

**Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)**

Re-review of "Mediterranean precipitation response to greenhouse gases and aerosols," by T. Tang et al., submitted to Atmospheric Chemistry and Physics.

The authors have responded to the referees, but have hardly addressed in the text the main issue, pointed out by both referees, that the models used do not treat aerosol-cloud interactions in any detail, so the results could change significantly if they did.

To remedy this problem, the authors need to (1) reflect more accurately in the text and the title of their manuscript that their study looks at the dynamical rather than microphysical response of aerosols and (2) be more transparent in the text about what aerosol-cloud treatments are and are not included in the models.

First, the title and abstract need to be changed to reflect accurately what the simulation performed is doing. Since aerosol-cloud interactions are either hardly treated or treated weakly in all models, as acknowledge by the authors, the study is really about the dynamical meteorological responses, not the cloud microphysical responses, of different aerosol loadings to precipitation.

[Response: accepted. Title and abstract revised and more description included in section 2.1 to clarify that the modeling was not designed to study aerosol-cloud interactions but to look at dynamic responses.](#)

Thus, the title should be changed to "Climate model dynamical response to greenhouse gases and aerosols in the Mediterranean" so as not to confuse readers into thinking the study treats microphysical responses, which it does not to any realistic degree.

[Response: accepted, changed along lines suggested.](#)

Similarly, the abstract should be changed to "Here, we compare the modeled dynamical response to individual forcing agents in the Mediterranean using a set of global climate models."

[Response: accepted.](#)

Please do not state that the models used are "State of the art," when none of the models used treat aerosol-cloud interactions in nearly the detail as some other models.

[Response: deleted.](#)

Please explain clearly in the abstract that the models do not include detailed aerosol-cloud microphysical interactions and state specifically that inclusion of such processes may change the results.

[Response: included statements on both these issues.](#)

Please state in the manuscript itself which aerosol-cloud processes are missing.

[Response: included in the section 2.1 and discussion sections.](#)

[The PDRMIP project aims to examine the similarity in model responses when driven with the same aerosol concentrations rather than including differences in both concentrations and responses. The aerosol-cloud interactions are not fully represented in the majority of models as these are concentration-driven. In some](#)

concentration-driven models the aerosol-cloud interactions are switched off, but even if they are on the aerosol concentrations are fixed so that these interactions are not realistic. These processes are included in some of the emissions-driven models, but these are a minority of the project.

In other words, aerosol-cloud interactions are not in the scope of the PDRMIP project though there are other projects investigating those (e.g. AeroCom). Hence this study focuses on aspects of the response that appear to be less sensitive to those interactions given that they are relatively robust across the models (despite some using interactive aerosols while others used climatological fields).

Please add the table from the response to referees describing the aerosol/cloud activation properties of each model in the manuscript itself.

Response: included.

If these steps are taken, at least it will be clear to readers that the responses examined are not the complete responses and where further work is needed.

Response: agreed. Thanks for ensuring that this is clear in the description of the modeling.

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It would be nice to have a more process level understanding of the trends shown here.

Response: the PDRMIP project aims to examine the similarity in model responses when driven with the same aerosol concentrations rather than including differences in both concentrations and responses. The aerosol-cloud interactions are turned off in some concentration-driven models. For the concentration-driven models with aerosol-cloud interactions switched on, the fact that the aerosol concentrations are fixed means they cannot fully interact with clouds (e.g. even if they get rained out, they persist).

In other words, process level understanding of aerosol-cloud interactions is not within the scope of PDRMIP project and there are already other projects investigating aerosol-cloud interactions (e.g. AeroCom). Hence this study focuses on dynamic aspects of the response that appear to be less sensitive to those interactions as they are relatively robust across the models (despite some using interactive aerosols while others used climatological fields), and hence we present analyses of both energy budgets and dynamic responses in these models.

The same for dust and cloud-aerosol interactions. Note that some changes in dust loading and patterns can be attributed to anthropogenic changes.

Response: dust is included in the background aerosols in the PDRMIP experiment. However, anthropogenic changes in dust loadings (e.g., land use/cover change) are not part of the PDRMIP simulations as the overarching goal of the MIP was to examine the response to prescribed changes in GHGs, sulfate and BC (not dust) and not to include interactive aerosol responses to climate variability or change. Hence there are no PDRMIP results relevant to the question of the role of changes in dust on Mediterranean precipitation. We've added a sentence to the text stating that it could be useful for future work to examine this.

Even if the collective GCM runs suggest that cloud-aerosol interactions and aerosol radiative effects are minor, I recommend that the authors will provide more details on them in the paper.

Response: Although the cloud-aerosol interactions appear to be minor in these results, the aerosol radiative effects are important and are already documented in the paper. Without them, there would be no impacts from aerosols. Aerosol radiative effects are discussed in the energy budget analysis and dynamical responses, and the revised paper points out explicitly that aerosol-cloud interactions do not seem to be important but that many of the models did not fully represent these and so this is another area meriting future work.

## **List of changes**

- 1) Changes in the title, abstract (review #1)
- 2) More descriptions about the aerosol treatment, mainly in section 2.1 and Table 1 (review #1 and 2)
- 3) The reasons of excluding Saharan dust are included in the section 2.1 (review #2)

# **Dynamical Response of Mediterranean Precipitation to Greenhouse Gases and Aerosols**

Tao Tang<sup>1</sup>, Drew Shindell<sup>1</sup>, Bjørn H. Samset<sup>2</sup>, Oliiviér Boucher<sup>3</sup>, Piers M. Forster<sup>4</sup>, Øivind Hodnebrog<sup>2</sup>, Gunnar Myhre<sup>2</sup>, Jana Sillmann<sup>2</sup>, Apostolos Voulgarakis<sup>5</sup>, Timothy Andrews<sup>6</sup>, Gregory Faluvegi<sup>7</sup>,  
5 Dagmar Fläschner<sup>8</sup>, Trond Iversen<sup>9</sup>, Matthew Kasoar<sup>5</sup>, Viatcheslav Kharin<sup>10</sup>, Alf Kirkevåg<sup>9</sup>, Jean-Francois Lamarque<sup>11</sup>, Dirk Olivie<sup>9</sup>, Thomas Richardson<sup>4</sup>, Camilla W. Stjern<sup>2</sup>, Toshihiko Takemura<sup>12</sup>

10 <sup>1</sup>Nicholas School of the Environment, Duke University, Durham, USA

<sup>2</sup>CICERO Center for International Climate and Environmental Research – Oslo, Norway

<sup>3</sup>Institute Pierre-Simon Laplace, Université Pierre et Marie Curie / CNRS, Paris, France

<sup>4</sup>University of Leeds, Leeds, United Kingdom

<sup>5</sup>Imperial College London, London, United Kingdom

15 <sup>6</sup>Met Office Hadley Centre, Exeter, UK

<sup>7</sup>Columbia University, New York, USA and NASA Goddard Institute for Space Studies, New York, USA

<sup>8</sup>Max-Planck-Institut für Meteorologie, Hamburg, Germany

<sup>9</sup>Norwegian Meteorological Institute, Oslo, Norway

<sup>10</sup>Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada

20 <sup>11</sup>National Center for Atmospheric Research, Boulder, USA

<sup>12</sup>Kyushu University, Fukuoka, Japan

*Correspondence to:* Tao Tang ([tao.tang@duke.edu](mailto:tao.tang@duke.edu))

