Drivers of the Recent Tropical Expansion in the Southern Hemisphere: Changing SSTs or Ozone Depletion?

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ABSTRACT

Observational evidence indicates that the southern edge of the Hadley cell (HC) has shifted southward during austral summer in recent decades. However, there is no consensus on the cause of this shift, with several studies reaching opposite conclusions as to the relative role of changes in sea surface temperatures (SSTs) and stratospheric ozone depletion in causing this shift. Here, the authors perform a meta-analysis of the extant literature on this subject and quantitatively compare the results of all published studies that have used single-forcing model integrations to isolate the role of different factors on the HC expansion during austral summer. It is shown that the weight of the evidence clearly points to stratospheric ozone depletion as the dominant driver of the tropical summertime expansion over the period in which an ozone hole was formed (1979 to late 1990s), although SST trends have contributed to trends since then. Studies that have claimed SSTs as the major driver of tropical expansion since 1979 have used prescribed ozone fields that underrepresent the observed Antarctic ozone depletion.

1. Introduction

Analysis of observations and meteorological reanalyzes show a poleward expansion of the Hadley cell (HC) circulation since 1979, although there is uncertainty in the exact rate of expansion (Hu and Fu 2007; Seidel et al. 2008; Davis and Rosenlof 2012). Climate models are generally unable to reproduce the magnitude of the observed expansion, and the search for the cause of the expansion is still ongoing.

In the Southern Hemisphere (SH) the largest poleward shift in the edge of the HC occurs during summer (Davis and Rosenlof 2012), so we will confine our discussion to this season. Several previous studies have examined the role of different possible drivers in causing the austral summertime expansion, but they have reached contradictory conclusions. Specifically, Lu et al. (2009), Polvani et al. (2011), McLandress et al. (2011), Son et al. (2010), and Hu et al. (2013) all conclude that ozone depletion is responsible for at least 50% of the HC shift, and use phrases such as "largely attributed to," "caused by," or "predominantly a response to" to describe the role ozone depletion plays in the shift. In contrast, Staten et al. (2012), Quan et al. (2014), and Adam et al. (2014) conclude that warming sea surface temperatures (SSTs) are the "main driver" or "principal mechanism" or "can account" for the HC expansion. Hence, the relative importance of SSTs and ozone depletion for recent SH trends remain in dispute.

The goal of this paper is to shed light on the reasons for these inconsistent claims. We do this by performing a meta-analysis that quantitatively compares the results from studies that have used single-forcing model integrations

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TABLE 1. Specifications of integrations performed in previous studies.

No.	Reference	Abbreviation	Model(s)	SSTs	Ozone	Perturbation	Period	Evolution
1	Son et al. (2009)	Son	CMIP3 multi	Coupled	Prescribed	Fixed O3	1960–99	Transient
2	Polvani et al. (2011)	Pol	CAM3	Prescribed	prescribed	GHG+SST	1960, 2000	Time slice
3	McLandress et al. (2011)	McL	CMAM	Coupled	Chemistry	GHG	1979–2000	Transient
4	Staten et al. (2012)	Stat	AM2.1	Prescribed	Prescribed	SST	1870, 2000	Time slice
5	Hu et al. (2013)	Hu	CMIP5 multi	Coupled	Prescribed	GHG	1979–2005	Transient
6	Quan et al. (2014)	Quan	CAM4	Prescribed	Prescribed	SST	1979–2012	Transient
7	Garfinkel et al. (2015)	THIS	GEOSCCM	Prescribed	Chemistry	SST	1979–2009	Transient

to isolate the role of SSTs and other factors on the HC expansion in the SH. For simplicity, and to avoid adding further confusion, we consider a single metric for the HC extent that is common to all studies and then scrutinize the specifics (e.g., applied forcings and integration length) of the model runs analyzed in each paper. We conclude that the weight of the evidence clearly points to stratospheric ozone depletion as the dominant driver of the expansion of the HC since 1979. The single-forcing modeling studies that have claimed SSTs to be the major influence on tropical expansion are shown here to have used prescribed ozone fields that grossly underrepresent Antarctic ozone depletion.

2. Methods

In this analysis we quantitatively compare the results from several previous studies (listed in Table 1) that have used single-forcing model integrations to isolate the role of SSTs on the expansion of the Southern Hemisphere HC during austral summer. To help understand the cause of differences among some of these studies, we also examine the HC trends in a new set of integrations using the Goddard Earth Observing System Chemistry–Climate Model (GEOSCCM; Garfinkel et al. 2015).

