loss in life expectancy

Air quality metrics serve as vital tools in evaluating diverse levels of environmental standards, each carrying distinct legal statuses. The WHO air quality guidelines are supported by substantial research on the fundamental health effects associated with pollutant exposure. These guidelines establish thresholds that ensure public health remains protected by setting levels below which adverse health impacts are unlikely to occur. These guidelines are established without taking into account potential social, economic, or technological, factors that could impact their feasibility. Flexibility is incorporated into the system to accommodate practical challenges and the natural fluctuations in meteorological conditions from one year to another. In the field of environmental science, it is customary for short-term standards to permit the occurrence of numerous instances where a specific concentration level is surpassed within a span of one year, or even when considering an average over multiple years. In the realm of short-lived climate forcers, there exist certain complexities pertaining to the formulation of metrics for short-lived species, encompassing climate policy-driven frameworks and subjective assessments of their significance (Collins *et al.*, 2010; Samset *et al.*, 2013). The quantification of input parameters presents a significant challenge in environmental science, primarily due to the inherent uncertainty associated with atmospheric processes and feedback mechanisms. The metric frequently relies on the spatial and temporal factors associated with the emission of the species (Lund *et al.*, 2012). Peters *et al.* assert the necessity for an enhanced discourse on metrics pertaining to the phenomenon of global warming (Peters *et al.*, 2011).

Climate change metrics

The primary factor contributing to climate change since the 1950s has been the emissions of CO_2 resulting from human activities, commonly referred to as anthropogenic emissions. It is widely anticipated that these emissions will continue to be the dominant driver of upcoming climate change (Masson-Delmotte *et al.*, 2021). Nevertheless, it is important to acknowledge that short-lived climate-forcing pollutants (SLCPs) have exerted substantial impacts on past climate variations and possess the potential to influence forthcoming climatic conditions as well (Myhre *et al.*, 2014). The Kyoto protocol use a metric known as CO_2 equivalent emissions to assess greenhouse gas emissions in relation to CO_2. This metric serves to facilitate climate agreements and

emission trading. Nevertheless, the utilization of the CO_2 equivalent methodology may present certain challenges, since it fails to account for the varying impacts of CO_2 and methane-induced climate change. The Kyoto protocol used a Global Warming Potential (GWP) metric with a time frame of 100 years, which is determined by the equivalency of integrated radiative forcing over a 100-year period resulting from pulse emissions (Özelsel *et al*., 2019). The selection of metrics and time horizons can have a substantial impact on the perceived significance of various emission levels, especially after comparing SLCPs with CO_2. The selection of a metric and temporal range is contingent upon governmental objectives and societal assessments (Lin *et al*., 2013).

IPCC AR5 provides a list of GTP and GWP measures for SLCPs, including but not limited to BC, CH4, and NOx. However, the application of emissions in the context of policy presents more complexities. These complexities include significant uncertainties, variations in metric values across different geographical locations, seasons, and sectors, as well as the possibility of co-emitted species, such as organic carbon, playing a role in mitigating climate change. The reduction of CO_2 is necessary in order to restrict the extent of climate change over an extended period. Additionally, the simultaneous implementation of short-term mitigation strategies for SLCPs, when paired with CO_2 mitigation efforts, can prove to be beneficial. However, the act of comparing the emissions of SLCPs to CO_2 is not conducive to providing useful insights. It may be more advantageous to establish distinct short-term climate objectives that specifically address the reduction of SLCPs.

The establishment of climate-related objectives plays a pivotal role in discerning the potential positive or negative impacts on the climate system. It is of utmost importance to identify mutually beneficial scenarios that promote both air quality and climate policy. The assessment of SO_2 emissions in relation to climate is a matter of scientific inquiry, as it involves evaluating their dual impact. On one hand, these emissions possess a global cooling influence, which may be perceived as advantageous. On the other hand, they have the potential to disrupt rainfall patterns, which could be deemed as potentially detrimental. Thus, the classification of SO_2 emissions as either beneficial or harmful necessitates further examination and analysis within the realm of environmental science. The climate target exerts a substantial influence on the way trade-offs are seeming within the area of air quality and climate policy.

Conclusions and Recommendations

Despite the increasing awareness of the substantial interconnections between climate change and air pollution, there is a considerable need for further research and concerted efforts to address gaps in knowledge and effectively coordinate strategies for reduction and adaptation. In a broader perspective, the consideration of mitigation techniques within the framework of the atmosphere as a finite resource and a global common, rather than solely focusing on the intended target region (such as climate change), has the potential to prevent unexpected consequences. Promoting the utilization of diesel cars as a means to mitigate CO_2 emissions, so addressing the issue of climate change, has resulted in adverse consequences concerning the emissions of NOx and PM, which have a harmful impact on air quality. The difficulty in this domain frequently stems from the need for comprehensive comprehension and quantifiable measures to evaluate the consequences, while also considering integrated policy choices that account for both the effects on climate change and air quality.

