Air Quality, Climate, and Health in the Anthropocene

Ulrich Pöschl, Max Planck Institute for Chemistry, Hahn-Meitner-Weg 1,
55128 Mainz, Germany, u.poschl@mpic.de

30 August 2024

1. Anthropocene and Climate Change

The Anthropocene as the current period of Earth history is characterised by a globally pervasive and rapidly increasing influence of human activities on the planet - from the equator to the poles and from the land surface, atmosphere and biosphere to the oceans and deep sea. The intensive use of land and water as well as the emission of greenhouse gases and pollutants lead to climate change and put pressure on ecosystems, biodiversity, and human health.

In the geological epoch of the Holocene, which began around 10 thousand years ago, the atmospheric concentration of carbon dioxide (CO_2) in the Earth's atmosphere was fairly stable at around 260-280 ppm, and the fluctuations of global mean surface temperature and sea level were relatively small. Under these favourable conditions, human civilisation developed from the Neolithic Age to modern times. Since industrialization in the 19th century, however, there has been a strong increase in CO_2 and other greenhouse gases (GHG) such as methane (CH_4) and nitrous oxide (N_2O). The current atmospheric GHG concentrations of more than 420 ppm CO_2 and 1900 ppb CH_4 are not only far above the stable values of the Holocene. They are also far outside the range of natural fluctuations in recent Earth history, i.e., far above the approximately 200-300 ppm CO_2 and 400-800 ppb CH_4 that were characteristic for the regular cycling between of ice ages and warm periods during the last million years of the Pleistocene (Figure 1), during which global mean surface temperatures and sea levels varied by as much as 5 °C and more than a hundred meters, respectively (IPCC 2021; Intergovernmental Panel on Climate Change,).

The massive changes in the concentration of GHG and other trace gases in the atmosphere are a clear indicator of the extent to which humans are interfering with the global biogeochemical cycles that can be regarded as the metabolism of planet Earth. Particularly far-reaching are the human interventions in the carbon cycle through the release of CO_2 from the combustion of fossil fuels (coal, crude oil, natural gas) and the release of CH_4 from industrial and agricultural processes. Similarly, the nitrogen cycle is massively altered and enhanced by the industrial production and agricultural use of ammonia and nitrogen fertiliser as well as the release of nitrogen oxides such as N_2O from fertilised soils and NO or NO_2 from combustion and other high-temperature processes. The observed steep increase in GHG concentrations far outside the range of natural fluctuations is clearly attributable to anthropogenic emissions, and there is no plausible alternative explanation. The same applies to the rapid global warming of our time, i.e., the increase of global mean surface temperature by more than one degree Celsius in less than two centuries from 1850 until today (IPCC 2021).

At a scientific conference of the International Geosphere-Biosphere Programme (IGBP) in the year 2000, the atmospheric researcher and Chemistry Nobel Laureate Paul Crutzen realized and stated that the Earth system had transitioned from the Holocene to a new geological epoch shaped by humanity, for which he coined the term Anthropocene (Crutzen 2002, Benner et al. 2021). Since the 19th century, scholars had already recognised an increasing influence of humans on their environment and planet Earth (Leclerc, Marsh, Stoppani, Arrhenius, Vernadsky, Teilhard de Chardin et al.), but they had not yet realized that the Holocene has ended and a new epoch has begun. Since the discovery and conceptualisation of the Anthropocene by Paul Crutzen and colleagues, there have been different proposals to formally define its beginning. One option is the time of industrialisation in the 19th century, which led to the above-mentioned GHG increase that can be traced in ice cores but may not meet the formal requirements for the official definition of a geological epoch, which should be traceable in sediments worldwide. Another proposal referred to the beginning of agriculture in the Neolithic period, which led to regional changes but is difficult to detect on global scales, coincides with the beginning of the climatically very stable Holocene, and is thus not particularly meaningful from an Earth science perspective.

The Anthropocene Working Group (AWG) of the International Commission on Stratigraphy (ICS/IUGS) proposed to define the beginning of the Anthropocene on the basis of plutonium concentration peaks, which originate from radioactive fallout from nuclear weapons tests in the middle of the 20th century and are detectable worldwide. This period of the "Great Acceleration" of human activities and influence on the Earth system also saw particularly high growth rates and turning points in the characteristic S-shaped growth curves for the world population, global primary energy consumption, and numerous other indicators of human expansion. The AWG proposal to pin the beginning of the Anthropocene to a geological reference layer known as a global boundary stratotype section and point (GSSP; often called a golden spike) in the sediments of Crawford Lake, Canada, was not accepted by the Subcommission on Quaternary Stratigraphy (SQS) of the ICS (Zalasiewicz et al. 2024). Nevertheless, this or a similar definition for the beginning of the Anthropocene appears most meaningful from the perspective of Earth system sciences, where the term and concept originated, and it will likely prevail in the ongoing scientific discussion: For the overwhelming global human impact on planet Earth, which characterizes the Anthropocene, it would seem difficult to envision a more prominent signal than the global fallout and deposits of nuclear testing combined with the steep increase of human population, activities, alteration of landscapes, and emissions of GHG and other environmental pollutants in the mid-20th century.

Due to anthropogenic emissions, the CO_2 concentration in the Earth's atmosphere is now as high as it was around 3 million years ago, when the average global temperature and sea level were around 3 °C and 10-20 metres higher, respectively. If the GHG emissions and concentrations are not curbed, similarly strong warming and sea level rise are to be expected in accordance with modern earth system and climate models as well as earlier estimates of the greenhouse effect by natural science pioneers in the 19th century (Fourier, Arrhenius et al.). The transition from the stable conditions of the Holocene warm period into an Anthropocene hot period is expected - and partly already observed - to result in an increase in the frequency and intensity of extreme weather events (heat waves, droughts, heavy rainfall, landslides, etc.), the flooding of coastal areas where large parts of the world's population and economy reside, and corresponding mass migration (Röckström et al. 2009; Steffen et al. 2018; IPCC 2021).

