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Chapter 2: Impact of Climate Change on Atmospheric Chemistry: A Review of Mechanistic Pathways

Bhoj Ram

Faculty of Sciences, *ISBM University: Village-Nawapara (Kosmi) Block, Tehsil-Chhura, District: Gariyaband, Chhattisgarh - 493996*

Corresponding Author E-Mail Id: bhojram339@gmail.com

Abstract: The impact of the climate change on atmospheric chemistry is large due to the multi-component interaction among greenhouse gases, aerosols and oxidant. Changes in temperature, humidity, solar irradiance and atmospheric circulation patterns affect chemical reaction rates and traveling pollutants directly. This review identifies mechanistic pathways altered by climate change, and considers hydroxyl radicals, nitrogen oxides, volatile organic compounds (VOCs), alongside secondary species ozone and peroxyacyl nitrates. Important feedbacks considered are increased temperature feedback on the photochemical smog production and aerosol effect on cloud nucleation. The data tables and simulation-based figures illustrate global trends in oxidation capacity, lower troposphere ozone, and air pollutant chemical fate for global change.

Keywords: Climate Change, Greenhouse, volatile organic compounds and atmospheric.

1 Introduction

Its chemistry governs the chemical nature, transformations, and eventual removal of constituents from the atmosphere of the Earth. It serves as a thermostat for the radiation balance, the air quality and the long-term climate. The increased levels of green house gases and the changed world temperatures induced by their influence is now reshaping atmospheric chemical processes entirely in response to variations in physical environment, namely increased solar radiation, humidity, cloudiness and atmospheric circulation. Among atmospheric oxidants that catalytically remove methane, CO, and VOCs, the hydroxyl radical (OH) plays a central role. OH concentration is controlled by solar UV radiation, water vapor and ozone. Higher temperature speeds up photolysis and the faster chemical reaction rates and thus alter the atmospheric oxidating capacity. Elevated temperatures and increased emissions can also lead to increased production. of

tropospheric ozone and fine particulate matter, exacerbating air pollution and climate feedback.

This review investigates the mechanistic interplay between climate change and atmospheric chemistry. Emphasis is placed on reactive nitrogen and carbon cycles, the behavior of secondary pollutants, and feedback loops that reinforce warming trends. Tables and figures are used to synthesize mechanistic insights and quantify changes across chemical species and spatial scales.

2 Literature review

A significant body of research has documented the influence of climate variables on atmospheric chemical dynamics. Jacob and Winner (2009) reviewed how temperature affects ozone formation and VOC reactivity. Sitch et al. (2007) modeled the effect of rising methane emissions on hydroxyl radical availability, concluding that climate-induced decreases in OH could increase methane lifetimes. Fiore et al. (2012) emphasized the role of global transport and chemical feedbacks in determining ozone trends. Increased water vapor from warming amplifies OH production but also facilitates aerosol formation, which can influence solar radiation and cloud properties. Satellite observations have shown increased surface ozone levels in regions like India and China, while some developed regions have reported improvements due to mitigation policies (Cooper et al., 2014).

NOx emissions from transportation and industry are modulated by temperature and sunlight, contributing to ozone formation. VOCs from natural sources such as forests (isoprene, monoterpenes) increase with warming, intensifying secondary organic aerosol production. Additionally, wildfires—a growing concern in warming climates—emit a complex mix of reactive gases and particles that alter regional chemistry (Jaffe & Wigder, 2012).

3 Key Chemical Pathways Influenced by Climate Change

Table 1: Climate Impacts on Atmospheric Reactions

Chemical Species	Affected Mechanism	Climate Variable	Result	Reference
OH Radical	Photolysis of O3	Increased UV & H2O	Enhanced OH production	Sitch et al. (2007)
Methane (CH4)	Oxidation by OH	Temperature Rise	Longer CH4 lifetime	Fiore et al. (2012)
Ozone (O3)	NOx-VOC Reactions	Solar Radiation	Increased surface ozone	Jacob & Winner (2009)
SOA	VOC Oxidation	Higher Temps	More particle formation	Jaffe & Wigder (2012)

Table-1 illustrate atmospheric chemical species are strongly influenced by climate variables through changes in their reaction mechanisms. For example, the photolysis of ozone under conditions of increased ultraviolet radiation and higher water vapor enhances the production of hydroxyl (OH) radicals, which act as a primary atmospheric oxidant (Sitch et al., 2007). Methane (CH_4), one of the most important greenhouse gases, undergoes oxidation by OH; however, with rising temperatures, its atmospheric lifetime tends to increase due to reduced OH availability, thereby amplifying its warming potential (Fiore et al., 2012). Tropospheric ozone (O_3) is also highly climate-sensitive, as increased solar radiation intensifies the reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs), leading to elevated surface ozone concentrations (Jacob & Winner, 2009).

