Response to reviewers' comments.

We hereby provide a detailed response to the comments given by the two reviewers to the manuscript "Revisiting the Historical Drying of the Mediterranean in the LESFMIP Simulations". The reviewer's original text is presented in **bold**, and our responses are given inline, including major text changes we made in the manuscript.

Report #1

In this manuscript, the authors investigated the contributions of GHG and AER to the Mediterranean drying with LESFMIP output. The authors have revised once and I joined in the second round. I read the whole manuscript and the authors response to earlier comments. However, the manuscript still needs substantial revisions before the acceptance of publication. My comments are listed below:

(1) The major issue with the current manuscript is that it is not focused, and many irrelevant contents are presented which may distract the logic flow of the manuscript. Half of the manuscript is discussing the inter-model spread of the precipitation response. If the inter-model spread is large, does that mean your results in the Figure 4 is not reliable? In the title, abstract and introduction section, the authors clearly say that this work is mainly focused on winter time precip change. But in the manuscript, the precip change in other seasons are presented. In addition, the relative contributions of each forcing agent are not fully summarized. The authors conclude that GHGs lead to a 15% reduction in precipitation and much of it is offset by aerosols. What are the contributions of other forcing agents, what is the total precipitation change, and to what extent, the aerosols counteracted the effect of GHGs?

The reviewer notes that the major issue with the manuscript is that it is not focused, and raises three points explaining that. We thank the reviewer for the comment. It allows us to better clarify the context of the work and to improve the introduction of the methodology of the simulations analysis, thus making the content of the rest of the work more focused. We shall relate and answer the specific points raised by the reviewer one by one:

(a) The reviewer raises a question regarding Figure 4 being not reliable in light of the results that follow it. To answer this comment, we note that Figure 4 is the first part in our analysis: the analysis in the current work is based on a total of 240-400 individual simulations for the different experiments. These are the results from about 10 climate models, each of which include 10-55 ensemble members, which allow us for the first time to assess the extent that the different models agree with each other. Given this amount of data, we present the results in this manuscript in a hierarchical/"focused" manner: the multi-model mean (figures 1 and 4) is presented first to get a coarse picture, along with model-agreement and standard deviation marks (stippling and grey contours). Then, the individual models ensemble means are analyzed for a more detailed view, and last, the individual ensemble members of all models are treated, for the most detailed analysis. Thus, the purpose of figure 4 (as well as figure 1) is to show the coarse picture; the results presented in the figure, including the models-agreement stippling and the standard deviation contours, evaluate the inter-model spread. In that sense, Figure 4 is not 'not reliable', but is the first, concise, stage in presenting the results from 10 models and 240-400 individual simulations. To address this comment, we rewrite the text in the Data and Methodology section between lines 107-121 to better explain the stages and structure of the data analysis to the reader. The added text includes:

> "*Given the extensive amount of simulated data, the LESFMIP data is analyzed, and the corresponding results are presented, in a hierarchical manner. First, we analyze the multi-model mean to get a coarse picture: for each single-forcing experiment, and for the all-forcings run, we calculate the seasonal (…) multi-model means of the responses (1990-2014 vs. 1851-1920) for the precipitation and sea-level pressure fields. The multi-model mean responses allow to asses the relative contribution of each of the single forcings for the response over the NA, Europe and the Mediterranean. The multi-model mean is complemented with a model-agreement measure and the intermodel standard deviation. Second, for each model separately, we calculate the wintertime (DJF) ensemble mean responses for the eastward component of the wind at 700 hPa, sea-level pressure, near-surface temperature, and precipitation for the hist-GHG, hist-aer, and the all-forcings experiments, focusing on the above-mentioned regions. As shown below, the individual-models reveal a substantial intermodel spread in the forced responses in these regions. This intermodel spread motivates the third and last step of the analysis, where the individual ensemble members of each individual model provide the most detailed view. Namely, we regress the wintertime response of the Mediterranean region PSL with the wintertime responses of 9 large-scale climatic measures/metrics that previous literature has linked to Mediterranean drying*"

(b) The reviewer further comments that the manuscript presents results for seasons other than the wintertime although in the title, abstract and introduction we focus on the winter season. We fully accept the reviewer's comment. Accordingly, we update figures 1, 2, and 4 such that they now include only results that correspond to the boreal winter season (DJF). The figures that also include results for the other seasons are moved to the Supplemental text. We also adapted the manuscript results text to be focused on wintertime only.

