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LETTER

Role of the mean state for the Southern Hemispheric jet stream response to CO_2 forcing in CMIP6 models

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Abstract

Global climate models indicate that the Southern Hemispheric (SH) jet stream shifts poleward in response to CO_2 forcing, but the magnitude of this shift remains highly uncertain. Here we analyse the SH jet stream response to $4\times CO_2$ forcing in Coupled Model Intercomparison Project phase 6 (CMIP6) simulations, and find a substantially muted jet shift during winter compared with CMIP5. We suggest this muted response results from a more poleward mean jet position, consistent with a strongly reduced bias in jet position relative to the reanalysis during 1980–2004. The improved mean jet position cannot be explained by changes in the simulated sea surface temperatures. Instead, we find indications that increased horizontal grid resolution in CMIP6 relative to CMIP5 has contributed to the higher mean jet latitude, and thus to the reduced jet shift under CO_2 forcing. These results imply that CMIP6 models can provide more realistic projections of SH climate change.

1. Introduction

In response to CO_2 forcing, climate models commonly predict a poleward shift of the midlatitude jet streams, particularly in the Southern Hemisphere (SH) (e.g. Kushner *et al* 2001, Kidston & Gerber 2010, Barnes & Polvani 2013, Ceppi *et al* 2014, Grise & Polvani 2016), Quantifying the magnitude of this poleward shift is important because of the associated large-scale climate impacts in terms of temperature and the hydrological cycle (Thompson 2011, Kang *et al* 2011, Zappa 2019). Through wind stress coupling with the ocean circulation, changes in the position of the SH jet can also have global impacts, for example via changes in overturning, air-sea carbon exchange, and Agulhas leakage (Anderson 2009, Biastoch *et al* 2009, Abernathey *et al* 2011, Durgadoo *et al* 2013).

Unfortunately, however, the uncertainty in model projections of jet stream shifts has remained large—up to several degrees of latitude—in recent generations of coupled global climate models. Given this uncertainty, it would be helpful to identify relationships that constrain model projections based on observable climate features, e.g. the seasonal cycle (Klein & Hall 2015). A possible starting point for such a constraint on the SH jet response comes from a relationship between the present-day jet latitude and its response to future global warming, first found among Coupled Model Intercomparison Project phase 3 (CMIP3) models, such that lower-latitude jets tend to exhibit a stronger poleward shift (Kidston & Gerber 2010).

The usefulness of the relationship between mean jet latitude and jet shift as a constraint on model projections results from the large inter-model spread in present-day jet position in coupled climate models (Kidston & Gerber 2010, Ceppi *et al* 2012, Delcambre *et al* 2013). However, Simpson & Polvani (2016) showed that the relationship is restricted to mainly the austral winter half-year, and that the theoretical basis originally proposed by Kidston & Gerber (2010) does not hold. Consistent with Simpson & Polvani (2016), both Seviour *et al* (2017) and Son *et al* (2018) found little effect of the mean jet latitude on the December–February jet response to polar stratospheric ozone depletion across different sets of global climate models.

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Furthermore, it is important to mention that factors other than the mean state also contribute to the uncertainty in the future SH jet response; previous studies have pointed to the roles of changes in the lower- and upper-tropospheric baroclinicity and in the polar stratospheric vortex (e.g. Ceppi *et al* 2014, Ceppi & Shepherd 2019), Nevertheless, the mean state accounts for more than 60% of the inter-model variance in jet shift in the CMIP5 RCP8.5 scenario during June–August (Simpson & Polvani 2016, their figure 2(g)), and therefore remains a useful starting point for a constraint on the future SH jet response in wintertime.

