communications earth & environment

COMMENT

https://doi.org/10.1038/s43247-021-00245-0 OPEN

Above us only sky

Joshua Dean[1,8✉], Astrid Kiendler-Scharr[2,8], Nadine Mengis[3,8✉], Yinon Rudich[4,8✉], Kerstin Schepanski[5,8✉] & Ralf Zimmermann[6,7,8]

Greenhouse gas emissions and air pollution have changed the composition of the atmosphere, and thereby initiated global warming and reduced air quality. Our editorial board members note the need for a deeper understanding of atmospheric fluxes and processes to tackle climate and human health issues.

The atmosphere is a vital life source: it is the air we breathe and a protective shield from harmful radiation. However, increasing levels of greenhouse gases are warming our atmosphere at an alarming rate and pollution is threatening air quality. Reducing and removing greenhouse gases requires a good grasp of their existing sources and sinks, and a comprehensive understanding of the net benefits of different strategies. Similarly, both natural and anthropogenic aerosols affect the atmospheric energy balance, air quality, and human health. Here, our editorial board members discuss some of the paths forward.

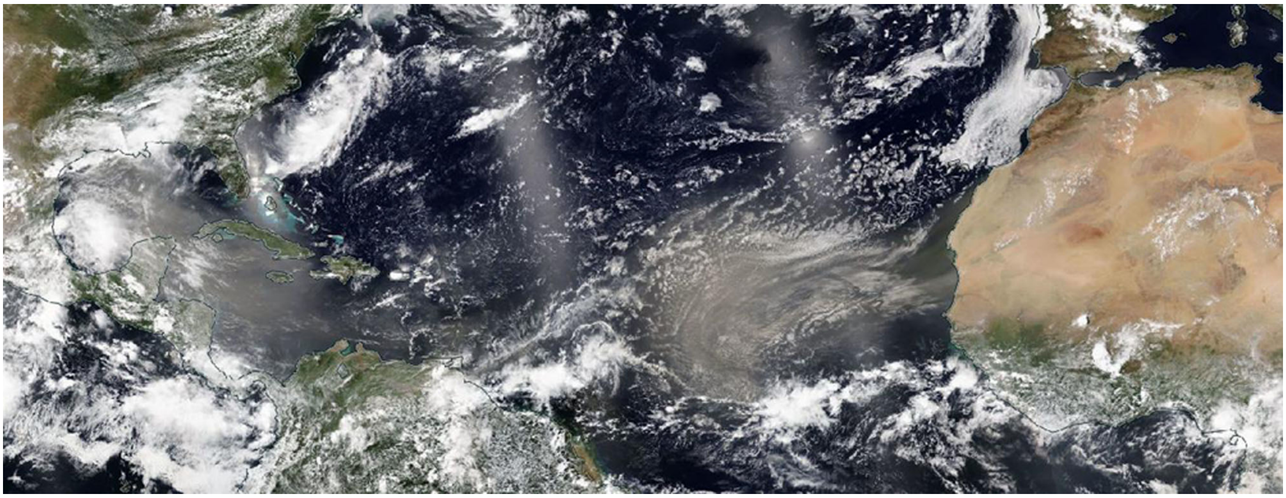
Joshua Dean: Time to reconcile methane inventories

Methane is a potent greenhouse gas driving climate change, second only to carbon dioxide. Unlike carbon dioxide, however, methane is naturally removed from the atmosphere quite quickly and lasts on average about 10 years before it is oxidized. This means if we stopped methane emissions, the remaining methane in the atmosphere would eventually be removed, which would slow climate change. The opposite is also true: sustained growth in atmospheric methane concentrations requires substantial growth in emissions. And grow they have; atmospheric methane concentrations have increased by ~0.5% per year since 2010[1].

Tellingly, during the height of the COVID-19 pandemic in 2020, growth in atmospheric carbon dioxide concentrations slowed while methane concentrations grew faster than ever. Roughly half the global methane emissions are from anthropogenic sources (mainly agriculture, waste, and the oil and gas industry), the other half from natural ecosystems (mainly wetlands). The sooner we reduce anthropogenic methane emissions, the greater the impact will be in the fight against climate change.

