AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061638

Key Points:
- NH circulation does not shift robustly poleward in response to increasing CO_2
- Direct radiative forcing of CO_2 causes poleward jet shift in each hemisphere
- SSTs dominate and cause NH asymmetric extratropical circulation response

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

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Citation:
Grise, K. M., and L. M. Polvani (2014), The response of midlatitude jets to increased CO_2: Distinguishing the roles of sea surface temperature and direct radiative forcing, *Geophys. Res. Lett.*, *41*, 6863–6871, doi:10.1002/2014GL061638.

Received 25 AUG 2014
Accepted 12 SEP 2014
Accepted article online 15 SEP 2014
Published online 3 OCT 2014

The response of midlatitude jets to increased CO_2: Distinguishing the roles of sea surface temperature and direct radiative forcing

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Abstract In Coupled Model Intercomparison Project Phase 5 (CMIP5) models, the zonal-mean tropospheric circulation shifts robustly poleward in the Southern Hemisphere extratropics in response to increased atmospheric CO_2 concentrations. However, in the Northern Hemisphere (NH) extratropics, the circulation response to CO_2 is largely absent in the zonal mean and is instead characterized by complex regional anomalies. This study decomposes the atmospheric circulation response to CO_2 forcing in CMIP5 models into two components: a direct component due to CO_2 radiative forcing and an indirect component associated with sea surface temperature (SST)-mediated changes. The direct radiative forcing of CO_2 drives a weak poleward jet shift in both hemispheres, whereas the indirect (SST) component of the CO_2 forcing dominates the total response and drives a zonally asymmetric response in the NH. Hence, understanding the SST-mediated component of atmospheric CO_2 forcing appears crucial to unlocking the mechanisms that contribute to forced extratropical circulation changes.

1. Introduction

It is widely reported that the midlatitude eddy-driven jet will shift poleward in both the Northern Hemisphere (NH) and Southern Hemisphere (SH) in response to increasing atmospheric greenhouse gas concentrations [e.g., *Yin,* 2005; *Lorenz and DeWeaver*, 2007; *Barnes and Polvani*, 2013]. In aquaplanet model experiments, the jet responses are, by construction, symmetric between the hemispheres [*Chen et al.,* 2010; *Lu et al.*, 2010], but in more realistic climate model simulations, the poleward shift of the SH jet is more robust [e.g., *Kushner et al.*, 2001]. In fact, in the recent assessment report of the Intergovernmental Panel on Climate Change, the zonal-mean zonal wind response projected over the 21st century by the latest generation of global climate models (those from phase 5 of the Coupled Model Intercomparison Project (CMIP5)) is shown to be statistically significant in the SH troposphere, but not in the NH troposphere [cf. *Collins et al.*, 2014, Figure 12.19] (see also Figure 1 (top left)). Hence, the NH extratropical circulation response is not zonally symmetric and cannot simply be described as a "poleward jet shift."

Simpson et al. [2014] (hereafter S14) have recently examined the NH extratropical circulation response projected over the 21st century by CMIP5 models and found that a poleward shift of the lower tropospheric zonal winds only occurs at certain longitudes and during certain seasons. During other seasons, the circulation response does not fit the paradigm of a poleward jet shift, particularly over the Atlantic and eastern Pacific basins during winter (see also *Harvey et al.* [2012] and *Cattiaux and Cassou* [2013] for CMIP5 models; see *Woollings and Blackburn* [2012] for CMIP3 models). However, a complicating factor in the interpretation of these studies is that they use 21st century forcings, the so-called Representative Concentration Pathway (RCP) scenarios for CMIP5. The RCP scenarios include many different forcings (not just increasing atmospheric CO_2 concentrations), not all of which are identical across all models or are monotonically increasing in time. Thus, it is conceivable that some of these additional forcings (e.g., aerosols and ozone) are contributing to the nearly nonexistent NH zonal-mean circulation response found in the RCP simulations.

In this study, we document the hemispheric asymmetries in the extratropical circulation response due to CO_2 alone (i.e., CO_2 is the only forcing considered here) and show that, although well mixed in the atmosphere, increasing CO_2 can drive very different circulation responses in the NH and SH. To understand the hemispheric asymmetries, we partition the CO_2-induced circulation response into a direct component associated with the

