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Key Points:

- Large intermodel spread in SW radiation response to global warming in CMIP5
- Spread in SW changes causes spread in SH jet response to global warming
- Different SW changes cause different changes in midlatitude baroclinicity

Supporting Information:

- Readme
- Table S1 and Figure S1

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The response of the Southern Hemispheric eddy-driven jet to future changes in shortwave radiation in CMIP5

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Abstract A strong relationship is found between changes in the meridional gradient of absorbed shortwave radiation (ASR) and Southern Hemispheric jet shifts in 21st century climate simulations of CMIP5 (Coupled Model Intercomparison Project phase 5) coupled models. The relationship is such that models with increases in the meridional ASR gradient around the southern midlatitudes, and therefore increases in midlatitude baroclinicity, tend to produce a larger poleward jet shift. The ASR changes are shown to be dominated by changes in cloud properties, with sea ice declines playing a secondary role. We demonstrate that the ASR changes are the cause, and not the result, of the intermodel differences in jet response by comparing coupled simulations with experiments in which sea surface temperature increases are prescribed. Our results highlight the importance of reducing the uncertainty in cloud feedbacks in order to constrain future circulation changes.

1. Introduction

The eddy-driven jet stream is a dominant feature of extratropical climate. Variations in jet latitude have been associated with large-scale changes in surface climate across midlatitude regions, particularly with regard to temperature and precipitation [*Thompson and Wallace*, 2001; *Hurrell et al.*, 2003; *Gillett et al.*, 2006]; therefore, accurate projections of the jet stream response to global warming are essential in order to correctly assess climate change impacts.

A majority of future climate simulations by state-of-the-art coupled models predict a poleward shift of the eddy-driven jets and of the associated storm tracks in both hemispheres in response to anthropogenic forcing [*Yin*, 2005; *Delcambre et al.*, 2013; *Barnes and Polvani*, 2013]. However, there is still little agreement on the magnitude of the jet response, and the complexity of the models makes it difficult to isolate the processes responsible for the uncertainties. Some of the intermodel spread in jet response is known to be related to biases in the mean state [*Kidston and Gerber*, 2010; *Grise and Polvani*, 2014]; however, the meridional structure of the warming patterns has also been shown to be important in idealized experiments [*Lu et al.*, 2010; *Chen et al.*, 2010], and intermodel differences in spatial warming patterns have been linked to the spread in jet and storm track responses [*Delcambre et al.*, 2013; *Harvey et al.*, 2013].

The purpose of this study is to suggest that a large fraction of the uncertainty in Southern Hemispheric jet shifts in future climate scenarios results from differences in the absorbed shortwave radiation (ASR) response to global warming. We show that the ASR response is determined mainly by cloud effects, while surface albedo changes, mostly related to sea ice declines, also play a role at high latitudes. Shortwave cloud feedbacks have already been identified as one of the dominant sources of intermodel spread in global-mean climate sensitivity [e.g., *Stephens*, 2005; *Soden and Vecchi*, 2011]. Here we demonstrate that differences in the meridional structure of the ASR changes are important in controlling the circulation response to global warming. In addition, we show that the ASR changes due to clouds are, to first order, model specific and not dependent on the circulation response. This suggests that thermodynamic rather than dynamic processes dominate the intermodel differences in cloud response to global warming.

2. Data and Methods

We use the output from 34 models of the Coupled Model Intercomparison Project phase 5 (CMIP5) archive [*Taylor et al.*, 2012]. The models considered in this study are listed in the supporting information, Table S1. To assess the changes in ASR and in jet latitude, we combine the historical and Representative Concentration Pathway 8.5 (RCP8.5) simulations and calculate differences between 1950–1999 and 2050–2099. We also

