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Key Points:
- There is twice as much Hadley cell expansion in Southern Hemisphere relative to Northern Hemisphere in models under CO_2 forcing
- Degree of asymmetry depends on season but is highly robust across models and Hadley cell definitions
- Due to smaller Northern Hemisphere sensitivity to static stability increase, pattern of sea surface warming and direct CO_2 radiative effects

Supporting Information:
- Supporting Information S1

Correspondence to:
O. Watt-Meyer,
oliverwm@uw.edu

Hemispheric Asymmetry of Tropical Expansion Under CO₂ Forcing

O. Watt-Meyer[1] [ID], **D. M. W. Frierson[1]**, and **Q. Fu[1]** [ID]

[1]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA

Abstract The degree of Hadley cell expansion under global warming will have a substantial impact on changing rainfall patterns. Most previous studies have quantified changes in total tropical width, focused on the Southern Hemisphere Hadley cell or considered each hemisphere's response to a multitude of anthropogenic forcings. It is shown here that under exclusive CO_2 forcing, climate models predict twice as much Hadley cell expansion in the Southern Hemisphere relative to the Northern Hemisphere. This asymmetry is present in the annual mean expansion and all seasons except boreal autumn. It is robust across models and Hadley cell edge definitions. It is surprising since asymmetries in simulated Hadley cell expansion are typically attributed to stratospheric ozone depletion or aerosol emission. Its primary cause is smaller sensitivity of the Northern Hemisphere Hadley cell to static stability changes. The pattern of sea surface warming and the CO_2 direct radiative effect also contribute to the asymmetry.

1. Introduction

The Hadley cell is a fundamental element of the atmosphere's zonal mean circulation that dominates the poleward transport of energy and angular momentum in the tropics. The locations of its ascending and descending branches are coincident with intense precipitation near the equator and the subtropical dry zones, respectively. A significant body of work has examined the expansion of the Hadley cell under global warming in both observations and numerical simulations (see recent reviews, Grise et al., 2019; Staten et al., 2018). However, the extent of the Hadley cell is also sensitive to natural variability of sea surface temperatures (SSTs; Grassi et al., 2012; Lu et al., 2008), anthropogenic emission of aerosols (Allen & Sherwood, 2011), and ozone depletion (Son et al., 2008). Furthermore, the Southern and Northern Hemispheres may respond differently to each of these forcings. Thus, in order to clarify the role of greenhouse gas emissions only, this study documents the response of each hemisphere's Hadley cell edge to increasing CO_2 concentration only in coupled climate models across the seasonal cycle.

Projected changes in the Hadley cell under global warming are an overall weakening of the overturning circulation, poleward expansion of its downward branch (Grise & Polvani, 2016; Held & Soden, 2006; Hu et al., 2013; Johanson & Fu, 2009; Lu et al., 2007), and possible contraction of its upward branch (Byrne & Schneider, 2016; Lau & Kim, 2015; Su et al., 2017). There has been observed expansion of the Hadley cell, the amount of which is due to an anthropogenic signal versus natural variability is still under some debate (Davis & Birner, 2017; Fu et al., 2006; Fu & Lin, 2011; Heffernan, 2016; Hu & Fu, 2007; Grise et al., 2019). The expansion of Hadley cell extent is typically thought to be a result of increased dry static stability in the subtropics (Frierson et al., 2007; Lu et al., 2007, 2008). However, the Hadley cell edge also shifts in response to changing eddy momentum fluxes (e.g., Walker & Schneider, 2006) and has been shown to be closely correlated with the position of the eddy-driven jet during Southern Hemisphere summer (Kang & Polvani, 2011). Substantial ozone loss in the Southern Hemisphere polar vortex has occurred during spring, which has driven lower polar stratospheric temperature and hence accelerated zonal winds. In turn, the eddy-driven jet in the Southern Hemisphere has shifted poleward due to this ozone loss (primarily in summer) and this has driven a portion of the Hadley cell expansion in the Southern Hemisphere during the observed record (McLandress et al., 2011; Son et al., 2008; Thompson & Solomon, 2002). In the Northern Hemisphere there has been comparatively little ozone loss, and for this reason, asymmetries in simulated Hadley cell expansion between the Southern and Northern Hemispheres are often attributed to the impacts of ozone-depleting substances onto the atmospheric circulation.