(c) The reviewer comments that the relative contributions of forcings other than GHG and aerosols for the precipitation response are not fully summarized and asks for their contributions and for the total precipitation change. Following the reviewer's comment, we complement Table 2 of the manuscript with the precipitation responses of the other forcings, based on their availability in the LESFMIP dataset. The responses are also updated for the historical (all-forcings) experiment. Typically, the precipitation responses in the other forcings are much smaller than these for GHG and aerosols. We update the manuscript with relevant text, and also relate to the lack of additivity of the single forcings responses relative to the all-forcings (lines 252-255). For a more fluent presentation of the results, Table 2 and the corresponding text are moved to the beginning of section 3.2 ("single-model ensemble means historical responses").

(2) Only Figure 4 is focused on the main goal of the question. However, what is the mechanisms behind the drying due to GHGs or the offset of the aerosols. The authors analyzed several other indices, but did not clearly show the mechanisms. How does the 2m temperature (or warming hole), land-sea temperature contrast, zonal wind or polar vortex modify the precipitation over Mediterranean?

The reviewer asks for the mechanism behind the drying due to GHG or aerosols, and about the mechanisms that link the precipitation response and the analyzed indices. Following the reviewer's comment we overhauled the Introduction section to include a more systematic review on the mechanisms that govern the Mediterranean precipitation in response to GHGs and aerosols as published based on previous studies (lines 28-51). The updated text includes:

> *"The wintertime Mediterranean precipitation response to global warming forced by increasing GHGs concentrations has been associated with several distinct but likely complementary dynamical pathways. \citet{seager_14} explain the projected drying over the Mediterranean based on a low level high anomaly and subsidence over the eastern Mediterranean that is responsible for a mean flow mass and moisture divergence anomaly. \citet{kushnir_15} associates the poleward expansion of the sinking branch of the Hadley cell under greenhouse warming \citep{lu_07} with weakening of the Mediterranean trough, suppression of cyclone activity, and reduction of precipitation. In addition, under climate change, the projected wintertime precipitation reduction in the eastern Mediterranean is associated with a*

decrease in the number of cyclones and in the precipitation per individual cyclone \citep{zappa_15a}. \cite{tang_18} suggest that the wintertime precipitation reduction in the Mediterranean in response to GHGs is due to a northward shift of the jet stream and storm track, caused by an enhanced sea level pressure in the North Atlantic and Mediterranean, local heating, and lower sea level pressure pattern in northern Europe. \cite{tuel_20} argue that slower-paced warming over the Mediterranean relative to adjacent land regions (i.e., relative Mediterranean cooling) will lead to a local ridge centered over the Mediterranean and, as a result, a precipitation decline. An additional mechanism involves regional SST changes in the North Atlantic: \citet{delworth_22} find that a weakened AMOC and the subsequent atmospheric response to the North Atlantic warming hole drive reduced precipitation over the Mediterranean \citep{keller_25}. Overall, the dynamical mechanisms that underlie the Mediterranean drying, as well as the drying across the subtropics in general \citep{seager_19, he_17}, are not yet fully understood and are still under active research, even as the uncertainty in future hydroclimate in these regions is driven almost exclusively by uncertainty in dynamical changes \citep{elbaum_22}. In other regions, climate drivers other than GHGs have been shown to play a large, and in some cases dominant, role in historical and future trends \citep[e.g.,][]{Kang_24}. An increase of the wintertime Mediterranean precipitation was found by \cite{Westervelt_18} in two out of three models in response to local reduction of aerosol emissions. Similarly, \citet{tang_18} find that adding global aerosols leads to reduced precipitation in this region. Such findings motivate the examination of the role of aerosols (among other drivers) on the large-scale atmospheric circulation and on decadal to centennial changes across the Mediterranean. "