While all studies isolate the role of different factors in causing changes in the tropospheric circulation, they greatly differ in their design. They differ in 1) whether integrations are from a single model or from multiple models (with the latter being "ensembles of opportunity" where other factors differ between the models), 2) whether SSTs are prescribed or computed interactively within the model, 3) whether stratospheric ozone is prescribed as zonal-mean values or computed using interactive chemistry, 4) the forcing agents [SSTs, greenhouse gases (GHGs), O_3] that are isolated, 5) whether "transient" or "time-slice" integrations are performed, and 6) the time periods considered. Table 1 lists each of these characteristics for the different studies.

With regard to isolating the response to different forcing agents, the studies varied in whether the impact of SSTs alone or the combined impact of SSTs and GHGs were isolated. In models with prescribed SSTs the role of CO_2 and SSTs can be isolated separately, but for coupled atmosphere–ocean models this is not possible and only the combined impact of CO_2 and SSTs can be isolated. However, previous studies have shown that the response in integrations where both CO_2 and SSTs change is very similar to the one obtained when only the SSTs change (Deser and Phillips 2009; Grise and Polvani 2014).

The studies also differed in the metrics used to quantify changes in the tropospheric circulation, which adds to the confusion. Fortunately, all studies reported the latitude where the meridional mass streamfunction at 500 hPa is zero as a diagnostic of the edge of the HC. We therefore focus on that metric in this paper, as it allows us to perform a meaningful quantitative comparison across this wide array of studies.

For each study we compare the change in the southern edge of the HC in December–February (DJF) for integrations where all forcing fields (SSTs, GHGs, ozone) change (referred to as "ALL-forcing") with that for integrations where only SSTs or only GHGs and SSTs change (referred to as "SST-only" or "SST/GHG-only"). To compare results between studies using time-slice or transient integrations, as well as integrations considering different periods, we express the change in the HC edge in degrees latitude per decade. For transient integrations this is the linear trend over the integration period, whereas for time-slice integrations the "trend" is the difference between pairs of time-slice integrations divided by number of years between SSTs fields used in the integrations [e.g., 40 yr for Polvani et al. (2011)]. An exception is the analysis of Staten et al. (2012): They examined the difference between 1870 and 2000 time slice integrations, but as the rates of increase of CO_2 and SSTs were not constant over this period we divide the difference between their integrations by a time less than 130 years to account for the change in CO_2 growth rate. Specifically, we divide by 60 years, which is approximately the number of years required for the 1870 to 2000 increase in CO_2 (81 ppmv) to occur if the average growth rate was the same as that from 1960 to 2000 (1.3 ppm yr^{-1}).

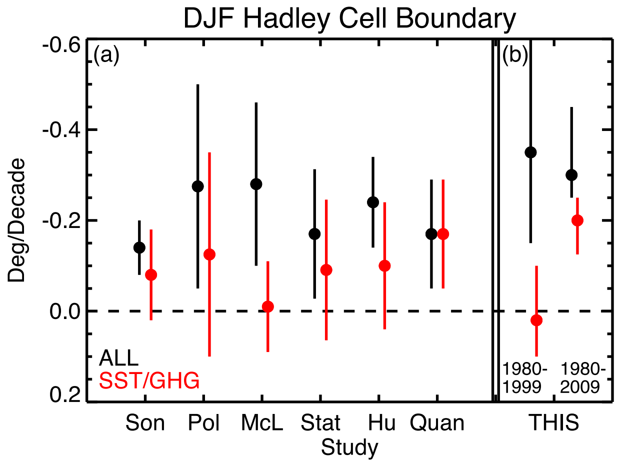

FIG. 1. Trends in December–February (DJF) HC edge for integrations with ALL-forcing (black) and SST/GHG (red) integrations from (a) previous studies and (b) this study; see Table 1 for abbreviations. Trends in (b) are for (left) 1980–99 and (right) 1980–2009. Errors bars correspond to twice the standard error for the Son, Hu, and THIS studies; one interannual standard deviation form controls for Pol, Stat, and Quan; and 95% confidence intervals for McL.