While admitting the importance of addressing climate change and air quality as separate issues, it is crucial to recognize the potential for combined advantages that can be achieved through a holistic approach that takes into account the interconnections between these two domains. Enhancing our awareness of the underlying physical and chemical mechanisms that establish the complex relationship among various compounds is important This knowledge, coupled with an in-depth awareness of the repercussions on climate change, as well as the well-being of both human beings and ecosystems, will undoubtedly facilitate the formulation of more astute and well-informed strategies to tackle the pressing environmental issues pertaining to climate change and air quality.

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Novelty Statement

Addressing climate change and air quality separately is important, but a holistic approach that considers their interconnections can offer combined advantages, highlighting the potential for combined benefits.

Author's Contribution

S. Saifullah: Conceptualization, Methodology, Data curation, writing first draft and writing revised drafts. T. kanwal: Methodology, Data curation, writing first draft and writing revised drafts. K. Rehman: Methodology, Data curation, writing first draft and writing revised drafts.

Conflict of interest

The authors have declared no conflict of interest.

References

Alahmad, B., Khraishah, H., Althalji, K., Borchert, W., Al-Mulla, F. and Koutrakis, P., 2023. Connections between air pollution, climate change, and cardiovascular health. Can. J. Cardiol., 39: 1182-1190. https://doi.org/10.1016/j.cjca.2023.03.025

Andreae, M.O. and Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Glob. Biogeovhem. Cycl., 15(4): 955-966. https://doi.org/10.1029/2000GB001382

Arneth, A., Niinemets, Ü., Pressley, S., Bäck, J., Hari, P., Karl, T., Noe, S., Prentice, I.C., Serça, D. and Hickler, T., 2007. Process-based estimates of terrestrial ecosystem isoprene emissions: Incorporating the effects of a direct CO_2-isoprene interaction. Atmos. Chem. Phys., 7(1): 31-53. https://doi.org/10.5194/acp-7-31-2007

Ashworth, K., Wild, O. and Hewitt, C., 2013. Impacts of biofuel cultivation on mortality and crop yields. Nat. Clim. Change, **3**: 492-496. https://doi.org/10.1038/nclimate1788

Athanasopoulou, E., Rieger, D., Walter, C., Vogel, H., Karali, A., Hatzaki, M., Gerasopoulos, E., Vogel, B., Giannakopoulos, C. and Gratsea, M., 2014. Fire risk, atmospheric chemistry and radiative forcing assessment of wildfires in eastern Mediterranean. Atmos. Environ., 95: 113-125. https://doi.org/10.1016/j.atmosenv.2014.05.077

Atkinson, R. and Arey, J., 2003. Gas-phase tropospheric chemistry of biogenic volatile organic compounds: A review. Atmos. Environ., 37: 197-219. https://doi.org/10.1016/S1352-2310(03)00391-1

Atkinson, R., 2000. Atmospheric chemistry of VOCs and NOx. Atmos. Environ., 34(12-14): 2063-2101. https://doi.org/10.1016/S1352-2310(99)00460-4

Barnes, E.A. and Polvani, L., 2013. Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. J. Clim., 26(18): 7117-7135. https://doi.org/10.1175/JCLI-D-12-00536.1

Becker, S., Sapkota, R.P., Pokharel, B., Adhikari, L., Pokhrel, R.P., Khanal, S. and Giri, B., 2021. Particulate matter variability in Kathmandu based on in-situ measurements, remote sensing, and reanalysis data. Atmos. Res., 258: 105623. https://doi.org/10.1016/j.atmosres.2021.105623

Bergamaschi, P., Houweling, S., Segers, A., Krol, M., Frankenberg, C., Scheepmaker, R., Dlugokencky, E., Wofsy, S.C., Kort, E. and Sweeney, C. 2013. Atmospheric CH4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. J. Geophys. Res. Atmos., 118(13): 7350-7369. https://doi.org/10.1002/jgrd.50480

Bousquet, P., Ciais, P., Miller, J., Dlugokencky, E.J., Hauglustaine, D., Prigent, C., Van der Werf, G., Peylin, P., Brunke, E.G. and Carouge, C., 2006. Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature, 443(7110): 439-443. https://doi.org/10.1038/nature05132

Boy, M., Mogensen, D., Smolander, S., Zhou, L., Nieminen, T., Paasonen, P., Plass-Dülmer, C., Sipilä, M., Petäjä, T. and Mauldin, L., 2013. Oxidation of SO 2 by stabilized Criegee intermediate (sCI) radicals as a crucial source for atmospheric sulfuric acid concentrations. Atmos. Chem. Phys., 13(7): 3865-3879. https://doi.org/10.5194/acp-13-3865-2013