With respect to the indices that we analyze in relation to the Mediterranean drying, we noted originally in the Data and Methodology section that these indices were previously linked to precipitation change in the Mediterranean. We now stress this point also in the Introduction section (lines 82-84). In addition, in the Data and Methodology section we specified the definitions of these indices and included relevant references for previous studies. For the various indices that we take into account, there exist published studies that discuss potential mechanisms for their role for the precipitation response. Following the reviewer comment, we now add a more detailed description regarding these mechanisms for each of the indices listed in the Data and Methodology section, including the relevant literature references (lines 131-187). This text includes:

"Mediterranean region land-ocean near surface temperature contrast: \cite{tuel_20} argue that slower-paced warming over the Mediterranean relative to adjacent land regions (i.e., Mediterranean cooling) will lead to a local ridge centered over the Mediterranean and, as a result, a precipitation decline. The circulation response was shown to be triggered by the wintertime low static stability over the basin, allowing the local cooling to propagate from the surface into the troposphere \citep{tuel_21}.

…

the warming hole influences the Atlantic storm track and has been mechanistically linked to the ridge over Europe \citep{Gervais:2019,keller_25}. Specifically, based on the thermodynamic budget, \citet{keller_25} conclude that the warming-hole cools the lower troposphere downstream of its location which, in turn, weakens the low-level winter zonal temperature gradient between the Atlantic Ocean and Europe; this altered zonal gradient and the accompanying dipole in zonal temperature advection must be balanced by a local ridge over Europe and the Mediterranean.

…

A larger increase in global mean temperature will be associated with a stronger thermodynamic response to climate change \citep{held_soden_06}. However, in many regions climate change arises not via a thermodynamic mechanism but rather through a change in the circulation that is not proportional to the global mean temperature rise \citep{grise_16,elbaum_22,garfinkel_24}.

…

Stratospheric polar vortex: is expected to influence precipitation in the Mediterranean region, with a weak vortex enhancing precipitation in the western and central Mediterranean \citep{dai_25} and intermodel uncertainty in the vortex response driving uncertainty in projections in this region \citep{simpson_18}. \citet{zhang_24} showed that a weak stratospheric polar vortex is accompanied by an enhanced eastward moisture transport from the North Atlantic Ocean to the Mediterranean, and that an increase in large scale ascending motion associated with vorticity advection has a dominant role in precipitation increase in the Mediterranean. Furthermore, these conditions are accompanied by enhanced frontogenesis and cyclone activity over most of the Mediterranean region."

Please see the manuscript for the full text (also for the other indices).
In this context, we want to stress that the work documented in the current manuscript is not designed for and cannot accomplish a mechanistic description for the precipitation response since it is based on (a very large) monthly dataset (rather than daily, or higher resolution), and thus this is not a goal of this study. We now also stress this point in the manuscript (lines 125-126).

(3) A thorough literature review is needed. Some published work on this topic should be discussed and compared with your results (Silva et al., 2018; Tang et al., 2018; Westervelt et al., 2018; Wilcox et al., 2023). These papers, more or less mentioned the impact of aerosols on the precipitation over Mediterranean and some of them might be different from your results. Relative to these studies, what are the new insights you provide in your manuscript?

The reviewer comments that a literature review is needed based on several suggested studies on the impact of aerosols on precipitation. We thank the reviewer for this comment. While two of the studies the reviewer mentions seem less relevant to our paper (e.g., Silva et al. focus on summer precipitation, and the primary figures in Wilcox et al are also for JJA only), the other two are relevant. We now include in the Introduction a more thorough review, including the relevant references, concerning the Mediterranean precipitation response to aerosols as well as to GHGs (see detailed text in our response to the first comment). Relative to these studies, the novelty in our study is using data from large ensemble single forcings from 10 models. This allows for a confident identification of the forced response for each model and to then understand the spread of these forced responses. The data and methodologies in our study and in the previously published studies are different (e.g., Westervelt et. al study the precipitation responses to regional changes in aerosols emissions in 3 models runs, and both Tang et. al and Westervelt et. al study the responses to specific types of aerosols), and hence limits the basis for comparing the results. In the Discussion section we note the similarity in our results with the precipitation and circulation responses in Tang et. al (lines 405-406).

References

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Report #2

The authors have significantly improved the manuscript. My previous comments have been mostly addressed and I only have a few suggestions for clarification.

