An Updated View of Hadley Cell Expansion from CMIP6 Models

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For further details, please see:

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A Brief Review of Hadley Cell Expansion

- Global climate models indicate that one of the most robust atmospheric circulation responses to climate change is a poleward shift in the subtropical edges of the Hadley circulation. *(Lu et al. 2007; Grise and Polvani 2016; Tao et al. 2016)*

- Various observational/reanalysis data sets show trends since 1979 consistent with a poleward expansion of the Hadley circulation, but the attribution of these observed trends (natural variability vs. anthropogenic forcing) has remained challenging. *(Seidel et al. 2008; Johanson and Fu 2009; Allen and Kovilakam 2017; Amaya et al. 2018)*

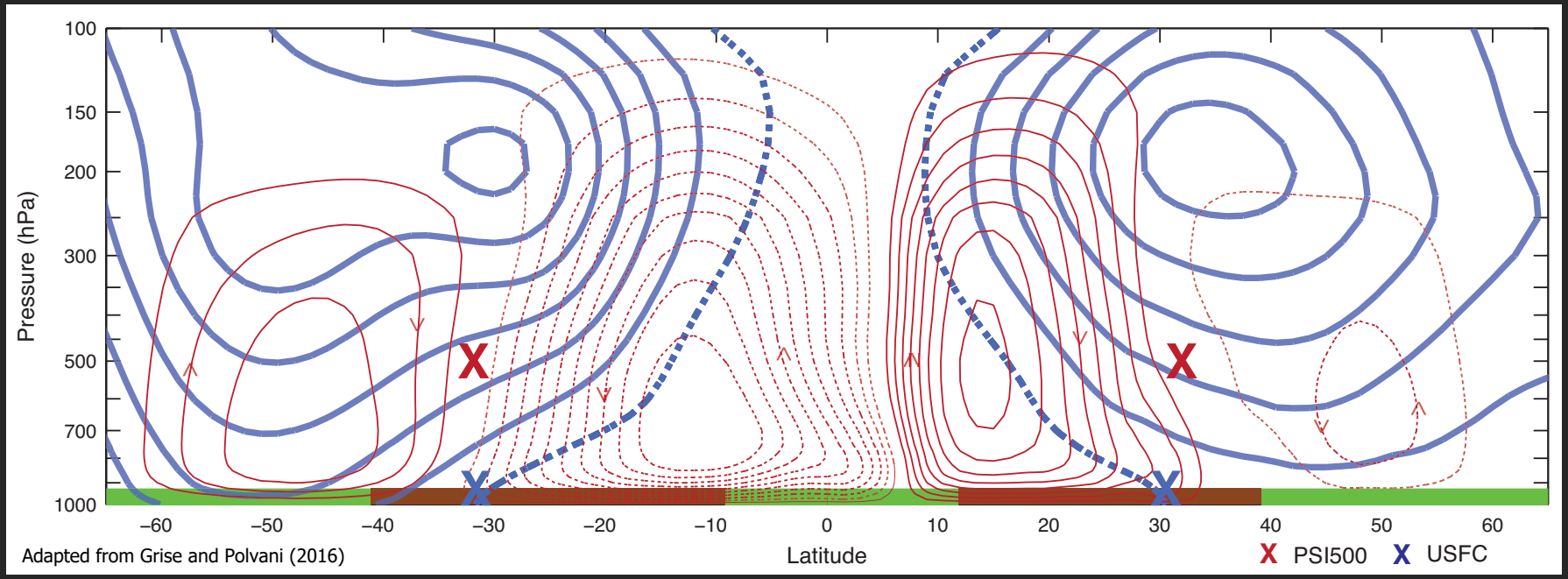
What We Learned from CMIP5 Models

- Using CMIP5 models, the recent US CLIVAR Working Group on the Changing Width of the Tropical Belt helped to synthesize current knowledge about Hadley cell expansion:
  - Observed Hadley circulation expansion since 1979 is modest (< 0.5° latitude per decade) and consistent with magnitudes found in CMIP5 model simulations. *(Grise et al. 2018; Staten et al. 2018)*
  - Anthropogenic forcing alone should yield 2-3 times greater rates of expansion in the Southern Hemisphere. *(Grise et al. 2019; Watt-Meyer et al. 2019)*
  - Observed sea surface temperature variability helps to account for similar observed expansion rates in the two hemispheres. *(Allen and Kovilakam 2017; Grise et al. 2019)*

Today's Question: Have any of these conclusions changed in CMIP6 models?

