Comment on “Rethinking the Lower Bound on Aerosol Radiative Forcing”

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(Manuscript received 7 September 2016, in final form 4 April 2017)

ABSTRACT

In an influential and interesting study, Stevens (2015) suggested that the global and also Northern Hemi-
spheric warming during the early industrial period implies that the effective radiative forcing ($F_{\text{aer}}$) by an-
thropogenic aerosols in the year 2000 compared to 1850 cannot be more negative than $-1.0 \, \text{W} \, \text{m}^{-2}$. Here
results from phase 5 of the Coupled Model Intercomparison Project are analyzed and it is shown that there is
little relationship between $F_{\text{aer}}$ and the warming trend in the early industrial period in comprehensive climate
models. In particular, some models simulate a warming in the early industrial period despite a strong (very
negative) $F_{\text{aer}}$. The reason for this difference in results is that the global-mean log-linear scaling of $F_{\text{aer}}$ with
anthropogenic sulfur dioxide emissions introduced and used by Stevens tends to produce a substantially larger
aerosol forcing compared to climate models in the first half of the twentieth century, when $SO_2$ emissions were
concentrated over smaller regions. In turn, it shows smaller (less negative) $F_{\text{aer}}$ in the recent period with
comparatively more widespread $SO_2$ emissions.

1. Introduction

Quantitative understanding of climate change during
the industrial era suffers from a highly uncertain effec-
tive radiative forcing (radiative forcing plus adjust-
ments) due to anthropogenic aerosols, $F_{\text{aer}}$ (Boucher
et al. 2013). Stevens (2015, hereinafter S15) proposed
that the temporal and spatial characteristics of the ob-
served warming since preindustrial times provide a
powerful constraint on the total anthropogenic aerosol
forcing. We follow S15 and assume that warming during
the 1860–1950 and 1920–50 periods is largely driven by
anthropogenic forcings, although climate internal vari-
ability and natural forcings should be accounted for
properly. S15 argues that one can exploit the fact that
due to their long lifetime, greenhouse gases accumulate
in the atmosphere whereas, with a lifetime of about
1 week, the forcing by anthropogenic aerosols is closely
related to the emissions. As such, the greenhouse gas
forcing increases gradually over time, but the aerosol
forcing shows more spatial and temporal fluctuations.
Based on process considerations, S15 develops a simple,
zero-dimensional model for the global-mean aerosol
forcing that combines a linear scaling of anthropogenic
global-mean sulfur dioxide emissions to represent the
radiative forcing (RF) due to aerosol–radiation in-
teractions and a logarithmic scaling of the same quantity
to represent the RF due to aerosol–cloud interactions.
The logarithmic contribution is of large importance for
the constraint, since it implies that anthropogenic sulfur
emissions had a relatively larger impact in the early

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industrial period than at later times, when atmospheric sulfate concentrations were already high. The reason to consider a logarithmic scaling is the fact that further increases in cloud condensation nuclei (CCN) concentrations become less effective as CCN concentrations increase. On the one hand, there are more CCN competing for the water vapor, reducing the activation, and on the other hand, cloud albedo is a nonlinear function of cloud optical thickness.

The link between the observed warming and aerosol forcing had been demonstrated earlier (e.g., Schwartz 2012; Forster et al. 2013) and was refined by S15 to focus on the early warming period (until 1950). S15 argues that since globally, as well as for the Northern Hemisphere alone, a steady warming was observed, the aerosol forcing could not have more than offset the greenhouse gas forcing either globally or above the Northern Hemisphere.

