



ARISTOTLE UNIVERSITY OF THESSALONIKI
SCHOOL OF GEOLOGY

DEPARTMENT OF METEOROLOGY AND
CLIMATOLOGY

School of Geology
541 24 – Thessaloniki
Greece

Tel: +30 2310-998480
e-mail: kalisort@geo.auth.gr

26 May 2026

Dear Editor

We have submitted our revised manuscript with title “*Temperature and radiative responses to anthropogenic aerosols over the Mediterranean Basin based on CMIP6 Earth system models*” for potential publication in Atmospheric Chemistry and Physics. We considered all the comments of the reviewers and there is a detailed response to their comments point by point (see below). We believe that our study represents a significant contribution in our understanding of the temperature amplification over the Mediterranean induced by changes in global emissions of anthropogenic aerosols, and we hope that you will consider our manuscript for publication.

Yours sincerely,

Alkiviadis Kalisoras
Ph.D. Candidate

Reply to O. Haugvaldstad (Reviewer #2)

We would like to thank O. Haugvaldstad for the constructive and helpful comments. The reviewer's contribution is recognized in the acknowledgments of the revised manuscript. Below follows our response point by point. The reviewer's comments are given in *italic* and our response is given in **bold** font.

1) The Reviewer notes: *"I do not find the way ARCSurf and ARCtoa are used and interpreted in the manuscript to be convincing. Quantifying the total radiative response to a change in forcing requires running the model into an equilibrated state. Reaching this adjusted state typically requires simulations on the order of 100 years. Therefore, if one wishes to obtain a representative estimate of the change in ARCSurf associated with an aerosol reduction, a similarly long integration is needed, see e.g. Zhang et al. (2021). In the current setup, however, only a 10-year mean is used. As a result, the diagnosed changes in ARC are not representative of the fully adjusted state, but rather reflect a mixture of fast and incomplete slow responses. In that sense, what is presented could be described as a kind of "quasi-ARC," lying somewhere between ERF and the fully equilibrated ARC. This is not discussed in the manuscript; this also makes it difficult to interpret the physical significance of ARC as used in the manuscript."*

The authors fully agree with the reviewer that the differences between the *historical* and *hist-piAer* simulations are not representative of the fully adjusted state, but rather reflect a mixture of fast and incomplete slow responses. To avoid confusion, we removed the term "total responses" and elaborated on the physical interpretation of the radiative changes calculated from the difference between the coupled experiments. We clarified this point in the revised manuscript as follows:

"Supplementarily with ERF, we calculated the AA-induced change in net radiative fluxes at the top-of-atmosphere and the surface (denoted as $\Delta F_{\text{TOA}}^{\text{coupled}}$ and $\Delta F_{\text{SURF}}^{\text{coupled}}$, respectively) using the same equations as above and by taking the difference between *historical* and *hist-piAer* this time. While ERF depicts the radiative perturbation caused by AAs after accounting for rapid adjustments and fast climate responses (since SSTs and sea ice are prescribed), the net radiative flux differences calculated from the coupled-ocean experiments ($\Delta F_{\text{TOA}}^{\text{coupled}}$ and $\Delta F_{\text{SURF}}^{\text{coupled}}$) quantify a quasi-radiative forcing caused by AAs, accounting for a mixture of fast and incomplete slow responses (due to climate feedbacks and ocean heat uptake) under the evolving transient historical conditions. Hence, the temperature differences from the coupled-ocean experiments represent transient climate responses being far from an equilibrium state (in which the initial radiative aerosol perturbation will be fully absorbed by the climate system response), since the ocean does not have enough time to fully equilibrate to the evolving historical forcings."

In the revised manuscript, ARC is no longer used. We instead use the top-of-atmosphere and surface net radiative fluxes from the coupled runs to diagnose the transient climate responses (including fast and incomplete slow responses). We further elaborate on this in our response to Point 3.

