

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 providing 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.

The manuscript documents and contrasts trends in the Hadley cell edge in current generation CMIP6 models, the previous generation CMIP5 models and multiple reanalysis products. The results are new, novel and will be of broad interest to the community. Put simply the manuscript is superb and I very little reserva-

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tion in recommending this for publication with only a few minor changes. The manuscript is skillfully written and clearly communicated. I particularly liked the perfectly simple and concise title, an excellent and well-motivated introduction, and plots of a consistently high quality and common style. The manuscript also has a nice balance of both the NH and SH perspectives. I would be happy to review the paper a second time should it be needed.

We thank the reviewer for her very positive assessment of our manuscript.

In the introduction the focus is very much Hadley cell edge rather than tropical edge. So I was a bit surprised then to see the EDJ metric used in the analysis. I think a more general description of Hadley cell edge vs tropical edge metrics is then needed in the introduction. Then bring this through to your second last paragraph in the introduction that describes the aims of the paper.

As discussed below, we have eliminated the usage of the EDJ metric in the analysis. As such, we believe that the aims of the paper in the Introduction are correct as stated.

My interpretation for the use of the EDJ is that your taking advantage of the correlations between the HC edge and the EDJ in order to get longitudinal variability. Can you explain why you used this approach over say a local HC method (eg Schwendike et al. (2014) or your own study Staten et al. (2019))? Is this to avoid adding more metrics (ie consistent with TropD and the idea that fewer/better methods are the goal) or is it that you have concerns about the local methods accuracy/applicability?

Given the comments from Reviewers 1 and 2, we have eliminated the usage of the EDJ metric from the manuscript, as it does not directly correspond to the location of the Hadley cell edge (although it is highly correlated with it). We now use the USFC metric to quantify longitudinal variability in the tropical edge. We appreciate the reviewer's recognition of our previous work that attempts to define the Hadley cell at individual longitudes through local overturning circulations. However, this concept is still relatively

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new and remains an area of active research, so we feel that using the USFC metric at individual longitudes will be more straightforward for readers to interpret.

To address the reviewer's concern, we have added the following text into the methods section:

"We also make brief use of the USFC metric to examine longitudinal asymmetries in the circulation response, as the PSI500 metric can only strictly be defined in the zonal mean. Some recent studies have attempted to generalize the zonal-mean Hadley cell edge (as defined by the PSI500 metric) to individual longitudes by isolating regional meridional overturning cells (Schwendike et al., 2014; Staten et al., 2019). However, interpreting these regional overturning circulations is challenging and remains an area of active research, and thus we do not examine these local overturning cells here."

Introduction: In addition to the papers already cited, there are a number of excellent papers on Hadley cell expansion from Chris Lucas and Hanh Nguyen at the Bureau of Meteorology which could also be cited here. I am thinking papers such as Nguyen et al. (2012, 2015, 2018) Lucas et al. (2012, 2013); Lucas and Nguyen (2015). I am not suggesting you cite them all, but one or two would be good.

We have added citations to Lucas et al. (2012), Lucas et al. (2014), and Nguyen et al. (2015) in the introduction. Many of their other papers focus on the tropopause height metric of tropical width, which does not co-vary interannually with the Hadley cell edge (e.g., Waugh et al. 2018), and/or regional aspects of tropical widening, which are not the focus of the text in the introduction.

The introduction would benefit from a brief discussion that the Hadley cell latitude (middle atmosphere mass stream function zero crossing latitude) is thought to be the most reliable measure of tropical expansion (this is touched on briefly in L45 but I think this could be expanded a little). I think there should also be mention to other tropical edge metrics (STJ, EDJ, OLR, P-E etc) which are

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used within the literature already cited, and include the relationships with the jets (strength and position) in terms of tropical edge metrics and relationships with the HC position Ceppi and Hartmann (2012); Menzel et al. (2019); Maher et al. (2019).

