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Is climate sensitivity related to dynamical sensitivity? A Southern Hemisphere perspective

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Key Points:
- Hadley cell expansion is strongly linked to climate sensitivity in all seasons
- Poleward dry zone and jet shift are not linked to climate sensitivity in winter
- Climate sensitivity does not explain all dynamical responses to CO_2 forcing

Supporting Information:
- Readme
- Table S1
- Table S2
- Table S3
- Figure S1
- Figure S2
- Figure S3

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Abstract This study examines whether the spread in the climate sensitivity of Coupled Model Intercomparison Project Phase 5 (CMIP5) models also captures the spread in the Southern Hemisphere dynamical response to greenhouse gas forcing. Three metrics are proposed to quantify the "dynamical sensitivity" of the Southern Hemisphere: the poleward expansion of the Hadley circulation, the poleward expansion of the subtropical dry zone, and the poleward shift of the midlatitude jet. In the CMIP5 abrupt $4 \times CO_2$ integrations, the expansion of the Hadley circulation is well correlated with climate sensitivity in all seasons; in contrast, the shifts in the subtropical dry zone and midlatitude jet are significantly correlated with climate sensitivity only in summer and fall. In winter, those responses are more strongly linked to the control climatology in each model. Thus, a narrow focus on traditional climate sensitivity alone might miss out on important features of the atmospheric circulation's response to increasing greenhouse gases, particularly in the extratropics.

1. Introduction

The response of Earth's climate to increased concentrations of atmospheric carbon dioxide (CO_2) is commonly characterized in terms of the climate sensitivity. Climate sensitivity (or, more precisely, equilibrium climate sensitivity) is defined as the steady state global mean surface temperature response to doubled atmospheric CO_2 [e.g., *Knutti and Hegerl*, 2008]. The value of climate sensitivity in the latest generation of global climate models, those that participated in Phase 5 of the Coupled Model Intercomparison Project (CMIP5), ranges from 2.1 K to 4.7 K [*Andrews et al.*, 2012; *Forster et al.*, 2013].

Climate sensitivity is often viewed as a "magic number" that captures all key aspects of a climate model's response to CO_2 forcing [*Knutti and Hegerl*, 2008]; as a consequence, much effort has been placed in narrowing the range in climate sensitivity across models. Yet it is now widely appreciated that the atmospheric circulation also changes substantially when CO_2 is increased and that the spread in the circulation response across different global climate models is also large. For example, in enhanced CO_2 scenarios, climate models indicate a poleward expansion of the Hadley circulation and the subtropical dry zones in both the Northern Hemisphere (NH) and Southern Hemisphere (SH) [*Lu et al.*, 2007; *Hu et al.*, 2013] and a poleward shift in the midlatitude eddy-driven jet in each hemisphere (most prominently in the SH) [*Kushner et al.*, 2001; *Barnes and Polvani*, 2013]. We term these circulation changes "dynamical sensitivity" and note that they are not uniform across seasons, hemispheres, or models [*Hu et al.*, 2013; *Barnes and Polvani*, 2013]. In our view, understanding the spread in this dynamical sensitivity may be more important for societal impacts than understanding the spread in global mean surface temperature.

The central question of this study, therefore, is whether the spread in dynamical sensitivity across CMIP5 models is captured by the spread in climate sensitivity. To our knowledge, a rigorous comparison between climate sensitivity and dynamical sensitivity has not been reported in the literature. One might naively assume that in a model with greater climate sensitivity, the atmospheric circulation might shift farther poleward for a given CO_2 forcing. But as we show below, the answer is not so simple, as we find strong seasonality to the relationship between dynamical sensitivity and climate sensitivity.

In this paper, we focus exclusively on the SH, where the atmospheric circulation is approximately zonally symmetric and where the results have a relatively straightforward interpretation. In a subsequent paper, we will address the dynamical sensitivity of the NH, which requires an in-depth discussion of zonally asymmetric dynamics.