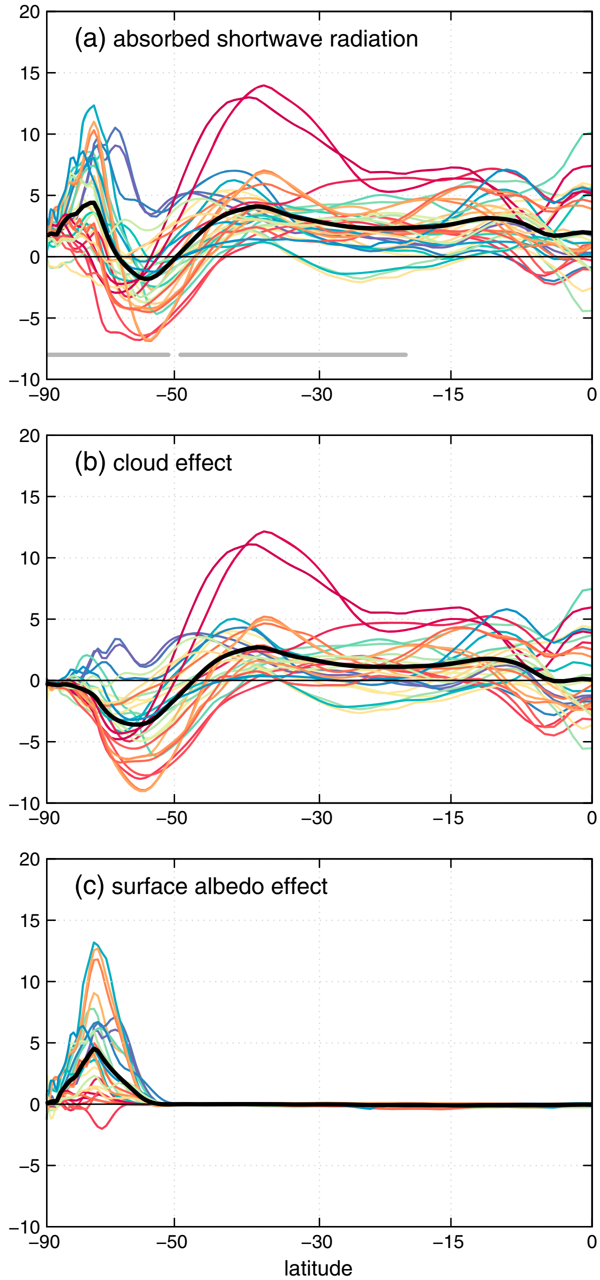

Figure 1. Change in annual-mean ASR (in W m^{-2}) between 1950–1999 and 2050–2099 in the RCP8.5 model integrations. Each curve represents a model, and the black curve denotes the multimodel mean. (a) Total all-sky ASR, (b) ASR cloud effects, and (c) effects of surface albedo changes (see text). The curves are colored according to the ASR index (defined later in the text), and the grey lines in Figure 1a denote the latitudes used in the ASR index calculation. The *x* axis is scaled by the sine of latitude.

make use of preindustrial control integrations (for all 34 models) and Atmospheric Model Intercomparison Project (AMIP) and AMIPfuture integrations, which are available for 11 of the models (see Table S1). The AMIP experiments are run with observed sea surface temperatures (SSTs) and sea ice during 1979–2005. In the AMIPfuture experiments the multimodel mean SST anomaly in the CMIP3 coupled models following a CO_2 quadrupling is added to the AMIP SSTs (experiment 6.6 in *Taylor et al.* [2012]). Note that both AMIP and AMIPfuture use 1979–2005 CO_2 concentrations, so any differences between the two sets of simulations are solely due to the effect of the SST increase.

We decompose the ASR changes into contributions due to surface albedo changes, cloud effects, and noncloud effects, following the approximate partial radiative perturbation (APRP) method of *Taylor et al.* [2007]. The method also allows us to further decompose the cloud ASR changes into effects related to cloud amount, cloud scattering, and cloud absorption. The calculations are performed at each grid point using monthly-mean values, but only annual-mean results are presented.