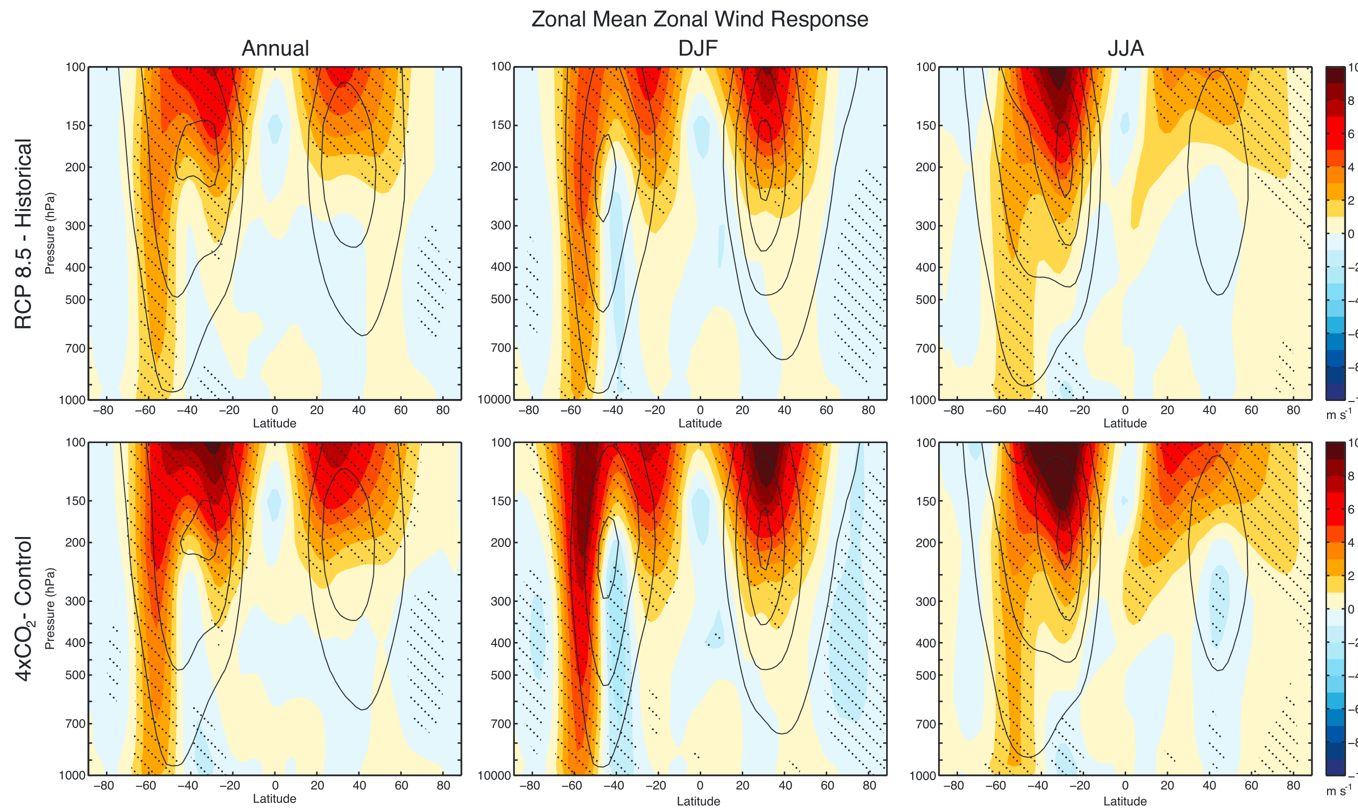

Figure 1. Multimodel-mean response of the zonal-mean zonal wind from 26 CMIP5 models (listed in Table S1) to climate change: (left column) annual-mean, (middle column) December–February (DJF) mean, and (right column) June–August (JJA) mean. (top row) The difference between the RCP 8.5 (2081–2100 average) and historical (1986–2005 average) runs; (bottom row) the difference between the abrupt 4xCO_2 (average of last 50 years) runs and the preindustrial control climatology. Thin contours denote the historical (top row) and preindustrial control climatology (bottom row) (contour interval: 10 m s^{-1}). Stippling indicates where the response is 95% statistically significant via Student's *t* test.

atmospheric radiative forcing of CO_2 and an indirect component associated with the accompanying sea surface temperature (SST) changes, as in *Deser and Phillips* [2009] and similar studies. We find that the direct atmospheric radiative forcing of CO_2 drives a small but consistent poleward shift of the midlatitude eddy-driven jet in *both* hemispheres, whereas the indirect forcing of the SSTs is responsible for the bulk of the asymmetries between the NH and SH circulation responses.

2. Methodology

The data used in this study are the monthly mean output from the global climate models that participated in CMIP5 [*Taylor et al.*, 2012], provided courtesy of the Program for Climate Model Diagnosis and Intercomparison at Lawrence Livermore National Laboratory. Here we use output from the 26 models (listed in Table S1 in the supporting information) with available runs from the following four scenarios: (1) preindustrial control (i.e., hundreds of years of unforced variability), (2) historical (driven by 1850–2005 forcings), (3) RCP 8.5 (projected forcings over 2006–2100, which reach a radiative forcing of 8.5 W m^{-2}, in excess of preindustrial levels, in 2100), and (4) abrupt 4xCO_2 (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. To estimate the response to 21st century forcings, we take the difference of the 1986–2005 mean from each historical run and the 2081–2100 mean from the corresponding RCP 8.5 run (exactly as in *Collins et al.* [2014]). To estimate the response to CO_2 forcing only, we take the difference of the preindustrial control climatology (of all available years) and the mean of the last 50 years of the corresponding abrupt 4xCO_2 run.