It is not clear what is driving the increase in atmospheric methane concentrations. We have a good handle on the overall numbers of the global inventory of methane sources and sinks, but uncertainty surrounds individual methane sources. If we add up all the observations of methane emissions from individual sources and upscale them for the whole globe (a bottom-up approach), we get values more than 25% higher than direct measurements of the whole methane inventory using atmospheric measurements (a top-down approach). While we can address anthropogenic emissions directly, it is much harder to reduce natural methane emissions. Thus, we must reconcile our top-down and bottom-up methane inventories to understand where methane emissions are coming from, which emissions we can directly prevent and

[1]School of Environmental Sciences, University of Liverpool, Liverpool, UK. [2]IEK-8: Troposphere, Forschungszentrum Jülich GmbH, Jülich, Germany. [3]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany. [4]Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot, Israel. [5]Freie Universität Berlin, Institute of Meteorology, Berlin, Germany. [6]Joint Mass Spectrometry Centre, Cooperation Group "Comprehensive Molecular Analytics", Helmholtz Zentrum München-German Research Center for Environmental Health GmbH, München, Germany. [7]Joint Mass Spectrometry Centre, Chair of Analytical Chemistry, Institute of Chemistry, University of Rostock, Rostock, Germany. [8]These authors contributed equally: Joshua Dean, Astrid Kiendler-Scharr, Nadine Mengis, Yinon Rudich, Kerstin Schepanski, Ralf Zimmermann. ✉email: Joshua.dean@liverpool.ac.uk; nmengis@geomar.de; yinon.rudich@weizmann.ac.il; kerstin.schepanski@fu-berlin.de



Credit: NASA worldview

which we cannot, and therefore constrain the future trajectory of atmospheric methane concentrations.

One key place where top-down versus bottom-up methane inventories disagree is in the oil and gas industry. Oil and gas bottom-up methane inventories, derived from industry reporting, underestimate methane emissions by 20–70%[2,3]. Natural gas, comprised primarily of fossil methane and an efficient energy source, is sometimes touted as a bridging fuel as we move towards a low-carbon future. This same fossil methane has also been targeted as a potential source of hydrogen to fuel a future hydrogen economy. But emissions of methane from the energy sector are currently far too high to offset the potential benefits of using it to generate energy. Perhaps renewable natural gas, generated from the decomposition of waste products in the agriculture and food industry, could play a role in a low-carbon future but only if methane emissions to the atmosphere are negligible.

No matter what our methane future looks like, it is crucial that we can account for the amount and sources of methane entering the atmosphere. Top-down and bottom-up researchers need to team up and combine their approaches to reconcile global and regional methane inventories. For example, by pairing broad atmospheric chemistry measurements with simultaneous ground-based observations to constrain specific methane sources, fluxes, and the processes at play.

Credit: Ralf Vetterle/Pixabay

Nadine Mengis: Down to Earth with carbon dioxide removal
Measures to remove carbon dioxide from the atmosphere have been hotly debated since the Paris Agreement and the Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5 °C (IPCC SR1.5). Most countries now include some form of carbon dioxide removal in their long-term low greenhouse gas emission development strategies. Natural sinks, rather than geological storage of carbon dioxide, are emphasized to meet national net-zero goals[4].

Yet, we know that applying any single carbon dioxide removal measure, even the perceived 'green' ones, as a silver bullet at the scale outlined in the IPCC SR1.5 scenarios will very likely cause breaches in our planetary boundaries[5]. Harvesting terrestrial biomass as a feedstock for negative emissions, for example, could cause stress on planetary boundaries concerning freshwater use, biosphere integrity, and biogeochemical flows[6]. Employing a broader portfolio of carbon dioxide removal options will likely help mitigate severe side-effects of single options.