4 Mechanistic Pathways and Feedback Loops

A detailed mechanistic pathway analysis reveals the complex role of climate change on the atmospheric chemistry. There are mechanisms that operate both directly and indirectly — from faster chemical reactions caused by a rise in temperature, to differences in the rates of multiphase chemical reactions on aerosols that are caused by changes in humidity, for instance. Specifically, recent studies have shown that the differences in the aerosol water components, phase states of particles and aerosol acidity together with their immature processes govern the rate and products of atmospheric chemical reaction and air quality and climate forcings (Su et al., 2020). They also indicate in scientific discussions the imperative to investigate the mechanisms as predictive models and sound regulatory action relies on them (Dessler & Parson, 2019). It is becoming ever more clear that a better understanding of these mechanistic links is critical if we are to characterise the impact of anthropogenic climate perturbation on the new threats to atmospheric composition and to provide adaptative interventions based on chemical science. Crucially, temperature-dependent effects have a dramatic effect on chemical reactivity, and pathways in the atmosphere. Moreover, the rates of some of the most important atmospheric processes, including the formation of secondary species (e.g., ozone, several aerosols) also increase with temperature (Filonchyk et al., 2024). Also fate of compounds (i.e., gas-particle partitioning) and kinetics of reactions not only but are also modified by temperature. Therefore, the higher temperature can enhance the volatilization of semi-volatile organic pollutants with an impact on trace gas emission and/or consumption through the change of biogeochemical pathways (Shakoor et al., 2020). Hence, the temperature induced atmospheric chemistry changes constitute an important element in feedback mechanisms governing air quality, climate forcing, and the preservation of the long-term atmospheric composition. Second, precipitation

changes from climate change have disproportionate impacts on atmospheric chemistry through a number of multiple pathways. Alterations in the frequency, quantity and chemical character of wet deposition are expected as a consequence of changes in patterns and intensities of rainfall, with implications for the removal and redistribution of atmospheric pollutants at regional and global scales (Likens et al., 2021). Long-term monitoring data also indicate that in some regions the reduction in precipitation has corresponded to decreases in acid-forming species, driven by both decreased emissions and atmospheric changes in weather patterns. In comparison, sedimentation chemistry and its spatial distribution effect are not only affected by changes to human, regional meteorological input and the general use of land, and there are still individual regions (such as arid, urban) present feature of cations or nitrogenous compound characteristic substance of cloud (Si & Li, 2024). Such changes in precipitation not only influence atmospheric cleaning efficiency but also an even transformed in the transport and transformations of some important reactive substances in the lower atmosphere. Furthermore, the interannual variability of winds is generally an important factor for atmospheric chemical species distribution and transformation. Variability in the large-scale circulation which is linked to changes in the Hadley and Brewer-Dobson circulation shifts the transport of ozone and its precursors vertically and horizontally, thereby redefining the regional air quality and chemical budget (Lu et al., 2019). Such interannual wind changes may drive the intensification or disruption of identifiable transport passages that form between source (receptor) regions, modulate the transboundary transport of emissions, and alter the dilution and removal dynamics of reactive gases and particles. This interannual variability in uptake into the in-cloud particulate phase and its contribution to TAPVship are important, given the timing of real-world annual variability in meteorological events (Di Nezio et al., 2016)—such as the El Niño–Southern Oscillation—and CT activity, as transport patterns will affect body burdens and depositions to the Earth's surface (Lu et al., 2019). In this context, climate change induced changes in the atmospheric circu- lation add another dimension of complexity to the challenging issue of forecasting future atmospheric composition, and thus to the assessment of the efficiency of a contemplated mitigation strategies. These gases, are then reach to through physical-chemical processes rates of these from gases greenhouse absorbing) between the sun/molecules radiation-solar active of absorption by composition the from atmospheric rates process atmospheric of recycle chemical (clean atmosphereial stimulated (CO2) carbon-dioxide for mainly and (N2O) oxide nitrous and (CH4) methane principally warm that gases greenhouse these accumulation into addition In -N2O rate) NITROGEN from oxide (from heat retain vegetation and earth"on in greenhouse the (CO2) dioxin carbon earth.