We have added the following text into the introduction to more fully describe the metrics used to define the edges of the tropics:

“Traditionally, the edge of the Hadley circulation has been defined using the poleward boundary of the zonal-mean meridional mass streamfunction in the mid-troposphere, but departures from mass conservation in reanalyses (particularly in older generation reanalyses) can lead to large spurious trends in the location of the Hadley cell edge defined using the mass streamfunction (Davis and Davis, 2018). Consequently, many studies have sought to estimate trends in the location of the Hadley cell edge using other metrics, including the transition from zonal-mean surface easterlies to zonal-mean surface westerlies (Grise et al., 2018, hereafter G18; Grise et al., 2019, hereafter G19), the subtropical sea level pressure maximum (Choi et al., 2014), the latitude of the subtropical jet (Maher et al., 2020), the altitude break in tropopause height in the subtropics (Seidel and Randel, 2007; Lucas et al., 2012), thresholds in outgoing longwave radiation (Hu and Fu, 2007; Mantsis et al., 2017), and total column ozone (Hudson et al., 2006). Some of the largest trends in recent decades arise from the metrics derived from tropopause height and outgoing longwave radiation, but it appears that these metrics are measuring changes unrelated to the poleward expansion of the Hadley circulation. While all of the metrics listed above co-locate climatologically with the poleward boundary of the mass streamfunction, only the surface wind and sea level pressure metrics co-vary interannually with the streamfunction boundary (Davis and Birner, 2017; Davis et al., 2018; Solomon et al., 2016; Waugh et al., 2018), at least in reanalyses and models. ”

We do not feel that it is necessary to provide a detailed discussion of the relationships among the strengths and positions of the subtropical and eddy-driven jets, particu-

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larly because we no longer use the EDJ metric in the manuscript. The focus of the manuscript is on the Hadley cell edge, not on the jets.

L21: I found ‘indicate’ awkward in this sentence. I suggest rearranging to the following or similar: ‘The poleward expansion of the Hadley circulation is one of the most robust aspects of the atmospheric general circulations response to a warming climate in global circulation models.’

Following the reviewer’s suggestion, we have changed the first sentence of the introduction to the following:

“The poleward expansion of the Hadley circulation is one of the most robust aspects of the atmospheric general circulation’s response to a warming climate in global climate models.”

The acronyms CMIP, SH and NH are already written in full in the abstract so I do not think you need to define them again in the introduction.

According to the ACP manuscript preparation guidelines, abbreviations “need to be defined in the abstract and then again at the first instance in the rest of the text.” So, per the guidelines, we define the acronyms in both the abstract and main text.

L79-90: I think this would be easier to read directly from Table S1/S2 rather than list in the paragraph. I would then move the tables from the supplementary into the manuscript. Instead of ‘x’ you could add the time window of the data, add a column for the reference for each model, add a column for indicating if CMIP5 or 6 (then you only need 1 table) and include the horizontal resolution of the model. This would probably then be a landscape whole page table which is common for CMIP papers. These are simply suggestions, proceed as you wish.

Following the reviewer’s suggestion, we have removed Tables S1 and S2 and placed the salient information into a new table (Table 1) in the main text. We have also added the horizontal resolution of each model into the table, as the reviewer requested. How-

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ever, we do not include the references for each of the 44 individual models used in this study, as we found it difficult to ascertain the appropriate references for some of the models. Referring to the citation requirements stated on the CMIP website (<https://pcmdi.llnl.gov/CMIP6/TermsOfUse/TermsOfUse6-1.html>), we follow their recommendation to cite the relevant articles published in the CMIP6 special issue of GMD. No mention is made of citing the papers from the individual modeling centers.

To keep Table 1 relatively concise, we have chosen to retain the information about the time periods of the runs in the first paragraph of section 2.1. However, we have rewritten this paragraph to include an enumerated list of the different model runs, which will hopefully make this paragraph easier to read.

L107-112: I would also use a table for the reanalysis data sets.