Brito, J., Rizzo, L.V., Morgan, W.T., Coe, H., Johnson, B., Haywood, J., Longo, K., Freitas, S., Andreae, M.O. and Artaxo, P., 2014. Ground-based aerosol characterization during the South American Biomass Burning Analysis (SAMBBA) field experiment. Atmos. Chem. Phys., 14(22): 12069-12083. https://doi.org/10.5194/acp-14-12069-2014

Bruhwiler, L., Dlugokencky, E., Masarie,

K., Ishizawa, M., Andrews, A., Miller, J., Sweeney, C., Tans, P. and Worthy, D., 2014. CarbonTracker-CH 4: an assimilation system for estimating emissions of atmospheric methane. Atmos. Chem. Phys., 14(16): 8269-8293. https://doi.org/10.5194/acp-14-8269-2014

Carslaw, D.C., Ropkins, K. and Bell, M.C., 2006. Change-point detection of gaseous and particulate traffic-related pollutants at a roadside location. Environ. Sci. Technol., 40(22): 6912-6918. https://doi.org/10.1021/es060543u

Clark, K.L., Skowronski, N., Renninger, H. and Scheller, R., 2014. Climate change and fire management in the mid-Atlantic region. For. Ecol. Manage., 327: 306-315. https://doi.org/10.1016/j.foreco.2013.09.049

Colette, A., Bessagnet, B., Vautard, R., Szopa, S., Rao, S., Schucht, S., Klimont, Z., Menut, L., Clain, G. and Meleux, F., 2013. European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios. Atmos. Chem. Phys., 13(15): 7451-7471. https://doi.org/10.5194/acp-13-7451-2013

Collins, W., Derwent, R., Garnier, B., Johnson, C., Sanderson, M. and Stevenson, D., 2003. Effect of stratosphere-troposphere exchange on the future tropospheric ozone trend. J. Geophys. Res. Atmos. 108(D12). https://doi.org/10.1029/2002JD002617

Collins, W., Sitch, S. and Boucher, O., 2010. How vegetation impacts affect climate metrics for ozone precursors. J. Geophys. Res. Atmos., 115(D23). https://doi.org/10.1029/2010JD014187

Cooper, O.R., Parrish, D., Ziemke, J., Balashov, N., Cupeiro, M., Galbally, I., Gilge, S., Horowitz, L., Jensen, N. and Lamarque, J.F., 2014. Global distribution and trends of tropospheric ozone: An observation-based review. Elementa, 2: 000029. https://doi.org/10.12952/journal.elementa.000029

D'Amato, G. and Akdis, C., 2020. Global warming, climate change, air pollution and allergies. Authorea Preprints. https://doi.org/10.22541/au.159526736.69654469

Doherty, R., Wild, O., Shindell, D., Zeng, G., MacKenzie, I., Collins, W., Fiore, A.M., Stevenson, D., Dentener, F. and Schultz, M., 2013. Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study. J. Geophys. Res. Atmos., 118(9): 3744-3763. https://doi.org/10.1002/jgrd.50266

Ehn, M., Thornton, J.A., Kleist, E., Sipilä, M., Junninen, H., Pullinen, I., Springer, M., Rubach, F., Tillmann, R., and Lee, B., 2014. A large source of low-volatility secondary organic aerosol. Nature, 506(7489): 476-479. https://doi.org/10.1038/nature13032

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. and Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. Nat. Geosci., 1(10): 636-639. https://doi.org/10.1038/ngeo325

Flanner, M.G., Zender, C.S., Randerson, J.T. and Rasch, P.J., 2007. Present-day climate forcing and response from black carbon in snow. J. Geophys. Res. Atmos., 112(D11). https://doi.org/10.1029/2006JD008003

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R. and Stocks, B.J., 2005. Future area burned in Canada. Clim. Change, 72(1-2): 1-16. https://doi.org/10.1007/s10584-005-5935-y

Fowler, D., Steadman, C.E., Stevenson, D., Coyle, M., Rees, R.M., Skiba, U., Sutton, M., Cape, J.N., Dore, A. and Vieno, M., 2015. Effects of global change during the 21st century on the nitrogen cycle. Atmos. Chem. Phys., 15(24): 13849-13893. https://doi.org/10.5194/acp-15-13849-2015

Fung, K.M., Heald, C.L., Kroll, J.H., Wang, S., Jo, D.S., Gettelman, A., Lu, Z., Liu, X., Zaveri, R.A. and Apel, E.C., 2022. Exploring dimethyl sulfide (DMS) oxidation and implications for global aerosol radiative forcing. Atmos. Chem. Phys., 22(2): 1549-1573. https://doi.org/10.5194/acp-22-1549-2022

Ghorbanzadeh, O., Blaschke, T., Gholamnia, K. and Aryal, J., 2019. Forest fire susceptibility and risk mapping using social/infrastructural vulnerability and environmental variables. Fire, 2(3): 50. https://doi.org/10.3390/fire2030050

Goldstone, M.E., 2015. Review of evidence on health aspects of air pollution-REVIHAAP project. Air. Qual. Clim. Change, 49(2): 35-41.

