Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology

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[1]   Future climate predictions by global circulation models in the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive indicate that the recent poleward shift of the eddy-driven jet streams will continue throughout the 21st century. Here it is shown that differences in the projected magnitude of the trend in the Southern Hemisphere are well correlated with biases in the latitude of the jet in the simulation of 20th century climate. Furthermore, the latitude of the jet in the models' 20th century climatology is correlated with biases in the internal variability of the jet stream, as quantified by the time scale of the annular mode. Thus an equatorward bias in the position of the jet is associated with both enhanced persistence of the annular mode, and an increased poleward shift of the jet. These relationships appear to be robust throughout the year except in the austral summer, when differences in forcing, particularly stratospheric ozone, make it impossible to compare the response of one model with another. These results suggest that the fidelity of a model's simulation of the 20th century climate may be related to its fitness for climate prediction. The cause of this relationship is discussed, as well as the implications for climate change projections. **Citation:** Kidston, J., and E. P. Gerber (2010), Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology, *Geophys. Res. Lett.*, *37*, L09708, doi:10.1029/2010GL042873.

1. Introduction

[2]   It is well established that there has been a poleward shift of the eddy-driven jet streams and embedded storm tracks during the last three decades [*Intergovernmental Panel on Climate Change*, 2007, and references therein]. Almost all of the global climate models (GCMs) contributed to the Coupled Model Intercomparison Project Phase 3 (CMIP3) predict that increasing greenhouse gas concentrations will cause the trend to continue throughout the 21st century, particularly in the Southern Hemisphere [*Meehl et al.*, 2007, and references therein]. There is, however, substantial disagreement between the models on the strength of the trend [e.g., *Yin*, 2005].

[3]   The poleward shift of the eddy-driven jet stream projects onto the positive phase of the annular mode [*Thompson and Wallace*, 2000], the leading mode of midlatitude climate variability. The annular mode characterizes the meridional vacillation of the jet stream on intraseasonal time scales. While models capture the gross features of internal variability, there is also considerable spread in the quality of its simulation by the CMIP3 models [*Gerber et al.*, 2008a]. In this paper, we connect the ability of a model to reproduce the observed mean state of the 20th century climate with its fitness in simulating both internal variability and the response to climate forcings.

[4]   The location and variability of the storm tracks have profound impacts on the hydrological cycle and regional climate of the midlatitudes. The position of the midlatitude barotropic jets, particularly in the Southern Hemisphere, may also play a critical role in regulating global climate on long time scales. The eddy-driven surface westerlies drive the Antarctic Circumpolar Current, and so influence the ocean's meridional overturning and the uptake of carbon in the southern ocean [*Toggweiler et al.*, 2006; *Anderson et al.*, 2009; *Toggweiler and Lea*, 2010]. The link between jet position and climate through carbon uptake has also been observed on intraseasonal timescales in connection with the Southern Annular Mode (SAM) [*Lovenduski et al.*, 2007]. As such, quantifying the magnitude of the poleward shift of the westerlies is important for accurate regional and long term global climate change forecasts, particularly for future generation models that attempt to model the carbon cycle.

2. Data and Methods

[5]   Output from the GCMs used in the World Climate Research Programme's (WCRP's) CMIP3 multi-model dataset [*Intergovernmental Panel on Climate Change*, 2007] is used. We analysed output from the pre-industrial control, 20C3M, and A2 scenario integrations for all models which archived both daily zonal winds as a function of height, and monthly zonal winds near the surface. This permitted use of 11 separate models, as listed in Figure 1a. The A2 ('business as usual') scenario was chosen for analysis of future climate as the large carbon dioxide forcing has the potential to overwhelm intermodel differences in other forcings, such as ozone recovery, and so differences in forcing should be smaller than in other scenarios. Only data for the Southern Hemisphere (SH) are analyzed. Data from the NCEP/NCAR reanalysis project [*Kalnay et al.*, 1996] from 1979–2007 is also utilized. The slight difference in the analysis period for the models and the reanalyses was allowed to improve statistical confidence and avoid pre-satellite era reanalyses. All of our key results are equivalent (but with less statistical confidence) if we restrict analysis to 1979–2000.