Methodology

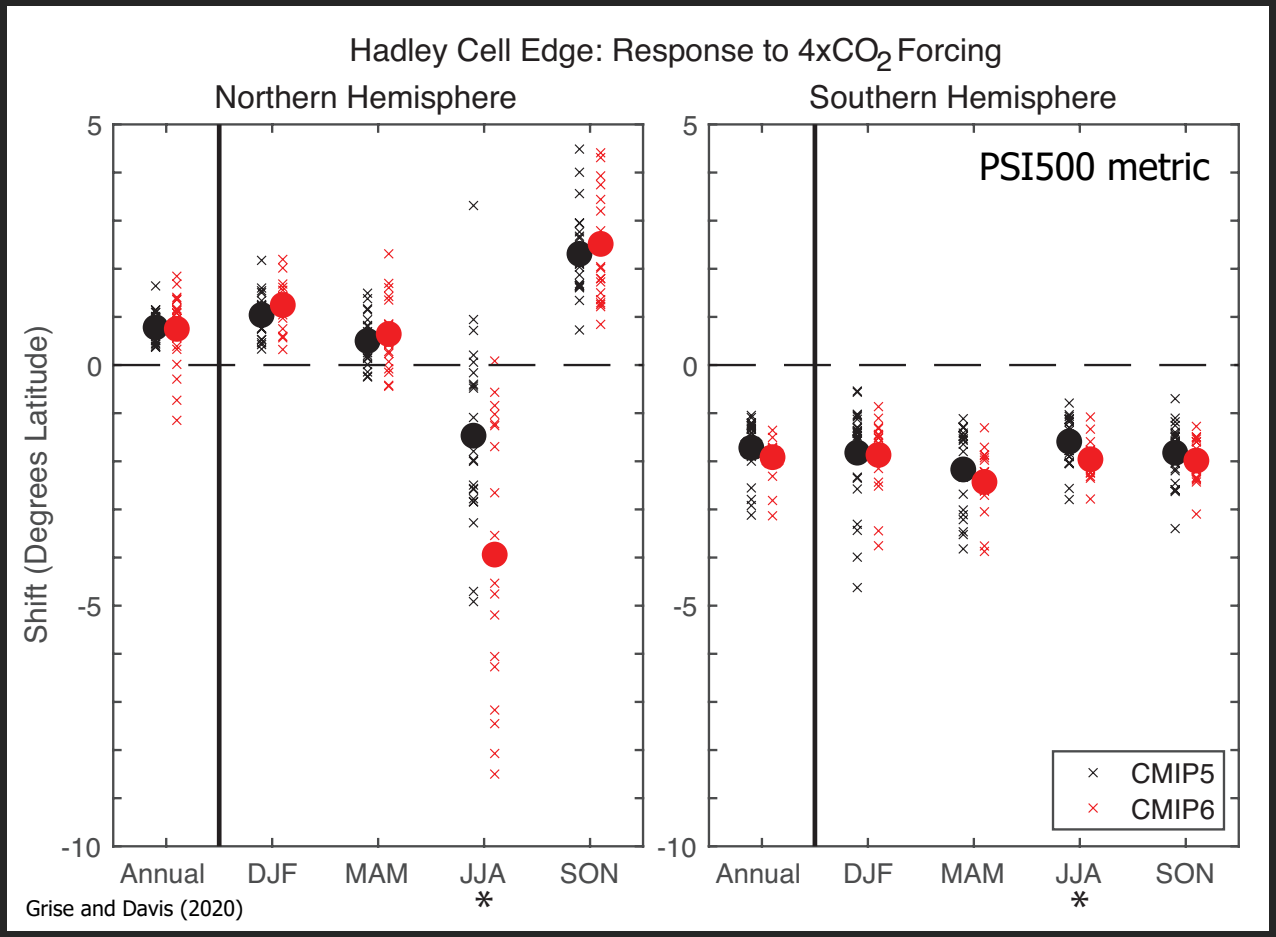
- Five reanalysis data sets (ERA-5, ERA-Interim, JRA-55, NASA MERRA-2, NCEP CFSR), 24 CMIP5 models, 20 CMIP6 models
- Poleward boundaries of Hadley cells are defined using two metrics:
  - PSI500: Zero crossing of 500-hPa mean meridional streamfunction
  - USFC: Zero crossing of near-surface zonal mean zonal wind