3. Changes in Top-of-Atmosphere Shortwave Radiation

Substantial changes in annual-mean ASR occur over the course of the RCP8.5 integrations (Figure 1a). Although there is considerable spread among the models, a majority of the simulations indicate ASR increases between about 10° and 40°S. Most models show a decrease around 50° to 60°S, with positive values again poleward of 65°S.

The all-sky ASR response mainly results from changes in cloud properties and declines in sea ice extent. Comparing Figures 1a and 1b reveals that the ASR changes are largely dominated by cloud effects, except at high latitudes. Poleward of about 50°, the changes in clouds tend to decrease ASR. The structure of the cloud-related ASR response is dipolar around the mean jet latitude in most models, consistent with the results of *Zelinka and Hartmann* [2012], who analyzed cloud radiative feedbacks in CMIP3 models. Using smaller sets of models, *Zelinka et al.* [2012] and *Zelinka et al.* [2013] ascribed the shortwave changes equatorward of 50° in both hemispheres mainly to decreases in cloud amount, while the increases in shortwave reflection poleward of 50° were mostly due to increases in cloud optical depth.

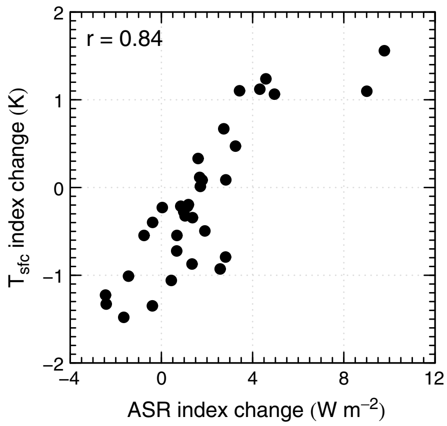

Figure 2. Change in surface temperature index versus change in ASR index in the RCP8.5 simulations between 1950–1999 and 2050–2099. Positive index values denote increasing equator-to-pole gradients.

The surface albedo ASR effects (Figure 1c) are confined to the edge of the Antarctic continent and are almost exclusively positive, reflecting albedo decreases due to declines in sea ice. The sum of the surface albedo and cloud effects equals the total ASR change minus a small positive term, typically of the order of 1–2 W m^{-2} (not shown). This term includes contributions of noncloud processes (water vapor, CO_2, ozone, aerosols, etc.) plus the error in the APRP technique; it has very little meridional structure and does not vary much across models, in agreement with the results of *Hwang and Frierson* [2010].

4. Changes in Zonal Mean Circulation

We now investigate the possibility that the large spread in ASR changes may explain some of the intermodel spread in zonal mean temperature and circulation changes. For the time being, we will assume that the ASR changes mostly cause the temperature and circulation changes, and not the other way around. Support for this hypothesis will be provided later in the paper. To assess this idea, we define simple indices of the meridional ASR gradient (hereafter ASR index) and of the zonal mean jet latitude. The ASR index is defined as the difference between the area-averaged ASR equatorward and poleward of 50°S (see grey lines in Figure 1a):

$$\text{ASR index} = \langle \text{ASR} \rangle_{20^\circ-50^\circ} - \langle \text{ASR} \rangle_{50^\circ-90^\circ}, \quad (1)$$

where the brackets denote an average over a latitude band.

Increases in the ASR index with global warming reflect increases in the ASR gradient about the climatological jet latitude (near 50° in the Southern Hemisphere). Such forcings would be expected to enhance midlatitude baroclinicity. As demonstrated in previous studies, forcings that tend to modify midlatitude baroclinicity are particularly effective at inducing shifts of the eddy-driven jet [e.g., *Chen et al.*, 2010; *Ceppi et al.*, 2012]. We verified that the ASR index changes are highly correlated with changes in a surface temperature index defined in an analogous way ($r = 0.84$; Figure 2).