Gomez, J., Allen, R.J., Turnock, S.T., Horowitz, L.W., Tsigaridis, K., Bauer, S.E., Olivié, D., Thomson, E.S. and Ginoux, P., 2023. The projected future degradation in air quality is caused by more abundant natural aerosols in a

warmer world. Comm. Ear. Environ., 4(1): 22. https://doi.org/10.1038/s43247-023-00688-7

Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., Denier van der Gon, H., Frost, G.J., Heil, A., Kaiser, J.W., Kinne, S. and Klimont, Z., 2011. Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period. Clim. Change, 109: 163-190. https://doi.org/10.1007/s10584-011-0154-1

Guenther, A., Jiang, X., Heald, C.L., Sakulyanontvittaya, T., Duhl, T.A., Emmons, L. and Wang, X., 2012. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2. 1): An extended and updated framework for modeling biogenic emissions. GMD, 5(6): 1471-1492. https://doi.org/10.5194/gmd-5-1471-2012

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I. and Geron, C., 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of emissions of gases and aerosols from nature). Atmos. Chem. Phys., 6(11): 3181-3210. https://doi.org/10.5194/acp-6-3181-2006

Haluza, D., Kaiser, A., Moshammer, H., Flandorfer, C., Kundi, M. and Neuberger, M., 2012. Estimated health impact of a shift from light fuel to residential wood-burning in Upper Austria. J. Exp. Sci. Environ. Epi., 22(4): 339-343. https://doi.org/10.1038/jes.2012.27

Han, S.Q., Zhang, M., Zhao, C.S., Lu, X.Q., Ran, L., Han, M., Li, P.Y. and Li, X.J., 2013. Differences in ozone photochemical characteristics between the megacity Tianjin and its rural surroundings. Atmos. Environ., 79: 209-216. https://doi.org/10.1016/j.atmosenv.2013.06.045

Hauglustaine, D., Lathiere, J., Szopa, S. and Folberth, G., 2005. Future tropospheric ozone simulated with a climate- chemistry- biosphere model. Geophys. Res. Lett., 32(24). https://doi.org/10.1029/2005GL024031

Heal, M.R., Kumar, P. and Harrison, R.M., 2012. Particles, air quality, policy and health [10.1039/C2CS35076A]. Chem. Soc. Rev., 41(19): 6606-6630. https://doi.org/10.1039/c2cs35076a

Heald, C., Coe, H., Jimenez, J., Weber, R., Bahreini, R., Middlebrook, A., Russell, L., Jolleys, M., Fu, T.M. and Allan, J., 2011. Exploring the vertical profile of atmospheric organic aerosol: Comparing 17 aircraft field campaigns with a global model. Atmos. Chem. Phys., 11(24): 12673-12696. https://doi.org/10.5194/acp-11-12673-2011

Heald, C.L., Jacob, D.J., Fiore, A.M., Emmons, L.K., Gille, J.C., Deeter, M.N., Warner, J., Edwards, D.P., Crawford, J.H. and Hamlin, A.J., 2003. Asian outflow and trans-Pacific transport of carbon monoxide and ozone pollution: An integrated satellite, aircraft, and model perspective. J. Geophys. Res. Atmos., 108(D24). https://doi.org/10.1029/2003JD003507

Hedegaard, G.B., Christensen, J.H. and Brandt, J., 2013. The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century. Atmos. Chem. Phys., 13(7): 3569-3585. https://doi.org/10.5194/acp-13-3569-2013

Hofmann, D.J., Butler, J.H., Dlugokencky, E.J., Elkins, J.W., Masarie, K., Montzka, S.A. and Tans, P., 2006. The role of carbon dioxide in climate forcing from 1979 to 2004: Introduction of the annual greenhouse gas index. Tellus B: Chem. Phys. Meteorol., 58(5): 614-619. https://doi.org/10.1111/j.1600-0889.2006.00201.x

Holmes, C.D., Prather, M.J., Søvde, O. and Myhre, G., 2013. Future methane, hydroxyl, and their uncertainties: Key climate and emission parameters for future predictions. Atmos. Chem. Phys., 13(1): 285-302. https://doi.org/10.5194/acp-13-285-2013

Horton, D.E., Skinner, C.B., Singh, D. and Diffenbaugh, N.S., 2014. Occurrence and persistence of future atmospheric stagnation events. Nat. Clim. Change, 4(8): 698-703. https://doi.org/10.1038/nclimate2272

Iriti, M., Piscitelli, P., Missoni, E. and Miani, A., 2020. Air pollution and health: the need for a medical reading of environmental monitoring data. MDPI, 17: 2174. https://doi.org/10.3390/ijerph17072174

Janssens-Maenhout, G., Pagliari, V., Guizzardi, D. and Muntean, M., 2013. Global emission inventories in the Emission Database for Global Atmos. Res. (EDGAR)–Manual (I). Gridding: EDGAR emissions distribution on global gridmaps, Publications Office of the European Union, Luxembourg, pp. 775.

