Response to Referee #1 for wcd-2021-34

The referee's comments are shown in black and italic. Our responses are shown in dark blue. When we paste text from the manuscript to the response, it is shown in dark red.

"Future summer warming pattern under climate change is regulated by lapse-rate changes" by Brogli et al uses a variety of regional and global simulations with climate models to investiagte the relationship between the spatial structure of surface warming and changes in tropospheric lapse rates particularly over Europe but also over other continents. Building on previous work, the authors conclusively show that – across the tropics and most interestingly across mid latitudes – surface warming and lapse-rate changes are intimately linked through low-level moisture availability. This idea has previously been used to understand the land-ocean warming contrast in the tropics and subtropics, but this is the first study to show its applicability to the extratropics. For this reason, I think this paper is important and significant, opening up interesting avenues for applying similar methods to understand and constrain regional temperature changes around the globe. In addition, I find the pseudo global warming simulations to be elegant and insightful for isolating the roles of uniform tropospheric warming vs changes in lapse rate for the surface warming pattern. I recommendation swift publicatio and have only a few minor comments to address:

We thank the referee for taking the time to review our manuscript and for the positive overall assessment.

Lines 134,135: Maybe I'm misunderstanding the results in Fig. 3, but it doesn't look to me like "the Mediterranean amplification is absent in TD". Rather there seems to be some Med amplification, but it's just weak compared to the FCC and TDLR simulations. Can you clarify this point?

We agree that this formulation was incorrect, as was also noted by Referee #2. We clarified this point in the text which now reads:

In contrast, the Mediterranean amplification clearly weaker in TD where we prescribe no large-scale lapse-rate changes (Fig. 3i). Quantitatively, the warming contrast between the Mediterranean and Northern Europe is around 1 K weaker in TD than TDLR and the magnitude of Mediterranean warming is more than 1 K weaker in TD than TDLR.

We also changed Figure 3 to make the differences between TD and TDLR more visible (showing anomalies and absolute changes). Furthermore, the more detailed description of the TD results was adapted, which now reads:

This follows from similar dynamic alterations of the imposed warming profiles as in TDLR, meaning that also in TD the lapse-rates adjust within the simulation domain. Also in TD, simulated lapse-rate changes are larger in Northern Europe than the

Mediterranean (Fig. 3i). This leads to a stronger surface warming in the Mediterranean in agreement with TDLR (Figure 3g,h), but the absolute magnitude of the warming is over 1 K smaller in TD.

Lines 160-165: The relatively homogeneous warming aloft in the summertime extratropics is interesting, and linking it to the weak eq->pole temperature gradient and associated weak baroclinicity is a neat idea. I hope future research investigates this hypothesis in more detail!

We think so too. Following your comment, we also explicitly state the opportunity for future research in the text.

It may be surprising that the middle to upper tropospheric temperature change in summer over Europe is spatially uniform. While this seems clear in the simulations we analyzed, the physical reasons behind it remain more speculative and can be an avenue for future research.

Lines 182,183: When discussing the below-average increase in specific humidity in the Med, it would be good to state that this implies a reduction in relative humidity in those regions. You could also show the changes in RH directly in an additional figure. More generally, it might be worth commenting on the effects of climatological dryness vs changes in dryness (i.e. decreasing RH) for the lapse-rate changes and surface warming pattern.

Thank you for this remark, a more in-depth discussion of the moisture availability is indeed a valuable addition to the manuscript. As suggested, we added Figure 4 showing the climatological relative humidity and the relative humidity changes in the experiments. We added a detailed description of the relation of relative humidity to lapse rates in lines (163-183). We also discuss the role of change in dryness vs. climatological dryness where the conclusion is repeated below for convenience.

Note that both regional climatological differences in relative humidity as visible in Figure 4a, as well as relative humidity changes in response to warming (Figure 4b-d) can contribute to the differences in lapse-rate changes projected by simulations. Yet, in both TD and TDLR we observe quite moderate changes in relative humidity compared to FCC (Figure 4b-c vs. d). Therefore, it is likely that in our idealized simulations, the climatological spatial differences in moisture availability are crucial to induce changes in lapse rates.

Response to Referee #2 for wcd-2021-34

Review for "Future summer warming pattern under climate change is regulated by lapse-rate changes"

In this paper, the authors argue that lapse rate changes are fundamental to understanding the pattern of summertime warming projected in a variety of regional and global climate models. The authors present results from idealized modelling experiments to support their hypothesis that lapse rate changes are fundamental to understanding the pattern of surface warming across the globe and that lapse rate changes are a major factor that generate the pattern of surface warming that manifests across climate models.