Here we revisit the relationship between mean jet latitude and jet shift in the newer generation of CMIP6 models, in order to gain confidence on its potential value as an emergent constraint. Understanding the mechanisms of this relationship is left for future work, although this remains a pre-requisite to developing a constraint (Klein & Hall 2015, Hall *et al* 2019). Compared with CMIP5, CMIP6 models simulate a more poleward control jet position, and correspondingly a much weaker poleward shift under global warming during the winter half-year. The higher-latitude control jet position reflects a reduced bias in the multi-model mean relative to the reanalysis, and is associated with improvements in the atmospheric components of the models, rather than with biases in sea surface temperatures. We provide evidence that increased horizontal grid resolution likely contributes to the reduced jet latitude bias of CMIP6 models.

2. Data and methods

Model simulations from the Coupled Model Intercomparison Project (CMIP) phases five and six (CMIP5, CMIP6 respectively) are used here for analysis. We use the piControl, abrupt-4xCO_2, historical and AMIP simulations. At the time of writing, data was available for 35 CMIP5 models and 37 CMIP6 models, although not all models provide data for all four experiments (tables S1 and S2). To facilitate comparisons, we use identical time periods for all CMIP5 and CMIP6 models. For historical and AMIP simulations, this coincides with the 25-year range spanning January 1980 through December 2004. We use years 1–30 for piControl and years 121–150 for abrupt-4xCO_2 simulations.

In addition to CMIP data, we also perform atmosphere-only model simulations using the Community Earth System Model (CESM) version 1.2.2, with the atmospheric component CAM4 (Neale *et al* 2010). For these simulations we use 1995–2005 climatological boundary conditions for sea surface temperature, sea ice concentration, and atmospheric constituents. The CAM4 simulations are run with two dynamical cores, finite-volume (the CAM4 default) and spectral, and at three different horizontal resolutions. The finite-volume simulations use 0.9° × 1.25°, 1.9° × 2.5° and 4° × 5° grids (latitude × longitude), while the spectral simulations use horizontal resolutions of T31, T42 and T85. All simulations use 26 vertical levels and are run for a minimum of 30 years, after discarding one year of spin-up.

To identify the Southern Hemispheric eddy-driven jet latitude, we follow previous work (e.g. Ceppi *et al* 2012, Grise *et al* 2017), and use the peak westerly zonal-mean zonal wind at 850 hPa between 30° and 60° S. Prior to finding the latitude of peak wind, the wind field is interpolated onto a fine grid of 0.1° resolution in latitude using cubic splines. Throughout the paper, climatological latitudes are defined in degrees North (i.e. mean SH jet latitudes are negative), but jet shifts are defined as positive poleward.

Differences between CMIP5 and CMIP6 models are tested with a two-sided t-test of the difference in means, with the null hypothesis that the two collections have the same means. To maximise the independence of the samples (Knutti *et al* 2013), where several models are available for a given modelling centre we use the mean over those models for the tests. For CMIP5 and CMIP6, data was available for 16 and 22 modelling centres respectively.

3. Austral jet shifts in CMIP5 and CMIP6 models

Figure 1 presents the meridional shifts of the eddy-driven jet in CMIP5 and CMIP6 coupled models in response to an abrupt quadrupling of CO_2. We consider results for the annual mean, and also for two half-year seasons defined between November and April (hereafter austral summer) and May to October (austral winter). In the annual mean, the jet consistently shifts poleward in both model collections, with only one CMIP6 model featuring a near zero shift. The mean response is weaker in CMIP6 (2.2° vs 3.0°; $p = 0.05$). For CMIP5, our results are quantitatively consistent with previous work (Grise *et al* 2017, their figure 5(a)).

Considering the seasonal dependence of the response reveals that the difference in annual-mean shift can be primarily ascribed to a substantially weaker shift in austral winter (May–October) in CMIP6 compared with CMIP5 (1.3° vs 2.5°; $p = 0.06$). If the outlier value in CMIP5 is omitted from the comparison (MIROC5, with a shift of 10.9°), then the mean CMIP5 shift is reduced to 2.2°, but the statistical significance of the difference relative to CMIP6 remains similar ($p = 0.07$). The seasonal dependence of the austral jet response to CO_2 forcing is therefore enhanced in CMIP6 models.