2. Air Quality and Public Health

Besides global warming by GHG, anthropogenic emissions also lead to a massive increase in the atmospheric concentration of aerosols, i.e., nanometer to micrometer-sized liquid or solid particles suspended in the air, and reactive trace gases like ozone and nitrogen oxides on local, regional, and global scales. For example, the average mixing ratios of ozone in continental background air have increased by a factor of ~2-4 from about 10-20 ppb at the beginning of the 19th century to 30-40 ppb in the 21st century. The amount of fine particulate matter in polluted urban air is typically ~10 times higher than in clean air of remote continental regions (~10-100 $\mu g\ m^{-3}$ compared to ~1-10 $\mu g\ m^{-3}$). The vastly different concentration levels result from primary emissions as well as secondary formation and growth of aerosol particles in the atmosphere, whereby aerosol acidity and its buffering by anthropogenic ammonia are of particular importance (Pöschl et al. 2005, 2015; Fröhlich-Nowoisky et al. 2016; Su et al. 2020; Zheng et al. 2020, 2024). Atmospheric aerosols play a central role in the formation of clouds and precipitation, influence the hydrological cycle and global energy budget, and are among the the largest uncertainty factors in the assessment and prediction of climate change (IPCC 2021). Recent studies contrasting the physicochemical properties, interactions, and effects of aerosols in pristine rainforest and polluted megacity environments as well as fundamental differences between nano- and microparticles (nano-size effects) help to constrain and reduce these uncertainties (Liu et al. 2020, 2023; Pöhlker et al. 2023a; Wang et al., 2023; Zhang et al. 2023; Chen et al. 2024). For example, Figure 2 shows how the uptake of water vapor by aerosol particles serving as cloud condensation nuclei depends on chemical composition and can be efficiently described by globally averaged hygroscopicity parameters for organic and inorganic particulate matter (Pöhlker et al. 2023a).

Exposure to fine particulate matter and other air pollutants leads to oxidative stress in human, animal, and plant organisms and to an increase in morbidity and mortality due to respiratory, cardiovascular and metabolic diseases. Epidemiological and toxicological studies show that pollutants from combustion processes and other anthropogenic emission sources are among the greatest risk factors for human health and life expectancy worldwide (Global Burden of Disease, www.healthdata.org/research-analysis/gbd; Health Effects Institute, www.healtheffects.org; World Health Organisation, www.who.int). The global average loss of life expectancy (LLE) attributed to air pollution is around ~3 years, which is higher than the global average LLE around ~2 years attributed to tobacco smoking (averaged over entire population, not just smokers) and to other risk factors like parasitic or vector-borne diseases (malaria, leishmaniasis, rabies, dengue, yellow fever etc.; ~0.7 yrs), HIV/AIDS (~0.7 yrs), and violence (including interpersonal conflicts and armed interventions; ~0.3 yrs; Lelieveld et al. 2020). Model results indicate that the global mean life expectancy could be increased by ~1 year without fossil fuel emissions and by ~2 years when all all potentially controllable anthropogenic emissions are removed. Around ~1 year of the global average LLE attributed to air pollution is related to natural sources that would be difficult to control (e.g., Aeolian dust and wildfire emissions; Lelieveld et al. 2020).

The exact mechanisms by which air pollutants are causing mortality and diseases, however, have not yet been resolved. Oxidative stress is assumed to play a key role, but the identity, quantity, and reaction pathways of the chemical species that mediate oxidative stress and its adverse health effects at cellular and humoral levels are not clear. Epidemiological studies show that the mass concentration of airborne fine particulate matter with diameters less than 2.5 µm (PM2.5), which is a complex mixture of organic and inorganic compounds, is responsible for most of the adverse health effects of air pollution, while elevated ambient concentrations of trace gases like ozone and nitrogen oxides are also noxious but less important. The oxidative potential of PM2.5, defined as its ability to produce reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) is frequently used and widely perceived as a marker for the toxicity of PM2.5.

Recent investigations, however, indicate that the total abundance of ROS in the epithelial lining fluid (ELF) of the human airways is largely determined by endogenous H_2O_2 as produced in the human body and circulated with the blood flow or the inhalation of ambient gas-phase H_2O_2, while the chemical production of H_2O_2 by inhaled PM2.5 is of minor importance. In contrast, the formation of hydroxyl radicals (OH) is closely related to Fenton-like reactions of transition metals (Cu, Fe), quinones, and other redox-active components of PM2.5, catalyzing the conversion of H_2O_2 and organic peroxides into highly reactive hydroxyl radicals (OH) that can react with most biomolecules and cause most oxidative damage in human cells and tissues. As illustrated in Figure 3, these findings suggest that the adverse effects of PM2.5 are related to the catalytic conversion rather than the production of ROS, which may imply a change of paradigms in elucidating and mitigating the health effects of air pollutants (Dovrou et al. 2023).

Related investigations and results may also explain why individuals with pre-existing inflammatory disorders like asthma or chronic obstructive pulmonary disease (COPD) are particularly susceptible to air pollution, which was hitherto unknown. As illustrated in Figure 4, the commonly elevated concentrations of endogenous nitric oxide (NO) in diseased individuals may increase the production of hydroxyl radicals via peroxynitrite ($ONOO^-$) formation and provide a molecular rationale and feedback mechanism how the adverse health effects of air pollutants may be exacerbated by inflammatory disorders and vice versa (Lelieveld et al. 2024).