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**Abstract.** Atmospheric aerosols and greenhouse gases affect cloud properties, radiative balance and thus, the hydrological cycle. Observations show that precipitation has decreased in the Mediterranean since the [beginning of the 20th century](#), and many studies have investigated possible mechanisms. So far, however, the effects of aerosol forcing on Mediterranean precipitation remain largely unknown. Here we compare [the modeled dynamical response of](#) Mediterranean precipitation to individual forcing agents in a set of global climate models (GCMs). Our analyses show that both greenhouse gases and aerosols can cause drying in the Mediterranean, and that precipitation is more sensitive to black carbon (BC) forcing than to well-mixed greenhouse gases (WMGHGs) or sulfate aerosol. In addition to local heating, BC appears to reduce precipitation by causing an enhanced positive North Atlantic Oscillation (NAO)/Arctic Oscillation (AO)-like sea level pressure (SLP) pattern, characterized by higher SLP at mid-latitudes and lower SLP at high-latitudes. WMGHGs cause a similar SLP change, and both are associated with a northward diversion of the jet stream and storm tracks, reducing precipitation in the Mediterranean while increasing precipitation in Northern Europe. Though the applied forcings were much larger, if forcings are scaled to those of the historical period of 1901-2010, roughly one-third ( $31 \pm 17\%$ ) of the precipitation decrease would be attributable to global BC forcing with the remainder largely attributable to WMGHGs whereas global scattering sulfate aerosols have negligible impacts. [Aerosol-cloud interactions appear to have minimal impacts on Mediterranean precipitation in these models, at least in part as many simulations did not fully include such processes; these merit further study.](#) The [findings](#) from this study suggest that future BC [and WMGHG](#) emissions may significantly affect regional water resources, agricultural practices, ecosystems, and the economy in the Mediterranean region.

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## 1 Introduction

Aerosols, fine particles in the atmosphere produced by both natural processes and anthropogenic activities, impact the Earth's climate by scattering and absorbing solar radiation (direct effect), or by modifying the properties of clouds (indirect effects) through a variety of mechanisms including atmospheric heating and changes in ice nuclei and cloud condensation nuclei (CCN), including their size, location and concentration. These changes may significantly affect solar radiation and precipitation (Ramanathan et al., 2001; Kaufman et al., 2002; Shindell et al., 2012; Bond et al., 2013; Boucher et al., 2013). The effects of aerosols on climate have been widely studied both on global and regional scales (Ramanathan and Carmichael, 2008; Shindell and Faluvegi, 2009). For example, Menon et al. (2002) reported slight cooling and drying trends in the northern part of China in the 2nd half of the 20th century, and attributed such trends to the emissions of BC aerosols based on model simulations. Similarly, Hodnebrog et al. (2016) reported a precipitation decrease in southern Africa due to local biomass burning aerosols based on analyses of model simulations and local energy budget. On the other hand, Koren et al. (2012) argued that aerosols could intensify rainfall events in the lower and mid-latitudes by analyzing satellite observations. However, Stevens and Feingold (2009) contended that the effects of aerosols on clouds and precipitation are very limited due to the buffering effects of the climate system itself. In addition to their influence on temperature and precipitation, aerosols may also affect large-scale atmospheric circulation. For example, Takahashi and Watanabe (2016) suggested that the Pacific trade winds were accelerated partially by sulfate aerosols during the past two decades. [Jacobson and Kaufman \(2006\) suggested a surface wind reduction due to aerosol particles in California and China, which may also impact air pollution and wind energy.](#) Dunstone et al. (2013) also reported that aerosols could modulate Atlantic tropical storm frequency due to aerosol-induced shifts in the Hadley circulation. These differing results suggest that aerosol effects on regional climate may depend on the aerosol types, seasons, and regions of interest.

A decreasing precipitation trend in the Mediterranean area since the 20<sup>th</sup> century has been reported and its possible causes have been investigated in many studies (Piervitali et al., 1998; Buffoni et al., 1999; Mariotti et al., 2002; Dünkeloh and Jacobeit, 2003; Xoplaki et al., 2004). For instance, Quadrelli et al. (2001) observed a strong correlation between winter Mediterranean precipitation and the NAO (Hurrell et al., 2001). Krichak and Alpert (2005) suggested that the East Atlantic-West Russia (EA-WR) pattern may also play an important role in modulating the precipitation in the Mediterranean. Hence, the responses of Mediterranean precipitation to these large-scale variability patterns (e.g., NAO, EA-WR), and to some extent how these patterns might be responding to external drivers, are fairly well-understood (Black et al., 2010). However, prior studies included all the drivers at once, so cannot discern the relative roles of WMGHGs and other agents. Anthropogenic aerosols have been reported to greatly influence the temperature in the Mediterranean (Nabat et al., 2014), but the effects of aerosols on Mediterranean precipitation have not been carefully examined. Since precipitation impacts water availability for both ecosystems and human societies, it is crucial to understand the different impacts of the climate drivers that are responsible for the Mediterranean precipitation trend. To bridge this knowledge gap, here we analyze

Mediterranean precipitation changes based on a group of state-of-the-art GCMs that examined the precipitation response to individual climate drivers, which could help inform management of water resources, regional societal activities such as agriculture, and even emissions mitigation.

## 2 Data and Method

### 5 2.1 Data

This study employed output from nine models participating in the Precipitation Driver and Response Model Intercomparison Project (PDRMIP), utilizing simulations examining the individual responses to CO<sub>2</sub>, sulfate and BC aerosols. In these simulations, perturbations were performed with each model at global scale: a doubling of CO<sub>2</sub> concentration (CO<sub>2</sub>×2), 10 times present-day BC concentration (BC×10), and 5 times present-day SO<sub>4</sub> concentration (SO<sub>4</sub>×5). All perturbations were abrupt. CO<sub>2</sub>×2 perturbations were applied relative to the models' own baseline values. For aerosol perturbations, monthly present-day concentrations were derived from the AeroCom Phase II initiative (Myhre et al., 2013a). The concentrations were multiplied by the stated factors (concentration-driven). A few models instead perturbed aerosol emissions (emission-driven), in most cases again using AeroCom Phase II data. In the majority of simulations with fixed concentrations, aerosol-cloud interactions cannot be realistically represented as, for example, changes in cloud lifetimes cannot affect aerosols. Hence the concentration-driven models can fully capture only direct aerosol effects (aerosol-radiation interactions), and the PDRMIP simulations are designed to examine dynamic responses of the hydrologic cycle rather than those that take place via aerosol-cloud microphysics. Hence this study focuses on aspects of the response that appear to be less sensitive to those interactions as they are relatively robust across the models (despite some emission-driven models using interactive aerosols while others used climatological fields). Many PDRMIP studies have taken this approach (Samset et al., 2016; Myhre et al., 2017; Stjern et al., 2017; Liu et al., 2018; Richardson et al., 2018; Samset et al., 2018), though further work with models incorporating more realistic aerosol-cloud interactions would of course be valuable in determining the veracity of all conclusions from the project.

Each perturbation was run in two configurations, a 15-yr fixed sea surface temperature (SST) simulation and a 100-yr coupled simulation. Each fixed-SST simulation is compared with its fixed-SST control simulation to diagnose the effective radiative forcing (ERF) due to each perturbation (Myhre et al., 2013b), whereas each coupled run is compared with its coupled control run to examine climate response. Saharan dust has been suggested to have a discernible impact over the Mediterranean (Bangert et al., 2012). In the PDRMIP experiments, all models include dust among the aerosols, but again as the PDRMIP protocol was designed to look at the dynamic climate response to prescribed aerosol and GHG changes, dust was held fixed in the concentration-driven simulations. Further work could usefully explore if changes in dust loading might



have contributed to Mediterranean precipitation changes. The nine models used in this study and their configurations, as well as the aerosol treatment are listed in Table 1.

