The Role of Hadley Circulation and Lapse-Rate Changes for the Future European Summer Climate

Supplemental Material

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Supplemental Figures for Summer

Figs. S1 – S3 show a comparison between the 2 m temperature change anomaly obtained by the simulations based on the warming of the CTRL simulation and those based on the cooling of the SCEN simulation for each driving GCM. In Fig. 2 of the manuscript the average of the two approaches is shown (see Section 2c). We find no substantial difference between the warming and the cooling approach which suggests that our separation is relatively robust independent of the background climate variability.

Fig. S4 shows the summer warming anomaly in the upper troposphere. Note that the upper level spatial warming differences are very small compared to the surface values (Fig. 2).

Figures for Winter

The results presented in the manuscript focus mainly on the European summer season. Here, we provide a reproduction of relevant figures presented therein for the winter months December, January and February. This allows for an analysis of seasonal differences between the processes that we discuss in the main text. The winter counterparts of Figs. 2, 3, 5, 7, 10 and 11 are shown in Figs. S5 – S10.

In winter, the spatial pattern of climate change exhibits the Arctic amplification, seen as a positive warming anomaly in the northern part of the domain (Fig. S5). Contributions to the arctic amplification stem from the meridional change, but in contrast to summer also the thermodynamic change (which includes e.g. the surface albedo feedback) and the high-frequency circulation change play an important role. The meridional lapse-rate change gradients seem to play a role for the arctic amplification because the near surface air masses in Northern Europe are largely decoupled from the upper tropospheric air masses and thus warm differently (Figs. S8 and S10), driven by radiative processes (Pithan and Mauritsen, 2014). Over the Mediterranean, lapse-rate changes are strong with up to 0.5 K km$^{-1}$ (Fig. S8). This strong increase in static stability could contribute to the precipitation decrease seen for the meridional change (Fig. S6). In contrast to summer, the average stratification over European land grid points differs substantially from the moist-adiabatic lapse rate (Fig. S9) and thus processes depending on lapse-rate changes are likely less important in winter (see also Fig. S5).

The Hadley circulation based on the stream function $\Psi_\chi$ is strong and clearly visible in Fig. S7. Also, the latitude of the northern Hadley cell edge is well defined, meaning in that the latitude where $\Psi_\chi = 0$, is fairly independent of altitude. All three GCM simulations show a mean winter poleward shift of the northern Hadley cell edge.

CNRM-CM5 Data

CNRM has recently released information regarding its CNRM-CM5 output that we use to drive the historical RCM simulations for the CTRL period. The simulations using the RCP 8.5 scenario are not affected. There was a technical mistake during the upload of the 6-hourly output to the ESGF CMIP5 data base (http://www.umr-cnrm.fr/cmip5/spip.php?article24 [accessed 16 August 2018]). The problem is caused by merging two different ensemble members. The uploaded 2D surface fields come from one member, and the 3D atmospheric fields from a different member. The different ensemble members have the same climate, but different variability. It is therefore expected that the issue will have a significant impact on the daily and monthly variability, while the impact on the mean climate should be smaller. Since we use the mean climate state of the CNRM-CM5 driven simulations mainly for the purpose of a comparison to other simulations, and the results seem to be in reasonable agreement, we decided to present the results as they are. However, readers should be aware that the results of this particular model are affected by this problem.

Role of the Mean-Lapse Rate Change

We found that lapse-rate changes and their modulations in meridional direction are crucial to explain the Mediterranean warming amplification. In our separation, the contribution of the mean lapse-rate
change results in a weaker Mediterranean Amplification than the meridional change (Fig. 2), which might seem surprising. Interestingly, the simulations driven by the mean lapse-rate change still produce a distinct meridional gradient in lapse rate changes as simulation result (i.e. weaker lapse-rate change over the Mediterranean compared to Northern Europe). CCLM thus generates the meridional gradient in lapse-rate changes even if no meridional gradient is prescribed at the lateral boundaries. Note that this should be expected under the assumption that the meridional gradient is caused by humidity contrasts (humidity contrasts are also present in the simulations including the mean lapse-rate change). This can be seen from Fig. S11, which shows a comparison between the vertical temperature profiles that were used to modify the lateral boundaries of the simulations, and those generated by the simulations during summer over the Mediterranean. It is evident, that the simulation driven by the mean lapse-rate change reduces the strength of the lapse-rate change in the Mediterranean compared to what was prescribed at the lateral boundaries. This is not the case over Northern Europe (not shown).