We separate the response to CO_2 forcing into two components: a direct component due to the atmospheric radiative effect of CO_2 and an indirect component associated with the corresponding SST changes. To accomplish

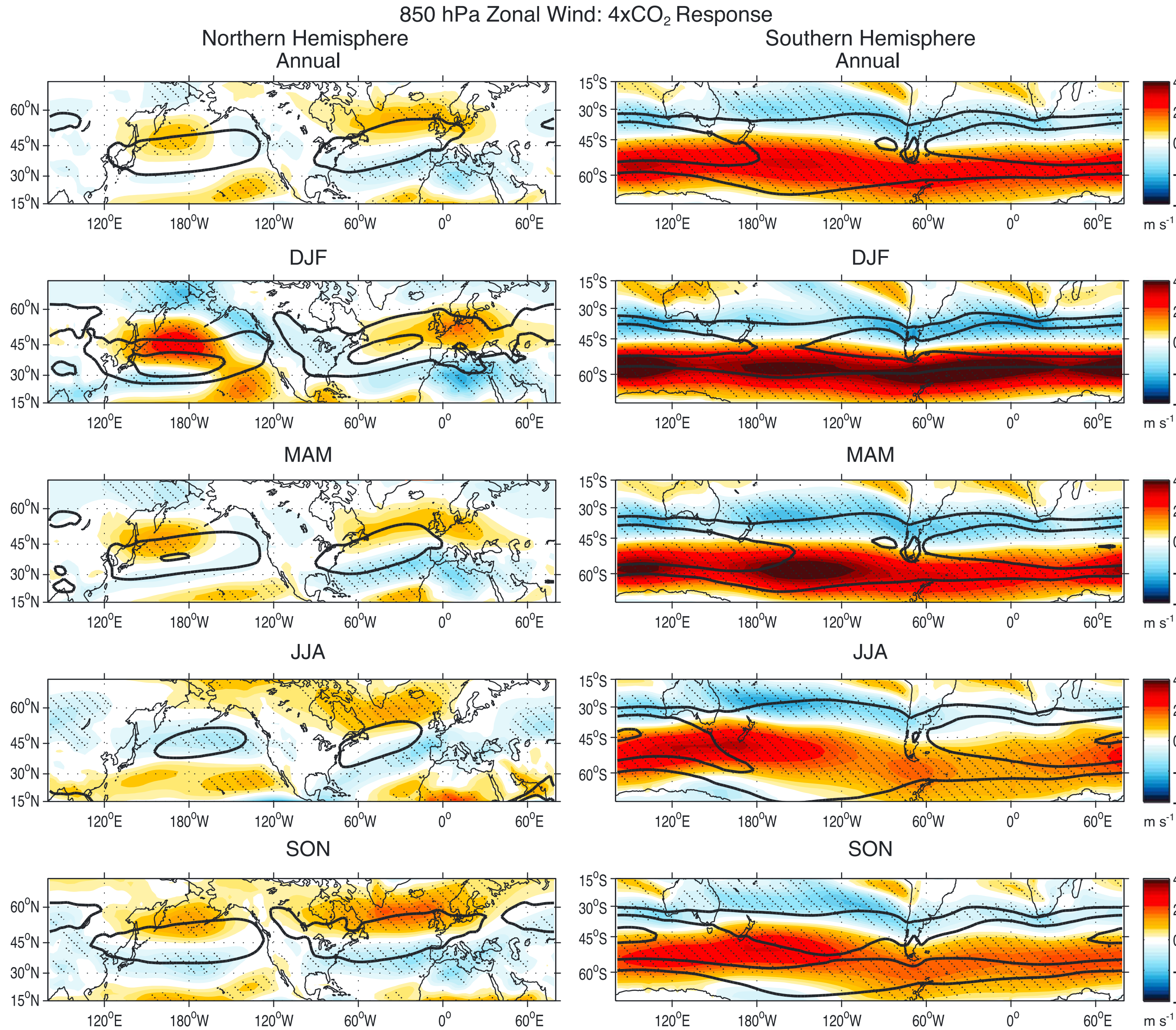

Figure 2. Multimodel-mean response of the 850 hPa zonal wind to $4xCO_2$ forcing for the indicated seasons. The response is calculated as the difference between the abrupt $4xCO_2$ (average of last 50 years) runs and the preindustrial control climatology from 26 CMIP5 models (Table S1). Thick contours denote the preindustrial control climatology (contour interval: 5 m s^{-1}). Stippling indicates where the response is 95% statistically significant via Student's *t* test.

