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Key Points:

- Climate models can capture recent HC expansion if internal variability is considered
- SSTs important for Northern Hemisphere, ozone depletion for Southern Hemisphere
- Models are not necessarily missing key processes

Supporting Information:

- Texts S1–S3 and Figures S1 and S2

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Recent Hadley cell expansion: The role of internal atmospheric variability in reconciling modeled and observed trends

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Abstract Several studies have reported that global climate models underestimate the observed trend in tropical expansion, with the implication that such models are missing key processes of the climate system. We show here that integrations of a chemistry-climate model forced with observed sea surface temperatures (SSTs), greenhouse gases, and ozone-depleting substances can produce 1980 to 2009 expansion trends comparable to those found in most reanalyses data products. Correct representation of the SSTs changes is important for the Northern Hemisphere, while correct representation of stratospheric ozone changes is important for the Southern Hemisphere. The ensemble mean trend (which captures only the forced response) is nearly always much weaker than trends in reanalyses. This suggests that a large fraction of the recently observed changes may, in fact, be a consequence of internal atmospheric variability and not a response of the climate system to anthropogenic forcings.

1. Introduction

The tropical tropospheric circulation has expanded poleward over the past four decades [*Hu and Fu*, 2007; *Seidel et al.*, 2007; *Davis and Rosenlof*, 2012], affecting weather and climate not only by altering the location of storm tracks but also by stressing water resources in the subtropical dry zones [*Kang et al.*, 2011; *Lucas et al.*, 2014]. Two important issues remain as to our understanding of these significant trends. First, coupled climate models, such as those submitted to the Coupled Model Intercomparison Project Phases 3 and 5, do not reproduce, in the multimodel mean, the magnitude of the expansion in observations or reanalyses [*Johanson and Fu*, 2009; *Hu et al.*, 2013; *Allen et al.*, 2014]. Second, the causes of this expansion are still unclear, with studies disagreeing on the role of greenhouse gases, stratospheric ozone depletion, tropospheric ozone and aerosols, and sea surface temperatures (SSTs) in causing the expansion [*Lu et al.*, 2009; *Polvani et al.*, 2011; *McLandress et al.*, 2011; *Son et al.*, 2010; *Allen et al.*, 2012; *Staten et al.*, 2012; *Hu et al.*, 2013; *Quan et al.*, 2014; *Allen et al.*, 2014; *Waugh et al.*, 2015; *Schneider et al.*, 2015]. These two important issues are linked, as models that are incapable of capturing the magnitude of the observed expansion may be missing crucial physical processes or forcings that cause the expansion [*Allen et al.*, 2012; *Kovilakam and Mahajan*, 2015]. As climate models are our best means for projecting future climate change, it is crucial that climate models accurately capture the observed changes in order to enhance confidence in their future projections.

The above mentioned studies have generally focused on comparisons of observed (or reanalysis) trends with the *mean* of an ensemble of simulations (from a single model or multiple models). However, such a comparison is inappropriate, since averaging over an ensemble of model runs removes the internal variability and retains only the forced response, whereas the observations include forced responses together with (a single realization of) internal variability. It is thus more appropriate to compare individual model simulations with observations.

Here we present an ensemble of experiments with a single chemistry-climate numerical model in which a realistic ozone hole is interactively generated in the presence of observed SSTs, and show that some ensemble members produce an expansion in each hemisphere that is comparable with the expansion estimated by reanalyses products (>0.5°/decade per hemisphere). Hence, if internal atmospheric variability is taken into consideration, there is no inconsistency between the modeled and reanalyzed trends.