Jiang, J., Stevenson, D.S., Uwizeye, A., Tempio, G. and Sutton, M.A., 2021. A climate-dependent global model of ammonia emissions from chicken farming. Biogeosci, 18(1): 135-158.

https://doi.org/10.5194/bg-18-135-2021

Jiang, S., Liu, Y.R., Huang, T., Feng, Y.J., Wang, C.Y., Wang, Z.Q., Ge, B.J., Liu, Q.S., Guang, W.R. and Huang, W., 2022. Towards fully ab initio simulation of atmospheric aerosol nucleation. Nat. Comm., 13(1): 6067. https://doi.org/10.1038/s41467-022-33783-y

Jokinen, T., Sipilä, M., Richters, S., Kerminen, V.M., Paasonen, P., Stratmann, F., Worsnop, D., Kulmala, M., Ehn, M. and Herrmann, H., 2014. Rapid autoxidation forms highly oxidized RO2 radicals in the atmosphere. Angew. Chem., Int. Ed., 53(52): 14596-14600. https://doi.org/10.1002/anie.201408566

Junkermann, W. and Hacker, J., 2022. Unprecedented levels of ultrafine particles, major sources, and the hydrological cycle. Sci. Rep., 12(1): 7410. https://doi.org/10.1038/s41598-022-11500-5

Karlsson, L., Baccarini, A., Duplessis, P., Baumgardner, D., Brooks, I.M., Chang, R.Y.W., Dada, L., Dällenbach, K.R., Heikkinen, L. and Krejci, R., 2022. Physical and chemical properties of cloud droplet residuals and aerosol particles during the Arctic Ocean 2018 expedition. J. Geophys. Res. Atmos., 127(11): e2021JD036383. https://doi.org/10.1029/2021JD036383

Kawase, H., Nagashima, T., Sudo, K. and Nozawa, T., 2011. Future changes in tropospheric ozone under Representative Concentration Pathways (RCPs). Geophys. Res. Lett., 38(5). https://doi.org/10.1029/2010GL046402

Lamarque, J.F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A. and Owen, B., 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. Atmos. Chem. Phys., 10(15): 7017-7039. https://doi.org/10.5194/acp-10-7017-2010

Laurent, A. and Hauschild, M.Z., 2014. Impacts of NMVOC emissions on human health in European countries for 2000–2010: Use of sector-specific substance profiles. Atmos. Environ., 85: 247-255. https://doi.org/10.1016/j.atmosenv.2013.11.060

Lee, S.H., Gordon, H., Yu, H., Lehtipalo, K., Haley, R., Li, Y. and Zhang, R., 2019. New particle formation in the atmosphere: From molecular clusters to global climate. J. Geophys. Res. Atmos., 124(13): 7098-7146. https://doi.org/10.1029/2018JD029356

Lefohn, A.S., Hazucha, M.J., Shadwick, D. and Adams, W.C., 2010. An alternative form and level of the human health ozone standard. Inhal. Toxicol., 22(12): 999-1011. https://doi.org/10.3109/08958378.2010.505253

Liao, H., Chen, W.T. and Seinfeld, J.H., 2006. Role of climate change in global predictions of future tropospheric ozone and aerosols. J. Geophys. Res. Atmos., 111(D12). https://doi.org/10.1029/2005JD006852

Lin, Y.K., Chang, S.C., Lin, C., Chen, Y.C. and Wang, Y.C., 2013. Comparing ozone metrics on associations with outpatient visits for respiratory diseases in Taipei Metropolitan area. Environ. Pollut., 177: 177-184. https://doi.org/10.1016/j.envpol.2012.12.010

Lund, M.T., Berntsen, T., Fuglestvedt, J., Ponater, M. and Shine, K., 2012. How much information is lost by using global-mean climate metrics? An example using the transport sector. Clim. Change, 113: 949-963. https://doi.org/10.1007/s10584-011-0391-3

Manders, A., Van Meijgaard, E., Mues, A., Kranenburg, R., Van Ulft, L. and Schaap, M., 2012. The impact of differences in large-scale circulation output from climate models on the regional modeling of ozone and PM. Atmos. Chem. Phys., 12(20): 9441-9458. https://doi.org/10.5194/acp-12-9441-2012

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L. and Gomis, M., 2021. Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2.