2) The Reviewer notes: *"The attribution changes to AA reductions. If you read the Collins et al. (2017) it states that "The climate impacts of the anthropogenic emissions of NTCFs, aerosols and ozone depleting halocarbons can then be diagnosed by subtracting the perturbed runs from the historical climate and evaluated against internal variability diagnosed from piControl." However, the differences between historical and hist-piAer have not been evaluated against the internal variability of piControl when testing for statistical significance of the presented results."*

We agree with the reviewer that evaluation of the internal variability of each individual model using *piControl* experiments is an important topic but the quantification of individual model uncertainty in the context of internal model variability was beyond the scope of this work. The accurate assessment of individual model uncertainty related to model internal variability would require initial condition large ensemble members from single models. In our multi-model study, we focused on inter-model variability using a comprehensive method commonly applied in the literature (Liu et al., 2018; Myhre et al., 2017; Samset et al., 2018; Szopa et al., 2021). Calculating the multi-model ensemble mean reduces internal model variability, as the averaging suppresses the random/internal component of each individual model (since internal variability is largely uncorrelated across the

different models) and enhances the common forced signal. This is further elaborated in a new paragraph we added to Section 2.2:

“Here, we give emphasis on inter-model variability, and the robustness of the multi-model ensemble results was estimated using a comprehensive method based on statistical significance and the agreement between ESMs on the sign of change. This is a common approach of quantifying uncertainty, and particularly inter-model uncertainty (e.g., Liu et al., 2018; Myhre et al., 2017b; Samset et al., 2018; Szopa et al., 2021). Calculating the multi-model ensemble mean reduces internal model variability, as the averaging suppresses the random/internal component of each individual model (since internal variability is largely uncorrelated across the different models) and enhances the common forced signal. It should be stressed that, although the multi-model mean dampens internal variability, there is still need of further analysis using long-term ensemble of *piControl* experiments (or ensemble spread) for each model to evaluate whether the remaining signal is statistically distinguishable from noise (Collins et al., 2017). The accurate assessment of individual model uncertainty related to model internal variability would require initial condition large ensemble members from single models (Jones et al., 2024; Parsons et al., 2020).”

3) The Reviewer notes: “*I am not convinced by the current description of atmospheric radiative cooling (ARC). In particular, the statement “ARC could also be implemented to quantify the fast radiative responses, but ERF was used for this purpose.” seems to conflate two quantities that, in my view, serve different purposes. ARC and ERF are not interchangeable diagnostics. As we agree, ARC relates to the absorption of radiation within the atmosphere. The key distinction between ARC and ERF becomes especially important for absorbing aerosols (see, for example, Carslaw be identical). For instance, consider a reduction in sulfate, which is a purely scattering aerosol. In that case, there would be no change in ARC: the reduced outgoing TOA SW flux would be balanced by an increased SW flux at the surface. However, this is not the case for changes in absorbing aerosols. In that case, changes in atmospheric absorption modify ARC directly. In an fSST simulation, any change in ARC must be balanced primarily by changes in the surface turbulent fluxes (sensible and latent heat), with the latent heat flux usually dominating. For this reason, changes in ARC are a useful diagnostic for quantifying fast precipitation responses to aerosol perturbations. These are precipitation processes that are relatively well represented in ESMs, since they do not depend directly on cloud microphysical parameterizations. I discuss this point in more detail in my 2025 paper.*”