this, we make use of three atmosphere-only (so-called Atmospheric Model Intercomparison Project or "AMIP" [*Gates et al.*, 1999]) experiments that are part of the CMIP5 archive: (1) amip (forced by observed time-varying 1979–2008 SSTs and sea ice concentrations and present-day atmospheric composition), (2) amip$4xCO_2$ (same SSTs and sea ice as amip, but with quadrupled atmospheric CO_2 concentrations), and (3) amipFuture (same CO_2 forcing and sea ice as amip, but with a patterned SST anomaly added to the amip SSTs). For the amipFuture experiment, the patterned SST anomaly (shown in Figure S1) is based on the CMIP3-multimodel-mean SST response to $4xCO_2$ but as mandated by the CMIP5 experimental design has been normalized so that the spatial response from each CMIP3 model is weighted equally and has the same global mean as a uniform 4 K warming (see http://cfmip.metoffice.com/CMIP5.html for further details). The three AMIP experiments are each 30 years in length and are available for 10 of the 26 models used in this study (see models denoted by asterisks in Table S1).

The direct component of the CO_2 response is estimated using the difference of the climatologies from the amip$4xCO_2$ and amip runs, whereas the indirect (i.e., SST) component of the CO_2 response is estimated using the difference of the climatologies from the amipFuture and amip runs. As discussed in *Deser and Phillips* [2009], the partitioning of the atmospheric circulation response to increased CO_2 into these direct and indirect components is a little artificial, as the prescribed SST changes are occurring in response to and in tandem with the direct atmospheric radiative forcing. Nevertheless, partitioning the atmospheric circulation response in this manner is an effective tool for unlocking the physical mechanisms involved.

3. Results

In Figure 1 (top row), we review the CMIP5-multimodel-mean zonal-mean zonal wind response to 21st century forcings (i.e., RCP 8.5−historical), as shown in Figure 12.19 of *Collins et al.* [2014]. The annual-mean response (Figure 1, top left) is characterized by the following: (1) a strengthening of the winds in the upper troposphere-lower stratosphere in both hemispheres (presumably in response to the increased equator-to-pole temperature gradient at these altitudes) and (2) a poleward shift in the SH midlatitude jet throughout the depth of the troposphere. As already mentioned, there is no *significant* zonal-mean zonal wind response at NH midlatitudes in the lower and midtroposphere. These three features largely occur irrespective of season (Figure 1, top middle and top right), but we note that a significant zonal-mean jet shift does occur in the NH midlatitude troposphere during autumn months [*Barnes and Polvani*, 2013; S14].

In Figure 1 (bottom row), we show the corresponding zonal-mean zonal wind response to 4xCO_2 forcing. The responses to the 21st century and 4xCO_2 forcings are remarkably similar (compare top and bottom rows of Figure 1), with the amplitude of the 4xCO_2 response being slightly larger (as could be expected from the stronger, more idealized nature of that forcing). One notable distinction between the responses occurs in SH summer. During this season, the recovery of the Antarctic ozone hole over the 21st century substantially weakens the SH zonal-mean circulation response in the RCP 8.5 scenario (compare middle panels in Figure 1) [*Barnes et al.*, 2014], as it acts to reduce the equator-to-pole temperature gradient in the upper troposphere-lower stratosphere and shift the SH tropospheric jet equatorward (i.e., in direct opposition to the sign of the response expected from greenhouse gas increases; see also *Perlwitz et al.* [2008] and *Son et al.* [2008]). The ozone hole recovery effect is, by definition, not included in the idealized abrupt 4xCO_2 scenario (Figure 1, bottom row).

The results in Figure 1 clearly confirm that the zonal-mean zonal wind response to CO_2 forcing is not symmetric between the NH and SH. A robust zonal-mean midlatitude jet shift is apparent in the SH troposphere throughout the year, whereas the zonal-mean zonal wind at NH midlatitudes does not show a robust response in most seasons. However, because individual models have different climatological jet latitudes, one might hypothesize that averaging with respect to latitude across models may be the cause of the weak NH multimodel-mean response. So following *Barnes et al.* [2014], we have repeated our analysis by averaging with respect to the latitude of the jet in each model and have found nearly identical results (see Figure S2). Thus, to understand the results in Figure 1, one needs to turn attention to the longitudinal distribution of the response in each hemisphere.

Figure 2 shows the CMIP5-multimodel-mean response of the 850 hPa zonal wind to 4xCO_2 forcing, for the annual mean and all four seasons. In the SH (Figure 2, right column), a strong, robust poleward shift of the midlatitude jet is present during all seasons at nearly all longitudes, thus confirming the zonal-mean signal shown in Figure 1 (bottom row). In contrast, in the NH (Figure 2, left column), the bulk of the zonal wind response is centered over the Pacific and Atlantic basins, where the climatological wind maxima are located (black contours in Figure 2). In the Atlantic basin, the midlatitude jet shifts poleward in all seasons but December–February (DJF), when the response is instead confined to the jet exit region [*Harvey et al.*, 2012; S14]. In the Pacific basin, the midlatitude jet only shifts robustly poleward in one season (September–November (SON)), and the zonal wind response is characterized by a quadrapole structure in DJF and a weakening of the jet in June–August (JJA).