[6]   The latitude of the eddy-driven jet stream, Φ, is taken as the latitude of the maximum near-surface (10 m elevation)
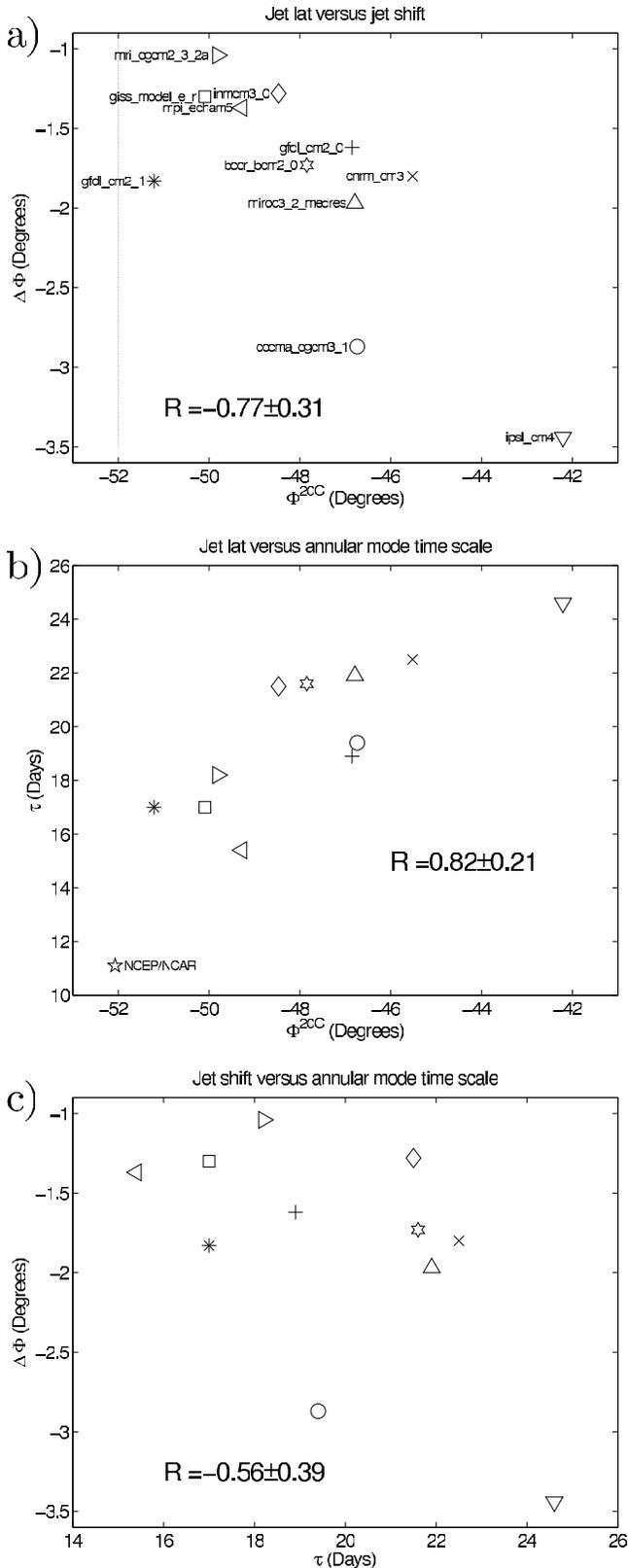
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time-mean zonal-mean zonal wind, $\bar{u}$. The surface winds reflect the convergence of westerly momentum aloft due to the meridional propagation of eddies away from the baroclinic source region, which is damped by friction near the surface [*Held*, 1975], and so serve as a good indicator of the

position of the barotropic jet streams. Φ was calculated by first linearly interpolating $\bar{u}$ onto the 2.5° NCEP/NCAR grid, and then fitting a quadratic to $\bar{u}$ between the two latitudes either side of the maximum.