2. Data and Methods

2.1. Data

Trends in the subtropical edge of the Hadley cell (HC) are compared between model output and reanalysis data. For reanalysis data, we analyze NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) [*Rienecker et al.*, 2011], ECMWF's ERA-Interim reanalysis data set [*Dee et al.*, 2011], and NCEP's reanalyses versions 1 and 2 [*Kalnay et al.*, 1996; *Kanamitsu et al.*, 2002]. Note that the team producing MERRA makes available two data products: one labeled "ana" and one labeled "asm." Both represent an atmospheric state that is the optimal blend of model and observations: the "ana" product is outputted before the incremental analysis update described in *Bloom et al.* [1996] has been applied, while the "asm" product is outputted after this technique has been applied in preparation for the next 6 h of model integration [*Rienecker et al.*, 2011, see also appendix A of http://gmao.gsfc.nasa.gov/products/documents/MERRA_File_Specification.pdf]. It is not clear which algorithm produces the best estimate of the observed HC edge, and we show both products here. Note that both have been used in previous studies examining HC trends, e.g., *Davis and Rosenlof* [2012] use the ana product (S. Davis, personal communication, 2015) while *Adam et al.* [2014] use the asm product (O. Adam, personal communication, 2015). *Davis and Rosenlof* [2012] and *Lucas et al.* [2014] have compared HC trends among these and other reanalyses and shown that there is a large spread (see also below). This large spread among reanalysis trends is not due to internal variability but rather likely arises from differences in the data assimilation algorithm, as is evident from the differences between MERRA-asm and MERRA-ana trends (see below). The reanalysis products can only provide an estimate of the actual HC edge and its trends, and the large spread of the reanalysis trends limits how precisely we can compare model to observed expansion trends. Here we use the expression "comparable" to indicate agreement of a model trend with at least four of the five reanalysis products. There should be no expectation that the models should capture the largest reanalysis trend.

The reanalysis trends are compared to two 10-member ensembles of the Goddard Earth Observing System Chemistry-Climate Model, Version 2 (GEOSCCM). Full details of the integrations are provided in *Garfinkel et al.* [2015], but the key features are summarized here. The GEOSCCM couples the GEOS-5 atmospheric general circulation model (GCM) [*Rienecker*, 2008] with a comprehensive stratospheric chemistry module [*Oman and Douglass*, 2014]. A detailed comparison of the modeled ozone climatology to observations can be found in *Oman and Douglass* [2014]; they show that the model captures observed Southern Hemisphere (SH) ozone depletion. Further, GEOSCCM resolves daily and zonally asymmetric ozone variability that is not captured in CMIP5 models that use prescribed monthly mean zonal mean ozone, and these deviations have also been shown to be important for properly resolving the downward impacts of ozone depletion [*Gillett et al.*, 2009; *Waugh et al.*, 2009; *Neely et al.*, 2014]. The Southern Hemisphere (SH) circulation is biased slightly too far poleward in GEOSCCM as compared to reanalyses products (e.g., near-surface jet position at 53°S as opposed to 51°S). However, a poleward bias generally leads to a weaker response to ozone depletion [*Son et al.*, 2010; *Garfinkel et al.*, 2013]; we, therefore, doubt that this bias is critical for our main results.

Two 10-member ensembles have been created. In the first, only observed SSTs and sea ice concentrations from January 1979 through December 2009 from the HADISST project [*Rayner et al.*, 2003] force the model climate. Other than SST and sea ice changes, there is no externally forced variability. This first ensemble is referred to as the *SST-only* ensemble. In the second ensemble, both long-lived radiatively active gas concentrations (e.g., CO_2, CH_4, N_2O, CFCs, and other ozone depleting substances) and observed SSTs and sea ice concentrations force the model over the same period. By comparing theses two ensembles we can evaluate the radiative effects of ozone and greenhouse gases. For simplicity, this second ensemble is referred to as the *ALL-forcing* ensemble. Aerosols, tropospheric ozone, and solar forcing are fixed at climatological background values for both ensembles (i.e., there are no cycles in solar irradiance, time-varying anthropogenic aerosols, or volcanic eruptions), though we note that it is possible that these variations may enhance the poleward shift or have contributed to the SST trends in the first place [*Allen et al.*, 2012; *Kovilakam and Mahajan*, 2015]. Partitioning atmospheric trends into an SST-driven component and the full change is somewhat artificial, as the prescribed SST changes occur in response to and in tandem with the changing direct atmospheric radiative forcing; however, such a partitioning is an effective tool for disentangling the physical mechanisms leading to changes in the atmospheric circulation [*Deser and Phillips*, 2009].