We need to bring carbon dioxide removal approaches down to Earth, that is, assess them at the implementation scale and estimate their actual carbon dioxide removal potential, as well as implementation obstacles, like social acceptance, regulatory efforts, and infrastructural needs. To thoroughly assess the efficacy of broader portfolios of carbon dioxide removal options, we need to consider how much carbon dioxide can be removed with each measure, how the different carbon dioxide removal options interact with each other, and what other associated climate change impacts they cause. For instance, emissions of other greenhouse gases or changes in albedo resulting from each option could reduce the wider climate mitigation efficacy. More importantly, these assessments should follow life-cycle considerations, including the entire chain of events needed to produce negative emissions.

Anthropogenic carbon removals need to stem from human-made activities that aim to either enhance natural sinks or create new sinks. Accordingly, natural and anthropogenic carbon sinks need to be distinguished. Further, there needs to be a clear distinction between carbon dioxide avoidance through, for example, circular carbon approaches and post-hoc carbon removal. For instance, peatland rewetting has a two-fold effect of avoiding existing carbon dioxide emissions and increasing carbon sequestration[7]. Accounting for these two system services in a distinct manner will allow to allow transparent assessment of their separate contributions in national net-zero strategies.

Finally, to understand if and how carbon dioxide removal measures can compensate for our (remaining) fossil fuel emitting activities, assessments need to consider the entire impact a carbon dioxide removal measure would have on the climate and the surrounding environment, beyond only negative carbon dioxide emissions.

Down to Earth assessments of carbon dioxide removal measures will reduce uncertainties surrounding future side-effects from carbon dioxide removal options and help us understand their actual mitigation potential. What is more, they will guide the development of the social, political, and regulatory framework needed to accompany implementation.

Kerstin Schepanski: Mineral dust, globally

Mineral dust is a prominent aerosol type in the global atmosphere and it modulates the atmospheric energy budget, the water cycle, and the global carbon cycle. Originating from dry, bare soil surfaces and entrained into the atmosphere by wind, these tiny soil particles are distributed around the globe by prevailing circulation patterns. Once in the atmosphere, dust alters the radiation budget via scattering and absorption of solar radiation and impacts atmospheric stability through shadowing effects and heating of dust layers.

Dust aerosols also modulate cloud formation processes, precipitation distribution, and ultimately, the water cycle. Furthermore, the long-range transport of mineral dust by wind can provide an important source of micro-nutrients and stimulate bio-productivity in remote ecosystems. In a nutshell, the atmospheric dust cycle plays a significant role in global temperatures.

Mineral dust processes are highly complex and dust research has benefitted from advances in measurement techniques, data blending, and computational resources. Today, long satellite records and new sensors provide detailed observations of dust source characteristics and atmospheric composition, which have improved our understanding of source diversity and the influence of environmental changes on emission variability.

In-situ measurements now cover a broad range of scales from showing the role of tiny mineral dust aerosols in cloud particle formation processes to the presence of giant dust particles far from source regions. Such observations continue to improve our perception of dust radiative impacts. Finally, efficient computational infrastructure and numerical approaches available today allow for simulating the atmospheric dust cycle and its interactions at a much higher level of complexity. Together these efforts to illuminate the complex dynamics of dust have revealed its prominent role in the Earth system.

Mineral dust is a global player that demands a global view. It is intrinsically intertwined in wider Earth system processes through complex and wide-ranging interactions with other global cycles that strongly influence our climate. Thinking of the dust cycle globally, we will discover the diversity of dust sources across all latitudes, as well as the various transport routes that influence the atmospheric composition, air quality, and climate feedbacks. In this way, taking a global view clarifies that dust interactions are not local but of global impact and will allow us to better describe and predict the changing state of the Earth system.

Astrid Kiendler-Scharr, Ralf Zimmermann, and Yinon Rudich: Aerosols and health

Adverse health effects due to air pollution are the number one global environmental health risk. According to the World Health Organization (WHO), 7 million premature deaths worldwide per year can be attributed to exposure to outdoor air pollution. Significant causes of adverse health effects are atmospheric aerosol particles composed of a myriad of inorganic and organic components. More than 90% of the world's population lives in areas that exceed the WHO guideline value of 10 µg fine particulate mass—$PM_{2.5}$: particles smaller the 2,5 µm—per cubic meter of air.