However, as we note in this study, climate models forced exclusively with increased CO_2 concentration predict up to twice as much Hadley cell expansion in the Southern Hemisphere compared to the Northern

Hemisphere. This is true for the annual mean Hadley cell and for all individual seasons except boreal autumn. The smaller expansion in the Northern Hemisphere under CO_2 forcing only has been pointed out by some previous studies (e.g., Davis et al., 2016; Grise & Polvani, 2016), but these works do not focus on why there is a larger response in the Southern Hemisphere. In historical simulations with only greenhouse gas emissions changing ("historicalGHG"; Taylor et al., 2012) the differences between hemispheres are smaller (Hu et al., 2013; Tao et al., 2016), likely due to the relatively weak forcing in this experiment, the short duration of the historical period and possibly because of differences in the set of models that performed this experiment. Coupled model simulations forced by high greenhouse gas emissions scenarios (i.e., RCP8.5) do show larger expansion in the Southern Hemisphere by the end of the 21st century (Hu et al., 2013; Tao et al., 2016), but these experiments have complicating factors such as ozone hole recovery and aerosol cleanup, which may affect each hemisphere differently. In extended global warming runs (i.e., ECP8.5), greater expansion was also found in the Southern Hemisphere (Son et al., 2018) but this finding was based on a relatively small number of models. The mechanism behind the asymmetry of greenhouse gas induced Hadley cell expansion is not understood (Grise et al., 2019). This study provides, for the first time, a detailed discussion of the seasonality of differences between Southern and Northern Hemisphere expansion in response to greenhouse gas forcing and its robustness across models. We also discuss various possible mechanisms for this asymmetry including (1) the impacts of Arctic amplification, (2) the pattern of SST warming as well as CO_2 direct radiative effects, and (3) differing sensitivities of each hemisphere to vertical static stability increases.

## 2. Data and Methods

2.1. Model Data Used

In order to focus on the hemispheric asymmetry of the response to CO_2 forcing only, this study uses experiments in which comprehensive coupled atmosphere-ocean models are exclusively forced with increased CO_2. Specifically, the 16 models from the CMIP5 archive (Taylor et al., 2012), which performed the 1pctCO2, abrupt4xCO2, and piControl experiments, are used (listed in Table S1 in the supporting information). The 1pctCO2 and abrupt4xCO2 experiments are initialized from the piControl run: 1pctCO2 increases the concentration of CO_2 by 1% every year until it is quadrupled at year 140, while abrupt4xCO2 increases the CO_2 concentration by 4 times instantaneously and then the simulation continues for 150 years. In addition to these coupled atmosphere-ocean runs, specified SST runs are also analyzed in order to isolate the relative impacts of SST changes versus radiative forcing changes, as well as the role of nonuniform SST changes. For these experiments, the control is the amip simulation, in which atmospheric models are forced with the historical evolution of SSTs and sea ice from 1979 to 2008. Three perturbations are applied: amip4xCO2 in which CO_2 is quadrupled but SST remains the same, amip4K in which SSTs are increased by 4 K everywhere, and amipFuture in which SSTs are increased by a specified pattern. The pattern represents the estimated transient response to quadrupled CO_2 from a set of coupled models, but it is normalized to have a global mean of 4 K (see https://www.earthsystemcog.org/projects/cfmip/cfmip2-cmip5 for details). In all the perturbation experiments, sea ice remains the same as in the amip experiment. Nine models performed all of the necessary experiments (listed in Table S1).

2.2. Diagnostics

This study examines various aspects of the zonal mean atmospheric circulation, with a particular focus on Hadley cell extent. In order to ensure robustness of the results presented, the Hadley cell extent is computed with a variety of metrics (Davis & Birner, 2017; Waugh et al., 2018). Some of these metrics are based on the mass streamfunction, which is computed from the zonal mean meridional wind $\bar{v}$ as

$$\Psi(p, \phi) = \frac{2\pi a \cos(\phi)}{g} \int_0^p \bar{v}(p', \phi)\, dp'. \tag{1}$$