Mauldin Iii, R., Berndt, T., Sipilä, M., Paasonen, P., Petäjä, T., Kim, S., Kurtén, T., Stratmann, F., Kerminen, V.-M. and Kulmala, M., 2012. A new atmospherically relevant oxidant of sulphur dioxide. Nature, 488(7410): 193-196. https://doi.org/10.1038/nature11278

May, A., McMeeking, G., Lee, T., Taylor, J., Craven, J., Burling, I., Sullivan, A. P., Akagi, S., Collett Jr, J., and Flynn, M., 2014. Aerosol emissions from prescribed fires in the United States: A synthesis of laboratory and aircraft measurements. J. Geophys. Res. Atmos.m 119(20): 11, 826-811, 849. https://doi.org/10.1002/2014JD021848

McCoy, I.L., McCoy, D.T., Wood, R., Regayre, L., Watson-Parris, D., Grosvenor, D.P., Mulcahy, J.P., Hu, Y., Bender, F.A.M. and Field, P.R., 2020. The hemispheric contrast in cloud microphysical properties constrains aerosol forcing. Proc. Natl. Acad. Sci., 117(32): 18998-19006. https://doi.org/10.1073/pnas.1922502117

McDonald-Buller, E.C., Allen, D.T., Brown, N., Jacob, D.J., Jaffe, D., Kolb, C.E., Lefohn, A.S., Oltmans, S., Parrish, D.D. and Yarwood, G., 2011. Establishing policy relevant background (PRB) ozone concentrations in the United States. Environ. Sci. Technol., 45(22): 9484-9497. https://doi.org/10.1021/es2022818

Moch, J.M., Mickley, L.J., Keller, C.A., Bian, H., Lundgren, E.W., Zhai, S. and Jacob, D.J., 2022. Aerosol-radiation interactions in china in winter: Competing effects of reduced shortwave radiation and cloud-snowfall-albedo feedbacks under rapidly changing emissions. J. Geophys. Res. Atmos., 127(9): e2021JD035442. https://doi.org/10.1029/2021JD035442

Monks, P.S., Archibald, A., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K.S., and Mills, G., 2015. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. Atmos. Chem. Phys., 15(15): 8889-8973. https://doi.org/10.5194/acp-15-8889-2015

Myhre, G., Shindell, D. and Pongratz, J., 2014. Anthropogenic and natural radiative forcing.

Nabat, P., Kanji, Z.A., Mallet, M., Denjean, C. and Solmon, F., 2022. Aerosol-cloud interactions and impact on regional climate. In atmospheric chemistry in the mediterranean region: Volume 2-from air pollutant sources to impacts. Springer. pp. 403-425. https://doi.org/10.1007/978-3-030-82385-6_20

No, A.P.S., 2010. Hemispheric transport of air pollution.

O'Connor, F.M., Boucher, O., Gedney, N., Jones, C., Folberth, G., Coppell, R., Friedlingstein, P., Collins, W., Chappellaz, J. and Ridley, J., 2010. Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: A review. Rev. Geophys., 48(4). https://doi.org/10.1029/2010RG000326

Özelsel, T.J.P., Sondekoppam, R.V. and Buro, K., 2019. The future is now it's time to rethink the application of the global warming potential to anesthesia. Can. J. Anaesth., 66: 1291-1295. https://doi.org/10.1007/s12630-019-01385-w

Pani, S.K., Wang, S.H., Lin, N.H., Chantara, S., Lee, C.T. and Thepnuan, D., 2020. Black carbon over an urban atmosphere in northern peninsular Southeast Asia: Characteristics, source apportionment, and associated health risks. Environ. Pollut., 259: 113871. https://doi.org/10.1016/j.envpol.2019.113871

Peters, G.P., Aamaas, B.T., Lund, M., Solli, C. and Fuglestvedt, J.S., 2011. Alternative "global warming" metrics in life cycle assessment: A case study with existing transportation data. Environ. Sci. Technol., 45(20): 8633-8641. https://doi.org/10.1021/es200627s

Petters, M. and Kreidenweis, S., 2007. A single parameter representation of hygroscopic growth and cloud condensation nucleus activity. Atmos. Chem. Phys., 7(8): 1961-1971. https://doi.org/10.5194/acp-7-1961-2007

Poisson, N., Kanakidou, M. and Crutzen, P.J., 2000. Impact of non-methane hydrocarbons on tropospheric chemistry and the oxidizing power of the global troposphere: 3-dimensional modelling results. J. Atmos. Chem. 36: 157-230. https://doi.org/10.1023/A:1006300616544

Popescu, F. and Ionel, I., 2010. Anthropogenic air pollution sources. Air Quality, pp. 1-22. https://doi.org/10.5772/9751

Ramanathan, V. and Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci., 1(4): 221-227. https://doi.org/10.1038/ngeo156

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Fu, Q., Sikka, D.R. and Wild, M., 2005. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. Proc. Natl. Acad. Sci., 102(15): 5326-5333. https://doi.org/10.1073/pnas.0500656102

Reddington, C., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y., Arnold, S. and Spracklen, D., 2014. Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. Environ. Res. Lett., 9(9): 094006. https://doi.org/10.1088/1748-9326/9/9/094006

Samset, B., Myhre, G., Herber, A., Kondo, Y., Li, S.M., Moteki, N., Koike, M., Oshima, N., Schwarz, J.P. and Balkanski, Y., 2014. Modelled black carbon radiative forcing and atmospheric lifetime in AeroCom Phase II constrained by

aircraft observations. Atmos. Chem. Phys., 14(22): 12465-12477. https://doi.org/10.5194/acp-14-12465-2014