## 2.2 Method

In addition to direct analysis of meteorological fields (e.g. precipitation, sea-level pressure) in the models, we also analyse the energy budget associated with the hydrological cycle. Following Hodnebrog et al. (2016) and Muller and O’Gorman (2011), the precipitation change is related to diabatic cooling and the horizontal transport of dry static energy as follows:

$$L_c \Delta P = \Delta Q + \Delta H \quad (1)$$

Here  $L_c$  is the latent heat of condensation of water vapor, which is  $29 \text{ W m}^{-2} \text{ mm}^{-1} \text{ day}$ .  $\Delta P$  is the precipitation change.  $\Delta H$  is the column-integrated dry static energy flux divergence and  $\Delta Q$  is the column-integrated diabatic cooling, which is calculated as:

$$\Delta Q = \Delta LW + \Delta SW - \Delta SH \quad (2)$$

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where  $\Delta LW$  is the change of longwave radiation in the atmospheric column and  $\Delta SW$  is the change of shortwave radiation in the atmospheric column.  $\Delta SH$  is the change of upward sensible heat flux.

Since most of the precipitation events occur in the wet season (Oct-Mar) in the Mediterranean, roughly 70% of total annual precipitation (Mariotti et al., 2002; Kottek et al., 2006), the analysis was restricted to the wet season in the current study unless noted otherwise. All of the data used in this study were re-gridded into  $2.5^\circ \times 2.5^\circ$  horizontal resolution for analyses.

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## 3 Results

Fig. 1 shows the multi-model mean (MMM) of normalized  $\Delta P$  for each forcing. Both  $\text{CO}_2$  and BC caused a substantial drying over Mediterranean, with a larger magnitude from BC (Fig. 1a-b) whereas  $\text{SO}_4$  contributed very little in the Mediterranean region (Fig. 1c). Moreover, in stark contrast to the drying of the Mediterranean, Northern Europe shows increasing precipitation trends for  $\text{CO}_2$  and BC (Fig. 1a-b), which will be discussed in more details later. To compare the precipitation response quantitatively, the domain-averaged (purple rectangle in Fig. 1,  $30^\circ\text{N}$ - $45^\circ\text{N}$ ,  $10^\circ\text{W}$ - $40^\circ\text{E}$ ) trends are shown in Fig. 2. For  $\text{CO}_2$ , all of the nine models show drying trends (Fig. 2a). The MMM is  $-0.03 \pm 0.03 \text{ mm/day per W/m}^2$ , with individual model values ranging from  $-0.01$  to  $-0.06 \text{ mm/day per W/m}^2$ . For BC (Fig. 2b), all nine models again show drying trends, with the MMM value  $-0.12 \pm 0.07 \text{ mm/day per W/m}^2$ , which is four times as large as that of  $\text{CO}_2$ . When it comes to  $\text{SO}_4$  (Fig. 2c), the model results even differ in the sign of change and the MMM value is small ( $-0.01 \pm 0.04 \text{ mm/day}$

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per  $\text{W/m}^2$ ). These analyses show that the precipitation response is more sensitive to BC forcing than to  $\text{CO}_2$  and  $\text{SO}_4$  in this region.

In order to investigate the mechanisms governing the precipitation response, we performed an energy budget analysis for this region (Fig. 3). For  $\text{CO}_2$ , the drying is dominated by horizontal energy transport (gray box in the  $\text{CO}_2$  panel), albeit some offset by diabatic cooling (pink box in the  $\text{CO}_2$  panel). For BC, the net radiation change, which is primarily SW (red box in the BC panel), has a larger impact than the horizontal energy change (gray box in the BC panel), but the latter is nonetheless a substantial fraction of the net change. When it comes to  $\text{SO}_4$ , the small precipitation response results from the offsetting of net radiation change (pink box in the  $\text{SO}_4$  panel) and horizontal energy transport (gray box in the  $\text{SO}_4$  panel). The energy budget analysis implies that the dynamical responses to  $\text{CO}_2$  and BC played a crucial role in modulating the precipitation in this region.

We then analyzed the  $\Delta\text{SLP}$  from the model output (Fig. 4). Specifically, it is seen that  $\text{CO}_2$  induced strong SLP changes. The SLP increased at mid-latitudes, with increases extending from the North Atlantic to Southern Europe, and decreased at high latitudes (Fig. 4a). BC led to a similar pattern of SLP change, but with increased magnitude (Fig. 4b), characterized by two increases centered in Europe and the Western North Atlantic. Compared with  $\text{CO}_2$  and BC,  $\text{SO}_4$  caused an opposite change (Fig. 4c). The  $\text{CO}_2$  and BC forcings appear to induce a pattern similar to the positive phase of the NAO /AO (Lorenz, 1951), in which the jet streams and storm tracks are displaced northward, leading to a drier Mediterranean and precipitation increases in Northern Europe (Fig. 1a-b). Such a shift in response to forcings is more clearly seen in the changes of zonal winds (Fig. 5). The  $\text{CO}_2$  caused a strengthening of zonal winds in the whole upper atmosphere and a strengthening around  $60^\circ\text{N}$  from the near-surface to the top of the atmosphere, as well as weakening around  $30^\circ\text{N}$  from the near-surface to the mid-troposphere (Fig. 5a), as in prior studies (Shindell et al., 2001). The strengthening around  $60^\circ\text{N}$  is more apparent for BC (Fig. 5b). Similar results were seen in response to aerosol forcing in a prior study (Allen and Sherwood, 2011). This shift is possibly due to the enhancement of the tropospheric temperature gradient between mid-latitudes and high-latitudes, as suggested by Allen et al. (2012).

Our analyses illustrate that BC aerosols may modulate regional precipitation in part via modifying large-scale circulation patterns. Many previous studies suggest that BC could impact regional precipitation by changing the local vertical temperature profile, in which BC aerosols absorb solar radiation and heat the atmosphere, thus suppressing convection and cloud formation (Kaufman et al., 2002; Meehl et al., 2008; Ramanathan and Carmichael, 2008; Hodnebrog et al., 2016). Our results (analyses of the energy budget, SLP and zonal winds) suggest that a portion of the drying is also associated with large-scale circulation responses. In addition, our pattern of jet stream/storm track changes (Fig. 4 & 5) is also in agreement with the projections from the latest IPCC report (Collins et al., 2013) based on a set of CMIP5 models, with increasing storm activities in Northern Europe and decreasing storms in the Mediterranean. Such a shift of storm tracks may further reduce the

precipitation in the Mediterranean, though reductions in WMGHG or BC emissions may help to mitigate the projected drying.

#### 4 Case Study – Historical Observations and Scaled Model Results

The above analyses demonstrated how the precipitation and circulation responded to each forcing both qualitatively and quantitatively. In order to explore their potential relative contributions to the total precipitation change, here we apply linear scaling to the model output. Since PDRMIP utilized large aerosol and greenhouse gas changes in order to achieve strong signals that could be statistically significant with a relatively modest amount of computational time, the precipitation change from those model outputs needs to be scaled in order to compare with observations. Uncertainties related to this approach are discussed further in section 5.

In this study, we focus on the period from 1901 to 2010. The scaled precipitation change for each individual forcing is defined as:

$$\Delta P_{scaled} = \Delta P \times (ERF_{1901-2010} / ERF_{model}) \quad (3)$$

In equation (3),  $\Delta P$  is the precipitation change over Mediterranean in the model during the last 50 years in the coupled run, since the model has reached near-equilibrium state after 30 years.  $ERF_{1901-2010}$  is the historical global ERF for the period of 1901-2010. The values were obtained from the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (Myhre et al., 2013b). The  $ERF_{1901-2010}$  value used for CO<sub>2</sub> is 2.33 W/m<sup>2</sup>, which is larger than the CO<sub>2</sub> value from the IPCC report as CO<sub>2</sub> was used to represent all WMGHGs in this case study.  $ERF_{1901-2010}$  values for BC and SO<sub>4</sub> are 0.28 W/m<sup>2</sup> and -0.33 W/m<sup>2</sup>, respectively.  $ERF_{model}$  is the global ERF in the PDRMIP models, which was obtained by calculating the energy flux change at the top of the atmosphere from years 6 to 15 of the fixed-SST simulations, since present models largely equilibrate within 5 years of fixed-SST running (Kvalevåg et al., 2013). In addition to the direct effects of the aerosols, the indirect effects of aerosols were also included in most of the models and thus, in the  $ERF_{model}$ . The value of  $(ERF_{1901-2010} / ERF_{model})$  is the scaling factor applied to model precipitation output to match historical forcing levels. They are 0.64 [0.57, 0.69], 0.33 [0.10, 0.68] and 0.11 [0.04, 0.16] for CO<sub>2</sub>, BC and SO<sub>4</sub>, respectively (where the values indicate the mean [min, max] across the nine models). An important assumption here is that the  $\Delta P$  changes linearly with  $ERF_{model}$ .

