Aerosol Forcing: Still Uncertain, Still Relevant

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Abstract

Under the auspices of WCRP Grand challenge on Clouds, circulation and climate sensitivity, a selection of experts have made an unprecedented effort to bound the global radiative forcing by atmospheric aerosol, presented in Bellouin et al. (2019, https://doi.org/10.1029/2019RG000660). In addition to an updated interval, confirming the progress made in the field, a main strength of the assessment is the conceptual framework, that with clarity invites to further range refinement. The sense of conflict between process understanding and large-scale effects, between bottom-up and top-down approaches, becomes evident and the review shows that both approaches are necessary, but neither is sufficient.

Plain Language Summary

Atmospheric aerosols are known to counteract the warming from increasing levels of greenhouse gases, but the degree of compensation is uncertain. A recent assessment in Reviews of Geophysics, compiled by a selection of experts in the field, provides an updated estimate of the climate effect of aerosols. The review sets up a useful framework that can encompass the broad range of possible pathways for aerosol influence on Earth’s energy budget and climate: cooling and heating by reflection and absorption of solar radiation and alteration of cloud properties. However, the uncertainty in estimated aerosol forcing lingers. Aerosol effects on climate are inherently difficult to quantify, being global-scale manifestations of a number of microscale processes that are partially counteracting each other and that are closely intertwined with meteorological variability. In addition, the quantification of the aerosol forcing is dependent on a preindustrial state that we cannot go back and observe. Therefore, it is essential to combine modeling and observations over a range of scales and to explore naturally occurring analogies to the aerosol forcing over the industrial era, to further improve understanding of relevant aerosol processes, distinguish processes that actually matter on global scale, and better constrain aerosol effects on climate.

1. Introduction

Atmospheric aerosols, liquid or solid particles suspended in the air, are an integral part of the Earth-atmosphere system. Efficient sinks in dry and wet deposition lead to short residence times and a heterogenous geographical distribution of different aerosol types, including wind-blown dust and sea spray, soot and sulfate from biomass burning and industrial activity, organic species from a range of biogenetic and anthropogenic sources, and more (see e.g., IPCC, 2013). Aerosols have a noticeable impact on visibility, and they also have significant negative effects on human health, affecting the respiratory organs and causing diseases and premature deaths worldwide (Goodman & Hänninen, 2014).

In addition, aerosols, through their interaction with radiation and through their role in cloud formation, affect climate. Alterations of amount and composition of atmospheric aerosol from preindustrial (PI) to present day (PD) due to human activity make aerosols a forcing agent, contributing to anthropogenic climate change by offsetting to an uncertain degree the better-constrained forcing by greenhouse gases (GHG). Thereby, the aerosol forcing is directly linked to the transient climate response and sensitivity and its inference from the observational record. In coarse terms, a large negative aerosol forcing suggests that the observed temperature change over the industrial era is the response to a small total forcing, indicating a large climate sensitivity, whereas a small negative aerosol forcing contrarily indicates a small climate sensitivity. The poorly constrained net aerosol forcing hereby hampers not only our ability to predict future aerosol impacts, but also any top-down attempt to quantify climate sensitivity. Although not made explicit by Bellouin et al. (2019), this is surely a strong motivation for the attempt at a tighter constraint.
2. Conceptual Framework

Aerosol forcing has been a topic of study for decades, and we, as a community, have certainly come a long way. In the first IPCC assessment report (IPCC, 1990), the climate effects of aerosols in general, and soot and sulphate in particular, were recognized, but quantitative estimates of their direct (scattering and absorption) and indirect (altered cloud properties) forcing were not given. As evident from the following IPCC reports, the scientific understanding has since steadily increased. More aerosol species have been mapped, and more possible modes of interaction with climate have been explored, but the estimates of aerosol radiative forcing have remained uncertain. The review by Bellouin et al. (2019) presents a range from \(-1.6\) to \(-0.65\) W/m\(^2\), (68% confidence interval), which is similar in width to the interval given in IPCC (2013) but shifted to slightly more negative values.