We find two key differences in Hadley cell expansion between CMIP5 and CMIP6 models:

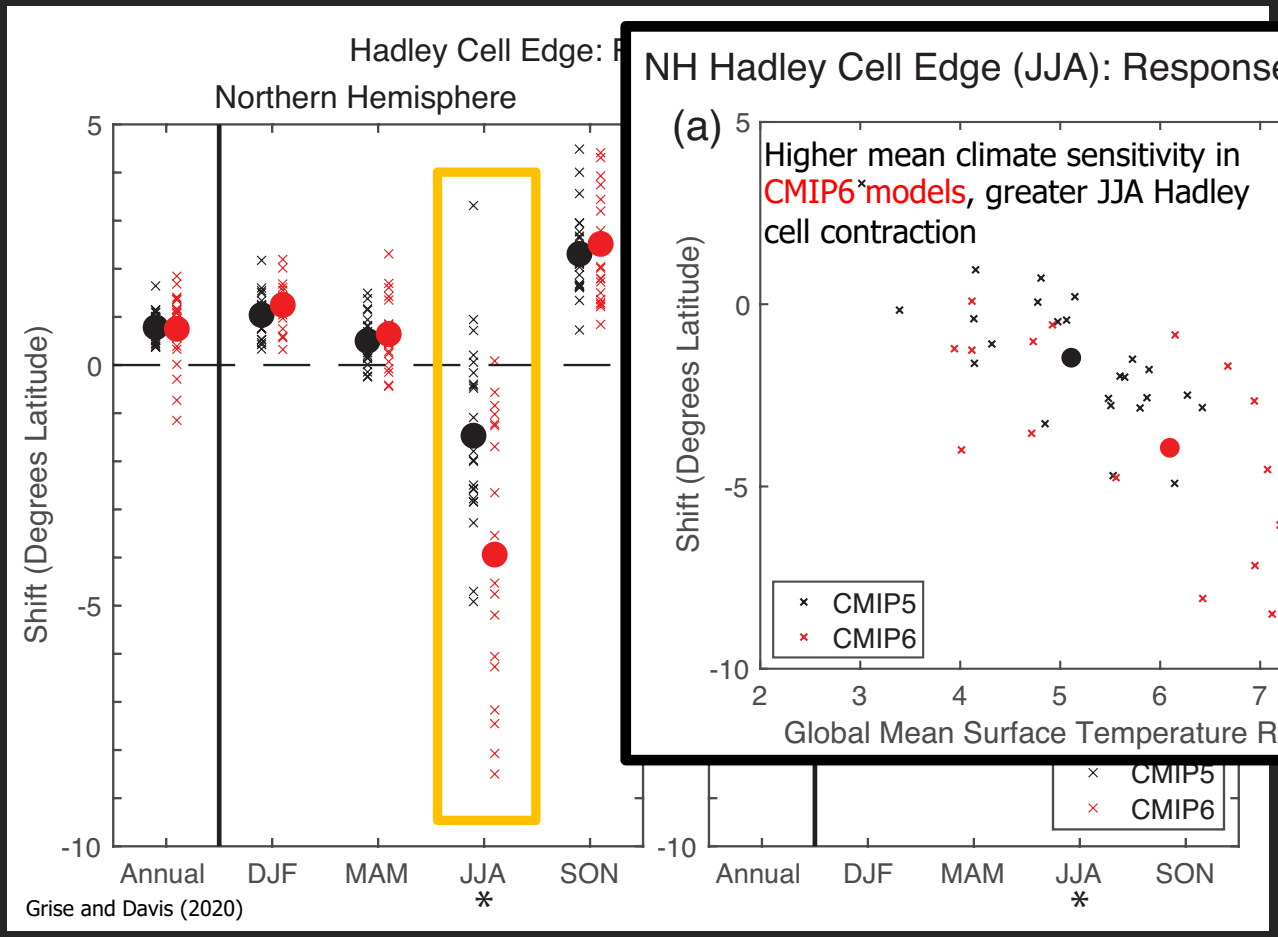
1) Northern Hemisphere summertime circulation trend in response to increasing greenhouse gases
2) Northern Hemisphere historical circulation trends