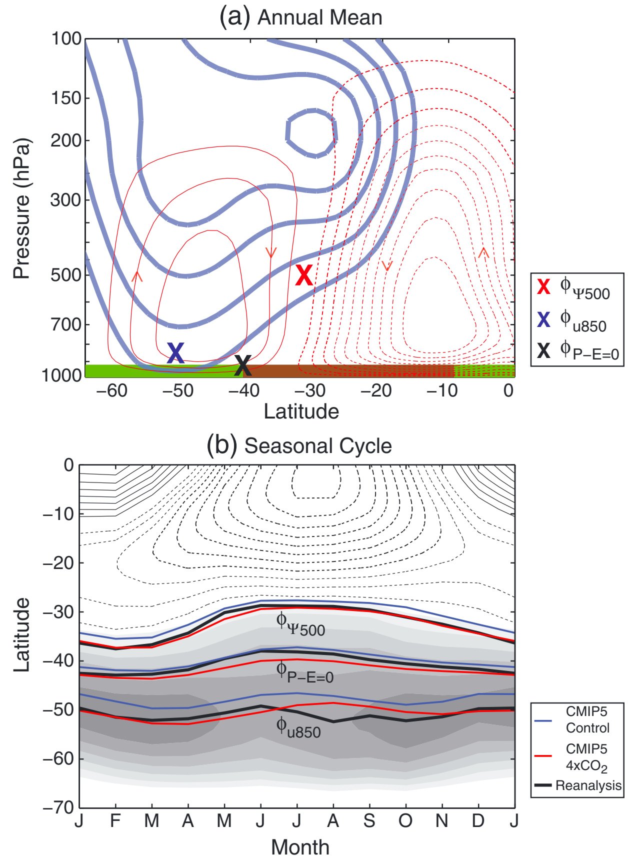

Figure 1. The 1979–2012 ERA-Interim reanalysis zonal mean climatology: (a) annual mean and (b) monthly mean. In Figure 1a, thick blue lines denote zonal mean zonal wind (contour interval: 5 m s^{-1} for values ≥10 m s^{-1}), and thin red lines denote mean meridional mass stream function (contour interval: 1.0 × 10^{10} kg s^{-1}; negative contours dashed; zero contour omitted). Regions where zonal mean precipitation is greater (less) than zonal mean evaporation are shaded in green (brown). In Figure 1b, gray shading denotes 850 hPa zonal mean zonal wind (contour interval: 2 m s^{-1} for values ≥2 m s^{-1}), and thin black lines denote 500 hPa mean meridional mass stream function (contour interval: 2.0 × 10^{10} kg s^{-1}; negative contours dashed; zero contour omitted). The locations of ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi500}$ are indicated for ERA-Interim reanalysis (thick black line), the multimodel mean CMIP5 preindustrial control climatology (blue), and the multimodel mean CMIP5 4 × CO_2 climatology (red).

2. Methodology

The primary data used in this study are the output from the global climate models that participated in CMIP5 [*Taylor et al.*, 2012]. Here we use data from the 23 models that have values of equilibrium climate sensitivity defined in the literature (Table S1 in the supporting information) [*Andrews et al.*, 2012; *Forster et al.*, 2013]. We analyze two different forcing scenarios from each of the models: (1) preindustrial control (hundreds of years of unforced variability) and (2) abrupt 4 × CO_2 (in which atmospheric CO_2 is instantaneously quadrupled at the beginning of a 150 year run). For each scenario, we use the first ensemble member (r1i1p1) from each model, as most models only have one ensemble member available for these experiments. We use all available years from each preindustrial control run and, to capture the best available estimate of the equilibrated 4 × CO_2 climate, only the last 50 years from each abrupt 4 × CO_2 run.

We use the abrupt 4 × CO_2 scenario instead of the Representative Concentration Pathway (RCP) scenarios for three key reasons. First, the abrupt 4 × CO_2 runs are exactly those that have been used to calculate climate sensitivity in earlier studies [*Andrews et al.*, 2012; *Forster et al.*, 2013]. Second, CO_2 is the only forcing in these runs: This is important for yielding unambiguous results (in RCP scenarios, different forcings have trends of different magnitudes over different periods). Third, the forcing in the 4 × CO_2 runs is substantially larger, and therefore produces a much clearer signal of dynamical sensitivity, than in the RCP runs.

