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

28 January 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 I. Pérez (Reviewer #1)

We would like to thank I. Pérez 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: "*The authors should think about procedures to increase the number of potential readers. Perhaps the authors should highlight the reasons for the selected region and they should underline if the procedure could be applied in different areas and they should compare the obtained results with those calculated for other regions.*"

In our study we used AerChemMIP experiments, which incorporate global anthropogenic aerosol emission databases (Hoesly et al., 2018; van Marle et al., 2017). Therefore, our methodology could be applied to any region. The Mediterranean Basin is considered a climate hotspot due to the accelerating surface warming it has experienced during the last decades, especially during the summer. The Mediterranean's sensitivity to global emission changes can have implications for heatwaves, droughts, and the water balance in a future climate state, affecting the lives of over 500 million people. With that in mind, we tried to fill some knowledge gaps in the literature by advancing attribution, mechanistic understanding, and quantification of the Mediterranean warming. Changes have been made to the Introduction to address the reviewer's comment.

2) The Reviewer notes: "*The authors consider the regions with impact on the Mediterranean basin. However, they should indicate the regions beyond Europe influenced by the studied area.*"

Our study focuses on how global anthropogenic aerosol changes have impacted the Mediterranean Basin during the last decades. While European and North American aerosol emissions have significantly decreased since around the 1980s, the changes over the Mediterranean discussed in this paper are induced by aerosol emission changes all over the globe. It is not possible to address how changes over the Mediterranean alone can affect other parts of the world using the AerChemMIP experiments, since the anthropogenic aerosol emissions used in CMIP6 Earth system models are taken from global databases. Therefore, global changes cannot be attributed to changes in emissions over a single source region. There are other experiments one could use for such attribution studies, such as the those developed for the Precipitation Driver Response Model Intercomparison Project (PDRMIP) or the Regional Aerosol Model Intercomparison Project (RAMIP).

3) The Reviewer notes: "*Monthly outputs were used. This period ignores short-term changes and the authors should value if these changes could be noticeable or not.*"

The focus of this study is on radiative, temperature, and circulation responses on climatological and seasonal time scales, rather than on short-term (synoptic or intraseasonal) variability. Anthropogenic aerosol radiative forcing is usually calculated at monthly (or longer) time scale. This is because it reflects persistent changes in atmospheric composition and energy (radiative) balance caused by a climate forcer (in our case anthropogenic aerosols) rather than transient fluctuations driven by weather patterns. Short-term variability at smaller time scales is expected to be dominated by internal atmospheric dynamics and does not significantly affect the multi-annual, ensemble-mean signals examined here. By averaging to monthly means reduces noise, allowing for robust identification of anthropogenic aerosol–induced changes across models. While short-term interactions between anthropogenic aerosols and meteorological processes may influence individual events, they are not expected to substantially alter the magnitude or sign of the long-term mean responses quantified in this work. Our paper focuses on annual and seasonal mean responses (from monthly mean data) over the Mediterranean Basin. Changes in extremes (e.g., daily maximum temperatures, maximum 1-day precipitation, etc.) are not considered here.

4) The Reviewer notes: "*The authors consider two ten-year periods, 1970-1979 and 2005-2014 where a noticeable change of human activity is expected. However, they should indicate if both periods are similar from a meteorological point of view or not, since the atmosphere response depends on both, natural and human processes.*"

The two decades considered in this study were selected to represent periods of contrasting anthropogenic aerosol forcing rather than distinct meteorological regimes. Initially two 20-year periods were used (i.e., 1965-1985 and 1995-2014) consistent with IPCC guidelines and qualitatively similar results were obtained. However, we focused on the periods of maximum (1970-1979) and modern (2005-2014) anthropogenic aerosol forcing to highlight the sensitivity of the Mediterranean to aerosol emission changes. In either case, internal meteorological variability is explicitly accounted for by using multi-model ensemble means and by averaging over ten-year periods, thus substantially reducing the influence of interannual variability associated with natural processes. Furthermore, the use of paired experiments with identical meteorological boundary conditions and forcings except for anthropogenic aerosol emissions (histSST minus histSST-piAer and historical minus hist-piAer) allows attribution of changes to anthropogenic aerosols. The experimental design of AerChemMIP isolates the anthropogenic aerosol contribution to the radiative budget, temperature and circulation irrespective of background meteorological differences between the two periods. As a result, the calculated differences primarily reflect the climate responses to changes in anthropogenic aerosol emissions rather than differences in the underlying meteorological state.

5) The Reviewer notes: "*The main inconvenience is the lack of references in the results section to compare this analysis with previous studies. Perhaps some references could be transferred from other sections to discuss the results or some new references could be introduced.*"

We agree that placing selected references directly in the Results section can help the reader better contextualize our findings relative to previous studies. Therefore, we have revised the Results section to include references where our results confirm, extend, or differ from earlier work.

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.