2.2. Methods

Trends in the HC subtropical edge are analyzed using the meridional mass stream function at 500 hPa. We identify the latitude where the meridional mass stream function at 500 hPa is zero following equation (1) of

McLandress et al. [2011], while, simultaneously, the meridional wind transitions from poleward to equatorward motion as one moves poleward. The two grid points surrounding the zero crossing are then used to construct a linear best fit, which is then evaluated at 0.04° resolution to find the zero crossing. The HC edge is calculated from monthly averaged fields and then seasonally or annually averaged. We focus on this definition of the HC edge because the mismatch between the multimodel mean and observations for this diagnostic is particularly egregious [*Allen et al.*, 2014, Figure 1]. We have also analyzed trends in subtropical sea level pressure, near-surface wind, and precipitation minus evaporation, and we have assessed sensitivity to focusing on the specific zero-crossing latitude as opposed to adjacent latitudes, and we find similar results (see section S1 in the supporting information).

As the trends in reanalysis data are largest in the respective summer for each hemisphere [*Davis and Rosenlof*, 2012], we show results separately for the summer in each hemisphere and for the annual mean. The trends in each hemisphere are presented separately, because the dominant forcing differs between the two (as demonstrated below). SH polar ozone depletion has stabilized since 2000 except for interannual variability [*Eyring et al.*, 2010], and hence we show trends separately for the first 20 years of the experiments (1980–1999) and for the entire length of the experiments. Sensitivity of the trends to the choice of starting and ending dates is considered in section S2.

The trends are calculated with a linear least squares fit. Statistical significance of the trends in individual ensemble members of GEOSCCM are computed using a two-tailed Student's *t* test, and the reduction in degrees of freedom due to autocorrelation of the residuals is taken into account with the formula $N(1-r_1)(1+r_1)^{-1}$, where N is the number of years and r_1 is the lag 1 autocorrelation [*Allen et al.*, 2014].

3. Results

The computed trends for GEOSCCM and reanalysis data for the NH and SH are shown in Figures 1 and 2, respectively. Green markers indicate reanalyses trends, blue markers indicate ALL-forcing trends, and red markers indicate SST-only trends. Each marker corresponds to a specific reanalysis product, ensemble member, or the ensemble mean, and the length of each bar indicates the 95% statistical uncertainty in the trend for that data source. The ensemble mean for the two GEOSCCM ensembles is indicated with a thicker bar (to the right of the individual members). The left column shows the summer trends, and the right column shows the annual averaged trends, as reanalysis products indicate stronger expansion during summer [*Davis and Rosenlof*, 2012; *Lucas et al.*, 2014]. The top row is for the full period of the GEOSCCM integrations (1980–2009), and the bottom row focuses on the first 20 years of the experiments (1980–1999).

3.1. Northern Hemisphere

We start with the summer (JJA) NH trends over the full period of the simulations (Figure 1a). As noted previously [e.g., *Davis and Rosenlof*, 2012; *Lucas et al.*, 2014], there is a large spread in the reanalysis trends, ranging from 0.13°/decade to 1.12°/decade. The difference between the two MERRA products is comparable to the difference between reanalyses trends from different modeling centers, highlighting the uncertainty in trends derived from reanalyses. The ensemble mean (i.e., forced) response from the ALL-forcing GEOSCCM integrations is 0.05°/decade, which is not statistically significant and less than the trends from all reanalyses products. This is consistent with previous studies, which have reported that the multimodel mean trend is substantially smaller than the trend found in the reanalyses.

However, it is notable that there is a large intraensemble spread in the trends from individual ensemble members, with some showing poleward expansion trends significant at the 90% level and others with contraction. Moreover, the trends in several of the individual ensemble members are comparable with those found in reanalysis data: four of the 10 individual ALL-forcing ensemble members simulate poleward expansions that exceed the weakest trend among the five reanalyses products (0.13°/decade), and two of the 10 individual ensemble members simulate poleward expansions that are statistically indistinguishable from all reanalyses products.