The primary metric used is Ψ_{500}, the first zero crossing of the 500-hPa mass streamfunction poleward of its tropical extremum (Frierson et al., 2007; Hu & Fu, 2007). For comparison, the zero crossing of the vertically integrated streamfunction ($\int \Psi dp$), the zero crossing of zonal mean surface zonal wind (U_{sfc}), and zero crossing of zonal mean precipitation minus evaporation ($P - E = 0$) are computed. These are calculated as in Davis and Birner (2017), and the same notation is used as in that study. The position of the eddy-driven jet is defined as the latitude of the maximum 700-hPa zonal mean zonal wind, which is computed by fitting a quadratic to the five grid points at and surrounding the maximum zonal wind (Simpson & Polvani, 2016)
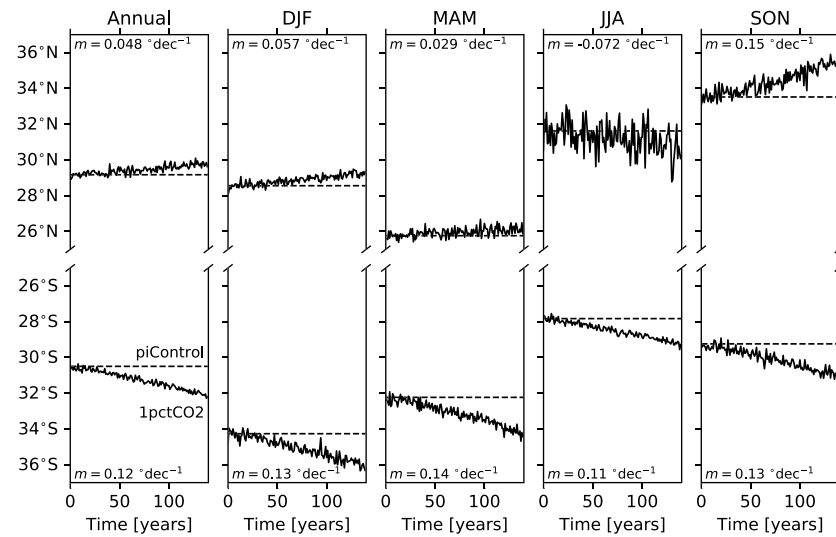
Figure 1. The evolution of the multimodel mean Hadley cell edge Ψ_{500} in the 1pctCO2 experiment (solid line) and the climatological value for the piControl experiment (dashed line). The trends of expansion (in degrees poleward per decade) for each season and hemisphere are shown in text at the top and bottom of each subpanel. The evolution for JJA in the Northern Hemisphere is noisier because the summer Hadley cell is very weak in the Northern Hemisphere and so the edge is not always well defined.

and is denoted U700. For all diagnostics, either the annual or seasonal mean is taken for the relevant variable (mass streamfunction, zonal wind or $P - E$) before the metric is computed. The seasons are December through February (DJF), March through May (MAM), June through August (JJA), and September through November (SON). In this study we do not focus closely on the Northern Hemisphere summer since its Hadley cell is weak and in some years not well defined (i.e., the streamfunction never becomes positive in the subtropics). In this case the local maximum of the streamfunction in the subtropics is used for the Hadley cell edge.

We define a measure of static stability in the subtropics to midlatitudes, C_{st}, as the difference between potential temperature at 400 and 850 hPa, averaged between 25° and 50° (Grise & Polvani, 2016; Lu et al., 2008). As this diagnostic gets larger, it indicates a stronger vertical stability.

3. Results

3.1. Trends in Hadley Cell Expansion Under CO$_2$ Forcing

There is a striking asymmetry in the simulated evolution of the Hadley cell extent between the Southern and Northern Hemispheres under the steady increase of CO$_2$ concentration (Figure 1). In the annual mean, the multimodel mean trend in Ψ_{500} in the 1pctCO2 experiment in the Southern Hemisphere (0.12° poleward per decade) is more than double that in the Northern Hemisphere (0.048° poleward per decade). Despite the strong seasonal cycle in the climatological position of the Hadley cell extent (dashed lines in Figure 1), Hadley cell expansion is approximately constant across the seasonal cycle in the Southern Hemisphere. Quantitatively, it ranges from 0.11° poleward per decade in JJA to 0.14° poleward per decade during MAM. On the other hand, in the Northern Hemisphere there is a strong seasonal cycle in Hadley cell expansion. During JJA, there is actually a slight equatorward contraction in the multimodel mean, although the Northern Hemisphere Hadley cell is often not well defined during summer and there is a substantial model spread for the trend in this season (from −0.36° to 0.33° poleward per decade). In other seasons, the trend ranges from 0.029° poleward per decade in MAM to 0.15° poleward per decade in SON. In summary, for the annual mean, DJF and MAM, the Hadley cell expansion in the Southern Hemisphere is at least twice as large as that in the Northern Hemisphere. Boreal autumn is the only season in which tropical expansion is approximately the same in both hemispheres.

The seasonality and hemispheric asymmetry of Hadley cell expansion that is found for the multimodel mean in the 1pctCO2 experiments (Figure 1) is highly robust across models: All 16 of the models analyzed have a larger trend in Hadley cell expansion in the Southern Hemisphere than the Northern Hemisphere for the

annual mean, DJF and MAM (not shown). The asymmetry, and its seasonality, is also reproduced in the quasi-equilibrium response in the abrupt4xCO2 experiments (Figure S1a; see also Davis et al., 2016; Grise & Polvani, 2016). The multimodel median shows larger Southern Hemisphere expansion for the annual mean, DJF and MAM, and similar expansion for SON, just as for the 1pctCO2 experiments. Using other metrics of Hadley cell extent (Figures S1b–S1d) results in qualitatively similar asymmetries between the hemispheres. Specifically, the two mass streamfunction metrics, Ψ_{500} and $\int \Psi \mathrm{d}p$, result in very similar estimates of Hadley cell expansion (Figures S1a and S1b), while U_{sfc} typically estimates a smaller expansion in the Northern Hemisphere and hence an even larger asymmetry between the hemispheres. The $P - E = 0$ metric estimates a similar hemispheric asymmetry of Hadley cell expansion for the annual mean, although has a slightly different seasonality, with more similar expansion in DJF and more asymmetric expansion in SON.