Essential comments:

Introduction

1) The Reviewer notes: "*The introduction gives a good overview of the literature, however, it does not properly introduce the knowledge gaps that are addressed by the study. Accordingly, the motivation for the present study is not entirely apparent.*"

Our study uses an ensemble of state-of-the-art CMIP6 Earth system models to provide a basin-wide quantification of the Mediterranean warming attributable to global anthropogenic aerosol emission reductions. Previous studies often focused on individual subregions of the Euro-Mediterranean region or used data derived from other sources (reanalysis products or regional climate models). Moreover, this work fills a methodological gap by connecting ERF (fast forcing) to ARC (total atmospheric energy adjustment) and then to vertical and horizontal total temperature responses and circulation responses. This study also addresses the performance of CMIP6 models in simulating the observed annual and seasonal land temperature trends over the Mediterranean by comparing them to observational datasets. This has been one of our main motivations as there is only little literature investigating this aspect. The Introduction was updated to address the reviewer's concerns.

2) The Reviewer notes: "*Line 49 -73: This paragraph lists the finding of several specific studies, however, it is not clear how each of these studies points towards the knowledge gap that the current study addresses, nor are these studies brought up again in the discussion or conclusion. Accordingly this paragraph could likely be shortened and focused toward the knowledge gaps that will be addressed through the objectives defined in the next paragraph. For example; what do the previous studies miss by not examining the fast and slow temperature responses to AA reductions jointly?*"

A new paragraph has been added in the Introduction focusing on the knowledge gaps from previous studies that are investigated in our study (see also our reply to Comment #1):

"Despite the plethora of studies investigating aerosol-driven changes over the Euro-Mediterranean region, there still remain several knowledge gaps: a) how do global climate models simulate the Mediterranean response to global anthropogenic aerosol emission changes on basin-wide scale, b) how do changes in aerosol optical depth, the radiative budget, and atmospheric circulation translate to horizontal and vertical temperature changes over the Mediterranean, c) how well do climate models perform when simulating the observed land temperature amplification on annual and seasonal scales?"

Data and Methodology

3) The Reviewer notes: "*The data and methodology covers the metrics and datasets used. However, the text could benefit from being more concise and understandable. For instance, rather than citing Eyring et al., 2016 and Collins et al 2017, repeatedly when referring to AerChemMIP and CMIP6, just use the name of the MIP instead of the reference.*"

The text was revised accordingly as suggested by the reviewer.

4) The Reviewer notes: "*When referring to names of the different model experiments, it would be more appropriate to use italic to emphasize the names rather than double quotes.*"

The manuscript (including table and figure captions) was revised accordingly as suggested by the reviewer.

5) The Reviewer notes: "*On line 104-105: It is not necessary to repeat that AerChemMIP has fixed SSTs and sea ice concentration. Just mention this one when the AerChemMIP simulations are introduced on line 100.*"

Lines 104-105 expand on the definition of prescribed SSTs and are not a simple repetition. It is essential that the *historical* experiment is described before it is explained that "SSTs and sea ice are prescribed to the monthly mean time-evolving values from the corresponding *historical* simulation of each model".

6) The Reviewer notes: "*On line 126-138: Avoid repeating the definition of ERF several times within the same paragraph.*"

It was revised accordingly as suggested by the reviewer.

7) The Reviewer notes: "*On line 149: ARC is defined in the manuscript as "ARC is defined as the net shortwave (SW) and longwave (LW) radiation loss of the atmospheric column", which is the common definition in the literature. Accordingly, from this definition, ARC should be the difference between the net radiative flux at the top-of-the-atmosphere and surface. However in Eq. 3 the authors introduce a new terminology of ARC_{TOA}^{NET} and ARC_{SURF}^{NET}, which in the manuscript simply refers to the net radiative flux at TOA and surface respectively when calculated from the hist-pier/ historically fully coupled simulations. Using the term ARC in this new context is confusing, since this is not actually radiative loss of the atmosphere. Furthermore, ARC does not strictly imply that it is derived from a coupled fully coupled simulation, as it is common to compare ARC from fSST simulations to examine fast versus slow precipitation responses. Therefore, it would be advisable to use a different terminology than ARC_{TOA}^{NET} and ARC_{SURF}^{NET} referring to radiative perturbations in this manuscript.*"

It is true that ARC does not need to be calculated strictly from coupled simulations. However, in our study we used ERF as a standard metric for the fast forcing due to anthropogenic aerosols, which (by definition) is calculated only from prescribed/fixed-SST simulations. To investigate the total forcing due to anthropogenic aerosols we therefore used another standard metric — ARC — calculated from coupled simulations because we already used ERF to calculate fast responses to the radiative budget. We did not intend to imply that ARC can only be calculated from coupled simulations. This paragraph was updated to clarify the above.

When it comes to the definition of ARC, we used it as a standard metric of the radiative loss of the atmosphere without deviating from its common definition in existing literature. We do not introduce a new terminology of ARC_{TOA}^{NET} and ARC_{SURF}^{NET}; we merely consider the energy flux as positive when exiting the atmospheric column (i.e., upward positive at TOA and downward positive at the surface). In previous studies SW and LW fluxes were considered positive towards opposite directions both at TOA and surface, and hence the need for subtraction (i.e., "the difference between the net radiative flux at the top-of-the-atmosphere and surface"). In Eq. 3, we calculated the sum of ARC_{TOA}^{NET} and ARC_{SURF}^{NET} as the former is positive upwards and the latter positive downwards. We simply changed the sign of one term without changing its physical interpretation. We believe that it would be easier for the reader to follow the discussion on ARC changes if both quantities were consistently considered positive when exiting the atmospheric column. This was clarified in the main text.