Hadley Cell Edges: Response to 4xCO_2



Both CMIP5 and CMIP6 models show larger Hadley cell expansion in the Southern Hemisphere and a distinct seasonality to the circulation trends in the Northern Hemisphere. *(Grise and Polvani 2016; Davis et al. 2016; Watt-Meyer et al. 2019)*

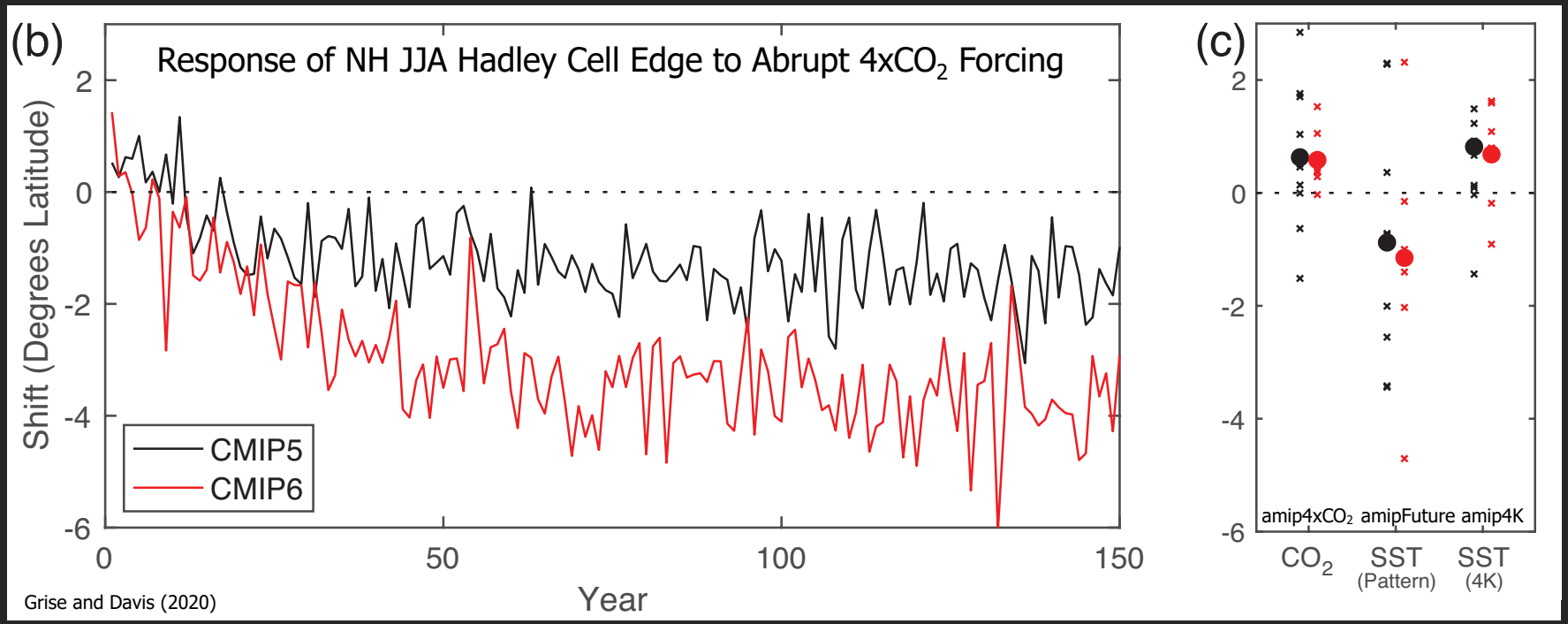
Hadley Cell Edges: Response to 4xCO_2



The Northern Hemisphere Hadley cell edge contracts equatorward during JJA. Some CMIP6 models even show Northern Hemisphere Hadley cell contraction in the annual mean!

Hadley Cell Edges: Response to 4xCO_2

Why does NH Hadley cell edge contract equatorward during JJA?



- Initial poleward expansion is consistent with the direct radiative forcing of CO_2. *(Grise and Polvani 2014; Shaw and Voigt 2015)*
- Subsequent equatorward contraction is driven by patterned sea surface temperature warming. *(Grise and Polvani 2014; Shaw and Voigt 2015)*
- Uniform sea surface temperature warming would also contribute to poleward expansion. *(Zhou et al. 2019)*