The study of Rotstayn et al. (2015) touched on the results of S15 by analyzing model simulations of phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), which called the argument in S15 into question. Rotstayn et al. (2015) suggested—and S15 discussed this argument as well—that threedimensional models (unlike the global-mean model used by S15) allow for transport of aerosol away from pollution sources (several 1000 km considering a lifetime of 1 week and a horizontal wind speed of 10 m s$^{-1}$) into pristine regions. In consequence, the forcing due to aerosol–cloud interactions saturates less quickly than would be the case if aerosols accumulated in the source regions only. Thus, the forcing may scale more or less linearly with emissions for many regions. This is in particular the case for marine clouds downwind of the continents, which are thought to contribute most to the global effective forcing due to aerosol–cloud interactions (e.g., Quaas et al. 2008).

2. Results

Figure 1 shows the relationship (or lack of relationship) between the warming trend from 1860 to 1950, as well as 1920 to 1950, from the historical simulations of CMIP5 averaged globally and over the Northern Hemisphere, respectively, as a function of global-mean \( F_{\text{aer}} \) diagnosed from the difference between the CMIP5 SSTClimAerosol and SSTClim simulations [see Taylor et al. (2012) for a description of these standardized simulations]. The correlation coefficients between \( F_{\text{aer}} \) and temperature trends are 0.04 and 0.06 globally for the 1860–1950 and 1920–50 periods, respectively, and 0.19 and 0.10 for the Northern Hemisphere. For the period 1860 to 1950, the models simulate global warming of between +0.2° and +0.45°C, encompassing the observed value of +0.3°C. The natural variability, as evident by the ensemble spread in warming for a given model, is rather large. For each given model (except one), the range from the ensemble historical simulations encompasses the observed value of the global warming for the period. As Forster et al. (2013) noted earlier, the CMIP5 models do not necessarily perfectly match the observed warming, which allows us to explore the potential relationship (or lack of thereof) between simulated temperature and \( F_{\text{aer}} \) (see also Rotstayn et al. 2015). The Northern Hemisphere analysis suggests that models with an \( F_{\text{aer}} \) less negative than −0.8 W m$^{-2}$ tend to show a too strong warming, and the model with an \( F_{\text{aer}} \) of −1.6 W m$^{-2}$ shows a warming that is too weak for most ensemble members, but the large intermodel variations prevent a strong emergent constraint. Note that this finding that models with a rather strong \( F_{\text{aer}} \) often compare well to observations is not restricted to the early warming period.

Ekman (2014) compared the warming trend 1965–2004 in the models to observations for different subregions of the globe and found that on average NorESM, CSIRO, GFDL-CM3, and HadGEM, which are models with strong \( F_{\text{aer}} \), performed best. This is consistent with the study by Cherian et al. (2014), which investigated the surface solar radiation trends over Europe from 1990 to 2005 and found that HadGEM, CSIRO, and GFDL-CM3 were closest to the observed trend. Wang (2015) also found that a group of models including NorESM, CSIRO, GFDL-CM3, and HadGEM was better at reproducing observed patterns of precipitation changes, compared with a group of models that included a less advanced description of aerosol–cloud interactions. When considering the short period 1920 to 1950, most models show less warming than the observations globally and also, to a lesser extent, for the Northern Hemisphere, but are consistent with the observations. The main conclusion from Fig. 1 is that no lower bound on \( F_{\text{aer}} \) can be inferred from the early anthropogenic warming on the basis of available climate models.