Peroxynitrite and other endogenous or exogenous reactive oxygen and nitrogen species (ROS/RNS) can also modify the chemical structure, properties, and effects of proteins, which may have important consequences for chronic neurodegenerative, cardiovascular or gastrointestinal diseases and allergies that are increasingly prevalent in modern societies (Franze et al. 2008; Fröhlich-Nowoisky et al. 2016, 2023; Reinmuth-Selzle et al. 2017, 2023; Ziegler et al. 2020; Mishra et al. 2024). In particular, air pollutants such as fine particulate matter, nitrogen oxides, and ozone can trigger or enhance oxidative stress, nitration and oligomerization of proteinaceous allergens and damage-associated molecular patterns (DAMPs), immune reactions, and feedback cycles of inflammation. Figure 5 illustrates how chemically modified DAMPs may amplify oxidative stress and innate immune responses through a positive feedback loop of pro-inflammatory signaling via pattern recognition receptors (PPR). Such self-amplification provides a potential explanation for the development of inflammatory disorders related to environmental pollution: Environmental pollutants may generate exogenous ROS/RNS and oxidative stress, triggering inflammatory processes that lead to the formation of endogenous ROS/RNS and release of DAMPs. The DAMPs can activate PRR (TLR, RAGE, etc.) that induce further pro-inflammatory signaling and responses via transcription factors (NF-κB, IRF3, etc.), cytokines and cytokine receptors (IL-1, IL-8, etc.). This positive feedback can be additionally enhanced if the DAMPs undergo chemical modification by ROS/RNS, and if the modified DAMPs lead to stronger activation of PRR than the native DAMPs, as observed in recent investigations (Reinmuth-Selzle et al. 2017, 2023; Ziegler et al. 2020; Fröhlich-Nowoisky et al. 2023).

3. Open Scholarship and Epistemic Web

As environmental pollution severely affects climate and public health in the Anthropocene, we need to understand how humanity can best deal with the sources and effects of environmental pollutants in relation to economic development and social welfare. Recent advances in scientific research provide deep insights into the underlying physical, chemical, and biological processes and reveal the relative importance of different pollutants and sources, including natural and anthropogenic contributions. This knowledge enables the development of efficient strategies and policies to mitigate and counteract the adverse effects of environmental pollutants on the Earth system, climate, and health ("planetary health"). With regard to the development, societal communication, and political implementation of appropriate policies for environmental protection, it seems worthwhile to emphasize that climate and health effects are two facets of global change that can and need to be handled together.

Further scientific, technical, and societal progress towards a climate-neutral, environmentally friendly and sustainable energy and circular economy appears urgently needed in order to achieve a lasting and stable Anthropocene, ensure the health, prosperity and continued existence of human civilisation, and avoid deteriorating or even losing the basis of our livelihood. The Anthropocene concept may help humanity to recognise and communicate both cognitively and emotionally: We are shaping the planet, so let's try to get it right. Not only but especially for the encouragement of young people who are facing major challenges, it may be worthwhile and promising to communicate not only the threats but also the opportunities of global change. Apart from the negative aspects and dangers of climate change and biodiversity loss etc., one may consider it a remarkable achievement and great opportunity that we as a species (*Homo sapiens*) have reached the ability to actively shape our environment and planet.

To avoid the perils and grasp the chances related to the power of shaping the planet, it seems critically important to explore and follow potentially suitable pathways according to the basic principles of critical rationalism, i.e., according to the best state of knowledge as validated by observations, experiments, and theoretical considerations, but without claiming absolute certainty. Multi- and transdisciplinary exchange will be required for proper consideration and communication of all relevant perspectives, for societal decision making, and for the practical implementation of suitable directives, regulations, and measures – with regard to climate protection and human health as well as economic prosperity, social justice, global equity and peace as are outlined in the 17 sustainable development goals of the United Nations (sdgs.un.org/goals) and related statements from political, religious, and scholarly institutions around the world.

Recent experiences at the science-policy interface related to the COVID-19 pandemic, air quality, climate, and human health confirmed that open scholarship including open access publications, open data, open source codes, open peer review, interactive public discussion, and the principles of critical rationalism are essential for efficient multi- and transdisciplinary exchange between scholars, politics, and society at large (Leopoldina 2019; Cheng et al. 2021; Pöhlker et al. 2023; www.mpic.de/5081943/studien-fls). New and improved forms of scholarly communication and quality assurance need to be developed while converting the existing corpus of scholarly journals from subscription to open access as outlined in the OA2020 Expression of Interest and the latest Berlin Open Access Conference (oa2020.org; oa2020.org/b16-conference).

To gain the full benefits of open scholarship, a dualism of complementary approaches is required ("as-well-as", not "either-or"): We need top-down approaches to achieve large-scale progress as well as bottom-up initiatives to maintain scholarly diversity. We need appropriate transformative agreements with traditional publishers to achieve an efficient conversion of subscription journals that are still important for some communities, and we also need to liberate and provide funds for proper OA publishers and new publishing platforms to maintain competition and innovation (www.mpic.de/4123205/open-access). Most importantly, we have to uphold and improve scholarly quality assurance, evaluation, and self-regulation. For this purpose, we need to maintain functioning elements of traditional peer review and add advances such as open review, interactive discussion, and article level metrics that are traceable, transparent, and inclusive for the global scientific community and society at large. Indeed, transcending hidden peer review and citation counting oligopolies by transparent forms of quality assurance that can be followed, reproduced, and refined by everybody around the world is among the main reasons why we need full and immediate open access to scholarly research publications.

In times of growing irrationality, alternative facts, postfactual discussions, and fake news, it seems ever more important to practice and promote open scholarship and critical rationalism, i.e., openly show and share the basis, methods, and rigor of the scientific discourse as a role model and reference for societal exchange, decision making, and evolution. Accordingly, open peer review and interactive public discussion are important steps on the way to an epistemic web that documents the scientific discourse in accordance with critical rationalism - openly telling the world not only what we know, but also how well we know it, and where the limitations are (iterative validation or falsification of theories by observations; Pöschl 2012; Hyman and Renn, 2012). Figure 6 outlines key elements of multi-stage open peer review as practiced in a growing number of scientific journals, preprint servers, and related publishing platforms in the geosciences (since 2001) and more recently also in other disciplines (Pöschl 2004, 2012;

Wolfram et al. 2020). The iterative process of review and discussion is rooted in the global scholarly community and will increasingly involve artificial intelligence and machine learning tools (AI/ML) as these become available and increasingly powerful on scholarly publishing platforms. Not only but also for this purpose, it appears desirable to train AI on quality-controlled scholarly knowledge available to all via proper OA licenses (CC-BY) rather than just arbitrary internet contents or restricted contents that are accessible and usable for monopolists/oligopolists rather than the public. A comprehensive global commons of knowledge and epistemic web with transparent quality assurance will help to augment, communicate, and utilize scholarly insights and understanding for rational and transparent approaches to resolving complex questions and problems in the Anthropocene.