Thus, although the simulated forced (i.e., ensemble mean) response is smaller than that in all reanalyses, when the possibility of internal variability is included (e.g., individual ensemble members), trends comparable to reanalyses can be simulated. This suggests that the observed HC expansion in recent decades may be substantially larger than the forced response simply because internal variability contributed to the poleward

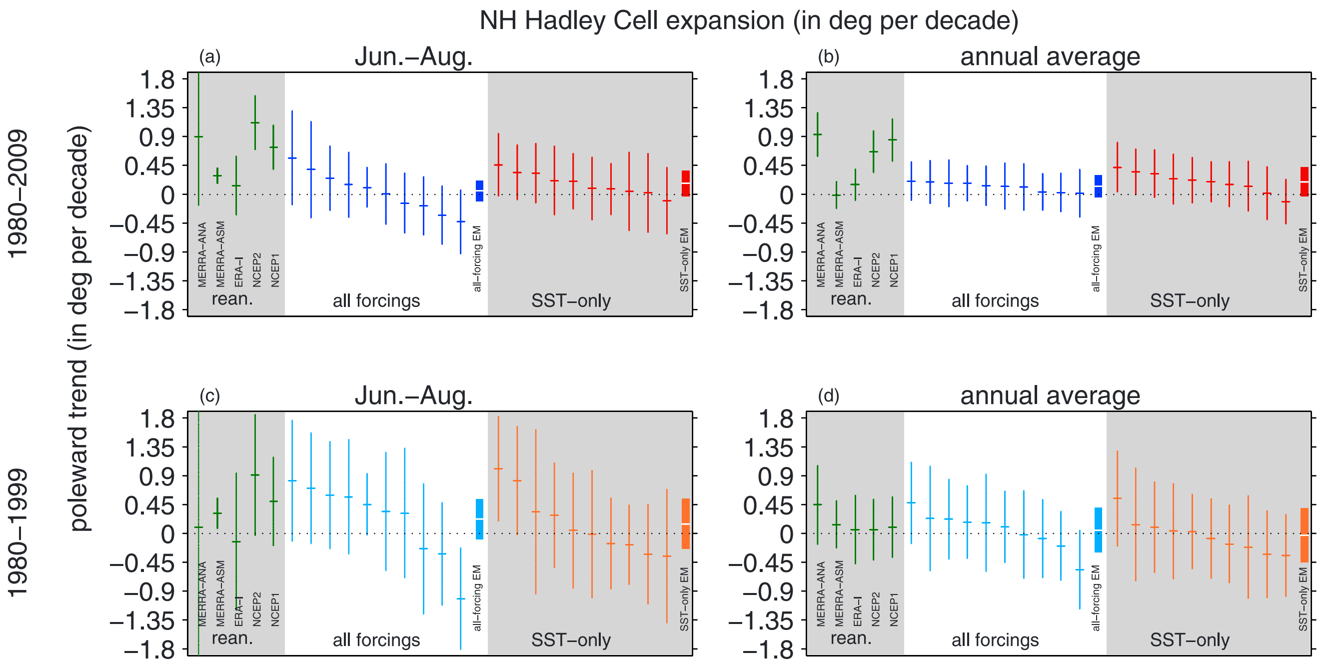

Figure 1. Poleward expansion of the NH Hadley cell (HC) as determined by the zero crossing of the 500 hPa stream function in each member of the GEOSCCM ensemble and in the ensemble mean in (a, c) JJA and in (b, d) the annual average. Vertical lines or bars represent the 95% confidence interval on the trend as deduced by a Student's *t* test, and the center line indicates the trend. The uncertainty for the ensemble mean trends are indicated by a rectangle, while that of individual ensemble members/reanalysis are indicated by a vertical line. The ensemble members for each ensemble are ordered by their expansion trend before they are plotted for clarity.

expansion. Further, it is important to note that since the same SSTs are used in all integrations, the intraensemble spread is due to internal atmospheric variability (and not ocean variability).