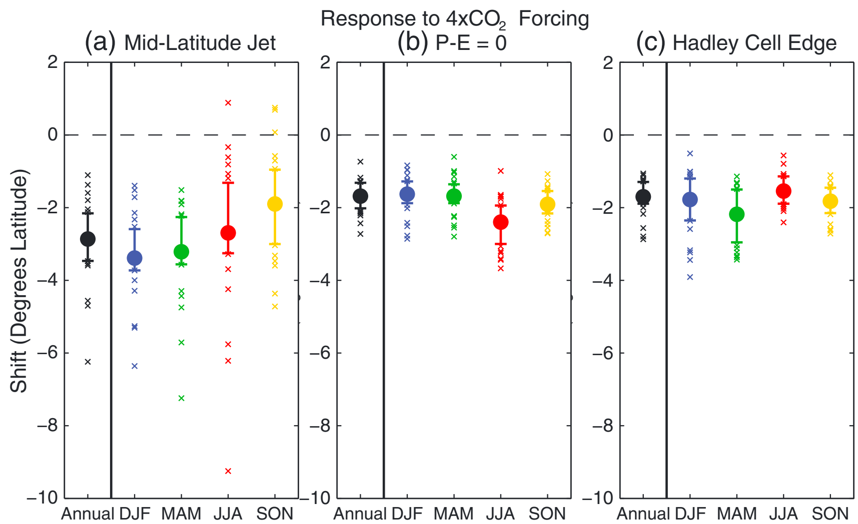

Figure 2. Magnitude of the shift in the SH (a) midlatitude jet (ϕ_{u850}), (b) subtropical dry zone ($\phi_{P-E=0}$), and (c) Hadley cell edge ($\phi_{\Psi 500}$) in response to $4\times CO_2$ forcing in the 23 CMIP5 models listed in Table S1. For each season, circles denote the multimodel mean, bars denote the range of the 25th–75th percentiles, and each cross denotes outliers about the 25th–75th percentiles.

We define the dynamical sensitivity of the SH using three simple metrics, illustrated in Figure 1a, where the SH annual mean, zonal mean circulation is plotted using the 1979–2012 ERA-Interim reanalysis climatology [*Dee et al.*, 2011]:

1. *The location of the midlatitude eddy-driven jet* (ϕ_{u850}). We define ϕ_{u850} as the latitude where the zonal mean, zonal wind field (Figure 1a, thick blue lines) reaches its maximum at 850 hPa. The 850 hPa level is chosen to effectively capture the location of the eddy-driven jet, while avoiding most topography and possible contamination from the upper tropospheric (angular momentum conserving) jet in the subtropics.
2. *The poleward edge of the subtropical dry zone* ($\phi_{PE=0}$). We define $\phi_{P-E=0}$ as the latitude where the zonal mean precipitation minus evaporation crosses zero poleward of its subtropical minimum (Figure 1a, brown zone).
3. *The poleward edge of the subtropical dry zone* ($\phi_{PE=0}$). We define $\phi_{\Psi 500}$ as the latitude where the 500 hPa mean meridional mass stream function (Figure 1a, thin red lines) crosses zero poleward of its tropical minimum.

Each latitude is found using a polynomial fit to the model data at a resolution of 0.01° [see *Barnes and Polvani*, 2013].

It is important to keep in mind that the annual mean picture (Figure 1a) masks rich seasonality in the SH zonal mean circulation, as shown in Figure 1b. The SH branch of the Hadley circulation is much weaker during summer yet extends ~8° farther poleward (Figure 1b, dashed lines). In contrast, the 850 hPa midlatitude jet is more sharply defined during summer but possesses little seasonality in its latitudinal location (Figure 1b, shading). Consequently, ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi 500}$ are more widely separated in winter than in summer.