The asymmetry of the response between the hemispheres is also highly robust across models for the abrupt4xCO2 experiment. All models except one have greater expansion in the Southern Hemisphere for DJF, MAM and the annual mean for the Ψ_{500} metric (Figure S2a). Since the degree of asymmetry and its seasonality are similar between the 1pctCO2 and abrupt4xCO2 experiments (cf. Figures 1 and S1a) for the rest of this study we will focus on the quasi-equilibrium (years 100 to 150) abrupt4xCO2 responses.

3.2. Mechanisms for Hadley Cell Expansion Asymmetry

Classical theories demonstrate that tropopause height and tropospheric static stability are critical for determining the extent of the Hadley cell (Held & Hou, 1980; Held & Coauthors, 2000). Indeed, the typical explanation for the cause of modeled tropical expansion as simulated in global warming experiments is that increased subtropical static stability allows poleward flow in the upper troposphere to reach higher latitudes before becoming baroclinically unstable (Kang & Lu, 2012; Lu et al., 2007, 2008). The increases in subtropical static stability occur because the vertical profile of temperature in the tropics roughly follows a moist adiabat, and thus, warming in the tropical upper troposphere is amplified relative to the surface. Previous work suggests that this theory is able to explain a significant fraction of the variance in Hadley cell expansion in the abrupt4xCO2 experiments, at least for the Southern Hemisphere, which is more zonally symmetric (Chemke & Polvani, 2019). However, it is not immediately obvious why there would be larger increases in static stability in the Southern Hemisphere versus Northern Hemisphere subtropics, in particular given that free tropospheric temperatures in the tropics tend to be close to uniform (e.g., Sobel et al., 2001). Furthermore, despite the success of axisymmetric theories for explaining Hadley cell changes under warming, there are some reasons to doubt their validity. For example, the assumption of angular momentum conservation in the upper troposphere is not true during all seasons (Walker & Schneider, 2006). Indeed, particularly during the summer season, there is evidence that the Hadley cell edge position is strongly controlled by eddy momentum fluxes generated in the midlatitudes (Kang & Polvani, 2011; Schneider & Bordoni, 2008; Walker & Schneider, 2006). It is reasonable to expect that changes in eddy momentum fluxes may be distinct in each hemisphere, because of significant differences in equator-to-pole temperature gradient changes in each hemisphere. In particular, greenhouse gas forcing is expected to cause amplified warming of the near-surface and midtroposphere Arctic (Manabe & Stouffer, 1980). This implies a tendency toward a smaller equator-to-pole temperature gradient near the surface and has been suggested to be one reason that less poleward shift of the eddy-driven jet is seen in the Northern Hemisphere (Barnes & Screen, 2015; Butler et al., 2010), although its impact on the Hadley cell extent has not been clearly documented. In the Southern Hemisphere, delayed warming of the Southern Ocean in the high latitudes (Armour et al., 2016; Marshall et al., 2014) has the effect of increasing meridional surface temperature gradients and could amplify the poleward shift of the Hadley cell edge and eddy-driven jet. Differences between the hemispheres in the climatological position and structure of the jet could also have impacts on future changes through different eddy feedbacks (e.g., Kidston & Gerber, 2010; Simpson & Polvani, 2016). Recent work has also demonstrated a role for Intertropical Convergence Zone position (Hilgenbrink & Hartmann, 2018; Kang & Lu, 2012) and width (Watt-Meyer & Frierson, 2019) to impact the extent of the Hadley cell by modifying the strength of the subtropical jet through changes in the angular momentum of air in the Intertropical Convergence Zone.

The following sections discuss in more detail the possible mechanisms discussed above for the hemispheric asymmetry of Hadley cell expansion. The hypotheses are tested by verifying whether they can explain the strong seasonal cycle in the Northern Hemisphere (and lack thereof in the Southern Hemisphere) and whether they can explain the intermodel spread in Hadley cell expansion in the two hemispheres.
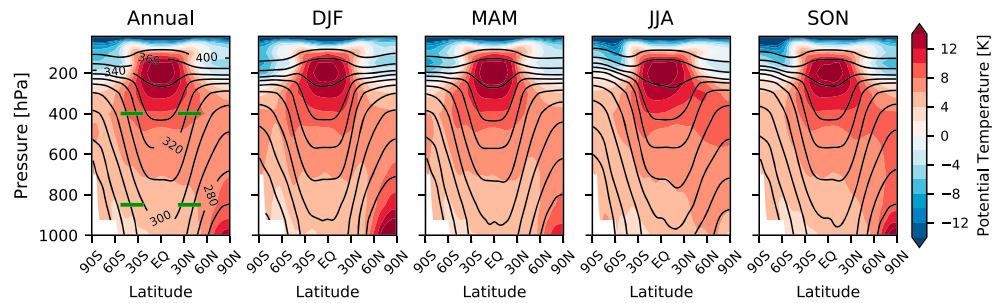
Figure 2. The multimodel and zonal mean atmospheric potential temperature averaged over 50 years of the piControl experiment (black contours) and the difference between years 100 to 150 of the abrupt4xCO2 experiment and the piControl experiment (shading). For reference, the latitudes and pressure levels used to compute C_{st} are shown in the annual mean plot (see section 2.2). DJF = December through February; MAM = March through May; JJA = June through August; SON = September through November.