Elevated concentrations of these gases increase infrared absorption, intensifying radiative forcing and triggering further temperature rise, which in turn accelerates

photochemical reactions and alters the lifetimes of reactive compounds such as ozone and hydroxyl radicals (Filonchyk et al., 2024). Higher greenhouse gas levels also interact with water vapor, modifying tropospheric oxidative capacity and contributing to greater production of secondary pollutants through feedback mechanisms. These interactions disrupt the atmospheric balance by altering removal rates of trace gases, shifting equilibrium distributions, and enabling the persistence of compounds with adverse environmental impacts (Filonchyk et al., 2024). The ongoing rise in greenhouse gas concentrations thus shapes atmospheric chemistry through a combination of radiative, kinetic, and compositional effects that reinforce feedbacks between climate change and chemical transformation processes.

In addition, interactions between the ocean and atmosphere introduce additional complexities to atmospheric chemistry, particularly as climate change alters both marine and atmospheric processes. Exchanges of gases, aerosols, and nutrients at the air-sea interface contribute to the cycling of nitrogen, sulfur, and other reactive compounds, ultimately influencing the oxidative capacity and pollutant concentrations in the troposphere (Hutchins & Capone, 2022). Climate-driven modifications in oceanic circulation and surface temperature can change the rates at which these substances are transferred to the atmosphere, with potential feedbacks that affect global biogeochemical cycling. Shifts in marine nitrogen cycling, including the emergence of new microbial groups and altered metabolic pathways, further adjust the chemical composition of emissions entering the atmosphere, thus affecting regional precipitation chemistry and deposition processes (Si & Li, 2024). Sustained study of these coupled ocean-atmosphere mechanisms is necessary to anticipate responses in atmospheric chemistry as the climate system evolves. Consequently, shifts in climate-induced environmental variables have pronounced effects on the atmospheric oxidation capacity, fundamentally influencing the rates and outcomes of key chemical reactions. Variations in oxidant concentrations, such as ozone, hydroxyl (OH), and nitrate (NO3) radicals, drive changes in the breakdown and transformation of trace gases, affecting pollutant lifetimes and secondary formation processes (Jung et al., 2022).

Indeed, multiphase chemical reactions controlled by organic aerosol (OA) water content, pH, and phase state have been found to contribute importantly to oxidant species concentrations, particularly in polluted settings in which aerosol- or oxidant-dominated interactions are intensified (Su et al., 2020). In this context, for instance, the modifications to the photochemical environment due to variations in the humidity or temperature alter the balance between gaseous- and multiphase-oxidations of important atmospheric species, and hence, the oxidative capacity and the removal rates. Thus, gas-

and multiphase-driven reactions should be considered in the prediction of the oxidative environment under changing climate. In this regard, aerosols are also an essential player in atmospheric chemistry, whose distribution and characteristics are to a large extent controlled by climate change. Anomalies in emission sources, meteorology, and land use lead to substantial interannual variability in aerosol loading, thus modifying the potential of this RF component to absorb or reflect solar radiation and to engage in heterogeneous chemical reactions (Kok et al., 2023). Recent studies report significant declines in particulate matter levels in areas with greater control over the sources of emissions (Ding et al., 2019), though seasonal and regional inter variability of the chemical content of aerosols continue to be observed at anthropogenic and climatic scales.

Conclusions

In general, the impact of climate change on the atmospheric chemistry is dominated by a variety of mechanistic pathways, i.e. via the temperature, humidity, rain, or the atmospheric circulation, that ultimately leads to a range of chemical processes and the sensitivity of pollutants. The ongoing accumulation of greenhouse gases, changes in emissions as well as alterations in biogeochemical cycles are all modifying air quality, the oxidative capacity and the distribution of significant atmospheric traces. Recent work has highlighted complexity and linkages among such changes, as well as the potential for synergistic risk to become manifest when two or more pollutants or climate drivers combine in Earth's atmosphere. Dealing with these challenges will continue to depend on further developing best scientific practices alongside shared policy responses, as accurate predictions and mitigation depend on detailed models and observational systems. Additional investigation will be key to resolving these uncertainties, guiding adaptive responses, and protecting environmental and human health in the context of continued climate change.

References

Jacob, D. J., & Winner, D. A. (2009). Effect of climate change on air quality. Atmospheric Environment, 43(1), 51–63.

Sitch, S., Cox, P. M., Collins, W. J., & Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature, 448(7155), 791–794.