The jet latitude ϕ_{jet} is calculated as

$$\phi_{jet} = \frac{\int_{u>0} \phi\, u(\phi)\, \mathrm{d}\phi'}{\int_{u>0} u(\phi)\, \mathrm{d}\phi'}, \quad (2)$$

where u is the zonal wind at 850 hPa, ϕ is the latitude, and the subscript $u > 0$ means that the integral is calculated over all latitudes where u is positive around the jet maximum. This corresponds to a zonal wind-weighted average of the latitudes of mean westerly wind around the jet. Using this definition instead of the latitude of peak winds allows us to account for changes in the width and mean latitude of the whole belt of westerlies. The choice of the 850 hPa level ensures that we are capturing the eddy-driven jet.

The changes in ASR index and in jet latitude between the two reference periods 1950–1999 and 2050–2099 are represented in Figure 3a. Larger increases of the ASR index correspond to larger poleward shifts of the eddy-driven jet. The correlation of 0.76 between the two indices is highly significant, with a p value smaller than 5×10^{-4}. The jet shifts poleward in all models, while the ASR index change is predominantly positive; the positive intercept of the relationship suggests that part of the jet shift is unrelated to the increase in meridional ASR gradient. Note that qualitatively similar results are obtained if a model-specific cutoff latitude is used in equation 1 (e.g., the climatological jet latitude), or if the jet latitude is simply defined as the latitude of peak zonal wind instead of using equation 2, but the correlation is slightly reduced in each case.

Breaking down the ASR index changes into components due to surface albedo and cloud properties, we find that both are well correlated with the jet response (Figures S1a and S1b). This means that changes in both sea ice and clouds affect the jet response through their shortwave effects. Changes in cloud amount and cloud scattering appear to contribute roughly equally to the changes in ASR index and to the jet response

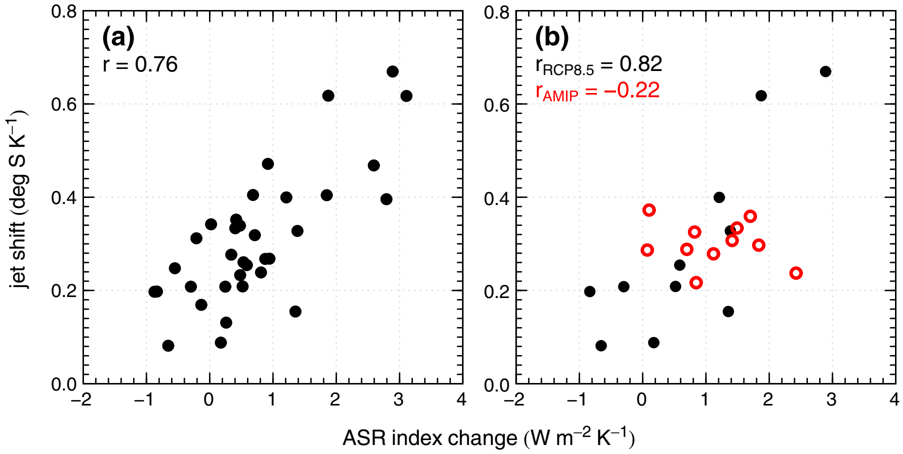

Figure 3. (a) Change in zonal mean jet latitude and in ASR index in the RCP8.5 experiments between 1950–1999 and 2050–2099 in each of the CMIP5 models. The changes are normalized by the hemispheric-mean surface warming. Poleward jet shifts are defined as positive. (b) As in Figure 3a but also showing the changes between AMIP and AMIPfuture (open red dots). Only the 11 models with both AMIP and RCP8.5 experiments are shown.

(Figures S1c and S1d). Changes in cloud absorption and noncloud components are very small and have a negligible effect on the ASR index (not shown).

The indices in Figures 3 and S1 are normalized by the hemispheric-mean surface warming to account for the possible impact of different climate sensitivities; however, the results are qualitatively similar if the values are not normalized. (Note that the hemispheric-mean, multimodel mean warming is 2.5 K.) It is worth noting that the jet response is only modestly correlated with the hemispheric-mean ASR change ($r = 0.42$; p value = 0.01) and surface temperature change ($r = 0.32$; p value = 0.07). This suggests that the meridional structure of the warming, more than the hemispheric-mean warming, is important in determining the jet response. This finding may explain the weak relationship between climate sensitivity and dynamical sensitivity recently noted by *Grise and Polvani* [2014] in the Southern Hemisphere (SH).