Although Figure 1 was constructed from reanalysis data, qualitatively similar figures can be constructed from the multimodel mean CMIP5 preindustrial control and $4\times CO_2$ climatologies (see Figure S1). For clarity, the seasonal cycles of ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi 500}$ from the preindustrial control (blue) and $4\times CO_2$ (red) climates are plotted in Figure 1b. We have plotted these lines on the same figure as the reanalysis (black) to indicate that the CMIP5 models, in both preindustrial control and $4\times CO_2$ climates, have similar large-scale structure in their SH circulation as the observed climate, such that the three metrics defined above are appropriate for the model climates. Needless to say, the values from the models and reanalysis should not be compared quantitatively, as they correspond to different climates.

3. Results

Contrasting the blue and red lines in Figure 1b, it is clear that in the multimodel mean, the CMIP5 models indicate a poleward shift in the SH midlatitude jet, subtropical dry zone, and Hadley cell edge—in all seasons—in response to $4\times CO_2$ forcing. Yet the multimodel mean masks large intermodel variability. Figure 2 shows the responses of ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi 500}$ to the $4\times CO_2$ forcing in each of the 23 CMIP5 models used in this study.

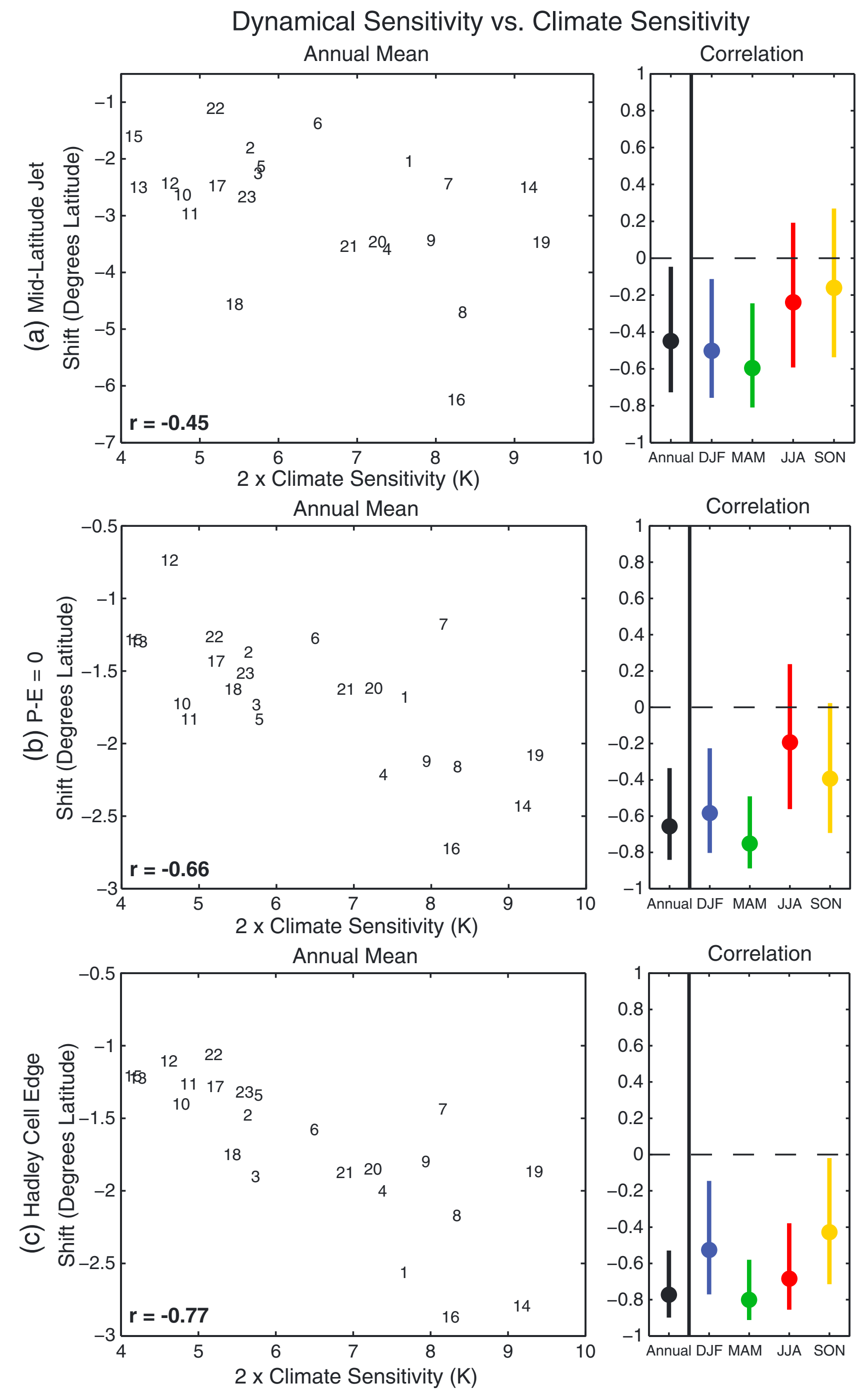

Figure 3. (left column) Scatterplots of the annual mean metrics of dynamical sensitivity (as shown in Figure 2) with twice the equilibrium climate sensitivity of each model. The numbers correspond to the CMIP5 models listed in Table S1. (right column) Correlations between the metrics of dynamical sensitivity and climate sensitivity for the annual mean and the four seasonal means. Error bars denote 95% confidence bounds on the correlation coefficients.

There is relatively little seasonality in the responses of $\phi_{P-E=0}$ and $\phi_{\Psi 500}$ to the $4 \times CO_2$ forcing, with most models clustering tightly around a poleward shift of ~2° latitude (Figures 2b and 2c). In contrast, the magnitude of the response of ϕ_{u850} (Figure 2a) is widely scattered across models, with the most robust poleward shifts occurring during December–February (DJF) and March–May (MAM). The magnitudes of the responses shown in Figure 2 are larger than those found in the RCP scenarios, but the seasonality of the responses is similar [*Barnes and Polvani*, 2013; *Hu et al.*, 2013].