In the analysis of the above single-forcing experiments it assumed the different factors are separate drivers of HC changes. This is a reasonable assumption for SSTs and stratospheric ozone: The long-term changes in Antarctic ozone are dominated by changes in ozone depleting substances (and not dependent on SSTs), while changes in stratospheric ozone have very limited impact on SSTs. Furthermore, in the suite of integrations in Polvani et al. (2011) the sensitivity of the HC edge to ozone depletion does not depend on the distribution of SST (i.e., same sensitivity for 1960 or 2000 SSTs); similarly, sensitivity of HC edge to SSTs does not depend on the ozone distribution.

3. Results

The results of the comparison described above are summarized in Fig. 1a for the studies listed in Table 1. The black symbols show the HC edge change for ALL-forcing integrations, while the red symbols show the change in SST/GHG-only integrations. There is considerable spread among the studies in the magnitude of the simulated trends, with the ALL-forcing trends varying from 0.15° to over 0.3° decade^{-1} and the SST/GHG-only trends varying from 0° to over 0.2° decade^{-1}. These modeled trends are smaller than the trends of 0.3° to 1.2° decade^{-1} calculated from meteorological reanalyses (Davis and Rosenlof 2012).

There are some consistent results among all (or nearly all) studies. First, in all studies there is a significant poleward expansion in the ALL-forcing integrations. Second, in all but Quan et al. (2014), the HC expansions in the SST/GHG-only integrations are much smaller than in the ALL-forcing integration and, more importantly, the error bars cross zero (indicating the lack of statistical significance). Thus, there is nearly unanimous agreement among studies that while changes in SST/GHGs may be making a contribution to the simulated HC expansion they are not the dominant factor.

As discussed in the introduction a possible driver of the southward shift of the HC edge is stratospheric ozone depletion. Only four of the studies considered performed integrations to isolate the impact of ozone depletion. In Polvani et al. (2011) and McLandress et al. (2011) the shift in the HC edge for the ozone-only integrations is statistically indistinguishable from the ALL-forcing integrations (shown in Fig. 1), leading both studies to conclude that ozone depletion is the dominant driver of the HC shift. In contrast, Staten et al. (2012) and Quan et al. (2014) the DJF shift in the HC edge in ozone-only integrations is only 20%–25% of that in their ALL-forcing integrations, leading them to conclude that ozone is not a major driver.

These different conclusions are due to differences in ozone depletion used in the integrations. In the Polvani et al. and McLandress et al. simulations the changes in ozone and SSTs/GHGs are both representative of the observed changes from 1960 to 2000. However, in the Staten et al. and Quan et al. simulations the SST changes are from 1850 or 1860 to 2000, but the ozone depletion is similar to that observed from 1980 to 2000.[1] So the weaker relative role of ozone in Staten et al. and Quan et al. comes from a comparison of the response to the 1980–2000 changes in ozone with the response from preindustrial to 2000 changes in SSTs/GHGs: this is not a meaningful comparison since, by design, it underestimates the role of ozone depletion.

Differences in time periods considered may also explain why Quan et al. (2014) is the outlier among the studies in terms of the relative HC shift in SST/GHG-only integration compared to the ALL-forcing integration. Quan et al. computed trends from 1979 to 2012, whereas all other studies using observed SSTs considered changes up to 2000 only.

To explore the sensitivity of the HC trends to the time period considered we examine the HC trend in

[1] The preindustrial ozone used in Staten et al. (2012) is based on observations for 1979 (Randel and Wu 2007), while that in Quan et al. (2014) comes from a chemistry–climate model that has a very weak ozone hole (e.g., Fig. 2f of Eyring et al. 2013), and the simulated preindustrial ozone depletion is similar to that observed since 1979. The Antarctic October ozone depletion from 1979 to 2000 is around 90 DU whereas for 1850 to 2000 it is around 160 DU (Cionni et al. 2011).

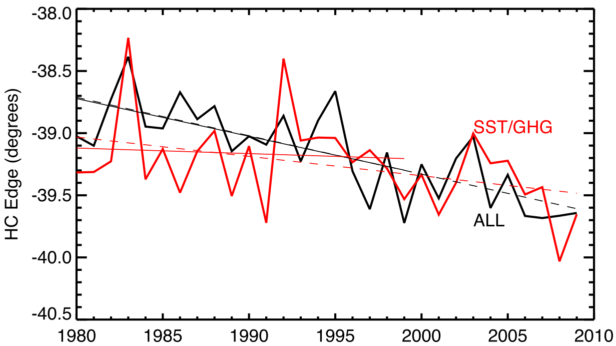

FIG. 2. Ensemble-mean trends in DJF HC edge for GEOSCCM ALL-forcing (black) and SST/GHG-only (red) integrations. Solid lines show trends for 1980–99 and dashed lines show trends for 1980–2009.