To better understand why the analysis of S15 fails when applied to climate models, we compare the \( F_{\text{aer}} \) from his global-mean model to estimates from climate models. Since no systematic diagnostic of the transient \( F_{\text{aer}} \) is available in CMIP5 [see discussion in Pincus et al. (2016)], we follow the approach of Forster et al. (2013) and Rotstayn et al. (2015) to estimate it for the subset of models analyzed in Fig. 1 for which an additional simulation with only anthropogenic aerosol varying in time over the historical period (historicalAA; Taylor et al. 2012) is available. Using this approximation to the transient \( F_{\text{aer}} \) in its global mean in relationship to anthropogenic SO$_2$ emissions (Fig. 2), we find an
approximately linear, or very slightly sublinear, scaling. When considering continental-scale regions (Fig. 2b), the curves are more bent; that is, they show a more nonlinear behavior (see below for more analysis). Note that the climate models assessed here parameterize the behavior of the cloud response to aerosols as being logarithmic at a local level. While the global-mean behavior is broadly consistent with the S15 model, the latter shows substantially larger aerosol forcing in the 1900–50 period compared to the four climate models; the opposite is found for 2000 for which $F_{aer}$ is assessed (Table 1). Please note that in the models there is a systematic difference between the $F_{aer}$ diagnosed from the dedicated simulations and the one estimated from the transient simulations, the former being about 25% stronger [see Sherwood et al. (2015) for a discussion of...
this difference. S15 simulates for 1950 (average 1945–55) an \( F_a \) that already is 65% (62%) of the \( F_a \) in 2000 (in the transient 1995–2005 period), whereas this ratio is only 34% (41%) in the climate models. The conclusion is that the S15 model shows a behavior that is substantially more logarithmic than the comprehensive models. A plausible reason for this is the large heterogeneity of the aerosol forcing as shown in Fig. 3. While the forcing was concentrated in relatively small regions in the first half of the twentieth century, it is much more spread out at the end of the twentieth century. It is only in small regions, thus, that the forcing is rather logarithmic in the climate models (cf. Fig. 2b), while in its global mean the forcing to a good approximation scales linearly with the anthropogenic sulfur emissions. In the early anthropogenic warming period, and toward the end of the twentieth century, emissions of carbonaceous aerosol, which is not considered in the S15 model, are also rather important (Lamarque et al. 2010; Stevens et al. 2017) and may be a reason for the more linear response in the complex models (Ghan et al. 2013). Carbonaceous aerosols not only have a temporal evolution that may be different from that of sulfate aerosols, but they also contribute a positive radiative forcing that

### Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>( F_a ) (W m(^{-2}))</th>
<th>2000 (W m(^{-2}))</th>
<th>1950 (W m(^{-2}))</th>
<th>1950 (% of ( F_a ))</th>
<th>1950 (% of 2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CanESM2</td>
<td>−0.87</td>
<td>−0.85</td>
<td>−0.46</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>−1.00</td>
<td>−0.80</td>
<td>−0.26</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>−1.41</td>
<td>−0.96</td>
<td>−0.30</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>GFDL CM3</td>
<td>−1.60</td>
<td>−1.23</td>
<td>−0.54</td>
<td>34</td>
<td>44</td>
</tr>
<tr>
<td>Average GCMs</td>
<td>−1.22</td>
<td>−0.96</td>
<td>−0.39</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>S15</td>
<td>−0.81</td>
<td>−0.81</td>
<td>−0.50</td>
<td>62</td>
<td>62</td>
</tr>
</tbody>
</table>
may have masked some of the earlier negative aerosol forcing.

3. Discussion

The discrepancies between the results presented here and those from S15 are due to the difference in the models applied. In his paper, S15 argues that comprehensive models may not be trusted to realistically simulate $F_{aer}$, since many of the relevant processes are poorly constrained. In turn, it may be questioned whether the simple global-mean model of S15 is superior to the comprehensive models assessed here. As such, further research is necessary. Dedicated climate model studies, such as those proposed by Pincus et al. (2016), may be instrumental. In addition, it is imperative to aim at an observationally based constraint of the effective RF by aerosol–cloud interactions (e.g., Quaas 2015) and, at the same time, to better understand the processes relevant for $F_{aer}$.

Acknowledgments. We thank the climate modeling community, PCMDI, and ESGF/WCDC for the CMIP5 results and are grateful to the Climate Research Unit (CRU), University of East Anglia, for providing the temperature observations. We thank Robert Pincus for valuable comments on this study. This work was funded by an ERC starting grant (“QUAERERE”, GA 306284). We thank Bjorn Stevens, Stephanie Fiedler, Stefan Kinne, and an anonymous reviewer for their help in clarifying and improving the manuscript.

REFERENCES