The patterns shown in Figure 2 compare well with those shown in S14, but the results here illustrate that these asymmetric patterns are driven by CO_2 forcing alone (and not by the other forcings included in the RCP 8.5 scenario). As in Figure 1, we have checked that differences in the climatological jet latitudes among the models do not influence the results in Figure 2 (see Figure S3). Additionally, the results are not dependent on our choice of the 850 hPa level, as we find qualitatively similar patterns to those shown in Figure 2 at

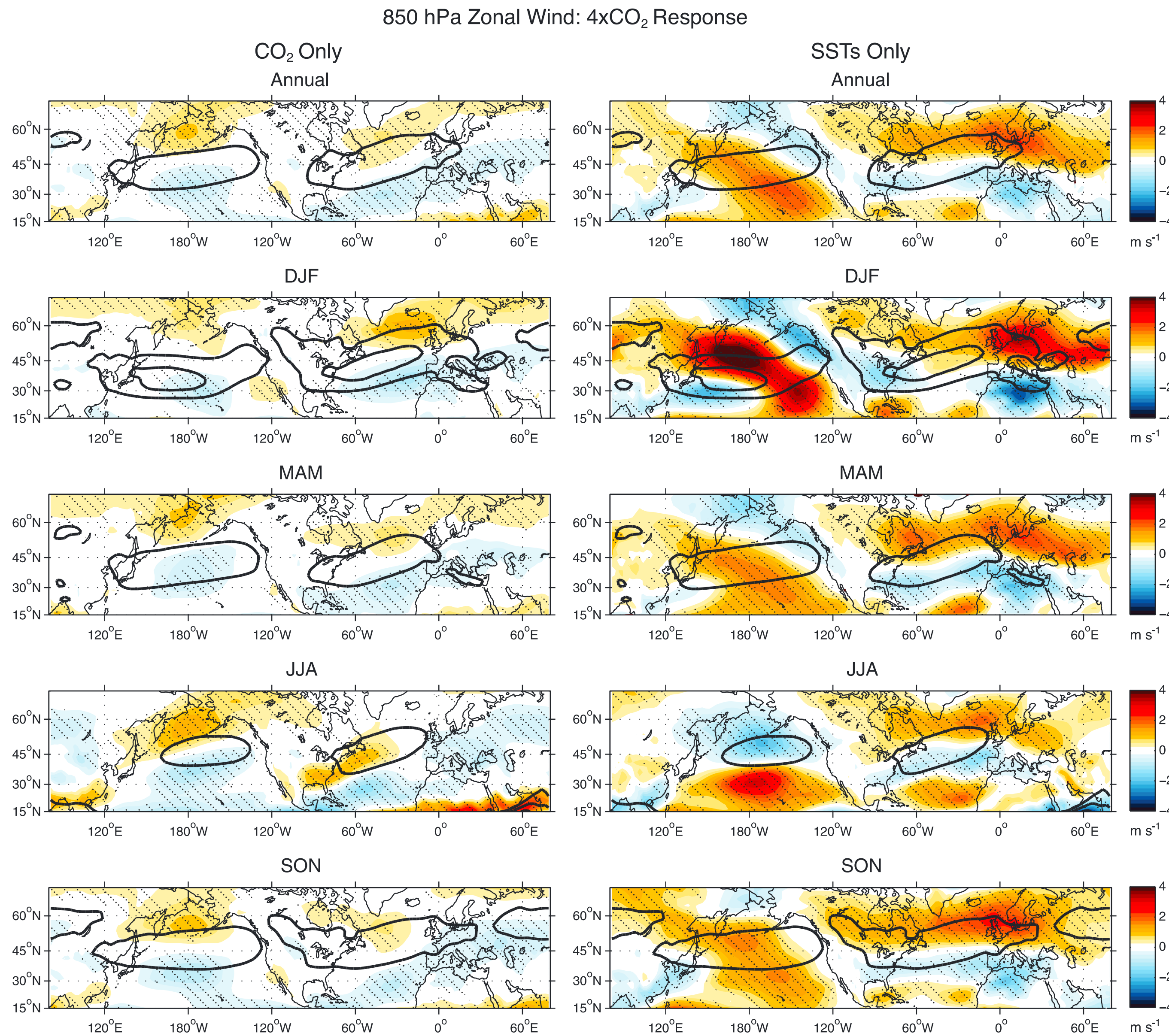

Figure 3. As in Figure 2 (left column) but for (left column) quadrupled atmospheric CO_2 concentrations with fixed sea surface temperatures (amip4xCO2−amip) and (right column) sea surface temperature increases in a $4xCO_2$ climate with fixed atmospheric CO_2 concentrations (amipFuture−amip). Results are calculated from 10 available CMIP5 models with these runs. Stippling indicates where eight or more of the models agree on the sign of the response.

different tropospheric levels (e.g., 500 hPa; not shown). Hence, given that the North Atlantic jet shifts poleward in most seasons in response to CO_2 forcing, the lack of a robust zonal-mean circulation response in the NH in Figure 1 seems to be directly tied to the behavior of the Pacific sector.