In agreement with *Kidston and Gerber* [2010], the jet shift is also correlated with the baseline (1950–1999) jet latitude ($r = -0.52$), although this effect is weaker than the ASR effect in our data set. Thus, the intermodel spread in SH jet shifts likely results from the combined influences of different effects.

If we repeat the analysis using seasonal-mean instead of annual-mean values, we obtain similar results but with somewhat weaker correlations, especially during winter ($r = 0.45$; not shown). The weaker relationship in winter is consistent with the reduced intermodel spread in ASR index due to reduced insolation.

5. Relationship Between Radiation and Circulation Changes

So far we have assumed that the spread in ASR changes is responsible for the spread in jet responses. However, it is not unlikely that the clouds and ASR could respond to the circulation changes, since jet shifts are accompanied by changes in the meridional distribution of large-scale ascent and subsidence, and possibly by shifts of storm track clouds [*Bender et al.*, 2012; *Grise et al.*, 2013; *Hartmann and Ceppi*, 2014]. To assess to what extent the changes in clouds and ASR are the cause or the effect of the jet shifts, we consider AMIP and AMIPfuture integrations of the CMIP5 models (see section 2).

Since the AMIPfuture simulations are forced with prescribed SSTs, any changes in ASR have little or no effect on midlatitude baroclinicity, because the radiation anomalies cannot change the SSTs. Thus, the relationship between ASR changes and jet shifts in the AMIP simulations should reflect the causal linkage between the two. Assuming the jet shifts result mainly from SST changes, we can make two hypotheses:

1. As the planet warms, the poleward shift of the midlatitude jet causes changes in the distribution of clouds and ASR. Therefore, intermodel differences in the jet response explain the various ASR and SST responses.
2. As the planet warms, changes in cloud properties and sea ice extent cause changes in the meridional gradient of ASR. Thus, spread in cloud and sea ice responses causes spread in ASR responses, leading to different SST changes and thus different jet shifts.

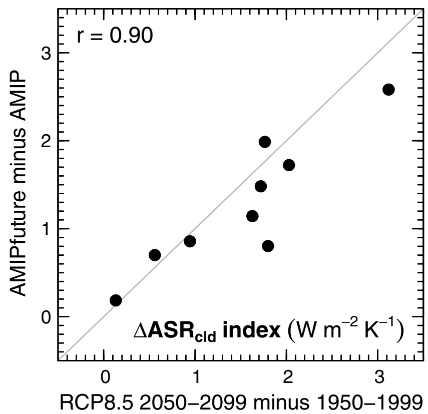

Figure 4. ASR index changes due to clouds in the AMIP simulations versus the RCP8.5 simulations. The one-to-one line is shown in grey. Note that only nine models have APRP data for both the AMIP and RCP8.5 experiments (see Table S1).

Comparing RCP8.5 with AMIP simulations allows us to test these hypotheses. If hypothesis 1 holds, then the relationship between ASR changes and jet shifts should be similar in both sets of simulations. However, if hypothesis 2 is true, then there should be no relationship between ASR index and jet shifts in the AMIP runs, since the ASR changes have almost no effect on baroclinicity due to the prescribed SSTs.

We compare ASR and jet latitude changes in the RCP8.5 and AMIPfuture simulations in Figure 3b. The black dots are the same as in Figure 3a, but only the 11 models with AMIP runs are shown. Despite the small number of models, the ASR index changes are still strongly correlated with the jet shift in the RCP8.5 experiments, and the correlation is highly significant (p value = 0.002). In the AMIP runs, however, a very weak negative correlation is observed (open red dots in Figure 3b). While the spread in ASR index change (as measured by the standard deviations) is reduced by 36% in the AMIP simulations, the spread in jet shift is reduced by a much larger 76%, consistent with expectations from a prescribed SST forcing. The results in Figure 3b strongly suggest that the spread in ASR index change cannot be attributed to differences in jet shift among models, disproving hypothesis 1.