Samset, B.H., Myhre, G., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T.K., Bian, H., Bellouin, N., Diehl, T. and Easter, R.C., 2013. Black carbon vertical profiles strongly affect its radiative forcing uncertainty. Atmos. Chem. Phys., 13(5): 2423-2434. https://doi.org/10.5194/acp-13-2423-2013

Seinfeld, J., 2008. Black carbon and brown clouds. Nat. Geosci., 1(1): 15-16. https://doi.org/10.1038/ngeo.2007.62

Seinfeld, J.H. and Pandis, S.N., 2016. Atmospheric chemistry and physics from air pollution to climate change. John Wiley and Sons.

Silva, R.A., West, J.J., Zhang, Y., Anenberg, S.C., Lamarque, J.F., Shindell, D.T., Collins, W.J., Dalsoren, S., Faluvegi, G. and Folberth, G., 2013. Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change. Environ. Res. Lett., 8(3): 034005. https://doi.org/10.1088/1748-9326/8/3/034005

Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J.F., Kuhn, U., Stefani, P. and Knorr, W., 2014. Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years. Atmos. Chem. Phys., 14(17): 9317-9341. https://doi.org/10.5194/acp-14-9317-2014

Sitch, S., Cox, P., Collins, W. and Huntingford, C., 2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature, 448(7155): 791-794. https://doi.org/10.1038/nature06059

Slezakova, K., Morais, S. and do Carmo, P.M., 2013. Forest fires in Northern region of Portugal: Impact on PM levels. Atmos. Res., 127: 148-153. https://doi.org/10.1016/j.atmosres.2012.07.012

Smith, K.R., Jerrett, M., Anderson, H.R., Burnett, R.T., Stone, V., Derwent, R., Atkinson, R.W., Cohen, A., Shonkoff, S.B. and Krewski, D., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: Health implications of short-lived greenhouse pollutants. Lancet, 374(9707): 2091-2103. https://doi.org/10.1016/S0140-6736(09)61716-5

Spracklen, D.V., Mickley, L.J., Logan, J.A., Hudman, R.C., Yevich, R., Flannigan, M.D. and Westerling, A.L., 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. J. Geophys. Res. Atmos., 114(D20). https://doi.org/10.1029/2008JD010966

Steinfeld, E.S., Lester, R.K. and Cunningham, E.A., 2009. Greener plants, grayer skies? A report from the front lines of China's energy sector. Energy Policy, 37(5): 1809-1824. https://doi.org/10.1016/j.enpol.2008.12.018

Sun, Z., Hüve, K., Vislap, V. and Niinemets, Ü., 2013. Elevated [CO2] magnifies isoprene emissions under heat and improves thermal resistance in hybrid aspen. J. Exp. Bot., 64(18): 5509-5523. https://doi.org/10.1093/jxb/ert318

Sutton, M., Reis, S., Riddick, S., Dragosits, U., Nemitz, E., Theobald, M., Tang, Y., Braban, C., Vieno, M. and Dore, A., 2013. Towards a climate-dependent paradigm of ammonia emission and deposition, Philos. T. Roy. Soc., B368: 20130166. https://doi.org/10.1098/rstb.2013.0166

Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H. and Grizzetti, B., 2011. The European nitrogen assessment: sources, effects and policy perspectives. Cambridge University Press. https://doi.org/10.1017/CBO9780511976988

Taatjes, C.A., Shallcross, D.E. and Percival, C.J., 2014. Research frontiers in the chemistry of Criegee intermediates and tropospheric ozonolysis. Phys. Chem. Chem. Phys., 16(5): 1704-1718. https://doi.org/10.1039/c3cp52842a

Tai, A.P., Mickley, L.J. and Jacob, D.J., 2012. Impact of 2000–2050 climate change on fine particulate matter (PM 2.5) air quality inferred from a multi-model analysis of meteorological modes. Atmos. Chem. Phys., 12(23): 11329-11337. https://doi.org/10.5194/acp-12-11329-2012

Templer, P.H., Pinder, R.W. and Goodale, C.L., 2012. Effects of nitrogen deposition on greenhouse-gas fluxes for forests and grasslands of North America. Front. Ecol. Environ., 10(10): 547-553. https://doi.org/10.1890/120055

Thambiran, T. and Diab, R.D. 2010. A review of scientific linkages and interactions between climate change and air quality, with implications for air quality management in South Africa. S.