$\Delta P_{scaled}$  is calculated for CO<sub>2</sub>, BC, and SO<sub>4</sub> separately. The total  $\Delta P_{scaled}$  is the combination of the three, assuming their responses to those forcings can be added linearly. It should be noted that in this analysis, we use the combined responses to WMGHGs, BC and SO<sub>4</sub> to approximate the total historical response over 1901-2010. Several additional factors may have also played a role, including natural forcing (solar and volcanic activities), land use/land cover change, contrails, ozone (O<sub>3</sub>)

(both tropospheric and stratospheric) and stratospheric water vapor, which have forcings of -0.03, -0.09, 0.05, 0.26 and 0.06 W/m<sup>2</sup>, respectively (Myhre et al., 2013b). As all these forcings are fairly small, simulations to isolate their impacts would be extremely computationally expensive and hence were not performed but to first order we expect their exclusion is unlikely to greatly affect our results. Characterization of the influence of these other drivers merits future study, particularly as some  
5 operate via different physical processes (e.g. tropospheric ozone is both a greenhouse gas and an absorber of incoming solar radiation). Similar analyses were also performed to obtain scaled SLP change ( $\Delta SLP_{scaled}$ ), zonal wind change and energy budget change in the atmospheric column.

Several observational and reanalysis datasets were also employed in this part of our study. For precipitation, Global  
10 Precipitation Climatology Center (GPCC) monthly precipitation data (Schneider et al., 2011), provided by NOAA/OAR/ESRL from their website (<https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html#detail>), is employed. It is a high quality gridded dataset that is mainly terrestrial station-derived. For SLP, we use HadSLP2 data (Allan and Ansell, 2006), which is created by combining marine observations from ICOADS data (Worley et al., 2005) and land (terrestrial and island) observations (available at <https://www.esrl.noaa.gov/psd/data/gridded/data.hadslp2.html>). We also use NCEP/NCAR  
15 reanalysis data (Kalnay et al., 1996), downloaded from <https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.surface.html>, for the comparisons of zonal wind. All these datasets have undergone rigorous quality control and have been widely used in the climate community, including the IPCC 2013 assessment report (Hartmann et al., 2013). The trends of the observed and reanalysis data were estimated by a simple linear regression applied to the same period of the datasets.

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The combination of WMGHGs, BC and SO<sub>4</sub> exerted a strong drying trend in the Mediterranean (Fig. 6a). The drying trends shown here are statistically significant and consistent with the observations (Fig. 6b), as well as previous studies (Buffoni et al., 1999; Mariotti et al., 2002; Dünkeloh and Jacobeit, 2003). When averaged over the whole domain, the scaled drying trends caused by WMGHGs, BC and SO<sub>4</sub> are  $-1.28 \pm 1.21$  mm/decade,  $-0.58 \pm 0.34$  mm/decade and  $-0.03 \pm 0.21$  mm/decade,  
25 respectively (not shown here). When combined (Fig. 6c), all nine models show decreased precipitation, with MMM value of  $-1.89 \pm 1.39$  mm/decade, which is roughly a 5% decrease relative to the climatology of the control simulations. Such a decreasing trend is indistinguishable from the observations ( $-2.78 \pm 1.10$  mm/decade, a 10% decrease compared with its 110-yr climatology). In spite of the dominant role of WMGHGs in the drying of the Mediterranean, BC contributed roughly one-third ( $31 \pm 17\%$ ) of the total forced precipitation decrease in this region whereas the contribution of the scattering aerosol-SO<sub>4</sub>  
30 is negligible ( $\sim 1.6\%$ ). We also examined the trend of precipitation in the control simulations and found only very weak responses (Fig. 6c), with a mean value of  $0.004 \pm 0.03$  mm/decade and maximum value of 0.03 mm/decade in any individual model. Since current GCMs are able to capture the broad spatial and temporal features of internal variability (Flato et al., 2013), and the forced drying signal is almost equal to the total signal (Fig. 6a-c), the consistent drying trend in the models is very unlikely to be attributable to unforced variability and appears realistic. The energy budget change (Fig. 6d) clearly

shows that the net precipitation decrease is mainly due to horizontal energy transport (gray box) rather than diabatic cooling (pink box), because the absorption of SW radiation (red box) and LW radiative cooling (green box) offset one another in total.

- 5 Fig. 7a shows the overall response of SLP to these forcings, with strong SLP increases at mid-latitudes and strong decreases at higher latitudes. Such patterns of SLP changes are also found in the observed datasets (Fig. 7b), albeit with a larger magnitude. The combined pattern of zonal wind responses shows winds intensified at the northern edge of the jet stream and weakened at the southern edge (Fig. 7c). The NCEP dataset depicts a similar pattern of changes, with winds intensifying at 60°N and weakening at 30°N, but as with SLP, with a stronger magnitude (Fig. 7d). Some previous studies have pointed out
- 10 that current GCMs significantly underestimate the tropical expansion and jet stream shift, which could be related to the short observational record, large internal variability or model deficiencies (Johanson and Fu, 2009; Allen et al., 2012). Despite the underestimations, our analyses clearly demonstrate the shift of the jet stream in response to these forcings that appears qualitatively consistent with observations.
- 15 Based on the model simulations in the current study, the pattern of climate response to BC forcing over the past ~110 years is similar to the response to WMGHGs over Europe and the North Atlantic, including precipitation, SLP and zonal winds. At the same time, our results suggest that SO<sub>4</sub> played a very limited role in modulating Mediterranean precipitation trends and North Atlantic storm tracks. In other words, the precipitation trends during the past 110 years in the Mediterranean are likely to be only weakly sensitive to scattering aerosols that were not modeled (e.g., organic carbon, nitrate) or the uncertainties in
- 20 aerosol negative forcing (probably not even for indirect forcing, as they were included in sulfate simulations for most models). The small sensitivity of SO<sub>4</sub> is likely due to compensation between local and remote effects (Liu et al., 2018). Combined with its small *ERF*, the role of SO<sub>4</sub> appears to be negligible during this period. However, the simulations examined here were not designed to determine whether the aerosol effects are due to local or remote emissions from the models. Initial analysis from PDRMIP regional experiments (in which BC over Asia only is multiplied by 10, with
- 25 everything else being held at present-day levels) indicate that BC from Asia contributes as much as 60% to the drying signal in the Mediterranean, and in fact a larger average rainfall change in the Mediterranean than averaged over Asia itself. This suggests that the remote effects of BC may have dominated the Mediterranean precipitation changes. Hence the response to global BC increases may be a reasonable proxy for the 20<sup>th</sup> century changes, although it would be useful to explore the effects of local reductions from Europe itself in the late 20<sup>th</sup> century. The relative impacts of local versus remote forcing will
- 30 be further explored in forthcoming PDRMIP analyses.