The details of the reanalysis data sets are now listed in Table 2.

It would be mentioning in this section the method used to test significance (it is stated in each of the plots already).

We had added the following paragraph at the end of section 2b to address how we calculate statistical significance:

“We evaluate whether the multi-model means of CMIP5 and CMIP6 models are statistically different from one another using a two-tailed Student’s t-test. When comparing values from CMIP5 and CMIP6 models, we use large asterisks in the figures to denote where the multi-model means of CMIP5 and CMIP6 models are statistically different at the 95 percent confidence level. For the significance testing, we treat each model as an independent sample. However, because many climate models are closely related to one another (e.g., Knutti et al., 2013), the actual value of significance is likely to be much lower.”

Fig 1 (and S1): I think this plot would look better and take up less space if it were 1 row and 2 column (ie side by side).

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Following the reviewer's suggestion, we have reformatted Fig. 1, Fig. S1, and Fig. S5 in a 1 row-2 column format.

I found the asterisk (and in later plots the circles) hard to interpret (are they in S1 too?). I think open and filled circles for the ensemble mean might communicate this clearer or have a lighter and darker versions of black/red. Likewise for Fig 4

We have added the following text into section 2b to clarify the meaning of the asterisks in the figures:

“When comparing values from CMIP5 and CMIP6 models, we use large asterisks in the figures to denote where the multi-model means of CMIP5 and CMIP6 models are statistically different at the 95 percent confidence level.”

We appreciate the reviewer's suggestion, but this would not be straightforward to apply in Figures 6–7, where two different significant tests are applied (i.e., testing whether the mean trend in both CMIP5 and CMIP6 models is statistically different from zero and testing whether the multi-model means of CMIP5 and CMIP6 models are statistically different). We prefer to use consistent symbols and formatting across all figures, so we prefer to retain the use of the asterisks to denote where the multi-model means of CMIP5 and CMIP6 models are statistically different.

The large dots in Figs. 6–7 follow the convention of Fig. 2 from G19 to test whether the mean trend is statistically different from zero, so we prefer to follow the same format to allow comparison with our previous study.

Was the goal of Fig 2-3 on focusing on the NH only to draw out the differences seen in Fig 1 for JJA in NH?

Yes. We now clarify in the text why we focus on the NH JJA response in Figs. 2–3:

“we further examine the largest difference between CMIP5 and CMIP6 models identified in Fig. 1: the response of the NH JJA Hadley cell edge to 4xCO₂ forcing”

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Fig 5: The legends are a little small and repeated. Suggest making larger and only having one (perhaps at the top or bottom of the panel). Might also help to add ‘ensemble mean’ for the purple line in the top panels of each sub-plot.

Following the reviewer’s suggestions, we have eliminated the repeated legends in Figure 5, enlarged the text of the remaining legend in panel d, and added a legend entry denoting the “multi-reanalysis mean” in the top panel of Figure 5d. See attached revised version of Fig. 5 at the end of this document.

L238: only 3 out of the models ‘greatly exceed’ historical and AMIP runs. Suggest mentioning the reanalysis models by name or putting in the clause ‘some of the reanalysis greatly exceed’.

Per the reviewer’s request, we have corrected this sentence to be more precise:

“For the PSI500 metric (Fig. 4, left column), trends from the ERA-Interim, MERRA-2, and JRA-55 reanalyses in the NH and from the ERA-Interim reanalysis in the SH are substantially larger than the trends from the models’ control runs and greatly exceed the trends from the historical and AMIP runs of most models (see also G18, G19).”

Fig 6-7: I can’t really tell one model from another. I am not sure this level of detail is helpful as I found these plots a little overwhelming. The ensemble mean bars are also easily lost in the scatter. This is my personal opinion and the authors can change or not change these figures as they wish.