Previous work has shown the existence of a relationship between the control jet latitude and the magnitude of the poleward shift in response to CO_2 forcing (Kidston & Gerber 2010), and that this link is strongest in austral winter (Simpson & Polvani

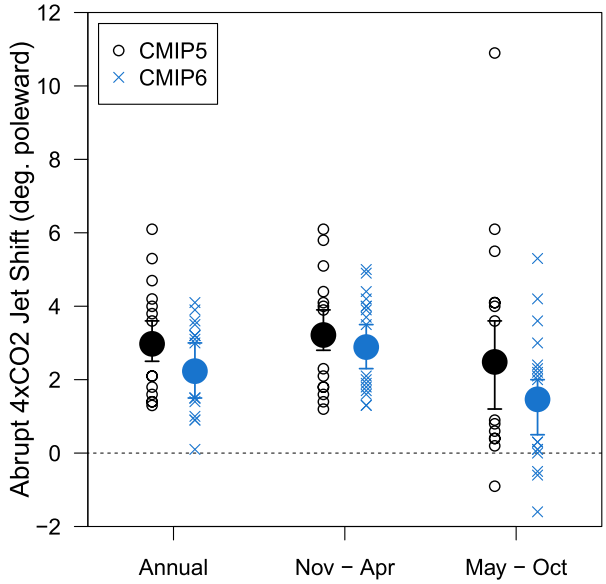


Figure 1. Jet shift (degrees poleward) calculated as the difference between abrupt4xCO_2 years 121–150 and piControl years 1–30, annually and seasonally using two half-year seasons (November–April and May–October). Bars represent the 25% to 75% percentiles of the inter-model ranges in the CMIP5 (black) and CMIP6 (blue) models, black open circles and blue crosses denote individual models, and solid circles denote multi-model mean values.

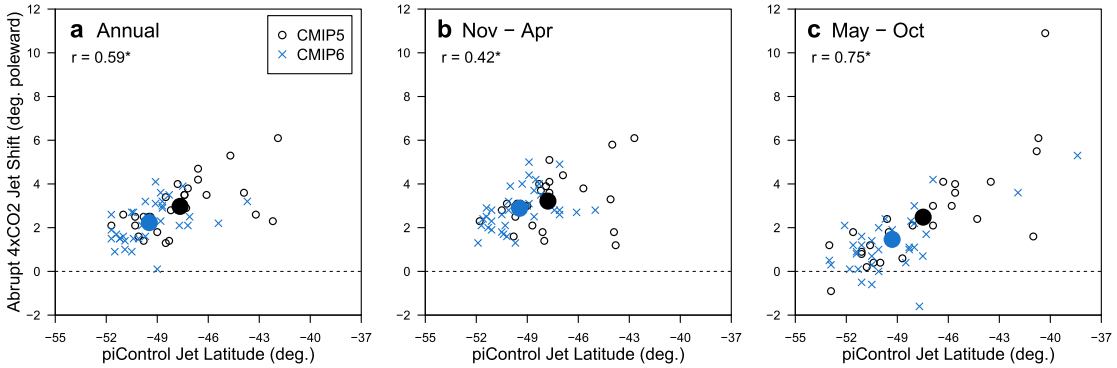


Figure 2. Jet shift against pre-industrial control jet latitude: (a) annual-mean values, (b) austral summer and (c) austral winter. Black open circles denote CMIP5 results, blue crosses denote CMIP6 results, solid circles denote multi-model mean values. Positive values indicate poleward shifts. Correlation values in each panel are obtained by pooling CMIP5 and CMIP6 values together, and asterisks denote p-values lower than 5%.