Acknowledgement: This manuscript provides an overview and synthesis of recent scientific exchange, studies, and publications of the author with numerous colleagues who are gratefully acknowledged - in particular T. Berkemeier, J. Fröhlich, K. Lucas, C. Pöhlker, M. Pöhlker, G. Lammel, H. Su, Y. Cheng, J. Lelieveld, and M. G. Weller. This article is dedicated to Paul J. Crutzen, whose curiosity, ingenuity, and wisdom have helped to prevent ozone layer destruction and nuclear winter, and will help to avoid the perils and grasp the opportunities of the Anthropocene.

References

Benner, S., G. Lax, P. J. Crutzen, U. Pöschl, J. Lelieveld, H. G. Brauch: Paul J. Crutzen and the Anthropocene: A New Epoch in Earth History, Springer 2021. link.springer.com/book/10.1007/978-3-030-82202-6

Chen, C., Wang, X., Binder, K., Pöschl, U., Su, H., Cheng, Y.: Convergence of dissolving and melting at the nanoscale. Faraday Discuss. 249, 229-242, 2024.

Cheng, Y., N. Ma, C. Witt, S. Rapp, P. Wild, M. O. Andreae, U. Pöschl, H. Su: Face masks effectively limit the probability of SARS-CoV-2 transmission, Science, 372, 1439-1443, 2021.

Crutzen, P. J., Geology of mankind. Nature, 415, 23-23, 2002.

Dovrou, E., S. Lelieveld, A. Mishra, U. Pöschl & T. Berkemeier: Influence of ambient and endogenous H2O2 on reactive oxygen species concentrations and OH radical production in the respiratory tract. Environmental Science: Atmospheres, doi: /10.1039/D2EA00179A, 2023.

Franze, T.; Weller, M. G.; Niessner, R.; Pöschl, U., Protein nitration by polluted air. Environ. Sci. Technol., 39 (6), 1673-1678. DOI: 10.1021/es0488737, 2005.

Fröhlich-Nowoisky J., C. J. Kampf, B. Weber, J. A. Huffman, C. Pöhlker, M. O. Andreae, N. Lang-Yona, S. M. Burrows, S. S. Gunthe, W. Elbert, H. Su, P. Hoor, E. Thines, T. Hoffmann, V. R. Després and U. Pöschl: Bioaerosols in the Earth system: Climate, health, and ecosystem interactions, Atmospheric Research 182, 346-376, doi: 10.1016/j.atmosres.2016.07.018, 2016.

Fröhlich-Nowoisky, J., N. Bothen, A. T. Backes, M. G. Weller & U. Pöschl: Oligomerization and tyrosine nitration enhance the allergenic potential of the birch and grass pollen allergens Bet v 1 and Phl p 5. Front. Allergy, 4, doi: 10.3389/falgy.2023.1303943, 2023.

Health Effects Institute: State of Global Air 2020. Special Report. Boston, MA, 2020.

Hyman, M. and Renn, J: Towards an Epistemic Web, Edition OA, RatSWD_WP_ 197, http://dx.doi.org/10.2139/ssrn.2104137, 2012.

IPCC 2021, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report, Cambridge University Press, doi:10.1017/9781009157896. www.ipcc.ch/report/sixth-assessment-report-working-group-i/

Lelieveld, J., A. Pozzer, U. Pöschl, M. Fnais, A. Haines & T. Münzel: Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective. Cardiovascular Research 116 (7), 1334, doi: 10.1093/cvr/cvaa073, 2020.

Lelieveld, S., J. Lelieveld, A. Mishra, A. Daiber, A. Pozzer, U. Pöschl & T. Berkemeier: Endogenous Nitric Oxide Can Enhance Oxidative Stress Caused by Air Pollutants and Explain Higher Susceptibility of Individuals with Inflammatory Disorders. Environ. Sci. Technol., 58, doi: 10.1021/acs.est.3c07010, 2024.

Leopoldina: Clean air – Nitrogen oxides and particulate matter in ambient air: Basic principles and recommendations, 2019. https://www.leopoldina.org/en/publications/detailview/publication/clean-air-nitrogen-oxides-and-particulate-matter-in-ambient-air-basic-principles-and-recommendations-2019-1/

Liu, LX., YF. Cheng, SW. Siwen, C. Wei, M. L. Pöhlker, C. Pöhlker, P. Artaxo, M. Shrivastava, M. O. Andreae, U. Pöschl & H. Su: Impact of biomass burning aerosols on radiation, clouds, and precipitation over the Amazon: relative importance of aerosol-cloud and aerosol-radiation interactions. Atmos. Chem. Phys. 20, 13283-13301, 2020.

Liu, Y., H. Su, S. Wang, C. Wei, W. Tao, M. L. Pöhlker, C. Pöhlker, B. A. Holanda, O. O. Krüger, T. Hoffmann, M. Wendisch, P. Artaxo, U. Pöschl, M. O. Andreae & Y. Cheng: Strong particle production and condensational growth in the upper troposphere sustained by biogenic VOCs from the canopy of the Amazon Basin. Atmos. Chem. Phys., 23, 251-272, 2023.

Mishra, A., S. Lelieveld, U. Pöschl & T. Berkemeier: Multiphase Kinetic Modeling of Air Pollutant Effects on Protein Modification and Nitrotyrosine Formation in Epithelial Lining Fluid. Environ. Sci. Technol., 57, 34, 12642–12653, doi: 10.1021/acs.est.3c03556, 2023.