The paper is well written and clear, and I think the investigation into the role of the atmosphere's role in generating land surface warming patterns is extremely important. However, in its current state, I don't think this paper provides an adequate explanation of the physics behind the creation of the amplification pattern over the Mediterranean; this makes the global analysis presented later in the paper less insightful. I was left wanting more evidence from the initial simulations to bolster the author's argument that the atmosphere's adjustment is crucial to understanding the warming pattern of summertime surface temperature.

We thank the referee for taking the time for a detailed review and the constructive feedback on our manuscript.

Major Comments

The authors allude (lines 39-40) to the fact that the spatial warming pattern is at least partially driven by energy partitioning between latent and sensible at the land surface. To me, this is a null hypothesis, and the authors must use their experiments to quantify the role of the atmosphere in amplifying the pattern of warming initially generated by the local differences in energy flux partitioning at the land surface. In my mind the authors need to show that convective activity or circulation adjustment to the warming pattern driven by energy flux partitioning near the land surface is amplified by the lapse-rate adjustment accomplished by the atmosphere for their conclusions to be valid.

*To me, the analysis of novel experiment done by the authors (application of a vertically uniform boundary condition) does not prove that lapse rate changes are the ultimate cause of the surface warming pattern because there is no evidence presented about the dynamical adjustment. As a reader, I would like to know how the retribution of energy that amplifies the warming in the Mediterranean is accomplished in the TDLR simulations (and not accomplished in the TD simulations). Could it be that an unrealistic (vertically uniform) boundary condition destabilizes the atmosphere, causing enhanced convection across all of Europe and a large dynamical adjustment that mixes out some component of the summertime warming pattern? Or is it that the realistic lapse rate boundary condition applied to the TDLR simulations induces large scale subsidence over the

Mediterranean and amplifies the local warming? In any case, I was left wanting an analysis of the atmospheric motions that give rise to the lapse rate changes shown in Figs. 3d and f. The authors approach this analysis in Fig. 4, but the moist enthalpy changes could also be driven by the surface flux partitioning; without a complementary analysis of the atmospheric adjustment, I think the argument is much less convincing.

In particular, the presentation of Fig. 3e needs to be changed. To my eye, removing the TD simulation domain mean (rather than the FCC domain mean) would reveal a pattern similar (but not exactly the same) as the TDLR experiment, suggesting that energy flux partitioning at the land surface is fundamentally responsible for the warming gradient and only accentuated by the atmospheric response.

We think that you raise a very relevant and interesting point. First, regarding Figure 3 we fully agree and did make the suggested adjustment to the figure, which is detailed also in an answer to a minor comment below. There is indeed an amplification of the warming also in TD, which we discuss in detail in the text (lines 149-157 in the revised manuscipt). We agree that the near-surface conditions (especially the moisture availability) do exert an important influence on the summer warming pattern. Yet from the profiles shown in Figure 3 it is also clear, that the surface influences the entire troposphere and vice-versa. This is now stated in the text (staring on line 215):

Overall, during European summer, the entire troposphere is relevant to understand the surface warming pattern: From TD we can observe that surface moisture gradients influence the warming up to 10-12 km height (Figure 3i). On the other hand, the extra upper tropospheric warming introduced in TDLR strongly affects near-surface warming levels (Figure 3f).

As suggested by the referee, we added an analysis of vertical motions within our simulation domain. This is shown in the newly added Figure 5. In summary we find that in our idealized simulations dynamical changes are insignificant, especially when compared to the fully GCM-driven run. This also agrees with Figure A1. This allowed us to state with more certainty that the adjustments of tropospheric lapse-rates are achieved by the warming/moistening of the atmosphere rather than from altered atmospheric dynamics. We now provide a much more extensive physical interpretation of the simulation results (lines 167-217), highlighting the importance of moisture availability for lapse-rate changes to occur. Also we argue using the thermodynamic equation that stratification changes can lead to warming in the absence of changes in vertical motions (lines 193-203). The moisture availability is also shown in the new Figure 4. Pasting the entire additional description of our experiments in this response would be to long but we add the new summarizing section from our manuscript below, which hopefully well addresses your concerns:

Bringing together the results from Figs. 3, 4, and 5 we interpret the results as follows: Warming which we artificially impose in the idealized simulations is vertically re-distributed throughout the troposphere. The vertical motions required to achieve the re-distribution of the warming are already present during summer in the CTRL simulation (Fig. 5). The warming and moistening of the atmosphere in the TD simulation suffices to induce lapse-rate changes. These lapse-rate changes are more pronounced in present-day moist regions than in dry regions (Fig. 3i and Fig. 4a) because the vertical mixing follows the temperature-dependent moist-adiabatic lapse rate more frequently in moist regions. While in both TD and TDLR the lapse-rates locally adjust according to the near-surface humidity and in both simulations lead to an amplification of the Mediterranean warming, the very high warming levels of more than 6K are reached only in TDLR because here we prescribe a stronger homogeneous upper-tropospheric warming than in TD. This upper-tropospheric warming affects the surface warming trough adiabatic descent in the Mediterranean. We suggest that only the combination of the strong large-scale upper-level warming, and vertically near-adiabatic re-distribution of the warming evokes the Mediterranean amplification.

Minor Comments:

Suggestion for lines 30-31: Since the dry adiabatic lapse rate is independent of temperature changes, the lapse rate changes driven by global warming are driven by the response of the moist-adiabatic lapse rate that decreases with warming.

We included the nice sentence as suggested, and we think this improves the clarity.

Line 44: In summer, however, also

Corrected

Lines 53-54: Do you really mean this? I think the argument is that lapse-rate changes accentuate the Mediterranean amplification, rather than cause it outright.

You are right, this was too strongly formulated and might be misleading in the context of climate change. As stated in the title we mean that lapse-rate changes “regulate” the warming. We changed the wording to “govern” here.

Line 71: are covering

Thank you, this is corrected.

Fig. 3c, e: Please remove the experimental mean, rather than the mean from the FCC experiment. This is a particular problem with panel e as I’ve noted above.

We acknowledge the point and were usure how to plot it in the first draft as well. As the referee suggests we now use each simulation’s domain mean to visualize the anomaly. We also added the absolute warming to the plot which we hope further improves the clarity.

Line 134-135: The Mediterranean amplification is not absent in the TD experiment, it's merely reduced and it's hard to tell because the relevant mean temperature has not been removed.

This was indeed an incorrect formulation and noted by both referees. As stated above we changed the figure to accord with the lower mean warming as in TD. We now state:

In contrast, the Mediterranean amplification is clearly weaker in TD where we prescribe no large-scale lapse-rate changes (Fig. 3g-i).

Line 137-139: This is part of my major comment above and the place for a deeper analysis of the circulation differences between the TD and TDLR experiments. How does this dynamically weakened lapse rate accomplished? I think this is crucial for the argument.

Thank you for pointing that out, we agree that this is an interesting point to further investigate. We have added an analysis of the vertical motions in the experiments (Figure 5) and overall found that the dynamic differences between TD and TDLR are small. Based on theory and previous literature we argue that the dynamically weakened lapse-rate is accomplished by vertical mixing of relatively dry air (especially adiabatic descent), which is now described in much more detail (see lines 166-217 in the revised manuscript).

Line 146-148: I'm not sure I understand this sentence. We expect the upper tropospheric warming to be larger than surface warming no matter what due to climate change. I think clarification here would help me understand the argument.

We agree that this was not well explained. We now state more clearly that lapse-rates within simulation domain change also in TD compared to what we impose at the lateral boundaries. The section now reads:

This follows from similar dynamic alterations of the imposed warming profiles as in TDLR, meaning that also in TD the lapse-rates adjust within the simulation domain compared to the warming profile imposed at the lateral boundaries. Also in TD, simulated lapse-rate changes are larger in Northern Europe than the Mediterranean (Fig. 3i). This leads to a stronger surface warming in the Mediterranean in agreement with TDLR (Fig. 3g,h), but the absolute magnitude of the warming is over 1 K smaller in TD.

Fig 4: Maybe mask the oceans, the enthalpy changes there are so high it's a bit distracting from the argument you're articulating

Good idea! We modified the figure as suggested.

Lines 216-217: This seems at odds with the contention at other points in the paper (Lines 53-54) that lapse-rate changes cause the warming pattern.

This is true, as stated above we changed the earlier statement and therefore left these lines unchanged.

Lines 250-251: Again, I don't think the analysis as currently constituted shows that lapse-rate feedbacks are "decisive". Some numerical comparisons between the TD and TDLR warming amplification patterns over Europe could help here.

We think that this conclusion is now backed with more data and more thoroughly shown and explained in the revised manuscript. Still, we weakened the wording here a bit and say that lapse-rate changes "regulate" the warming pattern, consistent with the title.