2016). We therefore consider the relationship between the pre-industrial control mean state and the forced response (figure 2). Consistent with Simpson & Polvani (2016), we find a strong relationship across models between $4\times CO_2$ forced jet shift and control jet latitude in austral winter (figure 2(c); $r = 0.75$, $p < 0.01$, combining CMIP5 and CMIP6), whereas this relationship is notably weaker in austral summer (figure 2(b); $r = 0.42$, $p < 0.01$). Similar correlations are found if CMIP5 and CMIP6 models are considered separately (not shown), suggesting the relationship between mean state and jet response is similar in both model collections. As an aside, we note that the relationships in figure 2 are not affected by inter-model differences in climate sensitivity: if we normalise the jet shifts by each model's climate sensitivity, we obtain very similar correlations to those shown in figure 2 (0.55, 0.35, 0.72 for panels a, b, c respectively).

Importantly, the results in figure 2(c) demonstrate that the suppressed jet shift in austral winter is consistent with a more poleward control mean jet position in CMIP6 (by about 1.8° in May–October; $p = 0.17$ for the difference in piControl jet latitude). While the mean jet position is more poleward year-round, the change in mean state is linked to the jet response mainly during austral winter, owing to the seasonal dependence of the relationship between jet response and control jet latitude. In May–October, a linear regression fit to the relationship in figure 2(c) predicts that the 1.8° change in piControl jet latitude would result in a 0.8° change in the abrupt-4xCO2 poleward shift, thus accounting for most of the actual 1.2° decrease in poleward shift. This supports the idea

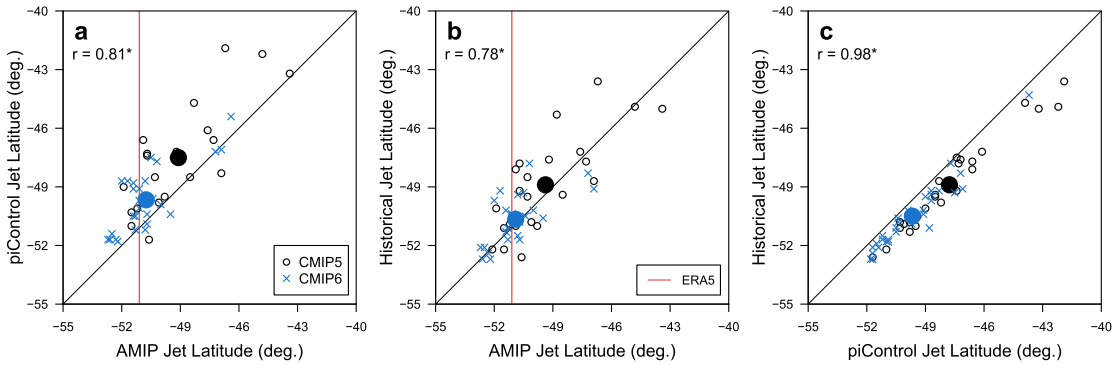


Figure 3. Annual-mean jet latitude in the AMIP, piControl, and historical experiments. (a) piControl versus AMIP; (b) historical versus AMIP; (c) historical versus piControl. For historical and AMIP data, we consider the average over 01/1980 to 12/2004; for piControl we consider the first 30 years of data. Red lines denote the ERA5 reanalysis mean jet latitude over the period 01/1980 to 12/2004. Black open circles denote CMIP5 results, blue crosses denote CMIP6 results and solid circles denote multi-model mean values. Correlation values in each panel are obtained by pooling CMIP5 and CMIP6 values together, and asterisks denote *p*-values lower than 5%.

that the change in mean jet latitude may explain the reduced shift under CO_2 forcing in CMIP6 versus CMIP5.