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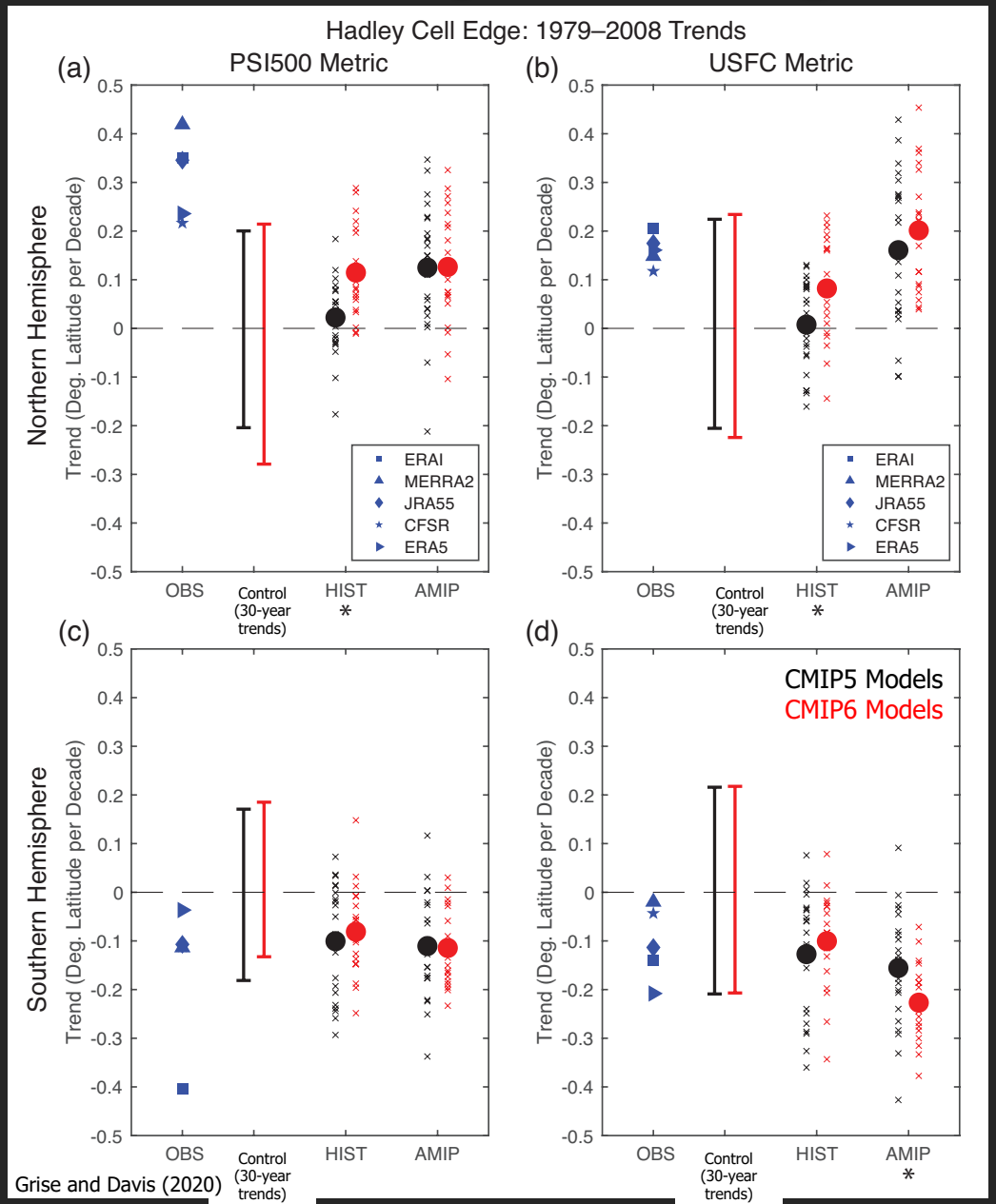