Rather than being caused by the jet response, the spread in ASR index changes seems to arise from a model-specific cloud sensitivity to SST warming, as shown in Figure 4. Because sea ice is prescribed in the AMIP runs, we compare the ASR index changes due to clouds only (hereafter ASR_{cld} index; cf. Figure 1b). We find a strong positive correlation ($r = 0.90$, p value = 9×10^{-4}) for the ASR_{cld} index changes between the AMIP and RCP8.5 simulations, and the values are close to the one-to-one line. Differences in ASR_{cld} index changes between RCP8.5 and AMIPfuture could arise for a variety of reasons, notably (a) the lack of forcing agents (e.g., CO_2, aerosols, and stratospheric ozone recovery) in AMIP that are known to affect clouds, and (b) the different SST changes. Despite all these differences, however, the ASR_{cld} index changes agree remarkably well between AMIPfuture and RCP8.5.

The results in Figure 4 support the idea that spread in the ASR response causes spread in SST gradient changes across models (Figure 2). An alternative interpretation of Figure 2 could be that clouds are merely *responding* to SST gradient changes caused by other processes, such as changes in ocean circulation. This appears implausible, however, since the spread in ASR_{cld} remains nearly unchanged even if the SST forcing is fixed (Figure 4).

Our results appear inconsistent with the common idea (and basic intuition) that shifts of the midlatitude jet should cause cloud and radiation anomalies [e.g., *Bender et al.*, 2012; *Grise et al.*, 2013]. To understand the effect of jet shifts on ASR, we use 100 year preindustrial control time series and regress annual-mean ASR onto the annual-mean jet latitude for each model (Figure 5), following a methodology similar to *Kay et al.* [2014]. In order to compare the ASR responses due to interannual jet shifts with the RCP8.5 forced response, we multiply the preindustrial regression coefficients by the multimodel mean RCP8.5 jet shift. While there are large intermodel differences in the ASR response to the poleward jet shift (thin grey curves in Figure 5), all of the models fail to reproduce the dipole-like characteristics of the mean RCP8.5 ASR response (Figure 5, dashed black curve; note this is the cloud-induced response). The mean ASR response to natural jet variability shows anomalies much weaker than the RCP8.5 response (thick black curve in Figure 5) and does not explain the ASR dipole around the mean jet latitude. Overall, Figure 5 suggests that much of the RCP8.5 ASR response is unrelated to the poleward jet shift; this agrees with the results of *Kay et al.* [2014] with the Community Earth System Model-Community Atmosphere Model version 5 (CESM-CAM5) and Community Climate System Model version 4 (their Figures 3c and S2c).

Taken together, our results strongly support the idea that the changes in ASR with global warming tend to be model specific, regardless of the details of the jet response. While jet shifts do cause a small ASR response, the general structure and the magnitude of the ASR changes do not appear related to the amount of jet shift. From this we validate hypothesis 2 and conclude that the ASR changes, through their effect on

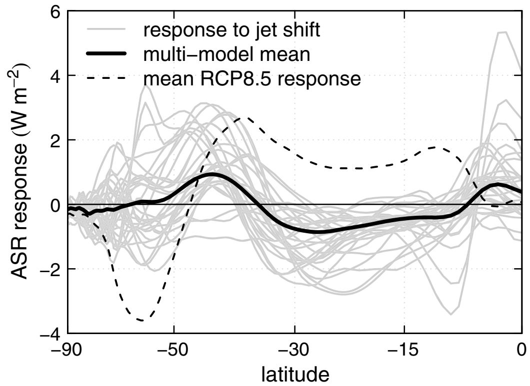

Figure 5. ASR response to interannual jet shifts (in W m^{-2}) in preindustrial control simulations of CMIP5 models. The model responses are calculated by least squares regression of the annual-mean ASR onto the annual-mean jet latitude using 100 year time series. The regression coefficients are multiplied by the multimodel mean RCP8.5 jet shift. The thick black line denotes the multimodel mean response, while the dashed line represents the mean RCP8.5 cloud-related ASR response (2050–2099 minus 1950–1999; cf. Figure 1b). The *x* axis is scaled by the sine of latitude.

surface temperatures, are causing a substantial part of the intermodel differences in jet response to global warming.