4. Causes of change in mean state

Having discussed the role of the control mean state for the austral jet response to forcing, we now wish to understand the differences in mean state between CMIP5 and CMIP6. Since we are considering coupled atmosphere–ocean models, we first test whether the differences in jet mean state could be due to differences in sea surface temperatures (SSTs). In particular, the meridional SST gradient around the midlatitudes has been shown to have a substantial impact on the mean jet position in idealised and realistic models (Brayshaw *et al* 2008, Chen *et al* 2010, Sampe *et al* 2010, Ceppi *et al* 2012). To assess the role of SSTs, we compare the coupled model simulations with their corresponding atmosphere-only models run with observed (AMIP) SSTs and sea ice. Figure 3(a) shows that the annual-mean jet latitudes are very well correlated between piControl and AMIP ($r = 0.81$), despite the different SST boundary conditions. Importantly, we find that the jet is substantially further poleward in the CMIP6 AMIP experiment relative to CMIP5, even though the SSTs are exactly the same. Thus, on average, the higher (more poleward) mean jet latitude cannot be attributed to changes in the simulation of the coupled SSTs in CMIP6.

We note, however, that the jet is on average slightly more poleward in AMIP relative to piControl, i.e. most data points lie to the left of the 1:1 line in figure 3(a). This is likely because of differences between the piControl and AMIP climates, particularly in terms of stratospheric ozone concentrations (Thompson & Solomon 2002, Arblaster & Meehl 2006). To verify this, in figure 3(b) we compare AMIP and historical jet latitudes using matching time periods (01/1980 to 12/2004) such that the atmospheric composition is the same, and find nearly identical mean jet latitudes in the multi-model mean, confirming that coupled SSTs cannot explain the mean change between CMIP5 and CMIP6. In further support of our reasoning, in figure 3(c) we observe that the historical and piControl jet latitudes are extremely well correlated across CMIP models ($r = 0.98$), but the historical jet latitude is systematically higher by 1.0° on average. Although figure 3 shows annual-mean results only, very similar results are obtained for the winter and summer seasons (not shown).

Since AMIP results are based on observed SSTs and sea ice, they can be compared directly with ERA5 reanalysis data (Hersbach 2019). We find that the higher-latitude mean jet position in CMIP6 brings the models into very close agreement with the reanalysis (figures 3(a)–(b)). Thus to the extent that the reanalysis accurately represents the real world, CMIP6 models perform better and, on average, are essentially unbiased in terms of the annual-mean austral jet position, unlike previous generations of global climate models (Kidston & Gerber 2010, Ceppi *et al* 2012, Wilcox *et al* 2012). Note, however, that a small equatorward bias remains in MJJASO in CMIP6 AMIP simulations: 0.7°, vs 0.3° in the annual mean. The corresponding CMIP5 AMIP bias values are much larger (3.0° and 1.8°, respectively).

Since the difference in mean jet position between CMIP5 and CMIP6 is the same in coupled and atmosphere-only models, it is likely due to the atmospheric component of the models. Broadly speaking, the difference between atmospheric models could come from the model physics, the model dynamics, or a combination of both. The physics schemes determine the spatial distribution of diabatic heating, and there is ample evidence that this affects the jet stream representation, e.g. via atmospheric cloud-radiative heating (Voigt & Shaw 2015, Li *et al* 2015, Ceppi & Hartmann 2016, Watt-Meyer & Frierson 2017). Another impact of model physics is via the parameterisation of surface drag, which affects the momentum budget (e.g. Garfinkel *et al* 2011, Pithan