Why is the Mediterranean Amplification in the mean lapse-rate change simulations still comparably weak then? The reason is an unrealistically low warming in the upper troposphere over the Mediterranean that arises because we prescribe the domain mean lapse-rate change (Fig. S11). The underlying problem is that the depth of the troposphere varies substantially within the RCM domain. Also, in contrast to the tropospheric warming, the stratosphere is cooling in the projections (Fig. 11). Since the troposphere over the Mediterranean is about 4 km higher than above Northern Europe, averaging the warming at altitudes that lie within the troposphere over the Mediterranean but in the stratosphere further north is problematic. If we calculate the domain mean warming at an altitude that lies within the troposphere in southern regions but within the stratosphere further north, the tropospheric warming and the stratospheric cooling cancel and we get a very weak warming on average (Fig. 11). Thus, in the simulations only including the mean lapse-rate change, the warming in the upper troposphere over the Mediterranean is prescribed too low compared to the total change (Fig. S11). As a result, the different lapse-rate changes induced in the simulations only lead to a slightly stronger warming in the Mediterranean since the too weak upper level warming is compensating for the lapse-rate change gradient.

References

Fig. S1: Same as Fig. 2 for the CCLM simulations driven by HadGEM2-ES, but separated into the simulations based on a warming of the CTRL simulation (left column) and a cooling of the SCEN simulation (middle column). The right column shows the difference between the two approaches shown in the middle and left column. Shading shows the temperature change anomaly (left two columns) or the absolute temperature difference (right column).
Fig. S2: Same as Fig. S1 but for the CCLM simulations driven by MPI-ESM-LR.
Fig. S3: Same as Fig. S1 but for the CCLM simulations driven by CNRM-CM5.
Fig. S4: Anomalies of the summer temperature difference on 8 km height between the SCEN and CTRL period with respect to the domain mean warming. The panels show the CCLM simulations driven by HadGEM2-ES (left), MPI-ESM-LR (middle) and CNRM-CM5 (right). Shadings show the deviation of the temperature change from the domain mean in the same way as in Fig. 2. The number on the upper left in each panel shows the domain mean warming in K.
Fig. S5: Same as Fig. 2 for winter.
Fig. S6: Same as Fig. 3 for winter.
Fig. S7: Same as Fig. 5 for winter.

Fig. S8: Same as Fig. 7 for winter.
Fig. S9: Same as Fig. 10 for winter.
Fig. S10: Same as Fig. 11 for winter. The dashed contours show the mean zonal wind with contours at 25 and 30 m s$^{-1}$ instead of 10, 15 and 20 m s$^{-1}$ as in Fig. 11.
Fig. S11: Vertical profiles of mean summer temperature differences over land grid points in the Mediterranean (between 30° and 44° N) between the SCEN (2070-2099) and CTRL (1971-2000) periods in CCLM driven by HadGEM2-ES (left column), MPI-ESM-LR (middle column) and CNRM-CM5 (right column). Colors show different separated contributions to climate change, where TOT is the total change, TD the thermodynamic change, LR the mean lapse-rate change and MC the meridional change (see Section 2c). The dashed lines show the respective summer vertical temperature change profile that is used to modify the lateral model boundary fields, i.e. the change prescribed at the model boundary around the Mediterranean. The solid lines show the mean changes resulting form the simulation. Here, the temperature change is expressed in absolute terms, i.e. as change caused by the respective effect compared to CTRL or SCEN. In other words, the meridional change shown here includes the mean lapse-rate change and the thermodynamic change, and is not expressed relative to the mean lapse-rate change. The mean lapse-rate change shown here includes the thermodynamic change.