Pöhlker, M. L., C. Pöhlker, J. Quaas, J. Mülmenstädt, A. Pozzer, M. O. Andreae, P. Artaxo, K. Block, H. Coe, B. Ervens, P. Gallimore, C. J. Gaston, S. S. Gunthe, S. Henning, H. Herrmann, O. O. Krüger, G. Mc Figgans, L. Poulain, S. S. Raj, E. Reyes-Villegas, H. M. Royer, D. Walter, Y. Wang & U. Pöschl: Global organic and inorganic aerosol hygroscopicity and its effect on radiative forcing. Nature Communications, 14, doi: 10.1038/s41467-023-41695-8, 2023a.

Pöhlker, M. L., C. Pöhlker, O. O. Krüger, J. Förster, T. Berkemeier, W. Elbert, J. Fröhlich-Nowoisky, U. Pöschl, G. Bagheri, E. Bodenschatz, J. A. Huffman, S. Scheithauer & E. Mikhailov: Respiratory aerosols and droplets in the transmission of infectious diseases. Reviews of Modern Physics, 95, doi: https://doi.org/10.1103/RevModPhys.95.04500, 2023b.

Pöschl, U.: Interactive journal concept for improved scientific publishing and quality assurance, Learn. Pub., 17, 105–113, 2004.

Pöschl, U.: Atmospheric aerosols: composition, transformation, climate and health effects, Angewandte Chemie International Edition, 44, 7520-7540, 2005.

Pöschl, U.: Multi-stage open peer review: scientific evaluation integrating the strengths of traditional peer review with the virtues of transparency and self-regulation, Frontiers in Computational Neuroscience, DOI: 10.3389/fncom.2012.00033, 2012.

Pöschl, U. and Shiraiwa, M., Multiphase Chemistry at the Atmosphere–Biosphere Interface Influencing Climate and Public Health in the Anthropocene. Chemical Reviews, 115 (10), 4440–4475. DOI: 10.1021/cr500487s, 2015.

Reinmuth-Selzle, K., C. J. Kampf, K. Lucas, N. Lang-Yona, J. Fröhlich-Nowoisky, M. Shiraiwa, P. S. J. Lakey, S. Lai, F. Liu, A. T. Kunert, K. Ziegler, F. Shen, R. Sagarbanti, B. Weber, I. Bellinghausen, J. Saloga, M. G. Weller, A. Duschl, D. Schuppan and U. Pöschl: Air Pollution and Climate Change Effects on Allergies in the Anthropocene: Abundance, Interaction, and Modification of Allergens and Adjuvants. 51, 4119-4141, doi: 10.1021/acs.est.6b04908, 2017.

Reinmuth-Selzle, K., I. Bellinghausen, A. Leifke, A. T. Backes, N. Bothen, K. Ziegler, M. G. Weller, J. Saloga, D. Schuppan, K. Lucas, U. Pöschl & J. Fröhlich-Nowoisky: Chemical modification by peroxynitrite enhances TLR4 activation of the grass pollen allergen Phl p 5. Front. Allergy, 4, doi: 10.3389/falgy.2023.1066392, 2023.

Rockström, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. Van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J. A. Foley, A safe operating space for humanity, Nature, 461, 472-475, 2009.

Steffen, W., J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix; J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann, and H. J. Schellnhuber: Trajectories of the Earth System in the Anthropocene, Proc. Natl. Acad. Sci. U.S.A., 115, 8252-8259, 2018.

Su, H., YF. Cheng & U. Pöschl: New Multiphase Chemical Processes Influencing Atmospheric Aerosols, Air Quality, and Climate in the Anthropocene. Acc. Chem. Research, doi: 10.1021/acs.accounts.0c00246, 2020.

Wang, J., H. Su, C. Wei, G. Zheng, J. P. Wang, T. Su, C. Li, C. Liu, J. E. Pleim, Z. Li, A. Ding, M. O. Andreae, U. Pöschl, Cheng, Y.: Black carbon-induced regime transition of boundary layer development strongly amplifies severe haze. One Earth, 6, 751–759, 2023.

Wolfram, D., Wang, P., Hembree, A., Park, H.: Open peer review: promoting transparency in open science, Scientometrics, 125, 1033–1051, 2020.

Zalasiewicz, J., J. Adeney Thomas, C. N. Waters, S. Turner, M. J. Head: What should the Anthropocene mean?, Nature, 632, 980-984, 2024.

Zhang, Y., Su, H., Kecorius, S., Ma, N., Wang, Z., Sun, Y., Zhang, Q., Pöschl, U., Wiedensohler, A., Andreae, M. O., Cheng, Y.: Extremely low-volatility organic coating leads to underestimation of black carbon climate impact. One Earth, 6, 158-166, 2023.

Zheng, G., H. Su, S. Wang, M. O. Andreae, U. Pöschl & YF. Cheng: Multiphase buffer theory explains contrasts in atmospheric aerosol acidity. Science 369, 1374-1377, 2020.

Zheng, G., H. Su, M. O. Andreae, U. Pöschl, Y. Cheng: Multiphasebuffering by ammonia sustains sulfateproduction in atmospheric aerosols. AGUAdvances, 5, e2024AV001238, 2024.

Ziegler, K., A. T. Kunert, K. Reinmuth-Selzle, A. Leifke, D. Widera, M. G. Weller, D. Schuppan, J. Fröhlich-Nowoisky, K. Lucas & U. Pöschl: Chemical modification of pro-inflammatory proteins by peroxynitrite increases activation of TLR4 and NF-κB: Implications for the health effects of air pollution and oxidative stress. Redox Biology, doi: 10.1016/j.redox.2020.101581, 2020.