10-member ensembles of ALL-forcing and SST-only transient (1979–2009) GEOSCCM integrations (Garfinkel et al. 2015). These integrations use the same prescribed SSTs as Quan et al. (2014), but GEOSCCM has interactive stratospheric chemistry whereas Quan et al. used prescribed ozone fields.

Figure 2 shows the evolution of the ensemble-mean HC edge for the ALL-forcing (black) and SST-only (red) GEOSCCM integrations from 1980 to 2009. In the ALL-forcing integrations there is a significant poleward expansion of the HC for both the 1980–99 and 1980–2009 periods (Fig. 1b), with a magnitude similar to that in the ALL-forcing integrations of Polvani et al. (2011), McLandress et al. (2011), and Hu et al. (2013). In contrast, for the SST-only integrations there is no significant trend over the period 1980–99, but a significant trend appears for the longer 1980–2009 period (Fig. 1b). This indicates that the conclusion one draws on the role of SSTs depends sensitively on the period considered: SSTs had a negligible impact on the HC edge before 2000 but caused a significant shift in the HC edge if changes in SSTs up to 2009 are considered.

The sensitivity of the SST-only HC trends to time period can be related to differences in the trends of observed SSTs. Figures 3a and 3b show the trends in SSTs for 1980–99 and 1980–2009. The most obvious difference between the 1980–99 and 1980–2009 SST trends is over the tropical eastern Pacific; the trends are small for 1980–99, but one can see a significant cooling for 1980–2009. This difference is due to a transition to a negative (cool) phase of the Pacific decadal oscillation (PDO) (Trenberth and Fasullo 2013), which can be clearly seen in the 1992–2009 SST trends (Fig. 3c).

To examine how these changes in SSTs impact the HC we calculate the interannual covariance between the edge of the zonal-mean HC and SSTs at each grid point in the SST-only integrations (see Fig. 3d). This figure shows that a poleward shift in the HC edge is associated with a cooling over the eastern Pacific and warmer SSTs in the subtropics and midlatitudes, consistent with previous studies linking poleward shifts to the negative phase of the PDO (e.g., Lu et al. 2009; Grassi et al. 2012; Allen et al. 2014). There is a striking agreement between the pattern of the 1992–2009 SST trends and the pattern associated with interannual HC edge variability (Figs. 3c,d); hence a poleward shift in the HC edge