There is no significant difference between the ensemble mean trend in June–August (JJA) and in the annual average (i.e., between Figures 1a and 1b), even though individual integrations simulate JJA trends larger than those in the annual mean, annual mean due to internal atmospheric variability. Furthermore, there is no

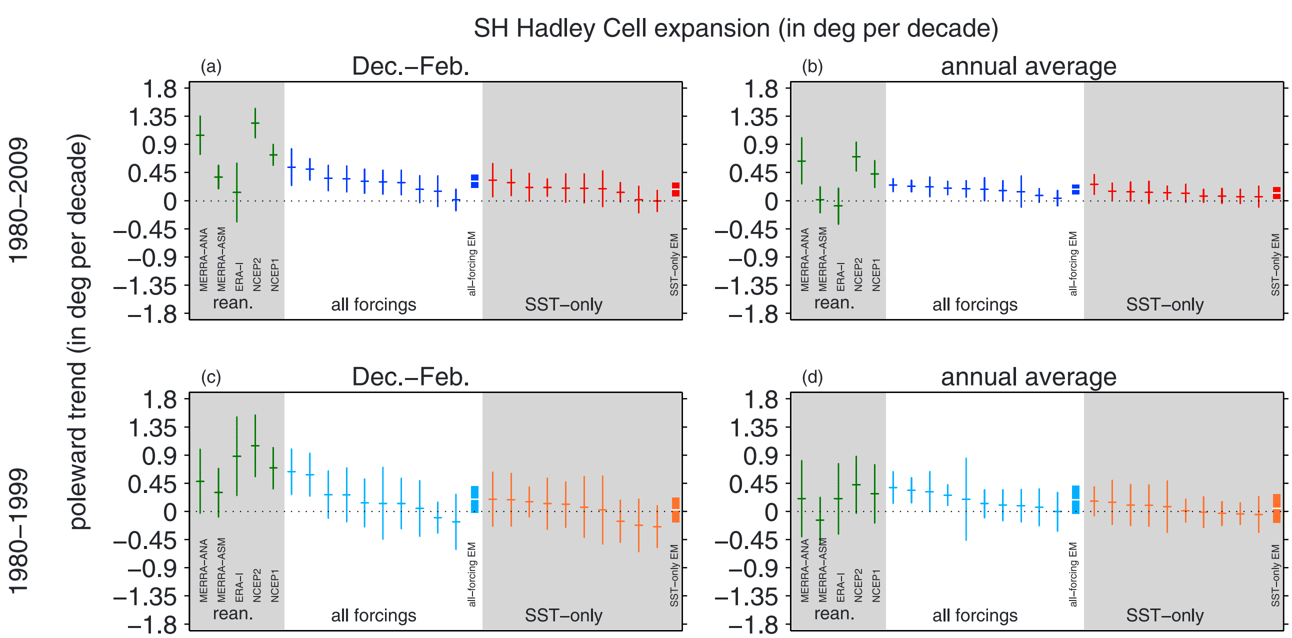

Figure 2. As in Figure 1 but for the SH. The SH summer (DJF) is shown.

robust difference in NH trends between the SST-only ensemble and the ALL-forcing ensemble (i.e., between red and blue markers) or between trends calculated over the years 1980–1999 and 1980–2009 (i.e., between Figures 1a, 1b and 1c, 1d). This indicates that neither stratospheric ozone depletion nor the direct radiative impact of increasing greenhouse gases are major factors for the NH trends (consistent with *Deser and Phillips* [2009]). Finally, we recall that neither ensemble includes time varying aerosols nor tropospheric ozone, and it is conceivable that these forcings might enhance the poleward shift or may have contributed to the SST trends themselves [*Allen et al.*, 2012; *Kovilakam and Mahajan*, 2015]. Nonetheless, when internal variability is taken into account, these additional forcings do not appear necessary, as several individual model runs are able to produce trends comparable to those in the reanalyses.

3.2. Southern Hemisphere

The trends in the SH (shown in Figure 2) share a lot of similarities with those for the NH. Here, too, we see a large spread among the reanalysis trends. The GEOSCCM ensemble mean ALL-forcing trend is statistically significant at the 95% level in both the annual average and in austral summer (December through February, DJF) but is smaller than most of the reanalyses trends (Figures 2a and 2b). There is a large intraensemble spread, with some ensemble members showing no discernible trend while others simulate trends that are significant at the 95% level and comparable with the reanalysis trends (e.g., simulated trends greater than 0.6°/decade for austral summer from 1980 to 1999 in Figure 2c). Thus, as in the NH, the reanalysis trends can be simulated if considered as a response to forcing together with internal variability.

