

Overexplaining or underexplaining methane's role in climate change

Michael J. Prather^{a,1} and Christopher D. Holmes^b

Methane lies at the nexus of climate and air quality, being both a major anthropogenic greenhouse gas—causing about one-half of the warming of carbon dioxide—and a precursor of tropospheric ozone pollution. Over the industrial era, atmospheric methane abundances rose from about 720 parts per billion (ppb) (10^{-9} mole fraction) to over 1,850 ppb today. Humans have driven this change largely through agriculture, waste, and fossil

fuel emissions. The community's regular review of the science of atmospheric methane via the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports [First Assessment Report (FAR), 1990 (1); Second Assessment Report (SAR), 1995 (2); Third Assessment Report (TAR), 2001 (3); Fourth Assessment Report (AR4), 2007 (4); and Fifth Assessment Report (AR5), 2013 (5)] has maintained both a scientific interest and political urgency as nations seek to mitigate near-term climate change and keep the overall warming to less than 2 °C (6–9). The recent history (Fig. 1), based on ref. 10, shows a complex overall growth with different rates and even a pause from 2000 to 2006. The many conflicting reports of this recent variability (11–23) suggest that it remains unexplained, or perhaps overexplained. Past work has separately used measurements of methane, its isotopes, and related gases to interpret the methane history. Two new publications (24, 25) combine these complementary data into a consistent Bayesian modeling framework and use advanced statistical methods to match all observations simultaneously subject to the prior constraints. Notably, they advance our understanding of what could have caused the variability. The similarities and differences of optimal solutions that emerge from both studies teach us about the information contained in present observations, as well as their limits.

Both Rigby et al. and Turner et al. suggest that oxidation of methane by tropospheric OH increased from the 1990s through the 2000s and that this loss process was mainly responsible for the brief plateau in global mean methane. In contrast, most past work pointed to stable emissions as the cause of the plateau. The new papers differ, however, on what explains the steady rise since 2007: Rigby et al. (24) find a high likelihood that methane emissions rose while OH fell; Turner et al. (25) suggest, counterintuitively, that methane emissions decreased but OH decreased even more. Nevertheless, both papers agree that the observational constraints can be accommodated with differing, nearly optimal solutions, including constant OH levels, so there is no contradiction between their conclusions.

Although there are many emission and climate processes that can change the amount of tropospheric OH and hence the rate of methane loss, neither model

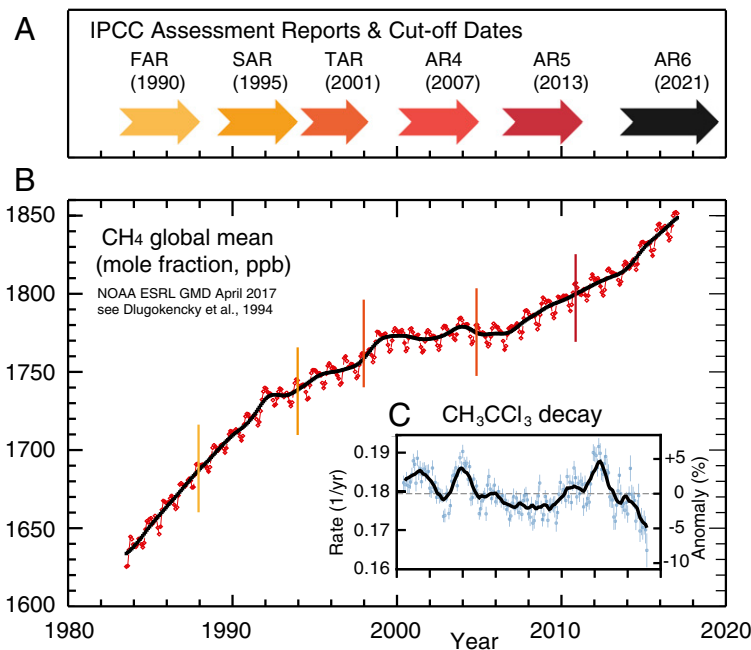


Fig. 1. (A) Timeline of the international assessments of methane (CH₄) as a greenhouse gas, denoting the period of data evaluated (fat arrows) and the publication date of each Intergovernmental Panel on Climate Change (IPCC) Assessment Report [FAR (1), SAR (2), TAR (3), AR4 (4), AR5 (5), and projected AR6]. (B) Observed global mean CH₄ [mole fraction in parts per billion (ppb), 10^{-9}] for 1983–2017, showing both monthly (red diamonds) and annual (thick black line) averages (https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/; downloaded on April 1, 2017). Thin vertical lines denote the end of the data record for each IPCC assessment. (C) The observed decay rate (1/y) of methylchloroform (CH₃CCl₃) calculated following ref. 22 for 2000–2016, showing monthly (blue dots with uncertainty) and 12-mo running average (thick black line). The anomaly about the average decay rate (dashed gray line) is labeled in percentage on the right axis. Note that a 5% anomaly sustained for 1 y would cause a 10 ppb change in CH₄.

^aDepartment of Earth System Science, University of California, Irvine, CA 92697; and ^bDepartment of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL 32306

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¹To whom correspondence should be addressed. Email: mprather@uci.edu.

identifies a likely causal explanation for the OH trends. In these inverse models, the OH levels are determined from an optimization that uses the observed decay of methylchloroform (CH_3CCl_3) (MCF) and prior estimates of MCF emissions. When integrating atmospheric chemistry over this period with 3D models that spatially and chemically resolve the atmosphere and incorporate our best knowledge of weather, climate, and human activity (e.g., refs. 13, 23, 26, and 27), these models predict much less decadal-scale OH variability and no clear peak in the mid-2000s. So we might conclude that an important process, some chemistry–climate feedback, is missing from the 3D models.