Bellouin et al. (2019) build on the conceptual framework introduced in IPCC (2013), of effective radiative forcing (ERF) as the sum of radiative forcing from aerosol-radiation interactions (RF\(_{ari}\), i.e., scattering and absorption) and rapid adjustments to RF\(_{ari}\) (semidirect effects such as cloud thinning/thickening due to aerosol heating) and aerosol-cloud interactions (RF\(_{aci}\), cloud brightening due to more numerous and smaller cloud droplets) and rapid adjustments to RF\(_{aci}\) (separating effects on cloud fraction and liquid water path and including suppression of precipitation and enhanced cloud-top turbulence and entrainment). In the equation, \(\tau_a\) denotes aerosol optical depth, R net radiative flux, \(N_d\) cloud droplet number, variables S sensitivities, and variables c effective cloud fractions. As described in Bellouin et al. (2019), in the diagram, blue and orange arrows indicate shortwave and longwave fluxes, respectively, and solid for initial and dashed for adjusted fluxes. Note that aerosol interactions with ice and mixed-phase clouds (including increased reflection and emissivity from more numerous ice crystals, as well as potential aerosol impacts on convection) are not accounted for. Aerosol-surface interactions via alteration in snow and ice properties from aerosol deposition are also not considered. Figure based on IPCC (2013), Ch. 7. fig. 3.

3. Estimating the Unobservable

One key problem in determining the aerosol forcing is the fact that it is defined in relation to a PI state that is not directly observable. Ice cores and other historical and paleoclimate records give valuable guidance (e.g.,

\[
ERF = \Delta \tau_a \left[ \xi_{clear} (1 - c_r) + \xi_{cloudy} c_r + \frac{dR}{d\tau_a} \right] + \Delta \ln N_d \left[ S_{NF} c_N + S_{C,N} c_r + S_{L,W} c_L + \ldots \right]
\]
McConnell et al., 2007; Duan et al., 2007), but their interpretation is complicated not least by the regionally varying distribution of aerosols. Hence, even if the numerous process sensitivities summarized in Figure 1 could be perfectly quantified, the quantification of the change in aerosol from PI to PD would remain outstanding.

In Bellouin et al. (2019), this problem is concentrated to the determination of $\Delta \tau_a$, the change in aerosol optical depth from PI to PD, which is done by way of relating $\Delta \tau_a$ to $\tau_{a,PD}$ (PD aerosol optical depth). In their fig. 4, $\Delta \tau_a$ is inferred from a linear fit to $\tau_{a,PD}$ in a perturbed physics ensemble (PPE) of the HadGEM, and an observational range for $\tau_{a,PD}$ is used to constrain the estimated $\Delta \tau_a$. Two single-realization ensembles of general circulation models (CMIP5 and AeroCom II) vaguely support a linearity, but the linear relation is still afflicted with uncertainty. Further, the model supplying the PPE is an outlier, with central values of $\tau_{a,PD}$ and $\Delta \tau_a$ far from the multimodel means and $\tau_{a,PD}$ far from the observed range. To alleviate issues of a high bias in the PPE and a potential high bias in observed $\tau_{a,PD}$, a downward adjustment of the derived range for $\Delta \tau_a$ is made.

The importance of the background PI aerosol state for determining aerosol forcing has been pointed out previously (Carslaw et al., 2013; Stevens, 2013). There is ample indication that models tend to underestimate the PI aerosol, for example, due to fire emissions (Hamilton et al., 2018) and biogenic new particle formation (Gordon et al., 2016; Kirkby et al., 2016), rendering a too large PI-PD difference and forcing. Hence, the downward shift of the $\Delta \tau_a$ interval made by Bellouin et al. (2019) may well be reasonable, but could use further support. Additional PPEs based on other models, accounting for physical uncertainty, would be expensive, but beneficial in elucidating the contribution of structural uncertainty to the HadGEM PPE bias.

There are also promising alternative ways towards constraints, e.g. using the remote Southern ocean as an analogy for the unperturbed PI aerosol state, and relating the hemispheric difference to the PI-PD difference in models as currently explored by I. McCoy, D. McCoy and colleagues.

In Bellouin et al. (2019) the uncertainty from the inference of $\Delta \tau_a$ propagates through the calculation of ERF, as it appears explicitly or implicitly in all terms of eq. 8, and the bottom-up approach is hence fully dependent on it.