Having established that CO_2 forcing alone can drive very different circulation responses in the NH and SH, we now focus on whether it is the direct radiative forcing component of CO_2 or its indirect SST-mediated component that is responsible for the asymmetry between the hemispheres. Figures 3 and 4 show the decomposition of the 850 hPa zonal wind response from Figure 2 into these direct and indirect components, for the NH and SH, respectively. As noted in section 2, the results in Figures 3 and 4 are derived from only 10 of the 26 CMIP5 models that were used above.

The direct (atmospheric radiative forcing) component of the CO_2 response manifests itself as a relatively weak, but very clean, meridional dipole in zonal wind anomalies over nearly all ocean basins (Figures 3 and 4,

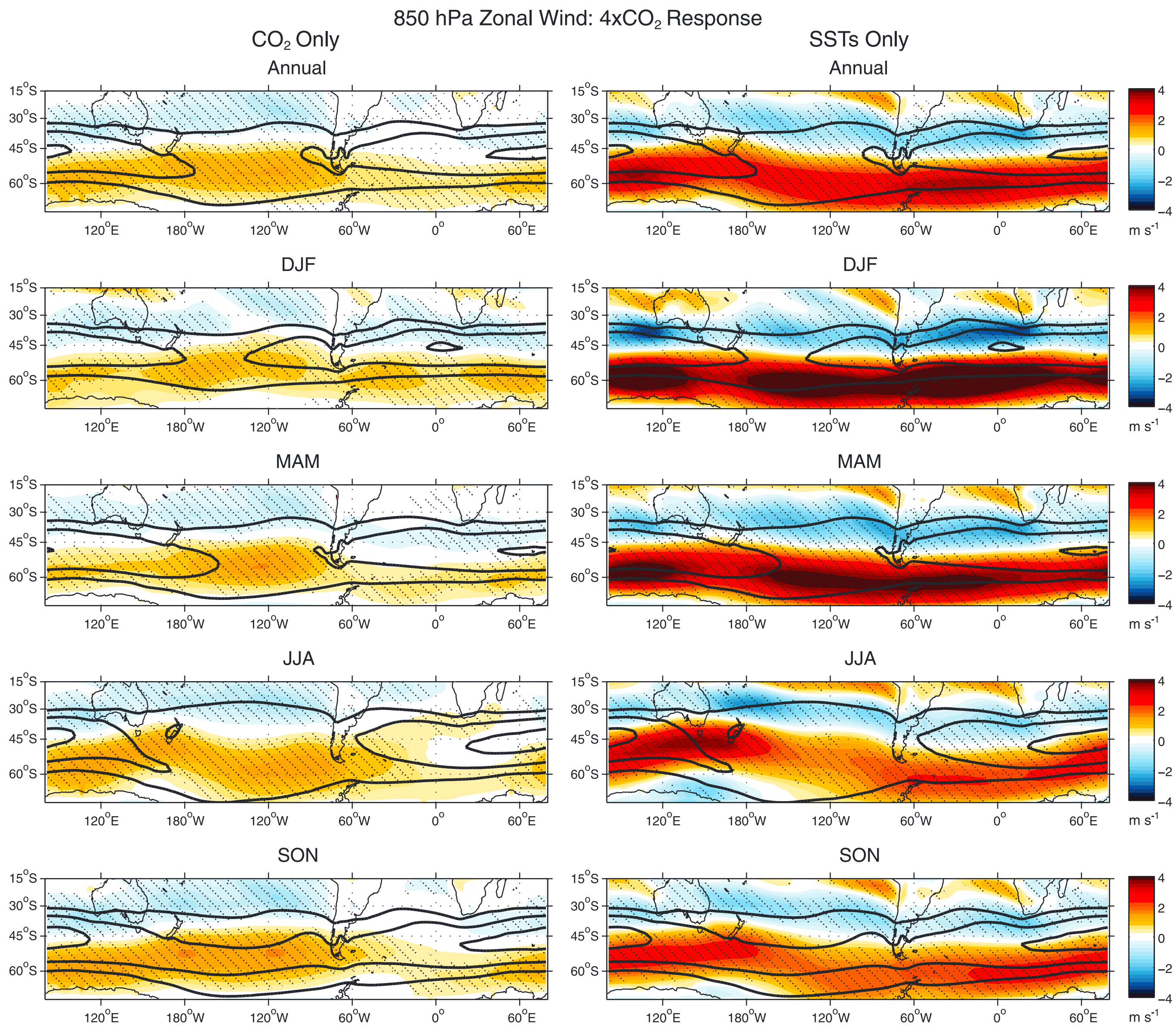

Figure 4. As in Figure 3 but for the Southern Hemisphere.