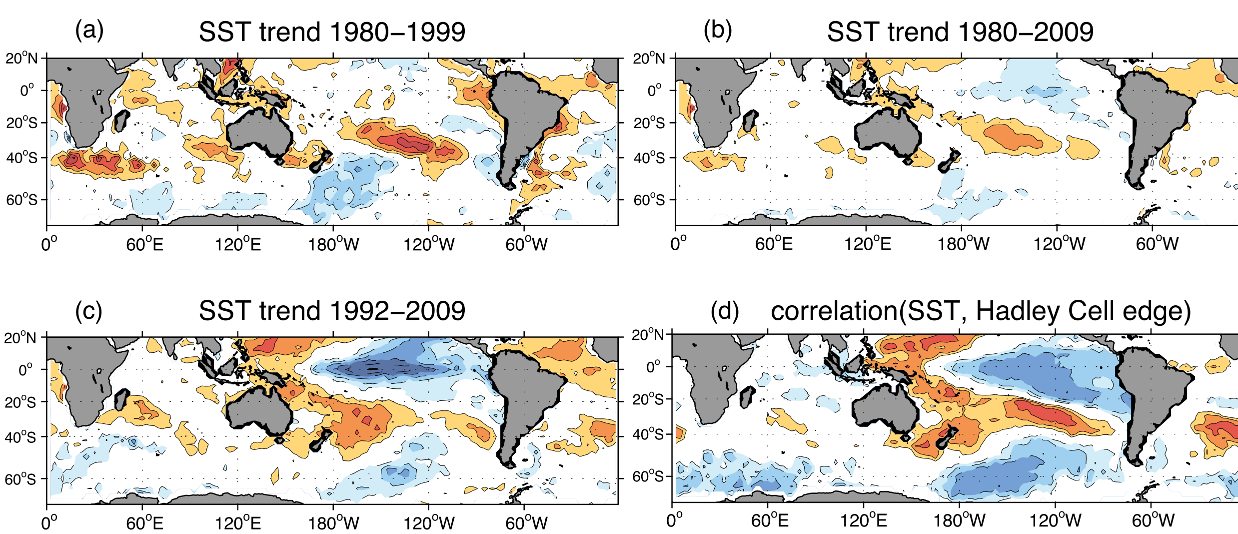

FIG. 3. Trends in observed DJF SSTs used in GEOSCCM integrations for (a) 1980–99, (b) 1980–2009, and (c) 1992–2009. (d) Interannual covariance between SSTs and HC edge. Contour interval is (a)–(c) 0.15 K decade^{-1} and (d) 0.15, with zero contour suppressed in all panels and ±0.15 contours also suppressed in (d) because such a correlation is not statistically significant at the 95% by a Student's *t* test.

during that period is to be expected in SST-only integrations (as is apparent in Fig. 2). In contrast, the SST trends from 1980–99 do not resemble the pattern that is associated with interannual variability, and consistent with this there are limited HC trends between 1980 and 1999.

Returning to the comparison between different studies; the GEOSSCM SST-only 1980–2009 trend is similar to that in the SST-only integrations of Quan et al. (2014) (see Fig. 1), indicating the two different models produce a similar response of the HC to changes in SSTs. But, more importantly, the 1980–2000 trend in the GEOSCCM SST-only ensemble is, like other studies that considered SSTs changes up to 2000, statistically insignificant. Thus differences in the period considered can explain much of the variation in trends in SST-only integrations among studies.

4. Concluding remarks

A careful, quantitative comparison of studies that have used single-forcing model integrations to isolate the role of different factors on the HC expansion during austral summer shows much consistency, and the main inconsistencies can be attributed to differences in the ozone forcing and time periods considered in different studies. There is nearly unanimous agreement among studies that HC trends in integrations with only SSTs (or SSTs and GHGs) forcing are statistically insignificant over the ozone hole formation period, and much smaller than the statistically significant HC trends in ALL-forcing integrations.

Studies that performed ozone-only integrations with Antarctic ozone depletion consistent with the time period for the ALL-forcing integrations indicate that ozone depletion is the dominant factor causing the HC expansion in austral summer in the last several decades of the twentieth century. Staten et al. (2012) and Quan et al. (2014) reported limited impact of ozone depletion, but these studies used weak Antarctic ozone forcing in their model integrations and compared the depletion with the impact of SSTs/GHGs from the preindustrial period to the present day and, as a result, underestimated the impact of ozone on the HC. Adam et al. (2014) also claim that ozone depletion has limited impact on the HC trends. However, this was based on a regression analysis that assumes that all changes in the HC were related to changes in SSTs. The mean SSTs and Antarctic ozone time series are qualitatively similar over the last few decades (monotonically changing from 1979 to 1997, and basically flat afterward), and the HC changes attributed to mean SSTs in their analysis could equally be attributed to ozone depletion. The actual causality cannot be established from regression analysis.

While the evidence clearly points to stratospheric ozone depletion as the dominant driver of the summertime HC expansion over the ozone hole formation period (1979 to 1990s), SSTs have contributed to the HC expansion since the late 1990s. During this latter period the ozone hole has been roughly constant (excepting interannual variability), but large changes in the tropical and subtropical Pacific SSTs have forced the HC edge poleward. Hence, studies that end their trend calculations in 2009 or later find a significant role for SSTs, while studies that end their trend calculation in 2000 do not.

While the above analysis has clarified the relative roles of SSTs and ozone depletion in the simulated expansion of the HC during austral summer, it does not address the mechanism(s) involved. The changes is SSTs and ozone discussed above will both modify the meridional temperature gradients near the tropopause, and several mechanisms have been proposed for how this will alter the tropospheric circulation (e.g., Gerber et al. 2012; Garfinkel et al. 2013, and references within) but the exact mechanism(s) involved remains unclear. Another unresolved issue is why models underestimate the observed expansion [the mean poleward shift in ALL-forcing runs is less than 0.3° decade^{-1} for all studies (Fig. 1), but the trends in reanalyses varies from 0.3° to 1.2° decade^{-1} (Davis and Rosenlof 2012)]. Part of the solution could be the need to correctly represent both the ozone hole and the tropical SSTs to simulate HC trends. Most previous studies have not done both. However, in some of the GEOSCCM integrations presented here, and some of the stratospheric-resolving CCMs in Son et al. (2010), the HC trends approach the observed values.

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