Any attempt at a constraint of an unobservable, based on one or several complex models will also be limited by the problem of equivariance, that is, that many different and deviating models or parameter settings may satisfy the constraint (Beven & Freer, 2001). This has been demonstrated not least for radiative forcing, for which the constraining power by observed aerosol concentration is limited (Lee et al., 2016) and calls for multiple, relational, and process-related constraints (Johnson et al., 2018).

4. Separating Intertwined Processes

Another category of problems with bottom-up approaches relates to the vast gap between the microscale where aerosol-radiation and aerosol-cloud interaction processes take place and the regional to global scale of climatic relevance. It has been shown that in global models that include parameterizations of individual aerosol-cloud interaction processes, these effects protrude to larger scales in a way that is not supported by observations (e.g., Bender et al., 2016, 2019), illustrating the conflict between process scale and analysis scale, (the “scale problem,” McComiskey & Feingold, 2012). Related to this is the action and counteraction of individual processes, resulting in a buffering of aerosol effects on clouds, which will not be captured by models that are inherently unable to account for the effects of all subgrid-scale processes (Stevens & Feingold, 2009), and also the confoundment between aerosol-cloud interaction and cloud variations induced by meteorological variability unrelated to aerosol, the so-called cloud problem (Stevens & Brenguier, 2009).

In CMIP5 models, indeed, more sophisticated aerosol representation has been found to coincide with better agreement with observed temperature evolution (Ekman, 2014; Wilcox et al., 2013). But correlation is not causation, and a simpler representation may be more beneficial than a complex one, in that the latter may result in exaggeration of the processes represented, with a false sense of certainty. Bellouin et al. (2019) recognize the difficulty of translating small-scale results to global averages, but it remains unsolved, and the community needs to address this problem better, by model hierarchies (in analogy with Held, 2005) and observational scale transitions. To circumvent the “cloud problem,” higher resolution modeling on global scale, which is currently developing, will be essential.
5. Not all Aerosols Are the Same

An example of process inclusion that is important, but somewhat overlooked in this review, is the separation between absorbing and scattering aerosols. As pointed out by Bellouin et al. (2019), estimates of the vertically integrated aerosol absorption ($\tau_{\text{abs}}$) have been revised downward in recent years, but observations have shown that radiative forcing from black carbon (BC or soot, the main absorbing aerosol component) may be three times larger at the surface than at top of atmosphere (TOA) (Satheesh & Ramanathan, 2000). This supplies a point of validation for global models, as well as an indication that BC reductions may have beneficial short-term effects on temperature beyond those indicated by its top of atmosphere (TOA) forcing. Aerosol emission reductions are necessary for air quality reasons. For absorbing aerosols—primarily BC, but also the absorbing portion of organic aerosols (brown carbon, e.g., Bahadur et al., 2012; Cho et al., 2019)—this has positive co-benefits for surface temperature, whereas for scattering aerosols, the cleaning of the air will reveal more warming. To avoid surprises, not least on regional scale, we need to understand the processes, which involve separating absorbing and scattering aerosols.

6. Top-Down Constraints: The Way Forward?

Given the problems with bottom-up approaches, it is tempting to seek top-down constraints. Bellouin et al. (2019), after producing a distribution for ERF from bottom-up reasoning in accordance with eq. 8, including all known effects except those on mixed phase and ice clouds, accordingly apply a top-down constraint, which is very powerful.

Based on the argument that temperature increase must be accompanied by positive net forcing (Stevens, 2015), Bellouin et al. (2019) make the assessment that a constraint for consistency with observed changes in temperature should be placed at $-1.6$ W/m$^2$. This is rightly less strict than was originally proposed by Stevens (2015), challenged by, for example, Booth et al. (2018) and Kretzschmar et al. (2017), but effectively cuts off a considerable part of the negative tail of the distribution derived from the other lines of argument.

Although providing a narrower total forcing range, this kind of approach bypasses process understanding—understanding that remains a goal per se and also applies directly to the detailed apprehension of effects of continued changes in aerosol, composition and amount, following altered emissions and meteorological conditions. Process understanding hence needs to be developed alongside top-down constraints, but climate models should avoid attempting the impossible, to represent all surveyed processes. This again rather points at the necessity of tracing processes through scales, in observations and models.