The Bayesian models used in these new papers reduce the available observations into hemispheric averages (24, 25), which makes their complex statistical methods computationally tractable. However, the spatial distributions of methane, its isotopes, and MCF may contain additional information that can distinguish between the alternative scenarios and provide causal explanations for the inferred OH trends. For example, 3D global atmospheric models show that MCF decay responds to the observed changes in tropical temperatures and water vapor, increasing in a warmer, wetter world. Also, the feedback of the primary isotope of methane on OH is well established (3, 28–30), and it increases the impact of emissions by 40% compared with the lifetime derived from MCF decay. The difficulty lies in deciding which of the many 3D model results provides the most useful priors.

In terms of deriving the change in methane loss frequency, one can prefer the most straightforward result, that is, that the decay rate of MCF (Fig. 1C) is simply a measure of the change in OH loss frequency. This Occam's razor principle (*lex parsimoniae*) has the fewest assumptions and makes it more readily tested and falsified. What assumptions are needed for this MCF decay to include larger changes in the OH loss frequency than those observed (e.g., $\pm 4\%$ maximum range)? Basically, the MCF decay rate can be perturbed by (i) a change in the globally integrated concentration of OH times the reaction rate (a sensitive function of temperature), (ii) continuing emissions of MCF, and (iii) large-scale redistribution of mass of MCF by atmospheric transport.

For *i*, a shift in the mean tropical temperatures (where most MCF and methane is destroyed) or a shift in the 4D correlation of OH and temperature could alter the MCF decay rate. For *iii*, one must recognize that our measurements of MCF are made at the surface and do not discern vertical gradients or the relative amounts in the stratosphere. Fluctuations in such mixing rates are not documented, but they could alter the apparent decay rate. The new models here use option *ii* to alter the decay rate and thus predict trends in OH. The problem with *ii* is that, to be effective, the continuing MCF emissions must follow the same decay rate as atmospheric MCF over 15 y. If emissions decayed more slowly, then they would produce a very large negative

signal at the end of the record (and this may explain the 2012–2015 record); if more quickly, then they would have little influence on the decay rate after 2000. The proposal that the residual emissions from the phased-out industrial production of MCF would follow the chemically driven decay rate over 3 e-folds to an accuracy of $\pm 4\%$ may be correct, but it is certainly in contrast to the principle of Occam's razor. Indeed, the paper by Turner et al. (25) considers the parsimonious case that methane loss frequency is constant over the period and they find a nearly optimal solution.

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On the other hand, why should the solution to the MCF–methane system be simple? In contrast to Occam's razor, textual scholars generally recognize that, when two transcriptions of a manuscript differ, the more difficult version (*lectio difficilior*) is often the more accurate rendering of the original because there is a human tendency to want to simplify the complex. Perhaps a preference for the simple reading of the MCF decay is simply a bias for the simplest explanation to a complex problem. Indeed, Turner et al. (25) show that counterintuitive solutions can still be statistically optimal, with large emissions occurring during the pause in methane growth being offset by even larger increases in OH, clearly *lectio difficilior* instead of *lex parsimoniae*.

It would be helpful for the next climate assessment [Sixth Assessment Report (AR6), 2021] if the community could convincingly establish the role of OH changes in methane trends and then identify causes so that future OH levels can be projected along climate scenarios. We posit that the methodology used here—that of Bayesian inverse box-modeling of an underdetermined system driven by prior assumptions—needs to be pushed closer to the real world and to the climate changes or human actions that alter methane emissions and OH levels. For instance, a specific year's variation, such as lightning production of nitric oxides or biomass burning, could be included as part of the prior data, with uncertainties based on the 3D models as to how that impacts OH. It is time to move on from the “could be” optimal solutions to the “how” and “why” solutions.

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- 1 Watson RT, Rodhe H, Oeschger H, Siegenthaler U (1990) Greenhouse gases and aerosols. *Climate Change: The IPCC Scientific Report*, eds Houghton JT, Jenkins GT, Ephraums JJ (Cambridge Univ Press, Cambridge, UK), Chap 1, pp 1–40.
- 2 Prather M, et al. (1995) Other trace gases and atmospheric chemistry. *Climate Change 1994, Intergovernmental Panel on Climate Change*, eds Houghton JT, et al. (Cambridge Univ. Press, Cambridge, UK), pp 73–126.
- 3 Prather M, et al. (2001) Atmospheric chemistry and greenhouse gases. *Climate Change 2001: The Scientific Basis. Third Assessment Report of the Intergovernmental Panel on Climate Change*, eds Houghton JT, et al. (Cambridge Univ Press, Cambridge, UK), Chap 4, pp 239–287.
- 4 Forster P, et al. (2007) Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis. Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Solomon S, Qin D, Manning M (Cambridge Univ Press, Cambridge, UK), pp 129–234.
- 5 Ciais P, et al. (2013) Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis, IPCC WGI Contribution to the Fifth Assessment Report*, eds Stocker TF, et al. (Cambridge Univ Press, Cambridge, UK), pp 465–570.
- 6 Shindell D, et al. (2012) Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335:183–189.
- 7 Penner JE, et al. (2010) Short-lived uncertainty? *Nat Geosci* 3:587–588.