3.2.1. Arctic Amplified Warming

One of the clearest differences in the thermal response to CO_2 increase between the hemispheres is the presence of strongly amplified warming in the Arctic, particularly near the surface (Figures 2 and S3). The signal occurs because of a combination of the positive lapse rate feedback in the Arctic (Pithan & Mauritsen, 2014), positive sea ice-albedo feedback (Manabe & Stouffer, 1980), and increased energy transport into the Arctic (Alexeev et al., 2005; Graverson et al., 2008). Such a signal does not occur in the Southern Hemisphere, likely due to the upwelling in the Southern Ocean (Marshall et al., 2014) reducing the high-latitude surface warming and the landmass and topography of Antarctica lessening the positive lapse rate feedback (Salzmann, 2017). The amplified surface warming in the Northern Hemisphere reduces the equator-to-pole temperature gradient and may act to dampen the poleward shift of the zonal mean eddy-driven jet in the Northern Hemisphere compared to the Southern Hemisphere (Barnes & Screen, 2015; Butler et al., 2010). Furthermore, experiments that isolate the effects of sea ice loss onto the atmospheric circulation tend to indicate that, in isolation, it tends to cause an equatorward shift of the eddy-driven jet and Hadley cell edge, although this shift is reduced or canceled out when the effects of sea ice loss onto tropical ocean heating are accounted for (Blackport & Kushner, 2017; Chemke et al., 2019; McCusker et al., 2017).

However, the seasonal cycle of Arctic amplification in the abrupt4xCO2 experiments (Figure 2) does not correspond to the degree of Hadley cell expansion across the seasons. Specifically, near-surface Arctic temperature increases are largest in DJF followed by SON and MAM, with no amplified surface warming in JJA. This does not support the idea that amplified warming in the Arctic lessens the degree of Hadley cell expansion in the Northern Hemisphere, since it is found that JJA actually has a slight equatorward contraction of the Hadley cell edge. Furthermore, the substantially larger expansion in SON versus MAM in the Northern Hemisphere (Figures 1 and S1) occurs despite stronger Arctic amplification in SON compared to MAM (Figure 2). The spread across models also indicates a lack of connection between polar surface warming and Hadley cell expansion in the abrupt4xCO2 experiments. The only season in either hemisphere that has a significant correlation between the amount of surface warming poleward of 60° and Ψ_{500} is Northern Hemisphere SON ($r = 0.58$), but it is of the opposite sense as expected: More polar warming tends to coincide with a greater poleward shift of the Hadley cell edge.

3.2.2. Patterned Response of SST and Direct Radiative Effects

Under increasing CO_2, SSTs do not increase uniformly across the oceans (Figure S3). For example, because it is a region of upwelling from the deep ocean, the Southern Ocean warms more slowly than the rest of the planet under greenhouse gas forcing (Armour et al., 2016; Marshall et al., 2014). Although lessened warming in the Southern Ocean is unlikely to contribute to the strong seasonal cycle of Hadley cell expansion in the Northern Hemisphere, it may be part of the reason that there is greater Hadley cell expansion in the Southern Hemisphere compared to the Northern Hemisphere. This section explores the role of the pattern of SST forcing in driving hemispherically asymmetric Hadley cell expansion, as well as the direct effect of CO_2 radiative forcing (without SST warming). Figure 3 shows the multimodel mean response of Ψ_{500} to quadrupling CO_2 concentration but maintaining SSTs fixed (amip4xCO2), increasing SSTs uniformly by 4 K (amip4K), and increasing SSTs by a patterned response with a global mean of 4 K (amipFuture). The pattern for amipFuture is derived from coupled model estimates of future SST changes and has less warming in
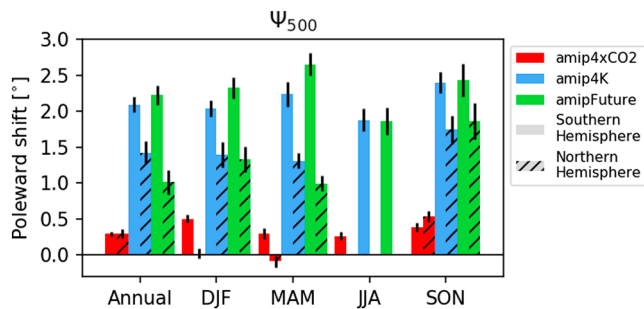
Figure 3. The difference in Ψ_{500} between each specified experiment (see legend) and the amip experiment, averaged over the years 1979–2008. See section 2.1 for details on each experiment. Solid bars are the Southern Hemisphere response, and dashed bars are the Northern Hemisphere response. Positive numbers represent a poleward shift. Error bars show the standard error in the mean. Responses for Northern Hemisphere JJA are not shown.