## 5 Discussion and Conclusion

Since PDRMIP experiments are equilibrium simulations while the real-world is transient, and we scaled PDRMIP forcing to match historical levels, we examined related experiments to test both these aspects of the methodology used in our comparison with historical observations. Historical GHG-only simulations using the same CMIP5 models (Taylor et al., 2012) that participated in the PDRMIP project were collected and analyzed (data available at <http://strega.ldeo.columbia.edu:81/CMIP5/.monthly/.byModel/>). Six models are available and each model has 1-5 ensemble members. All of the six models show drying trends (Fig. 8), with a MMM value of  $-1.32 \pm 1.65$  mm/decade ( $-1.29$  mm/decade when weighted by ensemble size) which is quite close to the WMGHGs result of our scaled equilibrium PDRMIP output ( $-1.28 \pm 1.21$  mm/decade). In fact, the overlap of their probability density functions is 0.85, assuming a normal distribution. This comparison indicates that our methodology does not appear to be a large source of uncertainty in the current study, though response to other agents may not be as linear as those to WMGHGs (unfortunately, simulations are not currently available to evaluate other forcings, and, given the enormous expense of running enough ensemble members to isolate the relatively small signals for individual aerosols, are unlikely to be anytime soon). Similar analyses were also performed for SLP and zonal winds, and again there is no appreciable difference between the historical transients and the scaled equilibrium responses. The consistent results suggest that the methodology works surprisingly well.

In addition to the wet season, precipitation during the dry season (Apr-Sep) for the PDRMIP model was also analyzed. The modelled dry season precipitation trends, however, do not match the observations well (not shown). The modelled results also show a statistically strong drying trend while the observations do not show significant changes. Two possible reasons may be responsible for the apparent discrepancies. One is that only 30% of the total precipitation occurs during the dry season (boreal summer months) and it is difficult to simulate the uneven distribution of infrequent rainfall events. The other is that there are large uncertainties in the observational data itself. Unlike the wet season, in which nearly half of the grid boxes show statistically significant trends (Fig. 6b), almost none of the grid boxes show statistically significant trends in the dry season, undermining the robustness of the observational results.

The drying influence of WMGHGs will be more prominent in the future due to their projected continued growth. In contrast, many studies suggest that aerosol concentrations may decrease rapidly in the future due to air quality and climate policies along with their relatively short lifetime compared with WMGHGs (Andreae et al., 2005; Myhre et al., 2013b; Shindell et al., 2013). Reductions of BC could, to some extent, slow down the drying trend in the Mediterranean. Overall, a drier Mediterranean region is expected owing to increasing WMGHGs, but the pace of change in global BC emissions may substantially modify the drying rate in the near term.

Some limitations and uncertainties still exist in our current study. First, it is important to keep in mind that the case study in Section 4 is not a formal attribution analysis, despite the estimation of BC contribution. Our aim is to give a first grasp of the effects of aerosol on regional precipitation in the Mediterranean. Second, although our comparison of scaled equilibrium and unscaled transient simulations indicates that our methodology works well at least for WMGHGs, there is no systematic study so far exploring the linearity (or non-linearity) of the precipitation responses to BC or the linearity of responses to multiple versus individual forcings on regional scales. Third is that the  $ERF_{1901-2010}$  of BC represents direct effects only (Myhre et al., 2013b). Semidirect and indirect effects, however, are included in many of our PDRMIP models, and thus in  $ERF_{model}$ . We did not include these effects in the scaling in this study for two reasons: first, the indirect effects of BC in the PDRMIP models do not include ice particles, as well as internal cloud absorption (Jacobson, 2012) and are difficult to evaluate as BC concentrations were prescribed in several of the models so that they cannot interact fully with clouds, indicating that they are not fully resolved, and second, the net  $ERF_{1901-2010}$  of semidirect plus indirect effects is likely small (-0.1 to +0.2 W/m<sup>2</sup>) with a very large overall uncertainty range (-0.4 to +0.9 W/m<sup>2</sup>) (Bond et al., 2013). If the semi-direct and indirect effects of BC (-0.1 to +0.2 W/m<sup>2</sup>) are considered in the scaling, the  $\Delta P_{scaled}$  of BC aerosol would be -0.44 to -0.87 mm/decade and still contribute a substantial part (25 to 40 %) to the drying. The situation is similar for sulfate aerosol, for which indirect effects are included in  $ERF_{model}$ , but not in  $ERF_{1901-2010}$ . We did not include indirect effects in our scaling as these were not attributed to individual aerosol species in the IPCC AR5 (Boucher et al., 2013). If the indirect effects are considered, the negative  $ERF_{1901-2010}$  could increase roughly by a factor of two (assuming indirect effects are largely associated with sulfate). However, the  $\Delta P_{scaled}$  of sulfate aerosol would still be very small compared with WMGHGs or BC, which would not impact our conclusions. As noted previously, the use of prescribed concentrations will also limit the ability of models to capture aerosol-cloud interactions realistically, affecting precipitation responses as well as ERF estimates. Since the responses do not obviously vary systematically between concentration-driven and emissions-driven models, such effects may be relatively small but merit future study. The final issue is related to the design of the model simulations. The perturbations are 5× or 10× present-day aerosol concentrations, which are time-invariant. The aerosols, however, have significant spatial and temporal variations. For instance, aerosol concentrations have been increasing in Asia continuously since 1950, but decreasing in Europe since the 1970s (Allen et al., 2013). As noted, further work is needed to determine how much of the Mediterranean trends result from local relative to remote forcing. To the extent that the trends are driven by remote forcing the potential influence of such spatio-temporal variations will be small. This will be explored in future PDRMIP simulations.

Our analyses show that both WMGHGs and BC influence wet season Mediterranean rainfall by causing an enhanced positive NAO/AO-like SLP pattern as well as by some local heating due to SW absorption. The SLP pattern is characterized by higher SLP in the North Atlantic and Mediterranean and lower SLP in the Northern part of Europe, which diverts the jet stream and storm tracks further northward, reducing the precipitation in the Mediterranean and increasing precipitation in Northern Europe. In contrast, global perturbations of the scattering aerosol SO<sub>4</sub> have a negligible impact. The results from this study may have important implications to the management of regional water resources, agricultural practice, ecosystems,

environment, and economics as well as social development and behavior in a warming climate. They also stress the importance of accounting for the aerosols (and generally short-lived forcings) for short-term (e.g., decadal) regional climate prediction.

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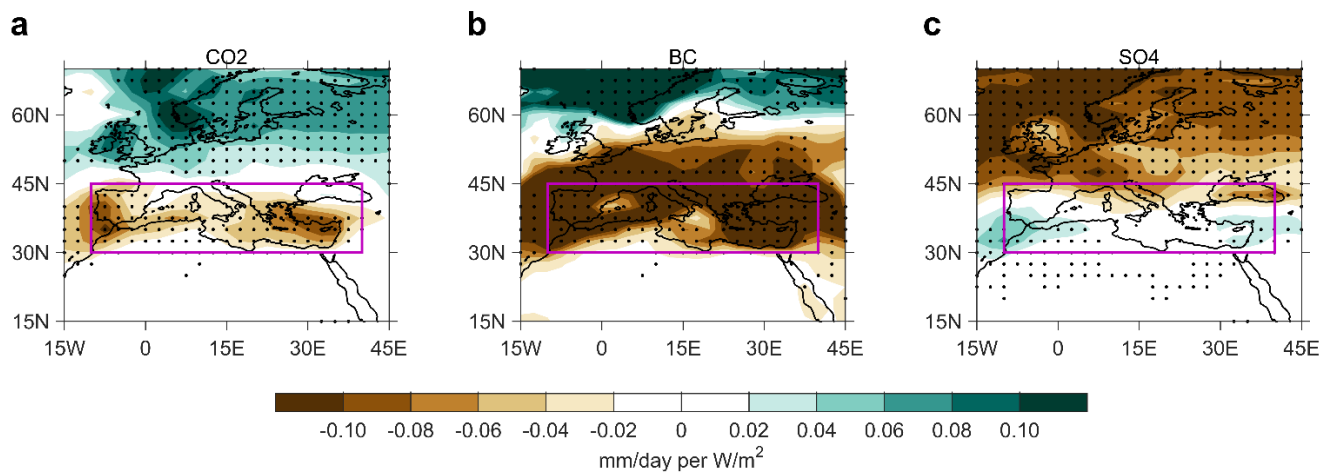
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**Table 1.** Descriptions of the nine PDRMIP models (adapted from Liu et al. (2018)). GA = Global Atmosphere. HTAP2 = Hemispheric Transport Air Pollution, phase 2.