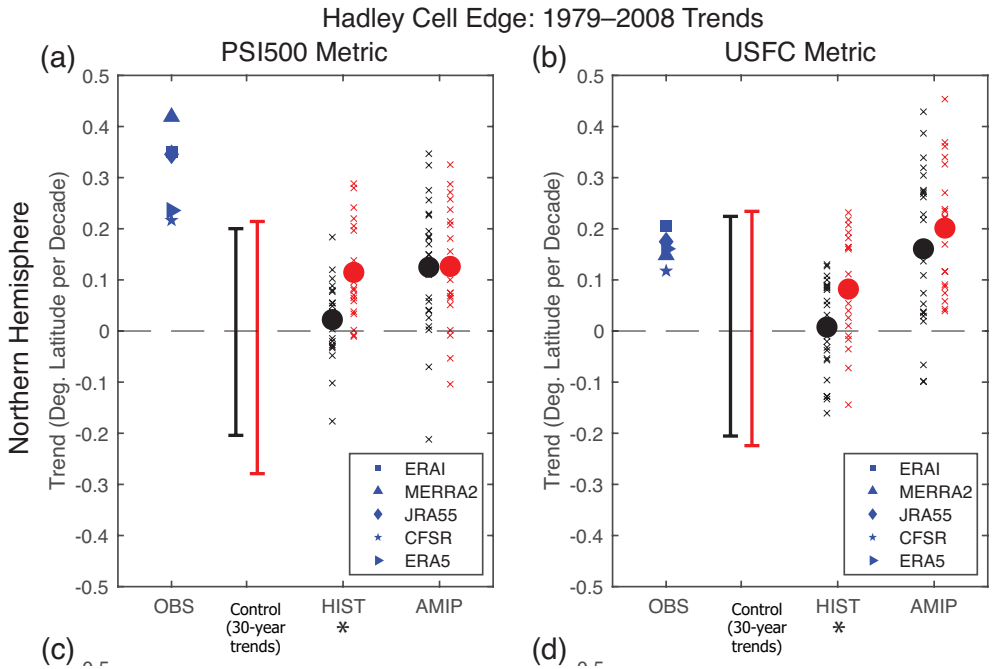
Hadley Cell Edges: Historical Trends