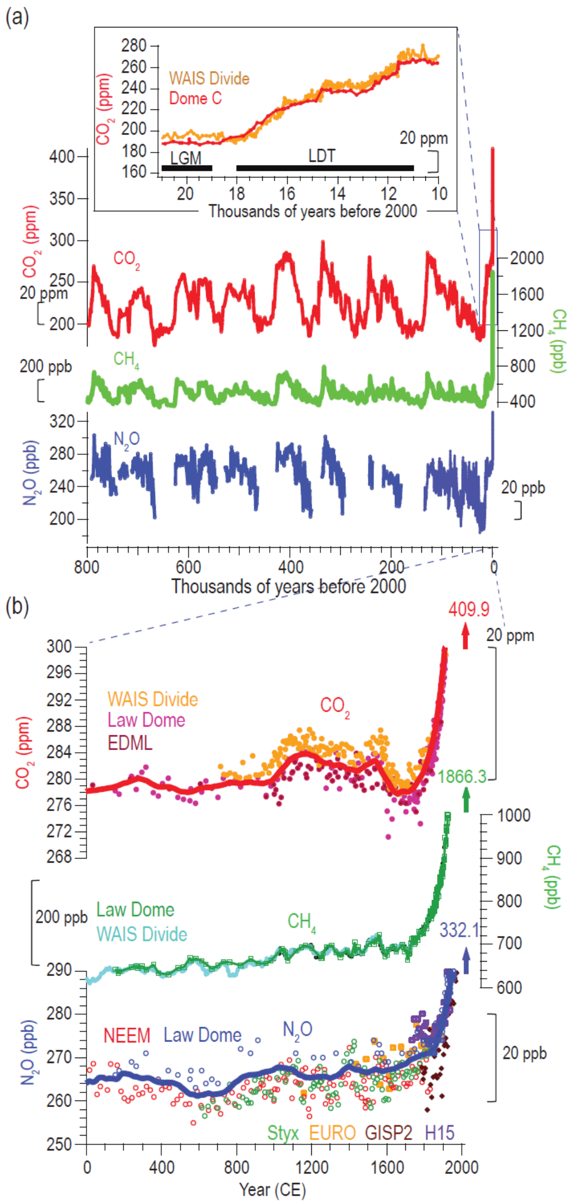

Figure 1. Temporal evolution of atmospheric well-mixed greenhouse gas concentrations in recent Earth history determined from ice cores. (a) Records during the last 800 kyr with the Last Glacial Maximum (LGM) to Holocene transition as inset. (b) Multiple high-resolution records over the CE. The horizontal black bars in panel (a) inset indicate LGM and Last Deglacial Termination (LDT) respectively. The red and blue lines in (b) are 100-year running averages for CO_2 and N_2O concentrations, respectively. The numbers with vertical arrows in (b) are instrumentally measured concentrations in 2019. Further details on data sources and processing are available in the IPCC report from which the figure has been adopted (Figure 2.4, Chapter 2, IPCC 2021).