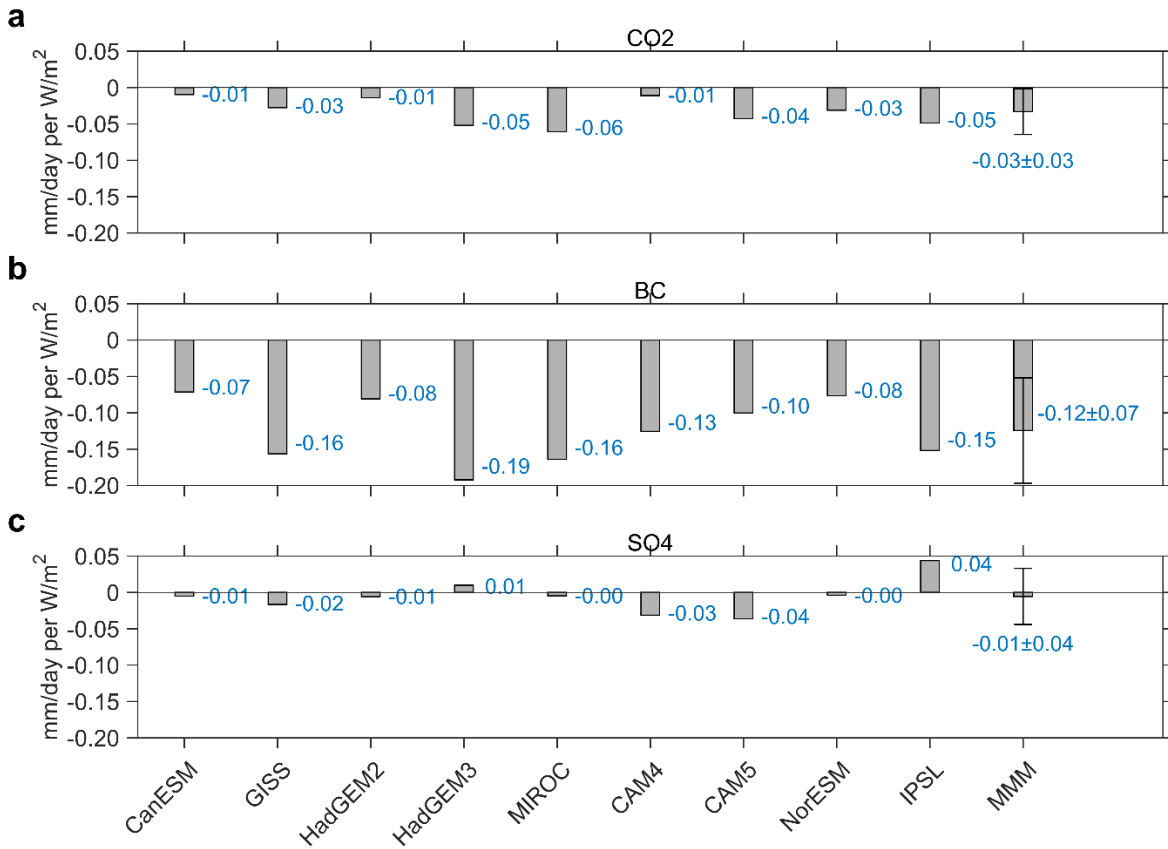
(Please use the table in the separately uploaded excel sheet instead of this one)

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Model	Version	Resolution	Ocean setup	Aerosol <u>emission</u>	References
Canadian Earth System Model (CanESM2)	2010	2.8×2.8 35 levels	Coupled	Emission	Arora et al. (2011)
Goddard Institute for Space Studies Model E2, coupled with Russell ocean model (GISS-E2-R)	E2-R	2×2.5 40 levels	Coupled	Fixed concentration	Schmidt et al. (2014)
Hadley Center Global Environment Model, version 2-Earth System (HadGEM2-ES)	6.6.3	1.875×1.25 38 levels	Coupled	Emissions	Collins et al. (2011)
HadGEM3	GA 4.0	1.875×1.25 85 levels	Coupled	Fixed concentration	Bellouin et al. (2011) Walters et al. (2014)
Model for Interdisciplinary Research on Climate-Spectral Radiation-Transport Model for Aerosol Species (MIROC-SPRINTARS)	5.9.0	T85 (approx. 1.4×1.4), 40 levels	Coupled	HTAP2 emissions	Takemura et al. (2005) Takemura et al. (2009) Watanabe et al. (2010)
Community Earth System Model, version 1 (Community Atmosphere Model, version 4) [CESM1-CAM4]	1.0.3	2.5×1.9 26 levels	Slab	Fixed concentration	Neale et al. (2010) Gent et al. (2011)
CESM1-CAM5	1.1.2	2.5×1.9 30 levels	Coupled	Emissions	Hurrell et al. (2013) Kay et al. (2015) Otto-Bliesner et al. (2016)
Norwegian Earth System Model (NorESM)	NorESM1-M (intermediate resolution)	2.5×1.9 26 levels	Coupled	Fixed concentration	Bentsen et al. (2013) Iversen et al. (2013) Kirkevåg et al. (2013)
L'institut Pierre-Simon Laplace Coupled Model, version 5A (IPSL-CM5A)	CMIP5	3.75×1.875 39 levels	Coupled	Fixed concentration	Dufresne et al. (2013)



5 **Figure 1: Normalized  $\Delta P$  (change per unit forcing) for (a) CO<sub>2</sub>, (b) BC and (c) SO<sub>4</sub>. Black dots indicate the change is significant at 0.95 confidence level. Please note that the sign for SO<sub>4</sub> is flipped due to its negative forcing. Thus, the results shown for SO<sub>4</sub> is the precipitation change per unit negative forcing.**



**Figure 2: Domain-averaged  $\Delta P$  (purple rectangles in Fig. 1) for (a) CO<sub>2</sub>, (b) BC and (c) SO<sub>4</sub>. Error bars of multi-model mean (MMM) are 90% inter-model spread.**

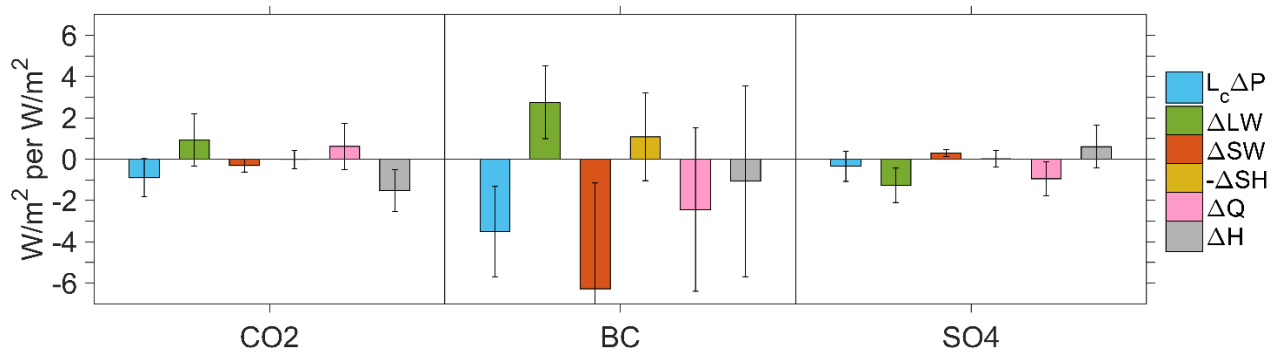
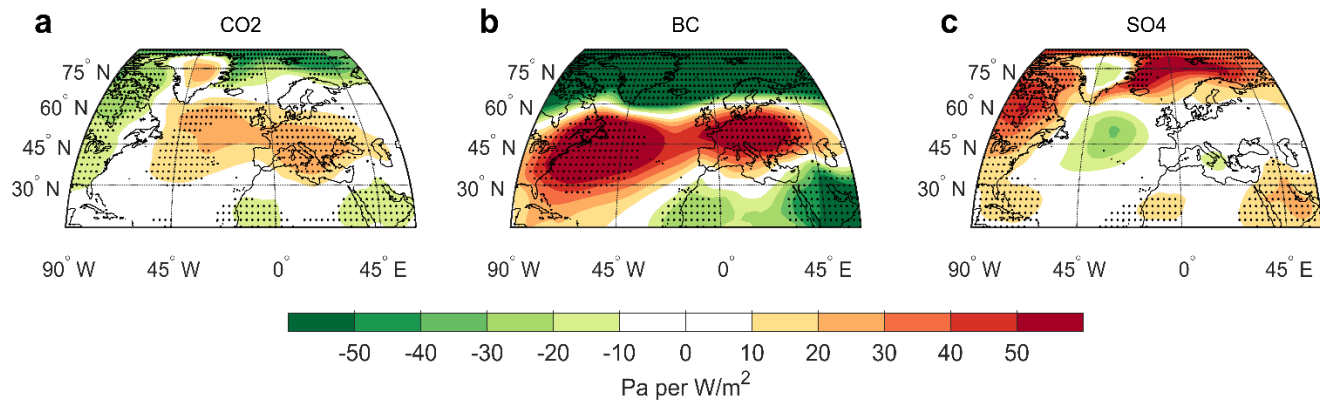