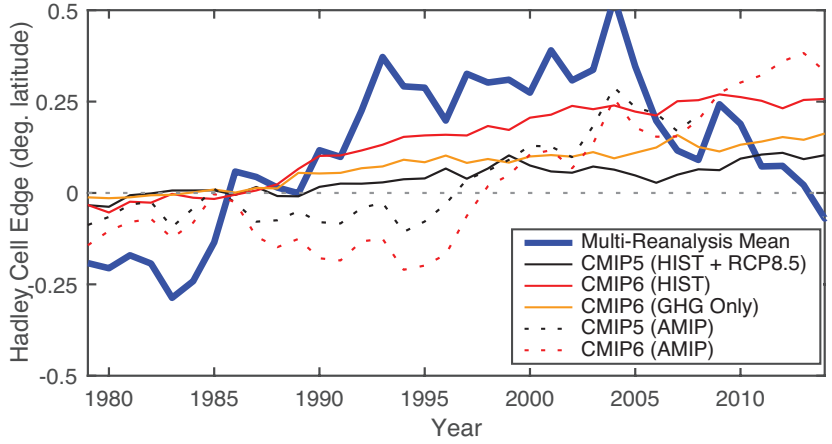
Grise and Davis (2020)

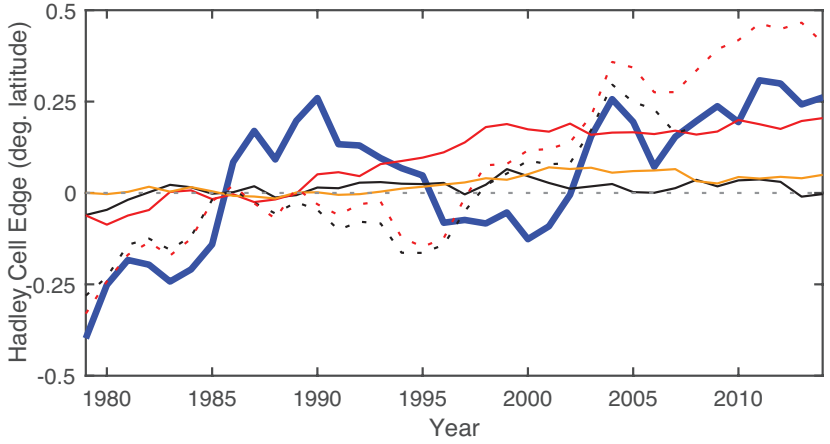
- For USFC metric, reanalysis trends are modest and not distinguishable from trends in the control runs of the models. They agree well with the multi-model mean of the AMIP runs in the Northern Hemisphere and the historical runs in the Southern Hemisphere.
- For PSI500 metric, many reanalysis trends exceed the model trends. Trends in the PSI500 metric in reanalyses may be biased (see Davis and Davis 2018).
- Note the statistically significant (*) difference between the Northern Hemisphere trends in the historical runs of CMIP5 and CMIP6 models. Why?

Hadley Cell Edges: Historical Trends



- Trends in **CMIP6 historical greenhouse gas only runs** are similar to those in **CMIP5 historical runs**.
- This suggests that the larger trends in **CMIP6 historical runs** are driven by other forcings (solar/volcanic, aerosols, ozone).





Grise and Davis (2020)

Summary

- The characteristics of Hadley cell expansion are very similar in CMIP5 and CMIP6 models, but we find two notable exceptions:

1) On average, the Northern Hemisphere summertime Hadley cell edge shifts further equatorward in CMIP6 models in response to increasing greenhouse gases, likely because of the higher mean climate sensitivity of CMIP6 models.

2) Over recent decades, poleward circulation trends are larger in the Northern Hemisphere in the historical runs of CMIP6 models than in CMIP5 models. Greenhouse gas forcing alone yields similar trends in CMIP5 and CMIP6 models, suggesting that non-greenhouse gas forcings may play a role in the discrepancy.

References

Allen, R. J., and Kovilakam, M.: The role of natural climate variability in recent tropical expansion, J. Climate, 30, 6329-6350, https://doi.org/10.1175/JCLI-D-16-0735.1, 2017.