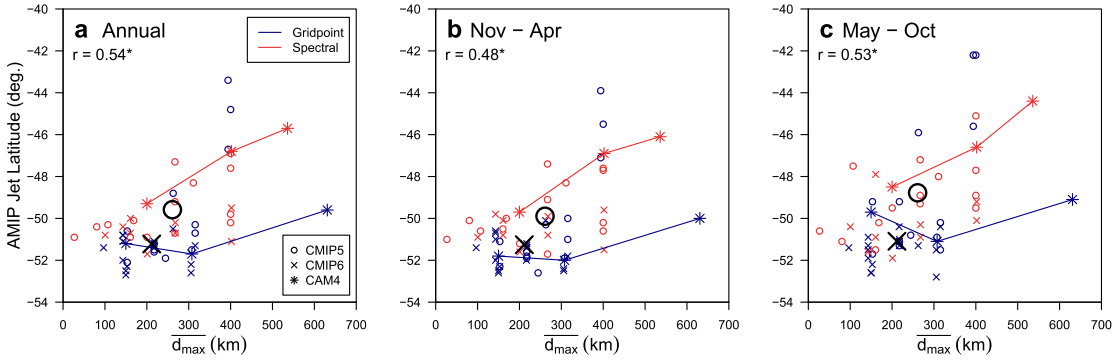


Figure 4. AMIP jet latitude against nominal model resolution $\overline{d_{\max}}$. Open circles denote CMIP5 results, crosses denote CMIP6 results and stars denote CAM4 results. Black circles and crosses denote CMIP5 and CMIP6 mean values, respectively. Navy and red symbols indicate gridpoint and spectral dynamical cores, respectively. Straight lines connect the sets of CAM4 simulations with varying atmospheric resolutions. The results include all models with AMIP data, except for the four CNRM models (tables S1–S2), for which we were unable to calculate $\overline{d_{\max}}$ owing to the use of irregular grids. Correlation values in each panel are obtained by pooling CMIP5 and CMIP6 values together, and asterisks denote p-values lower than 5%.

et al 2016). In terms of the dynamics, the formulation of the dynamical core and the grid resolution can affect the representation of the atmospheric circulation. In particular, evidence from models at different levels of complexity suggests that a higher horizontal grid resolution tends to favour a more poleward mean jet position (Gerber *et al* 2008, Hertwig 2015, Lu 2015). There is also evidence that the vertical resolution in the stratosphere affects the simulation of the jet response to forcing (Wilcox *et al* 2012), although impacts on the mean state have not been documented, to our knowledge.

We do not have adequate data to thoroughly investigate the contributions of changes in model physics and dynamics to the differences in jet position between CMIP5 and CMIP6. However, we are able to qualitatively test the hypothesis that increased horizontal grid resolution contributes to the change in mean jet latitude in CMIP6. To do this, we must first define a metric quantifying the horizontal grid resolution. We use a representative grid box distance $\overline{d_{\max}}$ (in km), calculated as the area-weighted mean distance across the diagonal of each grid box. This metric was introduced to quantify the nominal horizontal grid resolution in climate models under the CMIP6 conventions (cf appendix 2 of the CMIP6 data specifications document, http://goo.gl/v1drZl), but note that the nominal resolutions reported in CMIP6 data are based on the output grids, whereas we use the native grid specifications. For a Cartesian grid with latitudinal spacing $\Delta\phi$ and longitudinal spacing $\Delta\lambda$, we can write

$$\overline{d_{\max}} = \frac{a\Delta\phi}{2}\left(1 + \frac{\Delta\lambda^2 + \Delta\phi^2}{\Delta\lambda\Delta\phi}\arctan\frac{\Delta\lambda}{\Delta\phi}\right), \quad (1)$$

where $a = 6371$ km is the radius of the Earth.

We stress that the representative grid box distance $\overline{d_{\max}}$ is only a qualitative measure of model resolution (Lander & Hoskins 1997); more quantitative metrics of effective resolution have been introduced that rely on the wavenumber dependence of the kinetic energy spectrum of atmospheric motions (Skamarock 2004).

We test the effect of horizontal resolution in the AMIP simulations, where the role of inter-model differences in climate is minimised thanks to the identical SST and sea ice boundary conditions. Across CMIP models we find a positive correlation between $\overline{d_{\max}}$ and the AMIP annual-mean jet latitude (figure 4(a); $r = 0.54$, $p < 0.01$), indicating that lower-resolution models tend to produce a lower-latitude jet, consistent with previous findings (Gerber *et al* 2008, Hertwig 2015, Lu 2015). Furthermore, the relationship remains approximately constant throughout the seasonal cycle (figures 4(b)–(c)). There is no clear systematic difference between gridpoint models and spectral models in terms of the mean jet latitude, as both the lowest- and highest-latitude models use gridpoint dynamical cores. Consistent with the more poleward jet position, CMIP6 models are also higher-resolution on average relative to CMIP5 ($\overline{d_{\max}} = 212$ vs 281 km).