We are glad to read the reviewer's comment on the significant improvement of our manuscript following the reviewer's first round of comments. Currently, the reviewer notes few suggestions for clarification and we shall hereby respond to these suggestions.

1) In section 1, existing gaps in the literature are introduced. They are (A) insignificant observed trend despite robust future projection. (B) There is large uncertainty in the magnitude of future projection, and it is unclear whether the uncertainty is coming from structural uncertainty or internal variability.
The authors nicely address (A) by examining multimodel-mean responses of hist-GHG and hist-aer simulations. Authors now show that LESFMIP simulations capture the observed change, so this is well addressed.
(B) is not perfectly addressed by using LESFMIP. LESFMIP is a historical forcing simulation. There are limitations in addressing the uncertainties of future projections. If (B) is what motivated authors, the limitation of LESFMIP as a tool to investigate (B) has to be mentioned in the introduction, along with why LESFMIP is limited but still a useful tool.

The reviewer notes on a limitation of the LESFMIP in addressing uncertainties of future precipitation projections since the LESFMIP is a set of historical simulations. We agree with this, and in the introduction we de-emphasize this point. Specifically, we explicitly write in lines 73-75 that conclusions cannot be drawn regarding future projection based on the available LESFMIP data. More generally, the introduction has been overhauled to better focus on the novel science that can be performed using the LESFMIP output.

2) Dynamical mechanisms can be elaborated.
For the climate indices that were found to be significantly impactful for the multimodel spread, the dynamical mechanism connecting these indices and mediterranean responses has to be better described. For exmaple, how does North Atlantic warming hole lead to ridging? "mechanistically linked" is not sufficient. Similar for polar vortex and North Atlantic jet metrics.

The reviewer suggests that we include a description of the dynamical mechanisms that connect climatic indices and the mediterranean responses for the indices that have significant impact for the multimodal spread. As mentioned above, including in our reply to the second comment of Report #1, we have overhauled the Introduction and the Data and Methodology to discuss these mechanisms including references. The updated text in the Introduction includes (lines 28-51):

> *"The wintertime Mediterranean precipitation response to global warming forced by increasing GHGs concentrations has been associated with several distinct but likely complementary dynamical pathways. \citet{seager_14} explain the projected drying over the Mediterranean based on a low level high anomaly and subsidence over the eastern Mediterranean that is responsible for a mean flow mass and moisture divergence anomaly. \citet{kushnir_15} associates the poleward expansion of the sinking branch of the Hadley cell under greenhouse warming \citep{lu_07} with weakening of the Mediterranean trough, suppression of cyclone activity, and reduction of precipitation. In addition, under climate change, the projected wintertime precipitation reduction in the eastern Mediterranean is associated with a decrease in the number of cyclones and in the precipitation per individual cyclone \citep{zappa_15a}. \cite{tang_18} suggest that the wintertime precipitation reduction in the Mediterranean in response to GHGs is due to a northward shift of the jet stream and storm track, caused by an enhanced sea level pressure in the North Atlantic and Mediterranean, local heating, and lower sea level pressure pattern in northern Europe. \cite{tuel_20} argue that slower-paced warming over the Mediterranean relative to adjacent land regions (i.e., relative Mediterranean cooling) will lead to a local ridge centered over the Mediterranean and, as a result, a precipitation decline. An additional mechanism involves regional SST changes in the North Atlantic: \citet{delworth_22} find that a weakened AMOC and the subsequent atmospheric response to the North Atlantic warming hole drive reduced precipitation over the Mediterranean \citep{keller_25}. Overall, the dynamical mechanisms that underlie the Mediterranean drying, as well as the drying across the subtropics in general \citep{seager_19, he_17}, are not yet fully understood and are still under active research, even as the uncertainty in future hydroclimate in these regions is driven almost exclusively by uncertainty in dynamical changes \citep{elbaum_22}. In other regions, climate drivers other than GHGs have been shown to play a large, and in some cases dominant, role in historical and future trends \citep[e.g.,][]{Kang_24}. An increase of the wintertime Mediterranean precipitation was found by \cite{Westervelt_18} in two out of three models in response to local reduction of aerosol emissions. Similarly, \citet{tang_18} find that adding global aerosols leads to reduced precipitation in this region. Such findings motivate the examination of the role of aerosols (among other drivers) on the large-scale atmospheric circulation and on decadal to centennial changes across the Mediterranean. "*