However, unlike the NH, there are substantial differences between the SST-only ensemble and the ALL-forcing ensemble (i.e., between the red and blue markers in Figure 2c), between the annual average trends and the DJF trends (i.e., between the left and right columns), and between trends calculated over the years 1980–1999 and 1980–2009 in the SH (i.e., between the top and bottom rows). All of these differences reflect the importance of ozone depletion. As discussed in *Waugh et al.* [2015], stratospheric ozone is the dominant driver of DJF trends from 1980 to 1999, the period with intensifying ozone depletion. As shown in Figure 2c, trends comparable to the reanalysis trends occur in individual members of the ALL-forcing ensemble, whereas none of the individual members of the SST-only ensemble simulate trends approaching those calculated from reanalysis data or that are statistically significant. For the full period of the simulation (1980–2009, Figures 2a and 2b), significant trends approaching reanalysis trends are simulated by some SST-only members. This is due to a transition to a negative (cool) phase of the Pacific Decadal Oscillation [*Waugh et al.*, 2015; *Allen et al.*, 2014].

3.3. Comparison to Other Models

The above GEOSCCM integrations suggest that internal atmospheric variability is large enough to have contributed substantially to the recent observed trends in tropical expansion. However, one might object that this conclusion is obtained from a single model and that such large internal variability may be an artifact of this one model. To assess the robustness of the simulated internal variability, we compare the spread of the trends in GEOSCCM with that from recent studies using other models.

We first consider the 40-member ensemble of transient ALL-forcing simulations of Community Atmosphere Model version 3 (CAM3) introduced by *Gonzalez et al.* [2014]. These integrations cover 1950 to 2009 and use prescribed SSTs, greenhouses gases, and ozone based on observations. The Hadley cell width trends have been computed for each of the 40 members from 1980 to 1999 and from 1980 to 2009 (to match periods shown for the GEOSCCM simulations), and the standard deviation of the trends within the ensemble are shown in Figure 3. It is evident from this figure that GEOSCCM and CAM3 give similar values for intraensemble spread for both hemispheres, for both the annual average and the summer, and for both 20 year and 30 year trends. Note that the spread is larger for seasonal mean trends than for annual mean trends, and also for shorter than for longer periods (1980–1999 versus 1980–2009); both of these sensitivities are to be expected if the cause of the intraensemble spread is internal atmospheric variability, as internal atmospheric variability is uncorrelated between different seasons and between adjacent decades. Note, furthermore, that CAM3 is not a chemistry-climate model and thus, unlike GEOSCCM, all CAM3 ensemble members are forced with identical ozone concentrations (in addition to identical SSTs), so the internal variability is not due to variability in stratospheric ozone. The key point is that the internal atmospheric variability in HC width simulated by CAM3 is comparable with that in GEOSCCM.

Another comparison is possible with the Community Climate System Model version 4 (CCSM4) simulations presented in *Quan et al.* [2014]. The standard deviation of DJF trends in HC width for 30 year segments of a long control integration of the CCSM4 is 0.14°/decade for the SH width [see *Quan et al.*, 2014, Figure 3]. These values