[7] The annular mode definition is the same as in the work by *Gerber et al.* [2008a], i.e., the first empirical orthogonal function (EOF) of the zonal-mean geopotential height anomalies poleward of 20°S, latitude weighted to account for converging meridians toward the pole. Because daily geopotential height was not archived in the CMIP3 output, it was calculated from the zonal-mean zonal wind by assuming geostrophic balance. The climatology from which the anomalies were defined was the mean for each calendar day, after smoothing the daily data with a 31 day running mean. The principle component of the leading EOF (PC1) is the time series of the annular mode, and this was computed on each pressure level. The *e*-folding time scales, τ, were then computed at each level as in the work by *Baldwin et al.* [2003]. In addition to the seasonally dependent time scale, we computed an annual mean time scale without any seasonal decomposition. The time scales were then averaged from 850 hPa to 200 hPa to obtain one value characteristic of the entire troposphere. The *e*-folding period for any given model is the average from both the pre-industrial control and the simulation of 20th century climate (20C3M), and all ensemble members were included to improve statistical confidence.

3. Results

[8] We first consider the relationship between a model's 20th century climatology and its sensitivity to climate forcing in the A2 scenario. In Figure 1a we show the shift in the position of the annual mean SH surface westerlies over the 21st century, $\Delta\Phi$, as a function of the model's control climatology, measured by the latitude of the jet in 20C3M integration, Φ^{20C}. The plot reveals a strong relationship between Φ^{20C} and $\Delta\Phi$: models that place the jet toward the equator in the 203CM simulation tend to shift the jet further poleward under global warming. We note that the dashed line at 52 degrees marks the location of the observed 20th century wind maximum, indicating that the surface westerlies are too far equatorward in all of the models. The linear correlation coefficient between $\Delta\Phi$ and Φ^{20C} is -0.77 ± 0.33, where error corresponds to the 90% confidence limit.

[9] The relationship between jet position and response on a seasonal basis is explored in the first row of Table 1, where we repeat the correlation analysis of Figure 1a on

Figure 1. (a) The latitude of the Southern Hemisphere eddy-driven jet stream in the CMIP3 global circulation models 20C3M control simulations from 1960–2000, Φ^{20C}, versus the difference between Φ^{20C} and the latitude of the jet in the future A2 simulation during 2060–2100, $\Delta\Phi$. The shift in jet position $\Delta\Phi$ quantifies the respond of the circulation to climate forcing. The model name is to the right of each datum. (b) Φ^{20C} versus the *e*-folding time scale of the Southern Annular Mode, τ, which quantifies the persistence of the models internal variability. The NCEP/NCAR reanalysis datum was not included in the computation of the correlation coefficient. (c) τ versus $\Delta\Phi$. The uncertainty associated with the correlation coefficient in each figure corresponds to the 90% confidence interval.

Table 1. Correlation Between Jet Position Φ^{20C}, Shift $\Delta\Phi$, and Time Scale τ as a Function of Season

	SON	DJF	MAM	JJA	Annual[a]
corr(Φ^{20C}, $\Delta\Phi$)	−0.61	−0.08	−0.76	−0.81	−0.77
corr(Φ^{20C}, τ)	0.80	0.39	0.48	0.60	0.82
corr(τ, $\Delta\Phi$)	−0.31	−0.03	−0.21	−0.31	−0.56

[a]The annual mean correlations shown in Figure 1 are listed for reference.

seasonal mean values of the jet position and shift. The negative correlation between position and shift in all seasons suggests that the equatorward bias in the climatology increases the sensitivity to climate forcing throughout the year. The correlation, however, effectively disappears in austral summer. The breakdown of the relationship in summer is likely related to differences in model representation of the stratosphere, as the tropospheric jet stream is most sensitive to stratospheric conditions in this season. *Son et al.* [2008b] document that differences in ozone forcing can change the sign of the jet shift in the 21st century: the jet shifts equatorward in CMIP3 models where recovery of the ozone hole is simulated, but continues to shift poleward in models where ozone is kept constant at present day levels.