We caution that the relationships observed in figure 4 could be spurious if model resolution is correlated with other relevant factors, e.g. if higher-resolution models tend to also have an improved representation of physical processes. Therefore, to test causality, we perform atmosphere-only CAM4 simulations where we systematically vary the atmospheric horizontal grid resolution while keeping everything else unchanged. These experiments are run with two different dynamical cores (spectral and finite-volume) at three resolutions each (section 2). The CAM4 results are in partial support of the hypothesis that increasing horizontal resolution favours a more poleward austral jet position. While jet latitude varies only weakly (and non-monotonically) with grid resolution for the finite-volume core, we observe a clear dependence with the spectral core.

Taken together, the results in figure 4 show evidence that increasing horizontal grid resolution is

partly responsible for the higher mean austral jet latitude in CMIP6 versus CMIP5, and hence for the more muted poleward jet shift in response to CO_2 forcing. However, we reiterate that other factors are likely also contributing to this difference, both in terms of model dynamics (e.g. vertical resolution in the stratosphere) and model physics (particularly diabatic heating processes and surface drag). This is also clear from figure 4, where particularly for low nominal resolutions (large values of $\overline{d_{\max}}$) a wide range of jet latitude biases can be found for a given $\overline{d_{\max}}$.

5. Discussion and conclusions

We analyse the response of the Southern Hemispheric eddy-driven jet to $4 \times CO_2$ forcing in the latest generation of coupled global climate models, CMIP6. Although the jet robustly shifts poleward in the annual mean, the shift is substantially muted in the austral winter half-year (May–October) compared with the previous generation of climate models, CMIP5. We show that this muted response can be linked to a more poleward mean jet position, consistent with the understanding that a more poleward mean state is associated with a more muted poleward shift in response to CO_2 forcing during austral winter (Kidston & Gerber 2010, Simpson & Polvani 2016). We further demonstrate that the more poleward mean jet position results in a strongly reduced bias relative to the ERA5 reanalysis in the 1980–2004 period, and therefore reflects an improvement in the coupled climate models.

By comparing coupled with atmosphere-only (AMIP) simulations, we find that SSTs cannot explain the improved mean jet position in the coupled models. Instead, we find evidence suggesting that increased horizontal grid resolution contributes to the higher mean jet latitude, and therefore to the muted poleward jet shift in the austral winter half-year, in CMIP6 models compared with CMIP5. However, other aspects of the atmospheric model formulation—particularly physical processes responsible for diabatic heating—are also likely to contribute to the change in jet mean state between CMIP5 and CMIP6. We are unable to test these effects with the available CMIP data.

A physical understanding of the effect of the mean state on the jet response is currently lacking: while an initial interpretation was based on the fluctuation-dissipation theorem (Kidston & Gerber 2010), the seasonality of the relationship between mean state and response has since been shown to be inconsistent with this mechanism (Simpson & Polvani 2016). However, our results, combined with previous work (Kidston & Gerber 2010), show that the relationship is present in three successive generations of coupled climate models (CMIP3, CMIP5 and CMIP6), and that it is also consistent with the change in the multi-model mean response. These results suggest that the relationship between mean state and jet response is robust, rather than being due to chance. Gaining a physical understanding of this relationship will be a necessary step to developing an emergent constraint on future shifts of the Southern Hemispheric jet (Klein & Hall 2015, Hall *et al* 2019).

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Data availability statement

The data that support the findings of this study are openly available. CMIP data are available from https://esgf-node.llnl.gov/projects/esgf-llnl/, and the values used to produce figures 1–4 are archived on https://doi.org/10.6084/m9.figshare.11670603.

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