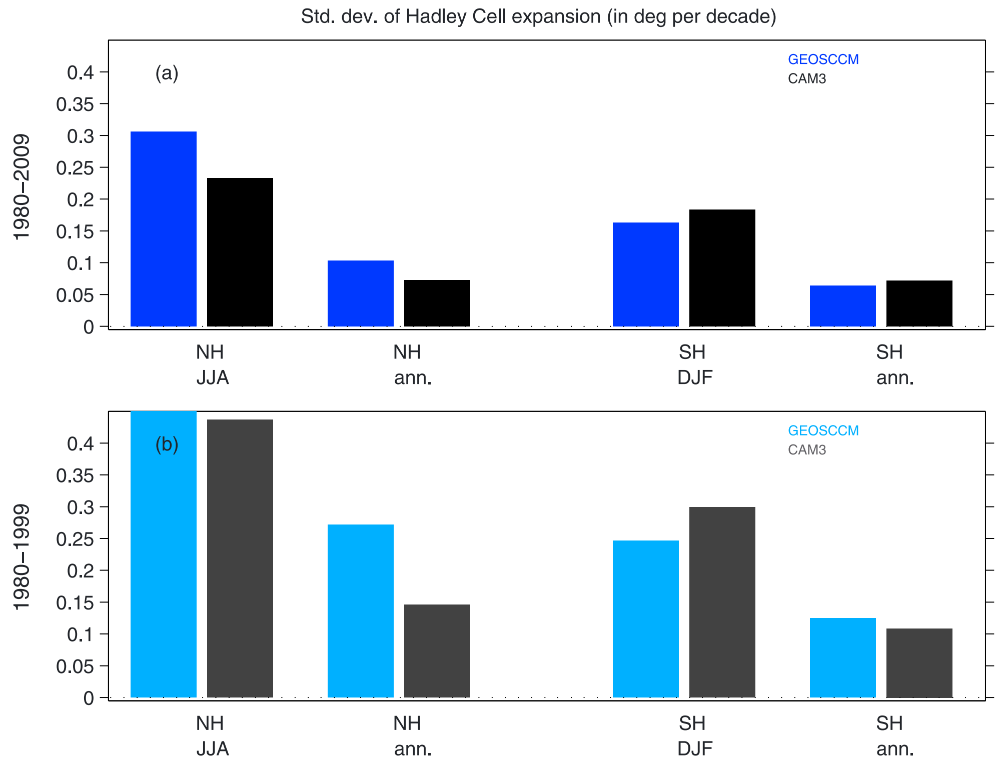

Figure 3. Standard deviation of the trend in HC width in the 40 all-forcing CAM3 ensemble members and in GEOSCCM for trends over (a) 1980–1999 and (b) 1980–2009.

are very similar to those for GEOSCCM (0.16°/decade), again indicating that the GEOSCCM values are comparable to those of other widely used climate models. Note that CCSM4 is a coupled ocean-atmosphere model, and the agreement between atmosphere-only models and CCSM4 suggests that the decadal-scale variability due to internal atmospheric variability may be comparable to the variability in the coupled atmosphere-ocean system. It is important to keep in mind that the ozone trends prescribed in these CCSM4 integrations are considerably smaller than the observed ones [see *Eyring et al.*, 2013, Figure 2f (dashed green line)], yet the internal tropospheric variability is likely independent of biases in the representation of stratospheric ozone.

Although our focus is on trends in the HC width, there is a similar large intraensemble spread in trends in the location of the midlatitude jet in GEOSCCM that can be compared with other model results. The standard deviation of trends in the latitude of the SH jet in DJF for the GEOSCCM ensemble is 0.45°/decade for 20 year trends and 0.24°/decade for 30 year trends. Virtually, the same standard deviations are calculated for the 40-member ensemble of CAM3 integrations. Furthermore *Thomas et al.* [2015] recently showed that the standard deviation of 25 year trends in the SH jet latitude in preindustrial control simulations by a collection of CMIP5 models is around 0.4°/decade (range from 0.3°/decade to 0.5°/decade), which is comparable to the variability for the GEOSCCM and CAM3 ensembles. This again indicates that the internal decadal-scale variability in GEOSCCM is comparable with other models, including coupled atmosphere-ocean models. Text S3 quantifies the range of trends that may be expected from internal variability.

4. Conclusions

This study shows that integrations of a chemistry-climate model with a realistic representation of the stratospheric ozone hole and observed SSTs over the period 1980 through 2009 can produce trends of tropical expansion comparable with those derived from most reanalyses, provided that the large internal atmospheric variability is accounted for. Correct representation of the SSTs changes is important for the NH (see also *Allen et al.* [2014]), while accurately representing stratospheric ozone changes is important for the SH (see also *Waugh et al.* [2015]). The ensemble mean trends are, however, considerably smaller than those in reanalyses, as the forced changes are masked (or supplemented) by internal atmospheric variability in individual ensemble members.

In conclusion, we suggest that the current generation of models are not (necessarily) missing key processes, as individual climate model runs can simulate trends similar to those in many reanalyses products. However, it is crucial that models represent ozone and SST forcings realistically and that internal atmospheric variability be properly accounted for by comparing observations to an ensemble of individual model simulations (and not to the average of the ensemble).

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