Causes of Future Mediterranean Precipitation Decline Depend on the Season

Supplementary Material

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1 Absolute Precipitation Changes

Changes in precipitation have been presented in relative terms in the main article. Additionally, Figure S1 shows absolute values for the precipitation change for different Mediterranean sub-regions. Note that the absolute precipitation decline in winter and summer is of similar magnitude.

2 Comparison of Global Driving Simulations

In the main text, simulation results have been shown as averages for the two driving GCMs (MPI-ESM-LR and HadGEM2-ES) in Figures 1-4. Here Figure S2 (S3) shows the summer (winter) changes in geopotential height anomaly and mean precipitation, separately for the two simulations. The changes in the geopotential height anomaly are an indication of the changes in the circulation, which are very different depending on the driving GCM. The resulting winter precipitation decline differs depending on the pattern of the circulation change. For instance, a winter precipitation decline can be found in regions where the geopotential increases (Figure S3).

3 Technical Simulation Details

Figure S4 shows the effect of smoothing the annual cycle of temperature or wind changes (Storch and Zwiers, 1999; Bosshard et al., 2011). This is done for all experiments either using domain mean values on every model level (TDLR, SSTE) or separately for every boundary grid point (MEA). The variability on timescales smaller than seasons is efficiently smoothed and thus not prescribed in the experiments. This is the same method as used in Kröner et al. (2017) and Brogli et al. (2019).

The experimental design in this study is adapted from Kröner et al. (2017) and Brogli et al. (2019). While our results are consistent with the mentioned studies, some improvements to the methodology regarding the suitability to study precipitation changes have been made. The improvements are related to the representation of lapse-rate changes in the TDLR experiment, and to a new experiment (SSTE), which was not performed in Kröner et al. (2017) and Brogli et al. (2019). Furthermore, we only modified the boundary conditions of the historical simulation in this study, while in Kröner et al. (2017) and Brogli et al. (2019), changes were added to the historical simulation and subtracted from the future simulation, and the average was analyzed. As both previous studies found very similar results for both approaches, we only retained the modification of the historical simulation in this study to save resources. In this work, we show changes in each experiment relative to the historical simulation, while Brogli et al. (2019) focused on incremental changes between the experiments. This is because herein we focus on decreasing precipitation and we are interested in whether a certain driver leads to drying in absolute terms. On the other hand, Brogli et al. (2019) focused on temperature changes where it was more informative to assess how much every driver contributes to the temperature change.

The TDLR experiment presented in the main text is adapted from the simulation to quantify mean lapse-rate change presented in Brogli et al. (2019). We change the temperature at each model level according to the domain mean change between the future and historical simulation. However, as described in Table 1, here we only prescribe mean tropospheric lapse-rate changes in TDLR, instead of using all model levels (Figure S5). The main purpose of this adaptation to the experimental setup is to be able to more accurately simulate the tropospheric temperature change. When using only mean tropospheric lapse-rate changes, the vertical summer temperature change profile of the full climate change simulation is accurately reproduced (Figure S5). When using the mean lapse-rate change from all model levels, lapse-rate changes are also reproduced, but the change in tropospheric temperatures is slightly smaller than in FCC (Figure S5). This occurs because the troposphere over the Mediterranean is deeper than the domain-mean, and some of the domain-mean stratospheric cooling is consequently affecting the troposphere in the Mediterranean. We can avoid this by not prescribing any stratospheric cooling and using constant warming throughout the stratosphere. Note that in MEA, spatially varying temperature changes are used to modify the boundary conditions, and thus also the stratospheric cooling can be prescribed without complications.
Figure S1: Absolute change in precipitation over land for summer (upper row) and winter (lower row). The columns show these changes from left to right for the four experiments TDLR, SSTT, MEA, and FCC (see also Table 1). In each panel, the differently colored bars represent a sub-region of the Mediterranean, namely the Iberian Peninsula (IP; blue), Central Mediterranean (CMD; yellow), Eastern Mediterranean (EMD; green) and the southern coast (SCO; orange). The three regions IP, CMD, and EMD include land areas north of the Mediterranean basin and the borders of the regions are the following: 36° N, 44° N, 10° W, and 3° E for IP, 36° N, 44° N, 3° E and 25° E for CMD, and 36° N, 44° N, 25° E and 40° E for EMD. The SCO region includes areas on the southern coast of the Mediterranean and is evaluated between 28° N, 36° N, 10° W, and 35° E.

For the mean state & circulation experiment, we additionally created experiments where relative humidity can vary according to the GCM instead of being held constant, but this makes virtually no difference (Figure S6). Experiments with varying relative humidity were used by Brogli et al. (2019) to quantify their 3D Change.

References

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Storch, H., and F. Zwiers, 1999: Statistical Analysis in Climate Research. Cambridge University Press, Cambridge, United Kingdom, doi:10.1017/CBO9780511612336.
Figure S2: Changes in the (1st and 3rd row) summer (JJA) geopotential height anomaly and (2nd and 4th row) mean summer precipitation. The top two rows show the regional simulations driven by MPI-ESM-LR and the bottom two rows the simulations driven by HadGEM2-ES. Columns show the experiments listed in Table 1.
Figure S3: Same as Figure S2 but for winter (DJF)
Figure S4: Example of the smoothed mean annual cycle describing a change in temperature. (blue line) Mean annual cycle of the difference in near-surface temperature between 2070-2099 and 1971-2000. (orange line) The remaining annual cycle after the smoothing with the spectral filter is performed. This smoothed annual cycle is subsequently used to modify the boundary conditions of the experiments at the matching altitude and location. Data is taken from the COSMO-CLM simulation driven by HadGEM2-ES.
Figure S5: The TDLR experiment used in this study compared to the related experiment from Brogli et al. (2019). The lines show mean vertical profiles of the summer temperature change over Mediterranean land grid points (30° N - 40° N). (blue line) Full climate change signal. (green lines) TDLR experiment used in this study (TDLR\_trop), where the green dashed line shows the initial summer mean profile used to modify the boundary conditions, and the solid green line shows the 30-yr mean simulation output. (yellow lines) The profile from the TDLR experiment (TDLR\_all) used in Brogli et al. (2019), whereas the dashed (solid) line is the initial (mean output) profile. Note that the dashed profiles are identical up to an altitude of \( \sim 10 \) km, and then diverge higher up. The profiles are taken from the HadGEM2-ES driven COSMO-CLM simulation, but similar results are obtained when COSMO-CLM is driven by the GCM MPI-ESM-LR.
Figure S6: Mean summer precipitation changes in two versions of the mean state & circulation experiment. (left) The experiment assuming constant relative humidity at the model boundary. (right) The experiment where the relative humidity was changed according to the GCM. The mean over the two GCMs is shown. Regions with a climatological rain amount of < 0.9 mm/season are masked and shown in gray.
Figure S7: Vertical cross-sections of simulated circulation in the driving GCMs and the RCM simulations where the respective GCM is downscaled. Shading shows the annual and zonal mean meridional wind component from the 2070-2099 period within the RCM domain. (top row) Regional simulation results. (bottom row) Global simulation results. (left column) Original and downscaled HadGEM2-ES simulation. (right column) Original and downscaled MPI-ESM-LR simulation.