In Figs. 6 and 7 (also Fig. S3), we have lightened the symbols for the individual models, so that the ensemble mean bars are more easily visible. We agree with the reviewer that there is a lot of information in these figures, but we are updating a similar figure from a prior study (Fig. 2 of Grise et al. 2019). We show the symbols for individual models for two reasons. First, for the common models that performed both CMIP5 and CMIP6 single forcing runs, it allows the reader to see whether the circulation response to a particular forcing notably changed between the CMIP5 and CMIP6 versions of

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that model. Second, because different models performed single forcing runs in CMIP5 and CMIP6, it allows the reader to assess which models may be contributing to the differences in the CMIP5 and CMIP6 ensemble mean responses to a particular forcing.

What is happening in Fig c-d bottom panels for the reanalysis between 1990-2000 – is this the PDO?

The equatorward anomalies in the SH Hadley cell edge in the early 1990s followed by the poleward anomalies in the SH Hadley cell edge in the late 1990s are consistent with the change in phase of the PDO from positive to negative. The AMIP runs of the models also capture this feature to a lesser extent, showing a pause in the poleward SH Hadley cell edge trend in the early 1990s followed by an acceleration of the poleward SH Hadley cell edge trend in the late 1990s. However, this feature is much larger in the reanalyses, likely because concurrent internal atmospheric variability also contributes to large decadal variability in the Hadley cell edge. Unlike coupled atmosphere-ocean variability, the timing of internal atmospheric variability is not necessarily the same in the AMIP runs of the models as in observations, allowing for notable deviations in the decadal variability of the reanalyses and models seen in Fig. 5.

While this feature is interesting, the focus of Section 4 is on the long-term trends, not on the decadal variability in the reanalysis time series. For this reason, we choose not to discuss the decadal variability in the observed Hadley cell edge in the paper.

Suggest starting this section with ‘The’ so that the 5 and 21 are separated.

We have changed the title of section 5 to be “Projected Hadley cell expansion over the 21st century.”

The first page would benefit from adding a title of the paper and stating it is the supplementary material (minimum) or adding title page (if you wish).

According to the ACP manuscript preparation guidelines, “supplements will receive a title page added during the publication process including title (“Supplement of”), au-

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thors, and the correspondence email. Therefore, please avoid providing this information in the supplement.” So, per the guidelines, we have not included a title page to the supplement.

Interactive comment on Atmos. Chem. Phys. Discuss., <https://doi.org/10.5194/acp-2019-1206>, 2020.

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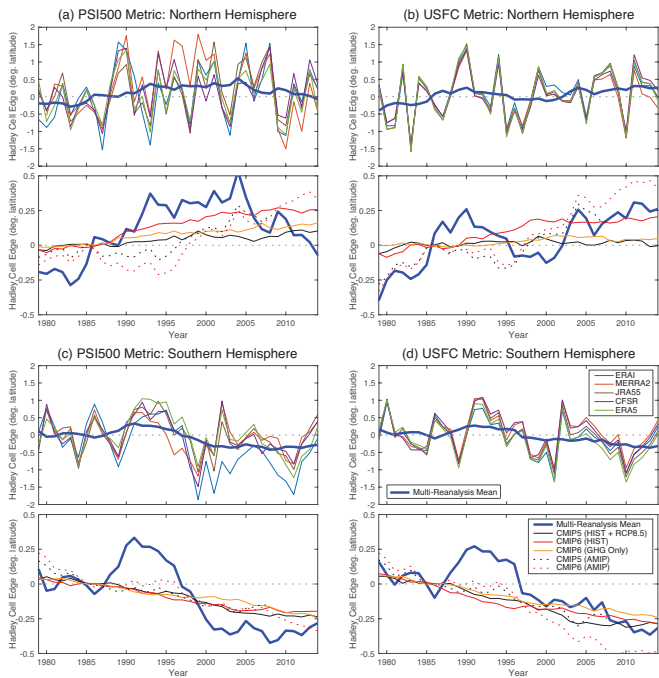


Fig. 1. Revised version of Figure 5