Figure 3: Domain-averaged (purple rectangles in Fig. 1) energy budget change for each forcing and energy component as shown in Equation (1) and (2). It holds that  $L_c \Delta P$  (blue) =  $\Delta Q$  (pink) +  $\Delta H$  (gray), where  $L_c \Delta P$  is the change in total latent heating,  $\Delta Q$  (pink) =  $\Delta LW$  (green) +  $\Delta SW$  (red) -  $\Delta SH$  (brown) is the change in diabatic cooling of the atmospheric column due to shortwave and longwave radiation, and sensible heat flux,  $\Delta H$  is the change in column-integrated dry static energy flux divergence. The error bars indicated 90% inter-model spread.



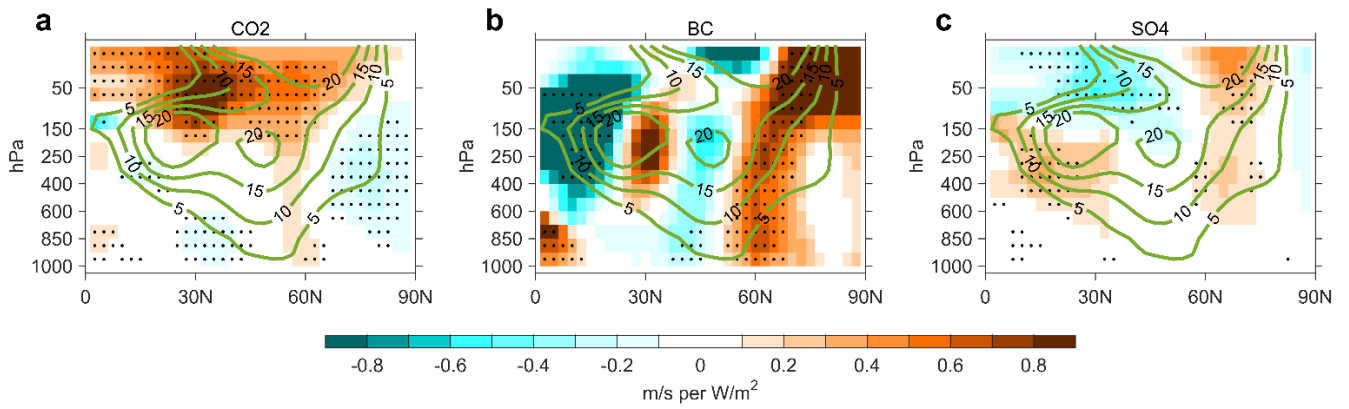


**Figure 4: Same as Fig. 1, but for sea level pressure (SLP).**

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**Figure 5:** Same as Fig. 1, but for zonal wind. The green contours represent the 50-yr climatology of the zonal wind in the control simulations. The contours are at the interval of 5m/s, with positive values indicating eastward winds.

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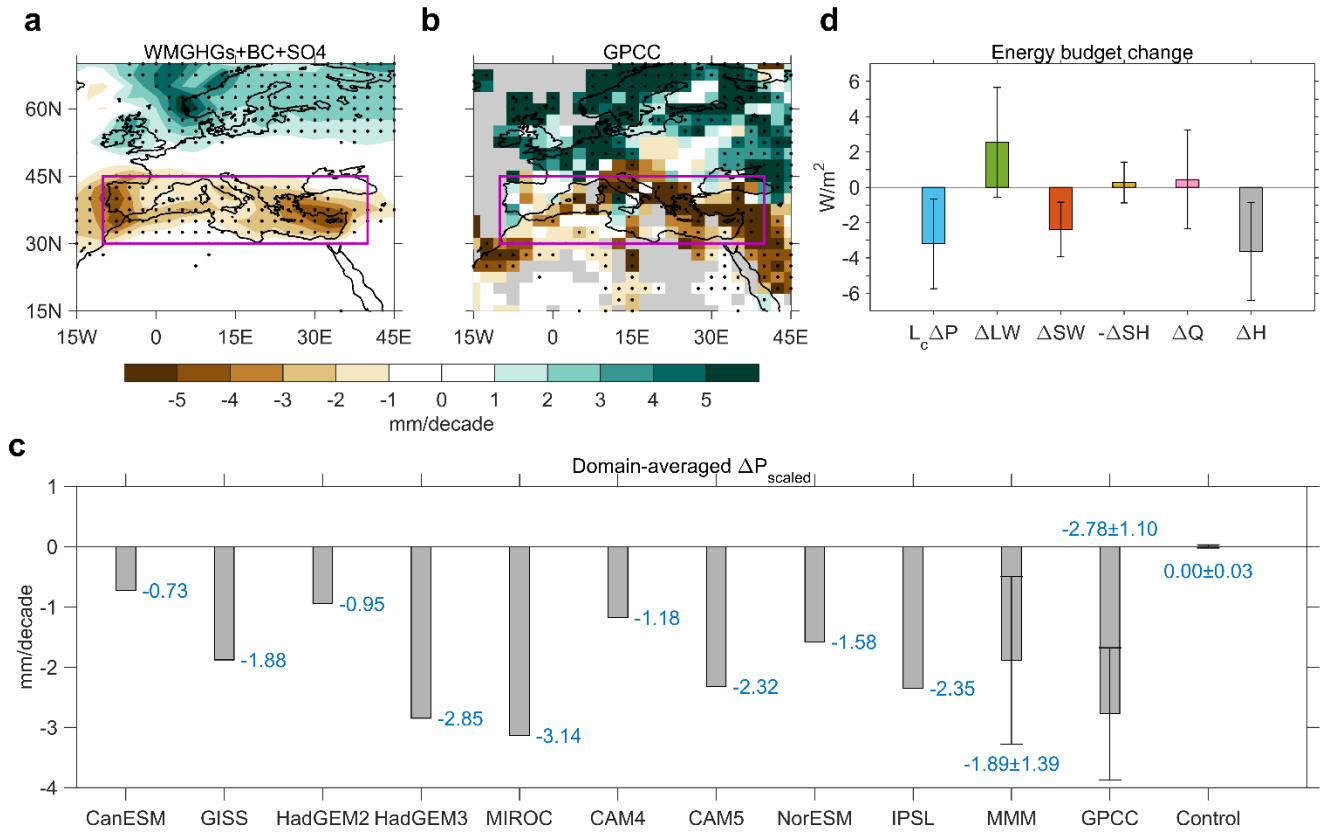


Figure 6: Scaled change for the combination of WMGHGs, BC and  $SO_4$  for (a) spatial pattern of precipitation, (c) domain-averaged precipitation change, and (d) energy budget change, along with 1901-2010 (b) GPCC observational data (for which gray indicate missing or incomplete data). The dots in (a) and (b) indicate changes are significant at 0.95 and 0.9 confidence level, respectively. Error bars in (c) and (d) indicate 90% uncertainty ranges.