Fiore, A. M., Naik, V., & Leibensperger, E. M. (2012). Air quality and climate connections. Journal of the Air & Waste Management Association, 62(6), 645–685.

Cooper, O. R., Parrish, D. D., Ziemke, J., Balashov, N. V., Cupeiro, M., Galbally, I. E., & Ogawa, T. (2014). Global distribution and trends of tropospheric ozone: An observation-based review. Elementa: Science of the Anthropocene, 2.

Jaffe, D. A., & Wigder, N. L. (2012). Ozone production from wildfires: A critical review. Atmospheric Environment, 51, 1–10.

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature, 525(7569), 367–371.

Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., & Zhang, H. (2013). Anthropogenic and natural radiative forcing. In Climate Change 2013: The Physical Science Basis.

Seinfeld, J. H., & Pandis, S. N. (2016). Atmospheric chemistry and physics: From air pollution to climate change. John Wiley & Sons.

Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., & Williams, M. L. (2015). Tropospheric ozone and its precursors from the urban to the global scale. Philosophical Transactions of the Royal Society A, 373(2051), 20140352.

World Meteorological Organization (WMO). (2022). WMO Greenhouse Gas Bulletin.

Ahmed, M. (2020). Introduction to Modern Climate Change. Andrew E. Dessler: Cambridge University Press, 2011, 252 pp, ISBN-10: 0521173159. Science of The Total Environment, 734, 139397. https://doi.org/10.1016/j.scitotenv.2020.139397

Dessler, A. E., & Parson, E. A. (2019). The science and politics of global climate change: A guide to the debate. In books.google.com. Cambridge University Press. https://books.google.com/books?hl=en&lr=&id=WnmrDwAAQBAJ&oi=fnd&pg=PT14&dq=climate+change+effects+on+atmospheric+chemical+reactions&ots=tDc6BJNdip&sig=gKII5iEM3hhbt09Zhp3ZfSeHEdQ

Ding, A., Huang, X., Nie, W., Chi, X., Xu, Z., Zheng, L., Xu, Z., Xie, Y., Qi, X., Shen, Y., Sun, P., Wang, J., Wang, L., Sun, J., Yang, X.-Q., Qin, W., Zhang, X., Cheng, W., Liu, W., … Fu, C. (2019). Significant reduction of PM2.5 in eastern China due to regional-scale emission control: evidence from SORPES in 2011–2018. Acp.Copernicus.Org, 19(18), 11791–11801. https://doi.org/https://doi.org/10.5194/acp-19-11791-2019

Filonchyk, M., Peterson, M. P., Zhang, L., Hurynovich, V., & He, Y. (2024a). Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Science of The Total Environment, 935, 173359. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.173359

Filonchyk, M., Peterson, M. P., Zhang, L., Hurynovich, V., & He, Y. (2024b). Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Science of The Total Environment, 935, 173359. https://doi.org/10.1016/j.scitotenv.2024.173359

Hutchins, D. A., & Capone, D. G. (2022). The marine nitrogen cycle: new developments and global change. Nature Reviews Microbiology, 20, 401–414. https://doi.org/10.1038/s41579-022-00687-z

Jansson, J. K., & Hofmockel, K. S. (2020). Soil microbiomes and climate change. Nature Reviews Microbiology, 18, 35–46. https://doi.org/https://doi.org/10.1038/s41579-019-0265-7

Jung, D., de la Paz, D., Notario, A., & Borge, R. (2022). Analysis of emissions-driven changes in the oxidation capacity of the atmosphere in Europe. Science of The Total Environment, 827, 154126. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.154126

Kok, J. F., Storelvmo, T., Karydis, V. A., Adebiyi, A. A., Mahowald, N. M., Evan, A. T., He, C., & Leung, D. M. (2023). Mineral dust aerosol impacts on global climate and climate change.

Nature Reviews Earth & Environment, 4, 71–86. https://doi.org/https://doi.org/10.1038/s43017-022-00379-5

Likens, G. E., Butler, T. J., Claybrooke, R., Vermeylen, F., & Larson, R. (2021). Long-term monitoring of precipitation chemistry in the US: Insights into changes and condition. Atmospheric Environment, 245, 118031. https://doi.org/https://doi.org/10.1016/j.atmosenv.2020.118031

Lu, X., Zhang, L., & Shen, L. (2019). Meteorology and climate influences on tropospheric ozone: a review of natural sources, chemistry, and transport patterns. Current Pollution Reports, 5, 238–260. https://doi.org/10.1007/s40726-019-00118-3