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Testing a theory for the effect of latitude on the persistence of eddy-driven jets using CMIP3 simulations

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[1] The effect of latitude on the persistence of north–south shifts in the position of the jet is investigated in 37 CMIP3 integrations over four forcing scenarios. The persistence of the Southern Annular Mode (SAM) decreases when the mean jet is located closer to the pole. An asymmetry is shown whereby the equatorward-shifted jet is more persistent than the poleward-shifted jet. The sphericity of the earth inhibits wave breaking on the poleward flank of the jet which decreases the feedback between the eddies and the mean-flow and yields a wider, less self-sustaining jet. The results suggest a decrease in e-folding time of the SAM of 3 days per degree of poleward shift of the jet. The mechanism described explains why models with jets too far equatorward relative to observations over-predict the timescale of the SAM and suggests that these models will also exaggerate poleward shifts of jets associated with global warming. **Citation:** Barnes, E. A., and D. L. Hartmann (2010), Testing a theory for the effect of latitude on the persistence of eddy-driven jets using CMIP3 simulations, *Geophys. Res. Lett.*, *37*, L15801, doi:10.1029/2010GL044144.

1. Introduction

[2] The Southern Annular Mode (SAM) represents a meridional shift of the eddy-driven jet in the Southern Hemisphere, and current General Circulation Models (GCMs) overestimate its persistence [*Gerber et al.*, 2008]. *Kidston and Gerber* [2010] showed that the persistence of the SAM in the 20C3M World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) GCMs decreases as the mean jet is found closer to the pole, and *Son et al.* [2010] found a similar relationship in 17 chemistry-climate GCMs.

[3] *Barnes et al.* [2010] used a non-divergent barotropic vorticity field on the sphere to show that the presence of a turning latitude near the pole inhibits wave breaking on the poleward flank of the jet and increases equatorward wave propagation. This in-turn reduces the positive feedback between the eddies and the mean flow, causing the persistence of the annular mode to decrease as the midlatitude jet moves poleward. Similarly, they showed that equatorward-shifted annular mode events are more persistent than poleward-shifted annular mode events in their barotropic simulations, similar to the asymmetry in the phases of the North Atlantic Oscillation (NAO) as shown by *Barnes and Hartmann* [2010a] and *Woollings et al.* [2010].

[4] In this work, we demonstrate the mechanism of *Barnes et al.* [2010] for 37 CMIP3 GCM integrations. We find that the effect of latitude on the persistence of the annular mode is strongly linked to the suppression of wave breaking on the poleward flank of the jet. Similarly, we show an asymmetry between the phases of the SAM for the reanalysis as well as for all 37 GCM integrations and demonstrate how it is consistent with the results for the mean state.

2. Data

[5] This work uses model output from the WCRP's CMIP3 dataset [*Meehl et al.*, 2007]. We present four scenarios (five time periods) over 12 models when available: pre-industrial control (40 years), 20C3M (1961–2000; 40 years), A2 (2046–2065; 20 years), A2 (2081–2100; 20 years) and 2xCO2 (20 years). The reanalysis data set spans 1958–2001 (44 years) and was obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-40) [*Uppala et al.*, 2005]. To analyze the variability of the atmosphere in each integration, we define daily anomalies by removing a smoothed seasonal cycle computed as the annual mean plus the first four Fourier harmonics of the daily climatology.

[6] The latitude of the eddy-driven, midlatitude jet is defined as the latitude of the maximum zonal-mean zonal winds at the surface (10 m) [*Kidston and Gerber*, 2010]. For each integration, the SAM is defined as the leading empirical orthogonal function (EOF) of the anomalous monthly-mean sea-level pressure field poleward of 20°S, however, results are similar if the vertically-averaged zonal wind is used instead. The SAM index Z is defined by projecting daily sea-level pressure anomalies onto the SAM pattern. Z is normalized to have a standard deviation of one and a mean of zero by construction. We represent the persistence of the SAM as the e-folding time of Z, denoted as τ_Z, which is calculated by interpolating the autocorrelation function to find at what temporal lag it equals exactly $1/e$. 14 models were analyzed, and two were found to have $\tau_Z \geq 30$ days. The analysis of these two outliers shows very different behavior from the other 12 models, and since the other 12 models and the reanalysis show $\tau_Z \leq 23$ days, these two outliers are not included in the analysis.