Given the great potential in top-down constraints on forcing, they do indeed deserve to be explored further, but with care so that models are not rejected on the wrong grounds. Refinement may for instance include focusing on one or several shorter time periods of varying aerosol influence, as illustrated by Jiménez-de-la-Cuesta and Mauritsen (2019) with regard to climate sensitivity, and investigated by C. Wallace, L. Wilcox and colleagues for aerosol forcing. Other pathways for top-down constraints to be studied in more detail include making use of analogies to the PI-PD contrast in aerosol, for example, comparing the pristine Southern Hemisphere to the polluted Northern Hemisphere (Feng & Ramanathan, 2010) and further exploring available natural and anthropogenically driven experiments like volcanic eruptions and industrial aerosol emission reductions over the past decades (as in e.g., Toll et al., 2017; Malavelle et al., 2017; McCoy et al., 2018; Bender et al., 2019).

7. Confidence in Statistics

For clarity, and for those inclined to refining the Bellouin et al. (2019) range further, it is important to emphasize how eq. 8 should be used to produce confidence intervals for $\text{ERF}_{\text{abs}}$, $\text{ERF}_{\text{act}}$ and the total ERF. The proper procedure is to assume a distribution for each original contributing factor and then, assuming independence, sample from the joint distribution to calculate an empirical distribution estimating the desired quantity, from which quantiles can be extracted to produce a confidence interval.

Furthermore, the assumptions made regarding the distributions of the contributing factors need to be justified. The underlying data supply a range of information, for example, means and standard deviations,
confidence intervals, and single point estimates, but for none of these cases, a uniform distribution with the given values as end points, as assumed by Bellouin et al. (2019), indicates a distribution with the same variance as the source data. Expanding intervals to 100% does not help; for a continuous distribution as these physical parameters must be assumed to represent, a 100% interval is infinite.

8. Expert Judgment and Expert Selection

In contrast with the latest IPCC reports and the expert elicitation of Morgan et al. (2006), the Bellouin et al. (2019) review does not explicitly refer to expert judgment, but attempts to take a more objective approach. This strive for transparency is honorable, but it is important to recognize that also in this report, there will be elements of subjective judgment at individual and group level. Biases are thereby likely to occur and perhaps even more so when the expert judgment is not made explicit (see e.g., Mach et al., 2017). Nonformalized expert judgment is involved in the Bellouin et al. (2019) assessment, not least in the crucial determination of a range for \( \Delta r_a \), and the similarly influential quantification of the final top-down constraint.

As such, the selection of experts participating is itself a potential source for bias; a different group may have evaluated, interpreted, and emphasized lines of evidence differently. In this context, it is noteworthy that only six out of the 33 selected expert authors are female. The progress from 13% female expert representation in Morgan et al. (2006) to 18% in Bellouin et al. (2019) gives less reason to celebrate than the corresponding progress in understanding aerosol forcing.

9. Conclusion

The framework provided by Bellouin et al. (2019) is elegant, and the formalization into a single equation describing the different components of total aerosol forcing is commendable. Rather than making the list of individual processes and mechanisms for aerosol-cloud interaction ever longer, this review can point at the joint effect of aerosol-cloud interaction adjustments as a main question mark. Aerosol interactions with ice and mixed-phase clouds are also pointed out as an area where knowledge and understanding is still not mature, although available evidence points at a small net effect.

The assessment makes clear, however, that there is not one single pathway to better understanding and constraint of aerosol forcing, but that the way forward will need to have several components. To bridge the gaps between scales, and between models and observations, ideally, future work should include efforts on model and observation hierarchies, multimodel PPEs, high-resolution modeling on global scale, and further exploration of top-down constraints and occurring analogies to the PI-PD contrast in aerosol.

For the aerosol and climate community, the assessment by Bellouin et al. (2019) will not only serve as an anchoring (Kahneman & Klein, 2009; Morgan, 2014), but will also provide a basis for continued fruitful discussions. New pieces of evidence will be added, and refine the range, or maybe even reach beyond it. Outside the community, it is likely that the range is adopted more literally. And at this, the problem remains, that aerosol forcing may correspond to well over 50% of the GHG forcing to date. The good news is that now, we have better justification for this being the case and a better idea of how to proceed.

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