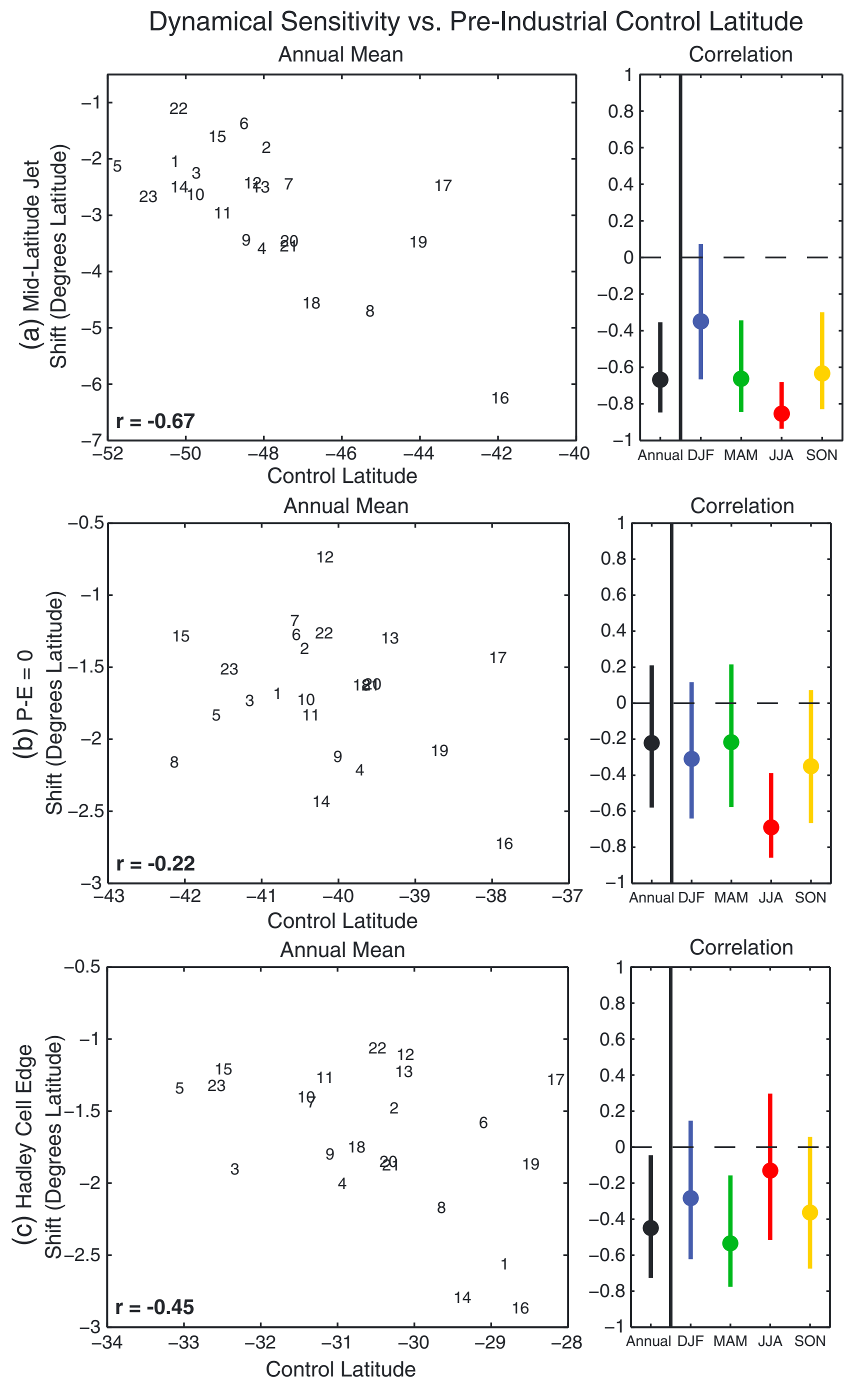

Figure 4. As in Figure 3 but for correlations of the dynamical sensitivity metrics with the associated preindustrial control latitude in each model.

We now come to the central question of this study: That is, whether the spread in the dynamical sensitivity of CMIP5 models (as shown in Figure 2) can be explained by the spread in climate sensitivity. Figure 3 presents correlations of the climate sensitivity with the responses of ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi500}$ to the $4\times CO_2$ forcing in each model. In this figure, we use twice the equilibrium climate sensitivity values computed by *Andrews et al*. [2012] and *Forster et al*. [2013] (reproduced here in Table S1 for completeness), such that both the dynamical sensitivity and climate sensitivity values correspond to a $4\times CO_2$ climate. The spread in climate sensitivity across models can also be approximated using a much simpler method: i.e., the global mean surface temperature difference between each preindustrial control run and the last 50 years of the corresponding abrupt $4 \times CO_2$ run (these values are correlated with equilibrium climate sensitivity at $r = 0.95$; see Tables S1 and S2 and Figure S2).

In the annual mean, the poleward shifts in SH ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi500}$ are significantly correlated with climate sensitivity. However, while the shift in $\phi_{\Psi500}$ is significantly correlated with the climate sensitivity during all seasons (Figure 3c), the shifts in ϕ_{u850} and $\phi_{P-E=0}$ are only significantly correlated with climate sensitivity during DJF and MAM (Figures 3a and 3b). It is perhaps not surprising that a consistent relationship is found between climate sensitivity and the width of the Hadley circulation during all months. Variability in $\phi_{\Psi500}$ is linked to tropical mean temperatures [e.g., *Lu et al.*, 2008], and because the tropics cover approximately half the surface area of the globe, the tropical mean surface temperature response to CO_2 forcing is very strongly correlated with climate sensitivity (see Table S2). More interesting though is the relative decoupling of the ϕ_{u850} and $\phi_{P-E=0}$ responses from climate sensitivity during June–August (JJA) and September–November (SON) (Figures 3a and 3b).