Amaya, D. J., Siler, N., Xie, S., and Miller, A. J.: The interplay of internal and forced modes of Hadley Cell expansion: lessons from the global warming hiatus, Clim. Dynam., 51, 305–319, https://doi.org/10.1007/s00382-017-3921-5, 2018.

Davis, N. A., and Davis, S. M.: Reconciling Hadley cell expansion trend estimates in reanalyses, Geophys. Res. Lett., 45, 11439–11446, https://doi.org/10.1029/2018GL079593, 2018.

Davis, N. A., Seidel, D. J., Birner, T., Davis, S. M., and Tilmes, S.: Changes in the width of the tropical belt due to simple radiative forcing changes in the GeoMIP simulations, Atmos. Chem. Phys., 16, 10083–10095, https://doi.org/10.5194/acp-16-10083-2016, 2016.

Grise, K. M., and Polvani, L. M.: The response of mid-latitude jets to increased CO_2: Distinguishing the roles of sea surface temperature and direct radiative forcing, Geophys. Res. Lett., 41, 6863–6871, https://doi.org/10.1002/2014GL061638, 2014.

Grise, K. M., and Polvani, L. M.: Is climate sensitivity related to dynamical sensitivity?, J. Geophys. Res.-Atmos., 121, 5159–5176, https://doi.org/10.1002/2015JD024687, 2016.

Grise, K. M., Davis, S. M., Staten, P. W., and Adam, O.: Regional and seasonal characteristics of the recent expansion of the tropics, J. Climate, 31, 6839–6856, https://doi.org/10.1175/JCLI-D-18-0060.1, 2018.

Grise, K. M., Davis, S. M., Simpson, I. R., Waugh, D. W., Fu, Q., Allen, R. J., Rosenlof, K. H., Ummenhofer, C. C., Karnauskas, K. B., Maycock, A. C., Quan, X.-W., Birner, T., and Staten, P. W.: Recent tropical expansion: Natural variability or forced response?, J. Climate, 32, 1551–1571, https://doi.org/10.1175/JCLI-D-18-0444.1, 2019.

Johanson, C. M., and Fu, Q.: Hadley cell widening: Model simulations versus observations, J. Climate, 22, 2713-2725, https://doi.org/10.1175/2008JCLI2620.1, 2009.

Lu, J., Vecchi, G. A., and Reichler, T.: Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34, L06805, https://doi.org/10.1029/2006GL028443, 2007.

Seidel, D. J., Fu, Q., Randel, W. J., and Reichler, T. J.: Widening of the tropical belt in a changing climate, Nat. Geosci., 1, 21-24, https://doi.org/10.1038/ngeo.2007.38, 2008.

Shaw, T., and Voigt, A.: Tug of war on summertime circulation between radiative forcing and sea surface warming, Nat. Geosci., 8, 560–566, https://doi.org/10.1038/ngeo2449, 2015.

Staten, P. W., Lu, J., Grise, K. M., Davis, S. M., and Birner, T.: Re-examining tropical expansion, Nat. Clim. Change, 8, 768–775, https://doi.org/ 10.1038/s41558-018-0246-2, 2018.

Tao, L., Hu, Y., and Liu, J.: Anthropogenic forcing on the Hadley circulation in CMIP5 simulations, Clim. Dynam., 46, 3337-3350, https://doi.org/10.1007/s00382-015-2772-1, 2016.

Watt-Meyer, O., Frierson, D. M. W., and Fu, Q.: Hemispheric asymmetry of tropical expansion under CO2 forcing, Geophys. Res. Lett., 46, 9231–9240, https://doi.org/10.1029/2019GL083695, 2019.

Zhou, W., Xie, S.-P., and Yang, D.: Enhanced equatorial warming causes deep-tropical contraction and subtropical monsoon shift, Nat. Clim. Change, 9, 834–839, https://doi.org/10.1038/s41558-019-0603-9, 2019.