The dose-response for adverse health effects is not well established, and there is no scientifically justified lower limit below which adverse health effects can be excluded. So far, implemented emission controls have not been overly successful in eliminating the health effects due to exposure. Furthermore, it has been observed that the relative toxicity of particulate matter can vary widely, depending on the chemical composition (for example, aromatic versus oxidized aromatic hydrocarbons), formation process (for example, combustion soot versus sea-spray salt particles), size (fine versus ultrafine particles) and morphology (spherical versus fibrous). This is in line with the observation that different emission sources, and thereby different aerosol compositions, can induce varied health outcomes.

Accordingly, the mass of fine particles ($PM_{2.5}$) per unit volume is not a good indicator for projecting health outcomes. In addition, atmospheric aerosols are a mixture of primary emitted and secondary formed and transformed components. How atmospheric chemistry modifies the aerosol composition and how the changes impact the downstream health outcomes is still not well established. Due to projected changes and reductions in anthropogenic emissions and climatic changes, the relative role of smoke, dust, and secondary components in inducing health effects is projected to increase in the future.

Mitigating climate change and pledges to become carbon-neutral within a few decades require rapid adaptation of technologies that would lead to substantial changes in emissions and atmospheric composition. The expected increase in wildfires, desertification, and extreme wind events, together with heatwaves and stagnation conditions will lead to higher levels of air pollution. People thus will be exposed to different and more aged aerosols in the future. Therefore, there is an urgent need to understand how these changes may modify the potency to induce biological and health effects.

Credit: Steve Buissinne/Pixabay

More sensitive instrumentation together with improved model systems to investigate the health impacts of a broad range of aerosol types will help to gauge how aerosol composition affects toxicity, the biological pathways activated by exposure, and health outcomes. Current research suggests that anthropogenic primary and secondary aerosols tend to be more toxic than biogenic ones and that atmospheric aging increases aerosol toxicity.

Developments in biological, analytical, and computational tools have to be directed towards more sophisticated, multidisciplinary approaches to assess the health effects of existing and emerging emission types. We will need better communication between policymakers, environmental protection agencies, and scientists to translate the accumulating knowledge into action.

An important goal is to consider the aerosol chemical composition, rather than simply the particulate matter mass per unit volume, as a metric for exposure and to substantially step up exposure monitoring. To achieve this goal, we need more studies that bridge emissions and atmospheric transformation with exposure and health effects.

Received: 2 August 2021; Accepted: 2 August 2021;
Published online: 02 September 2021

References

1. Fletcher, S. E. M. & Schaefer, H. Rising methane: a new climate challenge. *Science* https://doi.org/10.1126/science.aax1828 (2019).
2. Hmiel, B. et al. Preindustrial $^{14}CH_4$ indicates greater anthropogenic fossil CH_4 emissions. *Nature* https://doi.org/10.1038/s41586-020-1991-8 (2020).
3. Barkley et al. Analysis of oil and gas ethane and methane emissions in the Southcentral and Eastern United States using four seasons of continuous aircraft ethane measurements. *JGR Atmos.* https://doi.org/10.1029/2020JD034194 (2021).
4. Thoni, T. et al. Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments. *Front Clim.* **578**, 409–412 (2020).
5. Heck, V. et al. Is extensive terrestrial carbon dioxide removal a 'green'form of geoengineering? A global modelling study. *Global Planet. Change* **137**, 123–130 (2016).
6. Heck, V. et al. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change* **8.2**, 151–155 (2018).
7. Tanneberger, F. et al. The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives. *Adv. Sustain. Syst.* **5.1**, 2000146 (2021).

Additional information

Correspondence and requests for materials should be addressed to J.D., N.M., Y.R. or K.S.