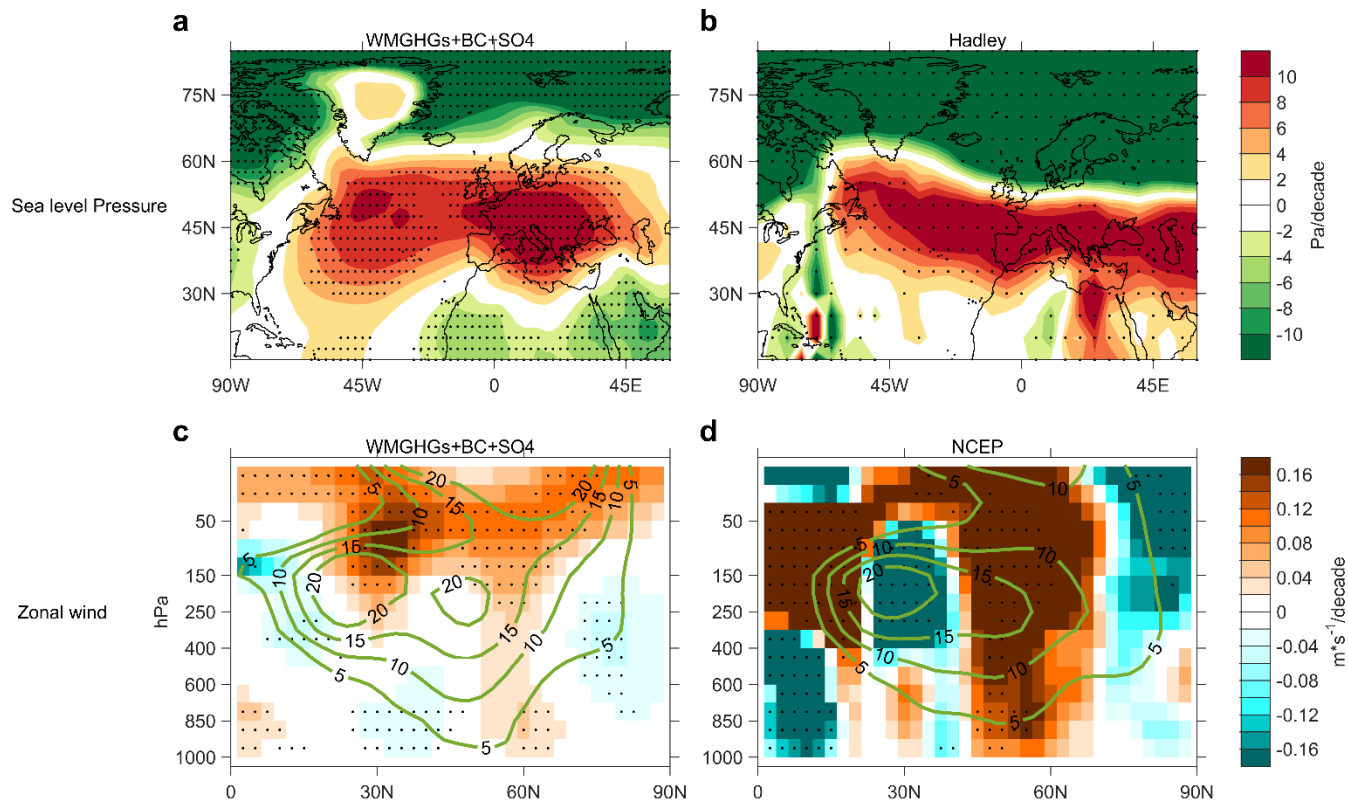


Figure 7: SLP (a & b) and zonal wind change (c & d). (a) and (c) are scaled change for the combination of WMGHGs, BC and SO<sub>4</sub>, while (b) and (d) are Hadley observational data and NCEP reanalysis data, respectively. Dots indicate the changes are significant at 0.95 confidence level. The green contours in (c) and (d) represent the climatology position of the zonal wind. The contours are at the interval of 5m/s, with positive values indicating eastward winds.

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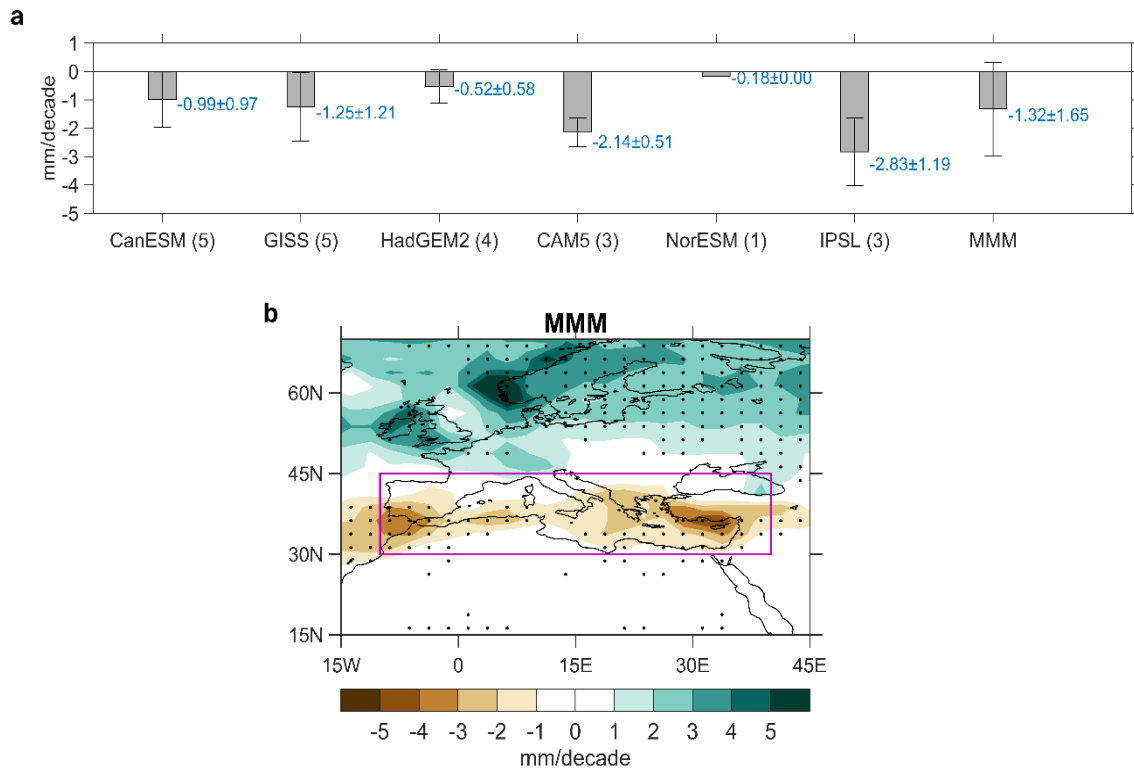


Figure 8: Precipitation trends of CMIP5 HistoricalGHG simulations during 1901-2005, (a) domain-averaged (purple rectangles in Fig. 1) trends for each model. Error bars of each model indicate 90% inter-ensemble spread and error bars of MMM indicate the 90% inter-model spread. The numbers in parentheses indicate the ensembles collected for each model. (b) spatial pattern of MMM value for the trends. Dots indicate that the change is significant at 0.95 confidence level.