[7] In 7 of the 12 models analyzed there are regions of missing data in the Southern Hemisphere in the lower troposphere (500–1000 mb) and we exclude these points from the averaging calculation. To ensure that this approximation is appropriate, we performed the analysis on the 5 models without missing data and found quantitatively similar results.

[8] Much of this analysis relies on demonstrating relationships in the data among different integrations. To

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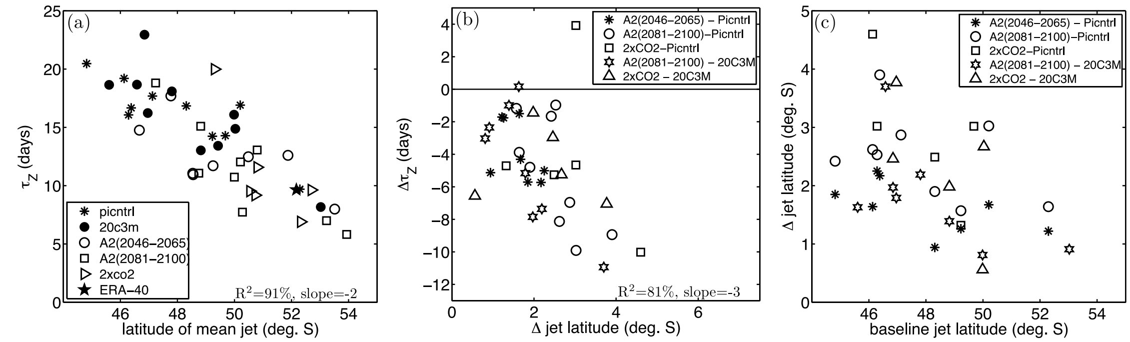

Figure 1. (a) The e-folding time of Z versus the latitude of the mean jet across scenarios and models. (b) The difference between scenarios of the e-folding time of Z ($\Delta\tau_Z$) versus the poleward shift of the latitude of the mean jet (Δ jet latitude). (c) Δ jet latitude between global warming and baseline scenarios versus the latitude of the jet in the baseline scenario.

quantify the strength of the linear relationship between two variables, we standardize the variables to unit variance and mean of zero and perform orthogonal least squares (OLS). The reanalysis data are not included in the OLS fit, and the percentage of total variance explained by the OLS fit (R^2) and its slope are displayed.

3. Results

[9] The main results of this study demonstrate the mechanism of *Barnes et al.* [2010] in the CMIP3 GCM integrations, whereby the persistence of a shifted eddy-driven jet decreases as the jet moves closer to the pole due to the decline of poleward wave-breaking and associated broadening of the jet. We present the results in two different contexts: (1) the relationship between the annular mode persistence and the mean jet latitude among different integrations, and (2) the asymmetry between the persistence of the phases of the annular mode in a single integration.

3.1. Mean State

[10] Figure 1a shows the e-folding time of Z versus the latitude of the mean jet. As demonstrated by *Kidston and Gerber* [2010] for the 20C3M integrations, we find that the relationship between the annular mode's persistence and the latitude of the jet holds over the 37 integrations for various forcing scenarios and models. Figure 1a demonstrates that the majority of the models place the midlatitude jet too close to the equator, and consistent with the mechanism of *Barnes et al.* [2010], these models also have annular modes that are too persistent when compared to the observed SAM (black star). Models that have the midlatitude jet at the latitude of the reanalysis also have similar e-folding times. This suggests that the discrepancy in SAM e-folding times between GCMs and observations found by *Gerber et al.* [2008] can be explained by the location of the mean jet. Although we use e-folding time here to quantify the persistence of the SAM, the conclusion is similar if we define the persistence of Z as the value of its autocorrelation function at a variety of lags.

[11] It remains to be seen whether the effect of latitude on τ_Z is large enough to be seen when the jet shifts within a single model. Figure 1b displays the intramodel change in e-folding time of the annular mode ($\Delta\tau_Z$) against the shift of the jet (Δ jet latitude) between different forcing scenarios. The integrations show a consistent decrease in τ_Z with a poleward shift of the midlatitude jet associated with climate change. Excluding the outlier that exhibits an *increase* of τ_Z, the OLS fit explains 81% of the variance and suggests that τ_Z decreases about 3 days for each degree of poleward shift of the jet.