6. Discussion and Conclusions

Large changes in absorbed shortwave radiation (ASR) occur over the course of the 21st century in the RCP8.5 simulations of CMIP5 models. The ASR changes are dominated by cloud effects, but changes in surface albedo also have a nonnegligible impact at high latitudes. The large intermodel spread in ASR changes affects the patterns of surface warming and midlatitude baroclinicity in climate models. We find that the jet response is well correlated with the ASR changes in the Southern Hemisphere (SH), such that models with an enhanced meridional gradient of ASR (and therefore enhanced midlatitude baroclinicity) also feature a larger poleward jet shift.

To determine the causal relationship between ASR changes and jet shifts, we consider the ASR and jet responses in simulations with a prescribed SST increase. In these simulations, in which changes in ASR cannot affect baroclinicity due to the prescribed SSTs, larger jet shifts are not associated with an enhanced ASR gradient around the midlatitudes, as one would expect if jet shifts cause shortwave anomalies. Moreover, the ASR changes are remarkably similar in both prescribed SST and RCP8.5 experiments, even though the jet responses are very different. This implies that the intermodel spread in ASR changes is mainly the cause, and not the result, of the spread in jet shifts with global warming.

The relationship between ASR gradient, SST gradient, and jet shift appears consistent with the results of *Harvey et al.* [2013], who found increases in the equator-to-pole temperature gradient to be associated with a strengthened and poleward-shifted storm track in the SH in CMIP5 models. While *Wilcox et al.* [2012] emphasized the role of the upper level temperature gradients on the jet response, *Harvey et al.* [2013] found both the lower and upper level baroclinicity changes to contribute to the storm track response. In our data set, the ASR gradient change is well correlated with the temperature gradient change at both the surface and 300 hPa (0.84 and 0.64, respectively).

One question that remains open with our results is that of the dynamical mechanisms responsible for the jet shift in response to an increase in midlatitude baroclinicity. One would naïvely expect an increase in midlatitude baroclinicity to cause a jet strengthening rather than a poleward shift. However, it has recently been suggested that increases in the strength of the eddy-driven jet may cause changes in wave propagation which result in poleward shifts of the jet [*Lorenz*, 2014; *Kidston and Vallis*, 2012]. While such a mechanism might play a role in our results, we have not investigated to what extent this or other mechanisms apply to the model simulations shown in this paper.

Our results support the conclusion of *Kay et al.* [2014] that the global warming responses of radiatively important clouds (RIC) and ASR are mostly unrelated to the poleward shift of the SH midlatitude jet. In a detailed analysis of an ensemble of CESM-CAM RCP8.5 simulations, *Kay et al.* [2014] found thermodynamic processes such as near-surface stability changes and warming to control the RIC response. In addition, recent work by K. M. Grise and L. M. Polvani (Southern Hemisphere cloud-dynamics biases in CMIP5 models and their implications for climate projections, submitted to *Journal of Climate*, 2014) shows that the RIC response to interannual jet variability is strongly model-dependent. Additional analyses of different climate models are needed to understand the causes of the large intermodel spread in RIC response to both SST warming and jet shifts.

An important conclusion from this study is that since the shortwave response is dominated by cloud effects, reducing the uncertainty in the cloud response to global warming is necessary to constrain future circulation changes. While we have focused on the eddy-driven jet, it is possible that other components of the atmospheric circulation, such as the Hadley cells and the intertropical convergence zone, are also sensitive to the shortwave changes in the models.

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