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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Hadley cell expansion in CMIP6 models" *by* Kevin M. Grise and Sean M. Davis

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We would like to thank the reviewer for taking time to review our manuscript and to provide helpful comments. Based on the reviewer's comments, we have made a number of minor changes and clarifications to the manuscript. Detailed point-by-point responses to all comments are provided below, and the original reviewer's comments are provided in bold type.

General comments: This is a very thorough and thoughtful study on the expansion of the Hadley cell across CMIP5 models/CMIP6 models/reanalyses. It clearly lays out the key similarities and differences between CMIP5 and CMIP6, and sets the differences between the models and reanalysis in a useful context. I have

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one main comment, and if it is addressed, the manuscript would be suitable for publication.

We thank the reviewer for their overall positive assessment of our manuscript and efforts to usefully compare CMIP5 models, CMIP6 models, and reanalyses.

My comment is that the role of the pattern of SST warming for the NH JJA contraction should be discussed. For CMIP5 models, there are significant differences in Hadley cell edge response between the amipFuture and amip4K experiments for the NH JJA season. So it would be helpful if results from the amip4K experiment were shown for comparison. Furthermore, Zhou et al. (2019) argue that an ITCZ shift related to the pattern of enhanced equatorial SST warming drives the subtropical circulation contraction during NH JJA. This is different from the present manuscript, in which it is argued that a general SST warming (pattern not required) forces the equatorial contraction during summer.

As requested by the reviewer, we have added results from the amip4K experiments to Figure 2c (also to Figure S2b). Please see the attached revised version of Figure 2. The reviewer is correct that the sign of the NH Hadley cell edge response changes when the uniform 4K SST warming is used instead of the patterned 4K SST warming. To clarify this, we have added the following text:

"However, as pointed out by Zhou et al. (2019), the exact pattern of SST warming is critical for capturing the equatorward contraction of the NH JJA Hadley cell edge seen in the abrupt 4xCO2 runs. A uniform 4K SST warming would instead result in a poleward expansion of the NH JJA Hadley circulation (Fig. 2c)."

We note that our original text largely followed from Shaw and Voigt (2015)'s results. They concluded that both the amip4K and amipFuture runs contribute to an equatorward contraction of the circulation in the Pacific basin, with the amip4K changes being slightly weaker. A subsequent careful examination of their paper shows that they exclude the western Pacific from their analysis (see red box in their Fig. 1). When

averaging over the entire Pacific basin (and thus also in the zonal mean) as we do here, a poleward expansion of the summertime circulation in the western Pacific basin is sufficient to overwhelm the equatorward contraction of the circulation in the eastern Pacific basin in the amip4K runs, but not in the amipFuture runs. This accounts for the apparent contradiction in the results of Shaw and Voigt (2015), who argue that the amip4K and amipFuture runs contribute to the same sign of the circulation response, and Zhou et al. (2019), who argue that the amip4K and amipFuture runs contribute to different signs of the circulation response.

1) How do you define the PSI500 Hadley cell edge for NH JJA if PSI never becomes positive in the tropics, and hence a zero-crossing does not exist? In my experience this occurs for some years in certain models.

The reviewer is correct that the NH JJA Hadley cell edge is undefined during some years. We have added the following text to the methods section to clarify this to the reader:

"We note that the NH summertime Hadley circulation is very weak, making it challenging to define the PSI500 metric during some years. We only consider the PSI500 metric from years in which there is a clear crossing of the 500-hPa streamfunction field from positive to negative in the NH subtropics. We consider the PSI500 metric to be undefined if no zero crossing in the streamfunction field occurs or if multiple zero crossings from positive to negative occur within a 20 degree latitude band (Lat Uncertainty = 20 in TropD)."

2) How exactly is the "response" defined for the abrupt4xCO2 experiment (Fig. 1)? I.e. over what period of the abrupt4xCO2 experiment are you averaging?

The reviewer must have missed this definition, which is stated in the second sentence of section 3: "difference in the Hadley cell edge latitude between its mean position during the last 50 years (years 101-150) of the abrupt 4xCO2 run and its mean position in the pre-industrial control run."

We have now also added this definition to the caption of Fig. 1 to make sure readers are aware of how the quantity plotted in Fig. 1 is defined.

References: Zhou, W., S.-P. Xie and D. Yang (2019): Enhanced equatorial warming causes deeptropical contraction and subtropical monsoon shift. Nature Climate Change. 9. 834- 839.

Thanks. We have added a citation to this paper.

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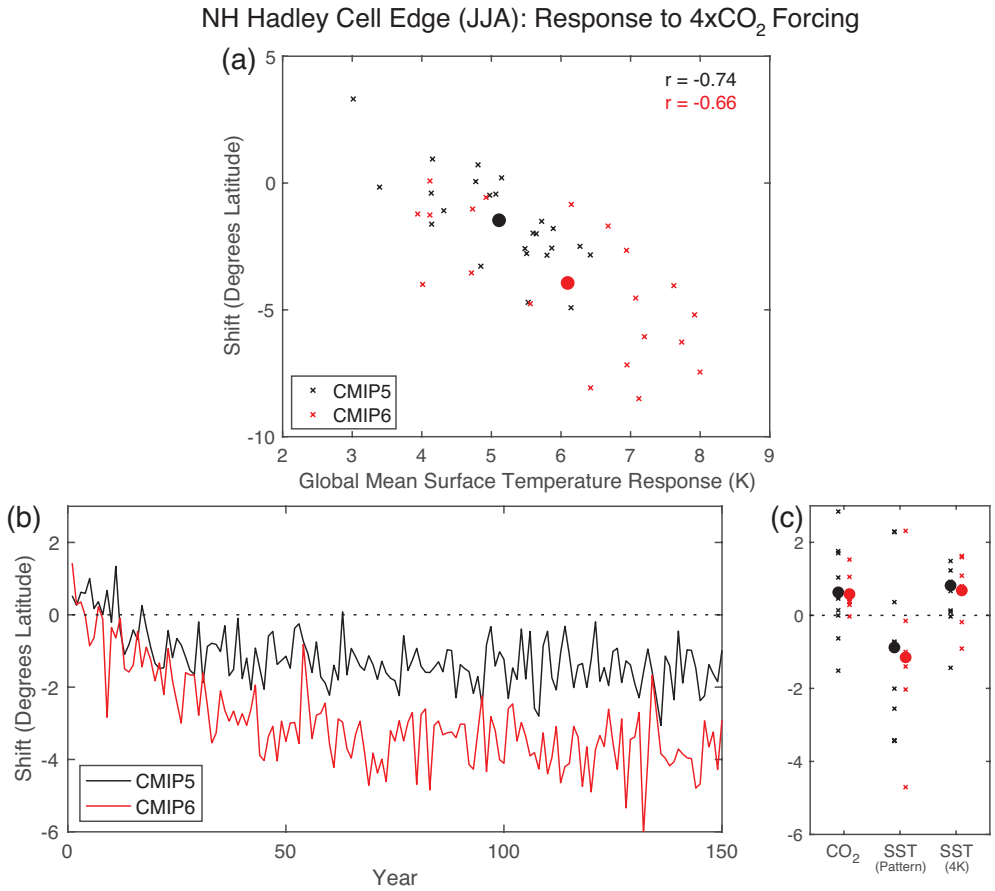

Fig. 1. Revised version of Figure 2

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