[12] *Barnes et al.* [2010] show in a barotropic model that as the mean jet moves nearer to the pole, poleward wave breaking is suppressed as the waves more readily find a turning latitude. The waves propagate preferentially equatorward and the easterlies on the poleward flank of the jet are reduced due to the lack of wave breaking there. To demonstrate this property in the GCMs, we plot the profiles of the vertically-averaged, zonally averaged zonal winds composited for integrations with $\tau_Z \leq 13$ (13 integrations), $13 < \tau_Z < 17$ (14 integrations) and $\tau \geq 17$ (10 integrations) in Figure 2a, and similarly the profiles of the meridional propagation of the waves ($-\overline{u'v'}$) at 300 mb times $\cos^2\theta$ in Figure 2b. Since the τ_Z is linearly related to the latitude of the jet, one can also interpret these composites as averages over integrations with varying jet latitudes. For runs with $\tau_Z \leq 13$, the mean-jet profile is significantly broader, with stronger westerlies on the poleward flank compared to the profile for runs with $\tau_Z \geq 17$. Similarly, the plots of the meridional propagation of the waves at 300 mb (Figure 2b) show more equatorward propagation and less poleward propagation for integrations that are less persistent. Scatter plots over all integrations show similar relationships (not shown).

[13] The width of the mean jet is a function of jet latitude due to the reduction in poleward wave breaking. We define the wavenumber K^*:

$$K^* = \left(\frac{q_y \cos^2\theta}{u - c}\right)^{1/2}, \qquad (1)$$

where q_y is the meridional gradient of absolute vorticity and c is the phase speed of the wave. Wave number k turns when it reaches the latitude where $K^* = k$ and propagates toward larger values of K^*, breaking near its critical latitude (K^* is large) [*Hoskins and Karoly*, 1981; *Held*, 1983].

[14] While K^* is derived for barotropic waves and those in the atmosphere are inherently baroclinic, K^* gives insight into wave propagation near the pole. K^* is calculated at 300 mb for a phase speed of 11 m/s, a common phase speed

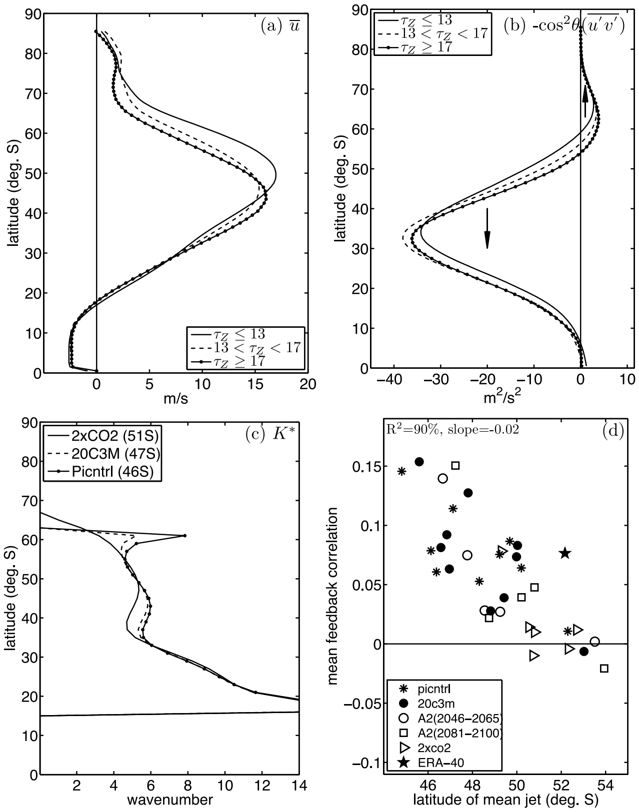

Figure 2. Profiles averaged over integrations with varying Z e-folding times (τ_Z) of the (a) vertically averaged zonal-mean zonal winds and (b) meridional wave propagation defined as the zonally averaged meridional flux of zonal momentum at 300 mb. (c) K^* times the radius of the earth at 300 mb for phase speed 11 m/s from 3 integrations of a single GCM. Only real values are plotted and latitudes of the mean jet are denoted in the legend. (d) The average cross-correlation over lags 0 to +20 days between Z and the eddy-forcing time series M vs the latitude of the mean jet.