left columns). This dipole response contributes to a poleward shift of the SH and North Pacific jets during all seasons, and to a poleward shift of the North Atlantic jet during all seasons but summer. However, in all hemispheres and basins, the indirect (SST-mediated) component of the CO_2 response is substantially larger in magnitude than the direct component (Figures 3 and 4, right columns). Consequently, the total response to CO_2 forcing (Figure 2) is dominated by the structure of the SST-mediated component as was previously found in the single climate model experiments of *Stephenson and Held* [1993] and *Deser and Phillips* [2009]. Note, however, that unlike these previous studies, changes in sea ice concentrations are *not* included in the SST-mediated component examined here.

Over the Southern Ocean and North Atlantic Ocean, the direct and indirect components of the CO_2 response generally work in tandem in most seasons to contribute to a poleward shift of the jet. In contrast, over the North Pacific Ocean, the direct and indirect components of the CO_2 response work in opposition to one another, with the direct component contributing to a poleward jet shift and the indirect (SST) component contributing to a weakening of the jet in summer and to northwest-to-southeast oriented wind

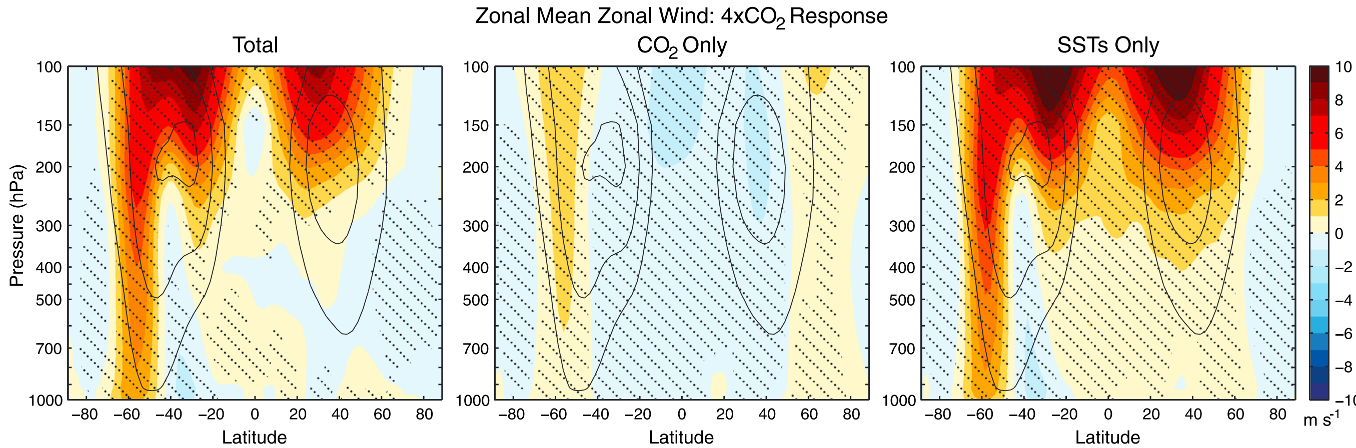

Figure 5. Multimodel-mean response of the annual-mean, zonal-mean zonal wind to $4xCO_2$ forcing: (left) total response (as in Figure 1, bottom left), (middle) contribution from atmospheric CO_2 forcing only (amip4xCO2−amip), and (right) contribution from SSTs only (amipFuture−amip). Results are calculated from 10 available CMIP5 models with these runs. Thin contours denote the climatology of the amip runs (contour interval: 10 m s^{-1}). Stippling indicates where eight or more of the models agree on the sign of the response.

anomalies in other seasons (Figure 3, right column). As a result, the total circulation response to the CO_2 forcing over the North Pacific basin (Figure 2, left column) reflects the competition of the direct and indirect components.

Using a single climate model, *Deser and Phillips* [2009] concluded that the direct and indirect components of the circulation response are approximately additive. However, the additivity of the response cannot be quantitatively verified in the CMIP5 experiments: the total response to CO_2 forcing (Figure 2) is derived from quadrupling atmospheric CO_2 from preindustrial levels (i.e., from ~285 ppm to ~1140 ppm), whereas the direct component of the response (Figures 3 and 4, left columns) is derived from quadrupling atmospheric CO_2 from 1979–2008 observed levels (i.e., from ~360 ppm to ~1440 ppm). Note also that the indirect component of the response (Figures 3 and 4, right columns) is derived from adding a 4 K global-mean patterned increase to observed 1979–2008 SSTs, which is larger than the ~3.4 K global-mean SST response to quadrupling atmospheric CO_2 from preindustrial levels.