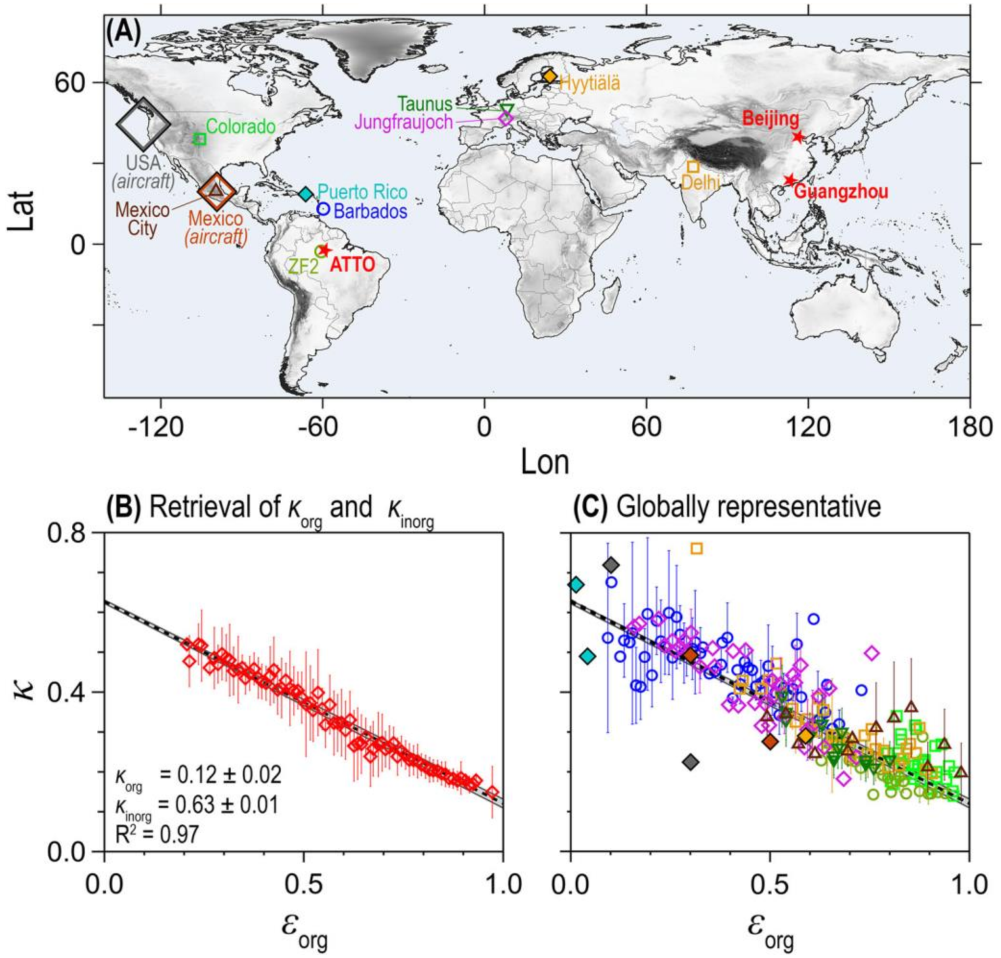

Figure 2. Retrieval of globally representative aerosol hygroscopicity parameters for organic particulate matter, κ_{org}, and inorganic ions, κ_{inorg}, based on cloud condensation nuclei measurements worldwide. Retrieval of $\kappa_{org} = 0.12 \pm 0.02$ and $\kappa_{inorg} = 0.63 \pm 0.01$ from linear bivariate regression fits of experimentally derived organic mass fraction, ε_{org}, and hygroscopicity parameter, κ, from the Amazon, Beijing, and Guangzhou in (B), along with further campaign data sets in (C), showing that κ_{org} and κ_{inorg} are representative for organic and inorganic aerosols under continental andmarine conditionsworldwide. The globalmap in (A) with topography in gray shows all measurement locations relevant for this study. The retrieval in (B) is based on the three extended campaign datasets: Program of Regional Integrated Experiments of Air Quality over the Pearl River Delta (PRIDE-PRD2006) in Guangzhou, Campaign of Air Quality Research in Beijing (CAREBeijing-2006), and at theAmazon Tall Tower Observatory (ATTO). Colors of data points in (B) and (C) correspond to site markers in (A) (Pöhlker et al. 2023a).

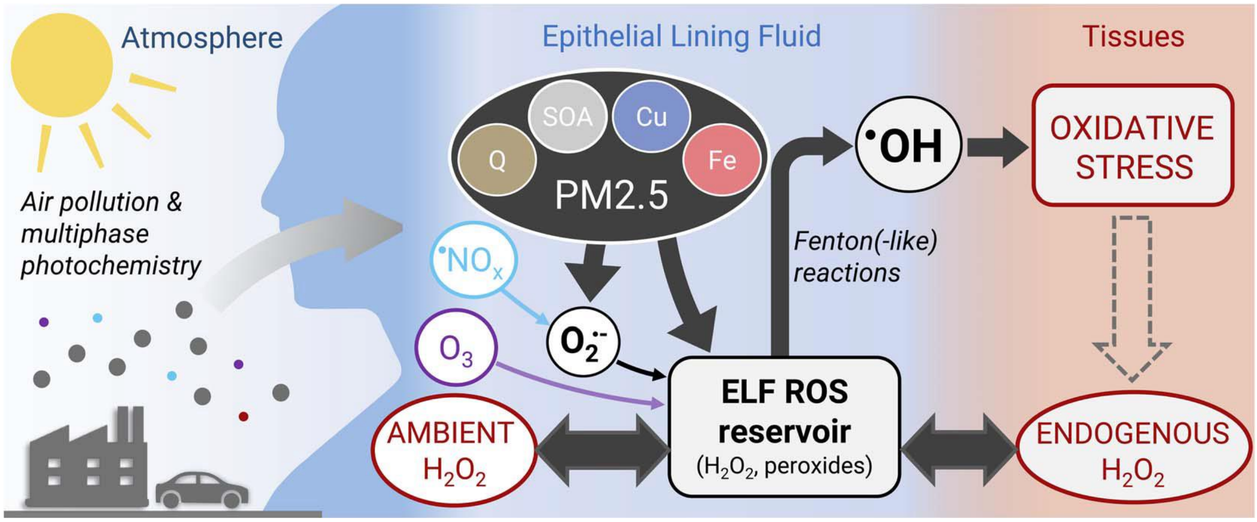

Figure 3. Health effects of atmospheric air pollution. The epithelial lining fluid (ELF) is a thin aqueous film at the air–body interface in which inhaled air pollutants dissolve and deposit. H_2O_2 and other peroxides form a reservoir of reactive oxygen species (ROS) in the ELF. H_2O_2 levels in the ELF are controlled by endogenous processes (endogenous H_2O_2 regime) or inhalation of gas-phase H_2O_2 (ambient H_2O_2 regime). A small fraction of H_2O_2 originates from conversion of superoxide (O_2^{-}) generated from interaction of fine particulate matter (PM2.5) and nitrogen oxides (NO_x) with ELF. Other peroxides are supplied through secondary organic aerosol (SOA) contained within PM2.5 or by chemical reactions of ozone (O_3). Transition metal-mediated, catalytic conversion of peroxides leads to formation of the highly reactive OH radical that can trigger oxidative stress and, ultimately, cell death (Dovrou et al. 2023).