The updated text in the Data and Methodology (lines 131-187) includes:

> *"Mediterranean region land-ocean near surface temperature contrast: \cite{tuel_20} argue that slower-paced warming over the Mediterranean relative to adjacent land regions (i.e., Mediterranean cooling) will lead to a local ridge centered over the*

Mediterranean and, as a result, a precipitation decline. The circulation response was shown to be triggered by the wintertime low static stability over the basin, allowing the local cooling to propagate from the surface into the troposphere \citep{tuel_21}.
…
the warming hole influences the Atlantic storm track and has been mechanistically linked to the ridge over Europe \citep{Gervais:2019,keller_25}. Specifically, based on the thermodynamic budget, \citet{keller_25} conclude that the warming-hole cools the lower troposphere downstream of its location which, in turn, weakens the low-level winter zonal temperature gradient between the Atlantic Ocean and Europe; this altered zonal gradient and the accompanying dipole in zonal temperature advection must be balanced by a local ridge over Europe and the Mediterranean.
…
A larger increase in global mean temperature will be associated with a stronger thermodynamic response to climate change \citep{held_soden_06}. However, in many regions climate change arises not via a thermodynamic mechanism but rather through a change in the circulation that is not proportional to the global mean temperature rise \citep{grise_16,elbaum_22,garfinkel_24}.
…
Stratospheric polar vortex: is expected to influence precipitation in the Mediterranean region, with a weak vortex enhancing precipitation in the western and central Mediterranean \citep{dai_25} and intermodel uncertainty in the vortex response driving uncertainty in projections in this region \citep{simpson_18}. \citet{zhang_24} showed that a weak stratospheric polar vortex is accompanied by an enhanced eastward moisture transport from the North Atlantic Ocean to the Mediterranean, and that an increase in large scale ascending motion associated with vorticity advection has a dominant role in precipitation increase in the Mediterranean. Furthermore, these conditions are accompanied by enhanced frontogenesis and cyclone activity over most of the Mediterranean region."

We wish to note that our goal is not to advance our understanding of these mechanisms, rather to assess whether the mechanisms can help to understand the intermodel spread.

3) This is a minor point of the paper, but I think the dynamic sensitivity context is confusing around 279. In Grise and Polvani, dynamic sensitivity not being climate sensitivity means that circulation resposnes are not correlated with surface warming across models. What is being emphasized there is whether the circulation responses can be constrained if one constrains climate sensitivity.
But what authors find is a significant correlation between a circulation variable and global surface warming. In this case, if one constrains climate sensitivity, they can constrain circulation response. Therefore, it is confusing to mention Grise and Polvani in this context.

I understand the authors are pointing to that the multimodel mean response is ridging with warming, but the cross-model relationship is troughing with warming. I agree that this itself is interesting, and bringing this up more straighforwardly is a good idea. (For those who don't know what to naively expect there) However, the emphasis of Grise and Polvani is on the cross-model relationship. Hence, how it is described in the manuscript is confusing.

Following the reviewer's comment, we rewrote the text related to the relation between the global mean temperature response and that of the Mediterranean sea-level pressure and the association with Grise and Polvani (beginning now in line 327), to ensure no confusion.
The revised text includes:

> "*In both hist-GHG and hist-aer, a larger global mean warming is associated with troughing (and wettening, r=0.52) over the Mediterranean. This result is opposite to naive expectations: if the thermodynamic response was dominant, enhanced global warming should be associated with more sub-tropical drying \citep{held_soden_06}. It is worth mentioning in this context that for the northern hemisphere the global-mean surface temperature response was found to be correlated only with the DJF Hadley cell edge response (but not with the DJF responses of the midlatitude jet or the subtropical dry zone edge) \citep{grise_16}.*"

4) Visualization suggestion
The aspect ratio of the scatter plots does not help figure out which correlations are strong or weak. Both appear very flat from the current aspect ratio of the panels. I think making the panels closer to a 1:1 ratio would help the readers. But this is not scientific, hence totally up to the authors to choose

Following the reviewer's suggestion, we improved the dimensions of the scatter plots figures.