To synthesize the results in Figures 3 and 4, we return to the zonal-mean framework. Figure 5 (left) reproduces the results from Figure 1 (bottom left), but using only the 10 CMIP5 models with AMIP experiments (i.e., those models used in Figures 3 and 4). The strong similarity in the annual-mean zonal-mean zonal wind responses between Figure 1 (bottom left) and Figure 5 (left) confirms that these 10 models are in fact representative of the pattern from the entire CMIP5 ensemble: i.e., the zonal-mean zonal wind shifts robustly poleward in response to $4xCO_2$ forcing in the SH midlatitude troposphere, but not in the NH midlatitude troposphere. Having confirmed this, we next decompose the zonal-mean zonal wind response shown in Figure 5 (left) into the components associated with the direct atmospheric radiative forcing of CO_2 (Figure 5, middle) and the indirect SST-mediated effects (Figure 5, right).

Consistent with Figures 3 and 4 (left columns), the direct atmospheric radiative forcing of CO_2 contributes to a zonal-mean zonal wind response that is quite symmetric between the two hemispheres (Figure 5, middle). Hence, the direct component of the CO_2 response does, in fact, contribute to a poleward jet shift in both the SH and NH. However, the indirect (SST-mediated) component of the CO_2 response causes the two hemispheres to deviate from symmetry. The SST component of the response reinforces the poleward jet shift in the SH but contributes to a strengthening of the zonal-mean zonal wind in the NH midlatitude troposphere (Figure 5, right). As shown in Figure 3 (right column), this strengthening (and thus the asymmetry between the NH and SH zonal-mean responses) appears to arise from the Pacific sector. As in Figures 3 and 4, the total zonal-mean response in Figure 5 (left) is dominated by the SST component (see also results from the single climate model experiment of *Staten et al.* [2012]). Recall, however, that in addition to the direct and indirect components shown in Figure 5 (middle and right panels), the total response also encompasses a nonnegligible sea ice component, which cannot be explicitly separated from the CMIP5 experiments.

4. Conclusions

In this study, we have shown that the zonal-mean extratropical zonal wind response to CO_2 forcing is considerably more robust in the SH, than in the NH, in accordance with previous studies [*Kushner et al.*, 2001] (Figure 1). The NH extratropical circulation response to CO_2 forcing reflects competing effects from different seasons and the Atlantic and Pacific Ocean basins and can only accurately be described as a zonally symmetric poleward jet shift during the autumn months [*Barnes and Polvani,* 2013; S14] (Figure 2). We have shown here that the direct (atmospheric radiative forcing) component of the CO_2 forcing does, in fact, contribute to a zonal-mean poleward jet shift in both the NH and SH (Figures 3 and 4 (left columns) and 5 (middle)). However, the indirect (SST-mediated) component of the CO_2 forcing dominates the total response and is thus responsible for most of the asymmetries seen between the SH and NH extratropical circulation responses to CO_2 forcing.

While the SSTs are clearly responsible for most of the asymmetries in the circulation responses between the hemispheres (Figures 3 and 4), we have not addressed here the reasons behind these asymmetries. *Wu et al.* [2012, 2013] have previously proposed that the direct radiative forcing of CO_2 contributes to a poleward jet shift in both hemispheres via downward coupling from stratospheric levels. But, at least in terms of the SST-mediated component of the response, the mechanisms responsible for the atmospheric extratropical circulation response to CO_2 forcing are unlikely to be identical between the two hemispheres. Stationary waves are likely to play a more important role in the NH response to SST changes, than in the SH (see also S14). Additionally, Arctic sea ice loss could be a direct cause of the asymmetry in the circulation responses between the hemispheres (C. Deser et al., The role of ocean-atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss, submitted to *Journal of Climate*, 2014). Although we do not explicitly assess changes in sea ice in this study, the SST-mediated component of the CO_2 response examined here may indirectly encompass some aspects of Arctic ice loss through the prescribed SST changes (see Figure S1). Future work will need to more carefully ascertain the relative roles of SSTs (as emphasized here) and sea ice (as emphasized by D14) in explaining the very different NH and SH extratropical circulation responses to CO_2 forcing.

Acknowledgments
We thank C. Deser, I. Simpson, R. Seager, L. Sun, and one anonymous reviewer for helpful comments during the preparation of this manuscript and H. Liu for assistance in obtaining CMIP5 data. All data used in this paper are freely available through the Earth System Grid Federation (http://pcmdi9.llnl.gov/esgf-web-fe/), as described in *Taylor et al.* [2012]. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table S1) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. K.M.G. and L.M.P. are supported by a National Science Foundation grant to Columbia University.

Noah Diffenbaugh thanks two anonymous reviewers for their assistance in evaluating this paper.

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