[10] The relationship between the model's 20th century climatology and the simulation of internal variability is shown in Figure 1a. There is a strong relationship between Φ^{20C} and the e-folding time scale of the annular mode, τ, with a correlation coefficient of 0.82 ± 0.21. The positive correlation implies that the natural variations of the jet tend to be more persistent in models where the jet is located more equatorward. A similar relationship between jet position and time scales of internal variability has been noted in studies of highly idealized GCMs [e.g., *Gerber and Vallis*, 2007; *Son et al.*, 2008a]. However, the fact that such a relationship is robust across a number of fully coupled GCMs has not previously been reported. The jet latitude and time scale based on NCEP-NCAR reanalysis is consistent with the model curve: the jet in the reanalysis is both poleward and less persistent than all of the models. The dynamics that give rise to the connection between the jet latitude and the time scale of internal variability are the subject of interest and ongoing investigation (e.g., E. A. Barnes et al., The effect of latitude on the persistence of eddy-driven jets, submitted to *Geophysical Research Letters*, 2010). Some speculations are offered in the discussion below.

[11] Taken together, Figures 1a and 1b suggest a relationship between $\Delta\Phi$ and τ. Figure 1c confirms this relationship; the jet position tends to shift more in response to greenhouse gas forcing in models that have a longer annular mode decorrelation time scale. As discussed by *Gerber et al.* [2008b] and *Ring and Plumb* [2008], correlation between the poleward shift of the jet (the response of the annular mode to external forcing) and the *e*-folding period of the annular mode (a measure of its unforced variability) is suggestive of fluctuation-dissipation behavior. Proper application of fluctuation-dissipation theory, however, requires knowledge of the correlation structure between a subset of modes sufficient to capture the dynamics [*Gritsun and Branstator*, 2007; *Majda et al.*, 2009]. Such an analysis is beyond the scope of this study. As discussed by *Leith* [1975], the simple fluctuation-dissipation relationship sug-

gested in Figure 1c applies only if the annular mode is uncorrelated with all other modes, and in the SH it has been shown that PC1 is not entirely independent of higher modes [*Monahan et al.*, 2009].

[12] The weak correlation between τ and $\Delta\Phi$ may also reflect uncertainty in the model time scales and differences in the forcing, ozone in particular. The seasonal breakdown of the relationship linking τ to Φ^{20C} and $\Delta\Phi$ shown in Table 1 suggests that both factors play a role. The correlation between time scale and jet position on a seasonal basis is robustly positive throughout the year, though notably weaker in austral summer. The correlation for any season, however, is weaker than in the annual mean, reflecting increased uncertainty in τ computed from shorter periods. *Gerber et al.* [2008b] document that τ is extremely slow to converge, and so more sensitive to sampling noise when averaged over shorter periods. The relationship between τ and $\Delta\Phi$ is consistently negative, but weaker at all times due to sampling errors, and effectively nonexistent in austral summer, when $\Delta\Phi$ is most affected by differences in stratospheric forcing.

[13] *Gerber et al.* [2008a] found no clear relationship between τ and $\Delta\Phi$ during NDJ across all A1B scenario integrations, finding a connection only when restricting the analysis to model pairs with identical forcing. In selecting NDJ to maximize differences in time scales, however, they inadvertently focused on the season when differences in the treatment of ozone forcing dominate the model response. Even when using the A2 scenario to amplify the signal to noise ratio, however, the correlations between τ and $\Delta\Phi$ in Table 1 are not statistically significant for any given season. Only by extending the analysis to the annual mean response does a statistically significant relationship between internal variability and the response to external forcing appear across multiple models, as shown in Figure 1c.

4. Discussion and Conclusions

[14] We have shown that biases in the latitude of the Southern Hemisphere eddy-driven jet stream in the CMIP3 simulations of the 20th century are well correlated with the response of the jet stream to enhanced greenhouse gas forcing predicted for the 21st century, as quantified by the magnitude of the poleward shift of the jet in the A2 scenario. There is also a robust correlation between biases in the latitude of the jet and a model's internal variability, as measured by the annular mode time scale. Although somewhat weaker, there is a statistically significant correlation between the annular mode time scale and the poleward shift of the jet.