Afr. J. Sci., 106(3): 1-8. https://doi.org/10.4102/sajs.v106i3/4.56

Turnock, S.T., Allen, R.J., Andrews, M., Bauer, S.E., Deushi, M., Emmons, L., Good, P., Horowitz, L., John, J.G. and Michou, M., 2020. Historical and future changes in air pollutants from CMIP6 models. Atmos. Chem. Phys., 20(23): 14547-14579. https://doi.org/10.5194/acp-20-14547-2020

Unger, N. and Pan, J.L. 2012. New directions: Enduring ozone. Atmos. Environ., 55: 456-458. https://doi.org/10.1016/j.atmosenv.2012.03.036

Val Martin, M., Honrath, R., Owen, R.C., Pfister, G., Fialho, P. and Barata, F., 2006. Significant enhancements of nitrogen oxides, black carbon, and ozone in the North Atlantic lower free troposphere resulting from North American boreal wildfires. J. Geophys. Res. Atmos., 111(D23). https://doi.org/10.1029/2006JD007530

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V. and Lamarque, J.F., 2011. The representative concentration pathways: An overview. Clim. Change, 109: 5-31. https://doi.org/10.1007/s10584-011-0148-z

Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T. and Mathur, R., 2014. A new scenario framework for climate change research: Scenario matrix architecture. Clim. Change, 122: 373-386. https://doi.org/10.1007/s10584-013-0906-1

Viana, M., de Leeuw, F., Bartonova, A., Castell, N., Ozturk, E. and Ortiz, A.G., 2020. Air quality mitigation in European cities: Status and challenges ahead. Environ. Int., 143: 105907. https://doi.org/10.1016/j.envint.2020.105907

Vitousek, P.M., Menge, D.N., Reed, S.C. and Cleveland, C.C., 2013. Biological nitrogen fixation: Rates, patterns and ecological controls in terrestrial ecosystems. Philos. Trans. R. Soc. B Biol. Sci., 368(1621): 20130119. https://doi.org/10.1098/rstb.2013.0119

Von Schneidemesser, E., Monks, P.S., Allan, J.D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W.T., Paasonen, P. and Righi, M., 2015. Chemistry and the linkages between air quality and climate change. Chem. Rev., 115(10): 3856-3897. https://doi.org/10.1021/acs.chemrev.5b00089

Voulgarakis, A., Shindell, D. and Faluvegi, G., 2013. Linkages between ozone-depleting substances, tropospheric oxidation and aerosols. Atmos. Chem. Phys., 13(9): 4907-4916. https://doi.org/10.5194/acp-13-4907-2013

Wang, Y., Shen, L., Wu, S., Mickley, L., He, J. and Hao, J., 2013. Sensitivity of surface ozone over China to 2000–2050 global changes of climate and emissions. Atmos. Environ., 75: 374-382. https://doi.org/10.1016/j.atmosenv.2013.04.045

Westerling, A. L. and Bryant, B., 2008. Climate change and wildfire in California. Clim. Change, 87: 231-249. https://doi.org/10.1007/s10584-007-9363-z

Williams, M., 2012. Tackling climate change: What is the impact on air pollution? Carbon Manage., 3(5): 511-519. https://doi.org/10.4155/cmt.12.49

Wu, D., Mao, J., Deng, X., Tie, X., Zhang, Y., Zeng, L., Li, F., Tan, H., Bi, X. and Huang, X., 2009. Black carbon aerosols and their radiative properties in the Pearl River Delta region. Sci. China Ser. D Earth Sci., 52(8): 1152-1163. https://doi.org/10.1007/s11430-009-0115-y

Xu, Y., 2011. Improvements in the operation of SO_2 scrubbers in China's coal power plants. In: ACS Publications. https://doi.org/10.1021/es1025678

Young, P., Archibald, A., Bowman, K., Lamarque, J.F., Naik, V., Stevenson, D., Tilmes, S., Voulgarakis, A., Wild, O. and Bergmann, D., 2013. Pre-industrial to end 21st century projections of tropospheric ozone from the atmospheric chemistry and climate model intercomparison project (ACCMIP). Atmos. Chem. Phys., 13(4): 2063-2090. https://doi.org/10.5194/acp-13-2063-2013

Young, P., Arneth, A., Schurgers, G., Zeng, G. and Pyle, J.A., 2009. The CO_2 inhibition of terrestrial isoprene emission significantly affects future ozone projections. Atmos. Chem. Phys., 9(8): 2793-2803. https://doi.org/10.5194/acp-9-2793-2009

Zanis, P., Akritidis, D., Turnock, S., Naik, V., Szopa, S., Georgoulias, A.K., Bauer, S.E., Deushi, M., Horowitz, L.W. and Keeble, J., 2022. Climate change penalty and benefit on surface ozone: A global perspective based on CMIP6 earth system models. Environ. Res. Lett., 17(2):

024014. https://doi.org/10.1088/1748-9326/ac4a34

Zhang, X., Han, L., Wei, H., Tan, X., Zhou, W., Li, W. and Qian, Y., 2022. Linking urbanization and air quality together: A review and a perspective on the future sustainable urban development. J. Clean. Prod., 346: 130988. https://doi.org/10.1016/j.jclepro.2022.130988