the Southern Ocean and North Atlantic and slightly amplified warming in the Eastern Tropical Pacific (cf. Figures S4 and S5).

For individual seasons, the direct radiative effect of CO_2 does cause somewhat differing effects in each hemisphere: For SON the response is slightly larger in the Northern Hemisphere, whereas in DJF and MAM the Southern Hemisphere poleward shift is between 0.4° and 0.5° larger. In the annual mean, the direct radiative effect is about the same in both hemispheres. These individual season asymmetries, however, are still small compared to those in the coupled response (Figures 1 and S1), and this suggests that the hemispheric asymmetry of Hadley cell expansion must predominantly arise from the effects of SST increases, and this is confirmed by the responses in the amip4K and amipFuture experiments (Figure 3). Despite consisting of a different set of models than those that went into Figure 1 (see Table S1), in all seasons and the annual mean, both the amip4K and amipFuture experiments have more Hadley cell expansion in the Southern Hemisphere than the Northern Hemisphere. As in the coupled experiments (Figures 1 and S1), the largest asymmetry occurs during MAM. Different from the coupled experiments, there is still somewhat more Hadley cell expansion in the Southern Hemisphere during SON compared to the Northern Hemisphere, even in the amipFuture experiment (possibly because the SST anomalies of the coupled abrupt4xCO2 and amipFuture experiments are somewhat different, cf. Figures S3 and S5, or because sea ice is fixed for amipFuture). In the Southern Hemisphere, the patterned SST increase (amipFuture) causes more Hadley cell expansion than the uniform increase (amip4K) in DJF and MAM, which are the seasons with the least Southern Ocean warming (see Figure S5). This suggests that delayed Southern Ocean warming does amplify Hadley cell expansion in the Southern Hemisphere (15% and 18% in DJF and MAM, respectively) although it is a relatively small impact compared to how much it effects the eddy-driven jet position (41% and 73% increases in poleward shift; not shown). In the Northern Hemisphere, the patterned SST somewhat decreases the MAM and annual responses, also contributing to the asymmetry of Hadley cell expansion. How the Hadley cell edge in the Northern Hemisphere responds to the SST pattern changes in detail is a subject of future research.

Despite the impacts of direct radiative effects and the pattern of warming that are outlined above, the globally uniform warming of amip4K is the largest contribution to the Hadley cell expansion asymmetry in most seasons (Figure 3), suggesting that there is a more fundamental aspect of the circulation in the Northern Hemisphere that makes it less responsive to an equivalent forcing. This will be discussed in the next section.

The amip experiments discussed here also provide further evidence that Arctic amplification is not necessary for the Hadley cell expansion asymmetry. This is because sea ice area is specified to remain constant for the perturbations, and hence, the degree of Arctic amplified surface warming is sharply reduced compared to the coupled abrupt4xCO2 experiments (cf. Figures S4 and S5 to Figure S3). However, as discussed above, the amipFuture and amip4K experiments both still show less Hadley cell expansion in the Northern Hemisphere relative to the Southern Hemisphere.

3.2.3. Sensitivity of Circulation to Static Stability Changes

In order to understand why the Northern Hemisphere might be less responsive to the same SST forcing, we compute the changes in the vertical static stability (C_{st}) for each hemisphere and season. In the Southern Hemisphere, it is well established that changes in subtropical static stability are closely connected with the expansion of the Hadley cell (Chemke & Polvani, 2019; Lu et al., 2008). The relationship between static stability and Hadley cell extent in the Northern Hemisphere in comprehensive models has been less explored, but it has generally been found that the statistical connections are weaker (e.g., cf. Figures 6 and 7 of Lu et al., 2008).