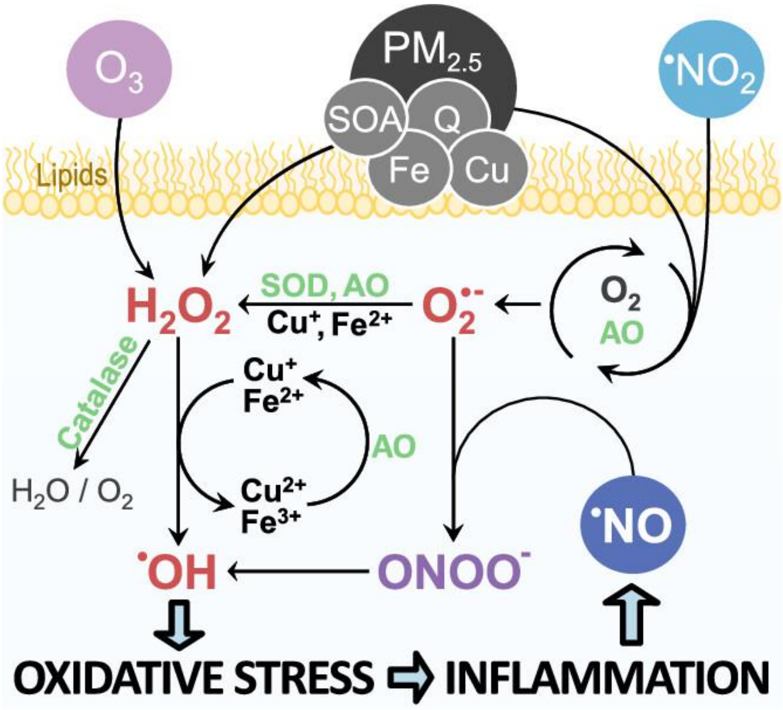

Figure 4. Production, interconversion, and scavenging of reactive oxygen species in the epithelial lining fluid (ELF). Reactions of PM2.5 constituents (copper, iron, quinones) and NO2 with antioxidants (AO) lead to superoxide (O_2^-) formation. O_2^- is converted into hydrogen peroxide (H_2O_2) by superoxide dismutase (SOD) and AO, followed by scavenging of H_2O_2 through catalase. Secondary organic aerosol (SOA) components also produce H_2O_2 and hydroxyl radicals (OH). Copper (Cu^+) and iron (Fe^{2+}) ions compete with catalase to form OH, the most reactive species driving oxidative stress. Through reactions of PM2.5 constituents with antioxidants, redox cycling is sustained in the ELF. Inflammation is promoted by oxidative stress and is associated with increased levels of nitric oxide (NO), which competes with the antioxidant defense system for O_2^- to form peroxynitrite ($ONOO^-$), a labile compound that can decompose to form OH (Lelieveld et al. 2024).

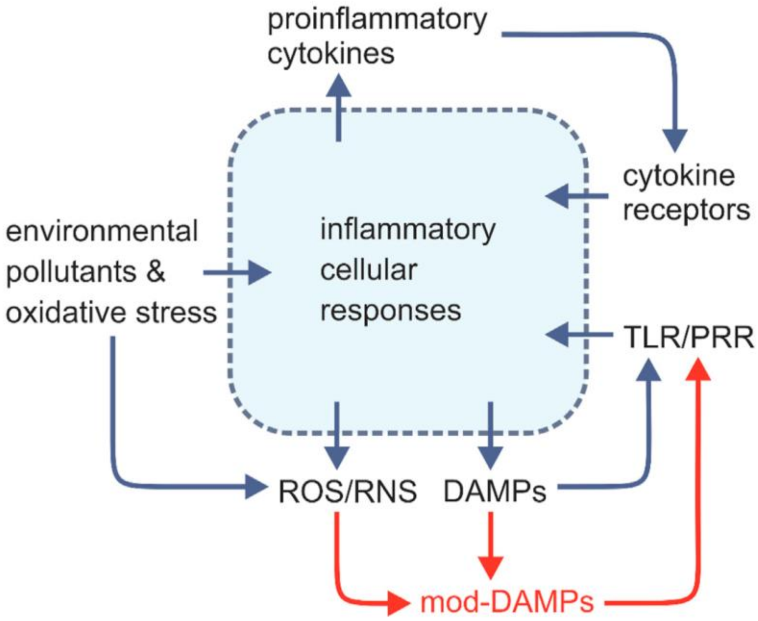

Figure 5. Amplification of inflammatory processes and innate immune responses through chemically modified DAMPs. Environmental pollutants and oxidative stress can induce an increase of reactive oxygen and nitrogen species (ROS/RNS), the formation of chemically modified damage-associated molecular patterns (mod-DAMPs), an increase of pro-inflammatory signaling via Toll-like receptors and other pattern recognition receptors (TLR/PRR), an increase of proinflammatory cytokines, and further inflammatory cellular responses (Ziegler et al. 2020).

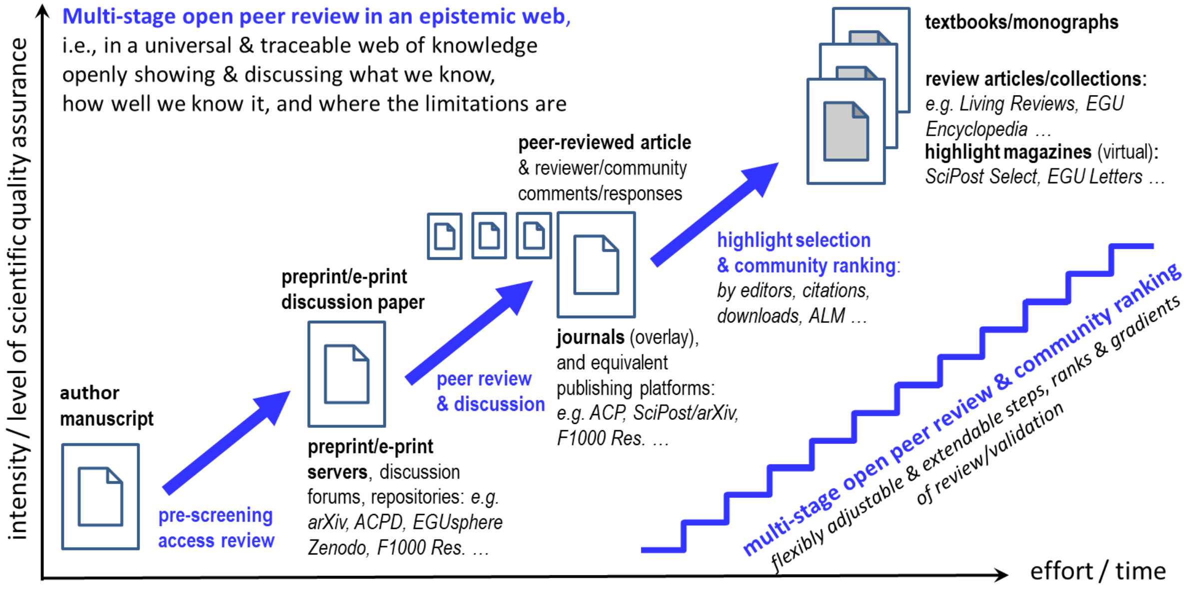

Figure 6. Key elements of multi-stage open peer review contributing to a global epistemic web, i.e., a universal and traceable web of knowledge openly showing and discussing what we know, how well we know it, and where the limitations are – in line with the principles of critical rationalism (iterative validation or falsification of theories by observations).