Results

8) The Reviewer notes: "*Overall the figures and results are well described and of good quality. However, due to very information dense and lengthy paragraphs that often span several figures and sometimes going back and forth between them, the section overall is very challenging to read. This was not helped by several paragraphs ending without any particular conclusion. The authors are advised to closely re-examine each paragraph and provide a red thread for the reader to follow.*"

The Results section was modified to provide a more linear reading of the manuscript.

3.1 Radiative changes

9) The Reviewer notes: "*The title of the subsection is not very informative, so it would be advisable to choose a title that relates to a research question.*"

We divided the Results section into more subsections where discrete topics are discussed.

10) The Reviewer notes: "*Line 180 - 183: ~~As described earlier,~~ AA concentrations peaked in the late 1970s to early 1980s in Europe and the MED. Consequently, AOD change reaches a maximum during that period (Fig. 1, left column). The AOD maximum ~~which is stronger~~ is larger in magnitude during the boreal summer (JJA) than the winter (DJF). Likewise, the transient annual mean ERF both at TOA and surface attained its most negative values during the late 1970s - early 1980s ~~on an annual basis~~, dominated by the evolution of ERF in JJA (Fig. 1, middle column).*"

It was revised accordingly as suggested by the reviewer.

11) The Reviewer notes: "*Line 183-185: Not sure what is the new information in this sentence, perhaps remove?*"

The new information is that ERF_{SURF} is weaker than ERF_{TOA} during the winter of 1975 – 1985 (in contrast to JJA and annual ERF_{SURF}). We have clarified this in the main text.

12) The Reviewer notes: "*Line 185-189: Here, one example of text that is very difficult for a reader to understand due to jumping between topics within the same sentence, e.g. inter-model spread, temporal evolution, magnitude of the ERF peak and ARC. This makes the paragraph as a whole difficult to comprehend. This could be simplified by for instance only describing the ERF and then in the next paragraph describing ARC.*"

It was revised accordingly as suggested by the reviewer.

13) The Reviewer notes: "*Line 207-209: The first sentence sets the expectation that the spatial pattern of ERF will be described next, then the reader would expect that the following sentence would build on this. However here the reader gets led astray when this sentence is followed by a listing of more tables and figures.*"

The second sentence ("The annual area-weighted … and 6 (for JJA).") was removed.

14) The Reviewer notes: "*Line 233 -268: This paragraph needs to be broken down into smaller paragraphs.*"

It was revised accordingly as suggested by the reviewer.

3.2 Temperature changes

15) The Reviewer notes: "*Again, the title of this section is not very informative. The section is started off by another massive paragraph, which is difficult to navigate. Overall, this section is as challenging to read as the previous section.*"

Same as Comment #9.

16) The Reviewer notes: "*It would also benefit more from a discussion that compares the findings of this study with previous studies.*"

It was revised accordingly as suggested by the reviewer.

4. Conclusion

17) The Reviewer notes: "*The conclusion gives a good summary of the findings of the study, however, what is lacking is the context from the literature. The conclusion does not fully answer the objective of the manuscript defined in the introduction, in particular with respect to quantifying the fast and total radiative response of global changes in AA emission. If this is written in the introduction, then there is an expectation that this will be brought up again in the conclusions.*"

We agree with the reviewer and have revised the Conclusions section to explicitly reconnect with the objectives stated in the Introduction. We now clearly summarize and quantify both the fast radiative response (ERF) and the total atmospheric energy response (ARC) to global anthropogenic aerosol emission changes, and place these results in the context of previous studies focusing on aerosol-driven changes over the Mediterranean.

Minor typographical comment:

18) The Reviewer notes: "*The manuscript uses hyphens in places where an en dash is typographically correct (for example "1980-2000"). Please replace hyphens with en dashes for numeric ranges (1980–2000), similarly hyphens should not be used for minus signs. Use hyphens only for compound words and em dashes for clause breaks.*"

The manuscript (including tables and figures) was revised accordingly as suggested by the reviewer. En dashes are now used for numeric ranges and minus signs.

References

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geoscientific Model Development, 11, 369–408, https://doi.org/10.5194/gmd-11-369-2018, 2018.

van Marle, M. J. E., Kloster, S., Magi, B. I., Marlon, J. R., Daniau, A.-L., Field, R. D., Arneth, A., Forrest, M., Hantson, S., Kehrwald, N. M., Knorr, W., Lasslop, G., Li, F., Mangeon, S., Yue, C., Kaiser, J. W., and van der Werf, G. R.: Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750–2015), Geoscientific Model Development, 10, 3329–3357, https://doi.org/10.5194/gmd-10-3329-2017, 2017.