Figure 4 shows the relationship between changes in C_{st} and Ψ_{500} across all sixteen models examined for the abrupt4xCO2 experiment, separately for the annual mean (Figure 4a) and each hemisphere and season (Figures 4b and 4c). In the annual mean, there is a strong connection between the magnitude of static stability increase and the degree of Hadley cell expansion for both hemispheres (correlations of $r = 0.85$ and $r = 0.70$ in the Southern and Northern Hemispheres, respectively; Figure 4a). Furthermore, the multi-
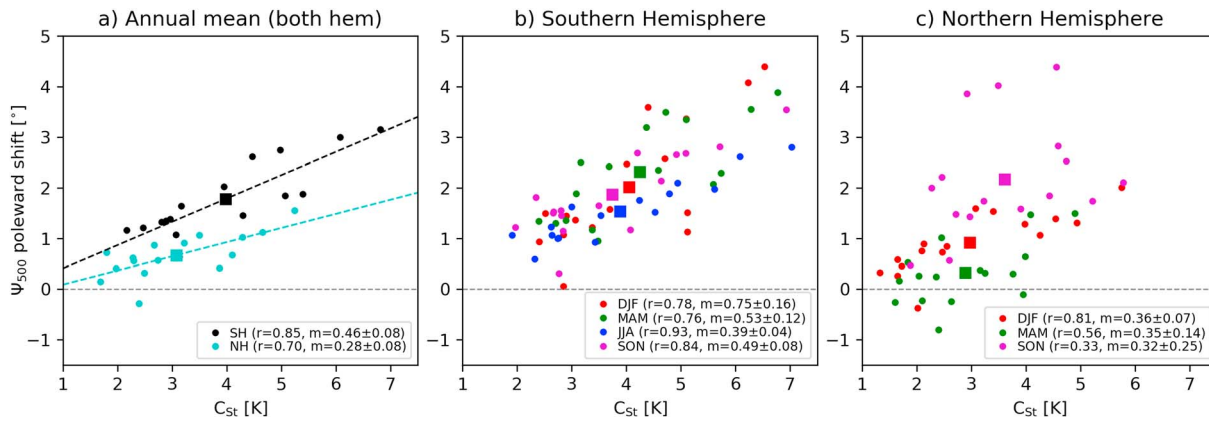
Figure 4. Scatter plots of the difference in Ψ_{500} and C_{st} between years 100 to 150 of the abrupt4xCO2 experiment and the piControl experiment for all individual models (circles) and the multimodel mean (squares) and for (a) the annual mean in both hemispheres, (b) each season for the Southern Hemisphere, and (c) each season for the Northern Hemisphere. The Pearson correlation and slope of the linear relationship (and its standard error) are included in the legends. JJA is not shown for Northern Hemisphere since the Hadley cell is poorly defined for this season. All correlations shown are significant at the 95% significance level except Northern Hemisphere SON. The best fit linear relationships are shown by the dashed lines in (a).

model mean static stability increase is larger in the Southern Hemisphere (4.0 K) compared to the Northern Hemisphere (3.1 K) and the Southern Hemisphere Hadley cell extent is more sensitive to static stability increases compared to the Northern Hemisphere ($0.46 \pm 0.08°$/K versus $0.28 \pm 0.08°$/K). Both of these factors contribute to the larger annual mean multimodel mean Hadley cell expansion in the Southern Hemisphere.

For individual seasons (Figures 4b and 4c) there is a clear relationship between C_{st} and Ψ_{500} except for Northern Hemisphere autumn (SON) when the correlation $r = 0.33$ is not significant at the 95% level. In the Southern Hemisphere, the multimodel mean C_{st} increase is roughly constant across seasons, while in the Northern Hemisphere, DJF and MAM have smaller static stability increases compared to SON. This is consistent with the largest multimodel mean Hadley cell expansion in the Northern Hemisphere occurring during SON (Figures 1 and S1). However, as mentioned above, the connection between C_{st} and Ψ_{500} is relatively weak for Northern Hemisphere SON. This raises the question of whether other factors may control the Hadley cell extent during this season. Indeed, SON is the season with strongest poleward shift of the eddy-driven jet in both the Atlantic and Pacific (Grise & Polvani, 2014; Simpson et al., 2014). We find that SON is the season with largest correlation ($r = 0.58$) between the Northern Hemisphere Ψ_{500} and eddy-driven jet latitude (U700) responses in the abrupt4xCO2 experiment. This suggests that part of the seasonal cycle of Hadley cell expansion in the Northern Hemisphere may be due to the differing connections with the eddy-driven jet throughout the seasonal cycle and differing multimodel mean Northern Hemisphere eddy-driven jet responses in different seasons.