Previous studies have noted strong linkages between ϕ_{u850} and $\phi_{\Psi500}$ in DJF, both in terms of their interannual variability and their responses to CO_2 forcing [*Lu et al.*, 2008; *Kang and Polvani*, 2011] (see also Figure S3 where correlations among our three metrics are reported). During JJA and SON, the poleward boundary of the Hadley circulation—and the subtropical angular momentum-conserving jet—is more separated from the midlatitude eddy-driven jet in the climatology (see Figure 1b), so the behavior of ϕ_{u850} and $\phi_{\Psi500}$ is less correlated during these seasons. Likewise, as $\phi_{P-E=0}$ is more separated from both ϕ_{u850} and $\phi_{\Psi500}$ during JJA and SON (Figure 1b), the $\phi_{P-E=0}$ response to CO_2 forcing is also less correlated with the responses of ϕ_{u850} and $\phi_{\Psi500}$ during these seasons (Figure S3). Consequently, because the poleward shift in the SH Hadley circulation is significantly correlated with climate sensitivity during all seasons, the poleward shifts in the SH subtropical dry zone and midlatitude jet are strongly linked to climate sensitivity during seasons (DJF and MAM) when the SH extratropical and tropical circulations are tightly coupled in the climatology (Figure 1b).

Since extratropical dynamical sensitivity appears to be largely unrelated to climate sensitivity in JJA and SON, it is natural to ask what additional factors might control the spread in dynamical sensitivity during these seasons. Previous studies have shown that climate models with an equatorward bias in the position of their climatological midlatitude jet tend to shift their jet farther poleward under enhanced CO_2 forcing [e.g., *Kidston and Gerber*, 2010]. In Figure 4a, we plot the correlations of the preindustrial control value of ϕ_{u850} from each model with the corresponding ϕ_{u850} response to the $4 \times CO_2$ forcing and confirm the relationship reported in previous studies. During certain seasons, we also find significant relationships between the preindustrial control values of $\phi_{P-E=0}$ and $\phi_{\Psi500}$ and their responses to $4 \times CO_2$ forcing (Figures 4b and 4c). The preindustrial control values of ϕ_{u850}, $\phi_{P-E=0}$, and $\phi_{\Psi500}$ are not entirely uncorrelated with climate sensitivity (and thus could influence the results in Figure 3), but we find the correlations for ϕ_{u850} and $\phi_{P-E=0}$ to be weak and statistically insignificant (see Table S3).

Note finally that the seasonality of the correlations in Figure 4 is distinctly different from that shown in Figure 3. Intriguingly, for ϕ_{u850} and $\phi_{P-E=0}$, the correlations between the preindustrial control value and the $4 \times CO_2$ response are most negative during JJA, exactly when the correlations with climate sensitivity are weak (Figures 3a and 3b). *Kidston and Gerber* [2010] found a similar seasonality for the SH midlatitude jet in their Table 1, and concluded that the seasonality was related to the ozone forcing used in CMIP Phase 3 models. Given that CO_2 is the only forcing in the model experiments used here, it seems more likely that the seasonality of the correlations in Figure 4 reflects the decoupling of the tropical and extratropical circulations during SH winter months (Figure 1b).

4. Conclusions

Our analysis of the abrupt $4 \times CO_2$ scenarios in 23 different CMIP5 models reveals that the spread in climate sensitivity across models is closely linked to the spread in the poleward expansion of the SH Hadley circulation under CO_2 forcing. The key finding of this study, however, is that climate sensitivity is only significantly correlated with circulation metrics at higher latitudes during select seasons (DJF and MAM). During other seasons, the shifts of the midlatitude eddy-driven jet and the SH subtropical dry zone edge in response to CO_2 forcing are still substantial (Figure 2) but are found to be largely uncorrelated with climate sensitivity. Consequently, while climate sensitivity can capture many aspects of a climate model's response to CO_2

forcing, it is not a "silver bullet" that can adequately capture all aspects of SH circulation changes, particularly in the extratropics. The spread among the preindustrial control climates of CMIP5 models seems to explain some additional features of SH dynamical sensitivity not captured by the climate sensitivity. Additionally, the meridional structure of each model's surface temperature response to CO_2 forcing likely contributes to the spread of dynamical sensitivity [*Chen et al*., 2010; *Lu et al*., 2010]. However, further work is needed to fully understand the spread in SH dynamical sensitivity in CMIP5 models, particularly during those seasons when it is poorly correlated with climate sensitivity.

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