[15] Analysis of these relationships on a seasonal basis suggests that the correlation between biases in the climatology, variability, and response of the jet to external forcing exist in all seasons except the austral summer. The breakdown in this season most likely reflects differences in the treatment of the stratosphere. As documented by *Son et al.* [2008b], the response of the jet stream in these months is particularly sensitive to the trends in ozone forcing. Recovery of the ozone hole over the course of the 21st century has the potential to reverse the poleward trend in the jet stream in this season. Ozone trends, however, were not specified for CMIP3 integrations and so handled differently by each modeling group. These differences likely overwhelmed the analysis of *Gerber et al.* [2008a], explaining why they were

unable to find a robust relationship between internal variability and the response to external forcing.

[16] The causes of these relationships are unclear. It is possible that the correlation between Φ^{20C} and $\Delta\Phi$ shown in Figure 1a can be explained in terms of basic geometric constraints. The jet stream simply has more room to shift poleward in models that begin with an equatorward bias, and so appears more sensitive to external forcing. In other words, the radiative forcing of the atmosphere ultimately sets a high-latitude limit on the location of the eddy-driven jet, and it is likely that models which are closer to this limit are unable to shift the jet very far. The correlations of the time scale τ with Φ^{20C} and $\Delta\Phi$, however, could point to a dynamical mechanism.

[17] The increase in the time scale of jet variability associated with an equatorward bias of the mean jet in Figure 1a may be caused by interaction between the eddy driven jet and the subtropical jet. As the eddy-driven jet moves equatorward it may interact with the subtropical jet in such a way that increases τ. Alternatively, it has been suggested that the dominance of annular modes is a result of the self maintenance characteristic of eddy-driven jets [*Gerber and Vallis*, 2007; J. Kidston et al., On the dynamical mechanism of mid-latitude jet stream variability and annular modes, submitted to *Journal of Climate*, 2010]. When the eddy genesis region is located towards the equator the jet could be more self-maintaining because the source region is narrower, increasing the momentum flux convergence. If the correlation between τ and $\Delta\Phi$ reflects a genuine relationship between internal variability and the response to external forcing, the bias in τ associated with the incorrect climatology becomes very important. Current work aims at addressing these hypotheses. that the dynamical response to increasing GHGs is strongly linear.

[18] The correlation between the jet latitude or internal variability and the jet shift (Figures 1a and 1c) implies that it is important for GCMs to have the correct climatology in order to make accurate predictions of global scale circulation changes. Comparison of NCEP/NCAR reanalysis with the GCMs in Figure 1a reveals that every GCM simulation of 20th century climate places the SH jet further equatorward than observed. The reanalysis annular mode time scale τ is also shorter, supporting the notion that the relationship between jet latitude and τ is a robust dynamical feature. This might imply that the GCMs overestimate the poleward shift of the jet stream. A linear fit of the of Φ^{20C} and $\Delta\Phi$ (Figure 1a) evaluated at the reanalysis jet location of $-52.1°$ predicts a poleward shift of the jet of $0.9 \pm 0.6°$ compared with the ensemble mean of the GCMs shown in Figure 1a of $1.8°$. The same analysis based on the reanalysis e-folding period (Figure 1c) predicts a poleward shift of $0.6 \pm 0.9°$.

[19] On shorter time scales, errors associated with jet position may be uncorrelated with other elements of climate change, including the surface temperature response. As next generation models begin to simulate the carbon cycle, however, errors in jet position may have a significant impact on global climate by influencing the meridional overturning circulation of the ocean, the ultimate sink of atmospheric carbon [*Toggweiler et al.*, 2006; *Anderson et al.*, 2009; *Toggweiler and Lea*, 2010]. In addition, regional climate simulations depend on large-scale GCMs as inputs, and errors

in the position of the jet streams and storm tracks have significant implications for the local hydrological cycle. Hence further improvement of GCM climatology is clearly warranted if we hope to make accurate predictions of future climate. While the simulation of cloud and aerosol feedbacks, and other physical processes that must be parameterized, may dominate the uncertainties associated with climate change, our results demonstrate that the simulation of large scale, midlatitude dynamics is also not yet fully adequate to accurately predict climate change.

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