In the Northern Hemisphere, there is a substantial seasonal cycle in static stability in the multimodel mean: it is 3.0, 2.9, and 2.8 K in DJF, MAM, and JJA, respectively, but 3.6 K in SON. Since the larger static stability increases in Northern Hemisphere SON are part of the reason for the greater Hadley cell expansion in that season compared to others, it is interesting to speculate as to why they are larger. Comparing the surface warming between winter/spring and summer/fall seasons (Figure S3), it is apparent that there is more warming in the subtropical and midlatitude Northern Hemisphere oceans in summer/fall (cf. the North Pacific warming). Quantitatively, the zonal mean SST averaged between 25°N and 50°N warms in the multimodel mean by 3.7 and 3.8 K in DJF and MAM but by 4.4 K in SON. The amount of surface warming is directly tied to the change in static stability aloft: Across the models, the change in surface temperature and C_{st} has a correlation of $r = 0.89$ in SON (and the smallest correlation is $r = 0.68$ during MAM and DJF). Thus, we believe that the amplified surface warming in the subtropical and midlatitude oceans during SON is part of the reason for the increased static stability and hence Hadley cell expansion during this season. This is consistent with recent work showing a dominant impact of subtropical and midlatitude warming on driving the poleward expansion of the Hadley cell edge and the eddy-driven jet in an aquaplanet model (Shaw & Tan, 2018). We speculate that the larger surface warming during SON may be due to the shallower mixed-layer depth in the midlatitude oceans during summer and fall (e.g., Alexander et al., 2018; Hartmann, 2016), but further work would be needed to confirm this.

4. Conclusions

This study demonstrates that there is a strong asymmetry between the hemispheres in the simulated response of the Hadley cell edge to increased greenhouse gas concentrations. This asymmetry is present in boreal winter, spring, and in the annual mean and is highly robust across models. In the multimodel mean, the expansion is about twice as large in the Southern Hemisphere during DJF and in the annual mean, and about 5 times as large during MAM (Figure 1), although the quantitative degree of asymmetry does vary across models (Figure S2). To understand the cause of this asymmetry, we consider various sources of interhemispheric differences under global warming. Arctic amplification is not likely to be responsible since the large difference between spring and autumn expansion in the Northern Hemisphere occurs despite similar magnitudes of Arctic warming (Figure 2). By comparing the Hadley cell expansion between experiments forced by a globally uniform SST warming and by a spatially varying SST pattern, it is shown that diminished warming in the Southern Ocean partially contributes to the larger expansion in the Southern Hemisphere in austral summer and spring, and the pattern of SST warming decreases Northern Hemisphere expansion in boreal spring and the annual mean (Figure 3). The direct CO_2 radiative also somewhat contributes to the greater Southern Hemisphere expansion in these seasons. However, even with a uniform warming pattern, there is still more expansion in the Southern Hemisphere. By computing changes in the static stability in each hemisphere, we find that (1) Northern Hemisphere static stability changes are greatest in SON and (2) the Northern Hemisphere Hadley cell edge is less sensitive to changes in static stability than the Southern Hemisphere.

In the historical record, the largest expansion of the Hadley cell has been in the Southern Hemisphere summer and fall and Northern Hemisphere fall (Grise et al., 2018, 2019). Given that the impacts of ozone depletion onto the Hadley cell edge are maximized in summer, it is typically thought that the ozone hole is the reason for the larger observed expansion in the Southern Hemisphere in that season. On the other hand, natural variability of SSTs (specifically, the Pacific Decadal Oscillation) has driven part of the Northern Hemisphere expansion (Allen et al., 2014; Grassi et al., 2012, 2018). However, this study indicates that even under only greenhouse gas forcing, we would expect a larger expansion in the Southern Hemisphere compared to the Northern Hemisphere in all seasons except boreal autumn. This has important implications for disentangling the effects of greenhouse gas emissions, ozone depletion, and natural SST variability onto the Hadley cell. In the Northern Hemisphere, the largest observed Hadley cell expansion has occurred in fall (Grise et al., 2018) and this is consistent with the results found in this study that SON is most sensitive to greenhouse gas increases in the Northern Hemisphere.

The fivefold difference between Northern Hemisphere Hadley cell expansion in spring and autumn (Figure 1) is surprising given one might naively expect similar responses in the two equinoctial seasons. Future work will focus on why the multimodel mean response to greenhouse gas forcing is different between these seasons, even with the same SST forcing (Figure 3). Intriguingly, the climatological extent of the Northern Hemisphere Hadley cell in the preindustrial control simulations is at its extremes in these seasons: most equatorward for MAM and most poleward for SON (Figure 1). The relevance of this for the differing connections between the Hadley cell edge and the eddy-driven jet in these two seasons would be a worthwhile avenue of future work. Furthermore, although we have focused on Hadley cell expansion in this study, a measure of the zonally symmetric overturning circulation, the atmosphere has strong zonal asymmetries in the Northern Hemisphere. Previous work has shown distinct expansions of the subtropics in the North Pacific and North Atlantic sectors (Grise et al., 2018) as well as different responses of the storm tracks in each ocean basin (Simpson et al., 2014). Future work will examine the longitudinally dependent expansion in the simulations studied in this paper.

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Erratum

In the originally published version of this article, the author affiliation "Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA" was incorrectly published as "Department of Atmospheric Sciences, University of Washington, Washington, DC, USA." This error has since been corrected, and the present version may be considered the authoritative version of record.