The authors agree with the reviewer that ARC and ERF are not interchangeable diagnostics. We realized that the whole misunderstanding is due to the decomposition of ARC using definitions of ARC_{SURF} and ARC_{TOA} for the SW and LW (in Eq. 4–7), which are simply the net (SW and LW) radiative fluxes at the top-of-atmosphere and at the surface (based on the coupled *historical* and *hist-piAer* simulations). To eliminate the misconceptions, we removed the ARC analysis and instead focused on aerosol-induced changes in the net radiative fluxes at the top-of-atmosphere and the surface. Without altering the initial scope of our work, we compared ERF with $\Delta F_{coupled}$, which represents the change in downward radiative flux calculated from the difference between the *historical* and *hist-piAer* simulations. In Section 2.2, we explain in detail the rationale behind the use of both ERF and $\Delta F_{coupled}$, and we clarify the definitions and limitations of the two diagnostics (in conjunction with our response to Point 1). While ERF calculated from the *histSST* and *histSST-piAer* experiments depicts the radiative perturbation caused by AAs after accounting for rapid adjustments and fast climate responses (since SSTs and sea ice are prescribed), the net radiative flux differences calculated from the *historical* and *hist-piAer* coupled-ocean experiments quantify a quasi-radiative forcing caused by AAs, accounting for a mixture of fast and incomplete slow responses (due to climate feedbacks and ocean heat uptake) under the evolving transient historical conditions. Finally, we pointed out the limitations of our work in the Conclusions.

References

Collins, W. J., Lamarque, J.-F., Schulz, M., Boucher, O., Eyring, V., Hegglin, M. I., Maycock, A., Myhre, G., Prather, M., Shindell, D., and Smith, S. J.: AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6, *Geosci. Model Dev.*, 10, 585–607, <https://doi.org/10.5194/gmd-10-585-2017>, 2017.

Jones, G. S., Andrews, M. B., Andrews, T., Blockley, E., Ciavarella, A., Christidis, N., Cotterill, D. F., Lott, F. C., Ridley, J., and Stott, P. A.: The HadGEM3-GC3.1 Contribution to the CMIP6 Detection and Attribution Model Intercomparison Project, *Journal of Advances in Modeling Earth Systems*, 16, e2023MS004135, <https://doi.org/10.1029/2023MS004135>, 2024.

Liu, L., Shawki, D., Voulgarakis, A., Kasoar, M., Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Sillmann, J., Aalbergstjø, S. G., Boucher, O., Faluvegi, G., Iversen, T., Kirkevåg, A., Lamarque, J.-F., Olivie, D., Richardson, T., Shindell, D., and Takemura, T.: A PDRMIP Multimodel Study on the Impacts of Regional Aerosol Forcings on Global and Regional Precipitation, *Journal of Climate*, 31, 4429–4447, <https://doi.org/10.1175/JCLI-D-17-0439.1>, 2018.

Myhre, G., Forster, P. M., Samset, B. H., Hodnebrog, Ø., Sillmann, J., Aalbergstjø, S. G., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivie, D., Richardson, T. B., Shindell, D., Shine, K. P., Stjern, C. W., Takemura, T., Voulgarakis, A., and Zwiers, F.: PDRMIP: A Precipitation Driver and Response Model Intercomparison Project—Protocol and Preliminary Results, *Bulletin of the American Meteorological Society*, 98, 1185–1198, <https://doi.org/10.1175/BAMS-D-16-0019.1>, 2017.

Parsons, L. A., Brennan, M. K., Wills, R. C. J., and Proistosescu, C.: Magnitudes and Spatial Patterns of Interdecadal Temperature Variability in CMIP6, *Geophysical Research Letters*, 47, e2019GL086588, <https://doi.org/10.1029/2019GL086588>, 2020.

Samset, B. H., Sand, M., Smith, C. J., Bauer, S. E., Forster, P. M., Fuglestedt, J. S., Osprey, S., and Schleussner, C. - F.: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions, *Geophysical Research Letters*, 45, 1020–1029, <https://doi.org/10.1002/2017GL076079>, 2018.

Szopa, S., Naik, V., Adhikary, B., Artaxo Netto, P. E., Berntsen, T., Collins, W. D., Fuzzi, S., Gallardo, L., Kiendler-Scharr, A., Klimont, Z., Liao, H., Unger, N., and Zanis, P.: Short-lived climate forcers, in: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, Ö., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 817–922, <https://doi.org/10.1017/9781009157896.008>, 2021.