of Southern Hemisphere synoptic waves [*Lee and Held*, 1993; *Berbery and Vera*, 1996]. The real part of K^* is plotted in Figure 2c for a single GCM, with integrations chosen such that their e-folding times coincide with the legends of Figures 2a and 2b. We choose to plot only a single model because averaging K^* over many integrations smooths out the critical latitudes of interest. The K^* profiles show that waves see a poleward critical latitude ($u = c$) when the mean jet is closer to the equator (jet position denoted in the legend). When the mean jet is at 51°S, waves reach a turning latitude before a critical latitude because $q_y \cos^2\theta$ decreases faster than u here. These waves turn and propagate equatorward, consistent with decreased poleward wave breaking.

[15] We have demonstrated that the increased jet width with latitude is due to a decrease in poleward wave propagation and decrease in wave breaking on the poleward flank of the jet due to the effect of latitude on K^* near the pole. A self-maintaining jet requires the export of eddy activity to the jet wings, such that the zonal winds at the latitude of eddy generation are locally enhanced, keeping the jet in place [*Robinson*, 2006]. The key to the self-maintenance is that the eddy momentum flux convergence be large and concentrated in the jet core. If waves see a turning latitude poleward of the jet, wave breaking decreases there, which broadens the convergence of momentum flux. If the eddy forcing region is broad it is less effective at reinforcing the jet at the jet core compared to nearby latitudes, and the jet is less likely to persist in its current position [*Hartmann*, 2007].

[16] To demonstrate the reduction in feedback between the eddies and the mean flow, we use time series analysis to quantify the feedback as done by *Lorenz and Hartmann* [2001]. The eddy-forcing time series M is defined as the projection of the upper-level eddy-forcing field onto the upper-level (200–400 mb) zonally-averaged zonal wind SAM pattern. *Lorenz and Hartmann* [2001] and *Barnes and Hartmann* [2010b] argue that the large correlations at positive lags (Z leads its forcing M) gives a measure of the feedback between the eddy forcing and the large-scale annular mode (correlation plots not shown). We average the cross-correlations between Z and M over lags 0 to +20 days for each integration and plot the results in Figure 2d. As the jet is located nearer to the pole, we confirm that the positive feedback between the eddies and the shifted-jet decreases with the decrease in annular mode persistence. The reanalysis shows a stronger feedback than integrations with similar jet latitudes, but the reasons for this are not examined here.

[17] This dependence of feedback strength on jet latitude can also give insight into the magnitude of future jet shifts. We plot the jet shift between global warming and baseline scenarios versus the latitude of the jet in the baseline scenario in Figure 1c. We consistently find that the jet shifts less under global warming when the initial jet is closer to the pole. Our mechanism suggests that jets nearer the pole are unable to shift further poleward since the poleward wave breaking is already suppressed and much of the sensitivity derives from suppression of poleward wave breaking. This also suggests that GCMs that place the jet too far equatorward may over-estimate the shift of the jet in future climates.

3.2. Asymmetry Between Phases

[18] We define high- (low-) phase annular mode events as days when Z is in its top (bottom) 5%, and these events are associated with a poleward (equatorward) shift of the jet. *Barnes and Hartmann* [2010a] and *Woollings et al.* [2010] demonstrated that high-phase NAO events are less persistent and exhibit a reduced feedback compared to low-phase events, and *Barnes et al.* [2010] demonstrated that this is true for the annular modes of a barotropic model. Figure 3a shows that for the GCM integrations, the fraction of low-phase events that persist for at least 8 days always exceeds the fraction of high-phase events that persist for at least 8 days in each integration and in the reanalysis. In addition, the decrease in persistence of the high-phase events appears to be strongly linked to the latitude of the mean jet.

[19] Figure 3b plots the meridional wave propagation at 300 mb for the two-phases averaged over all integrations (results are similar for individual integrations). Consistent with the results of the mean-state analysis (Figure 2b), the poleward-shifted jet (high-phase) exhibits less poleward wave propagation and more equatorward propagation. As in the mean state, less poleward wave breaking implies a wider jet, and we find that the width of the jet during high-phase

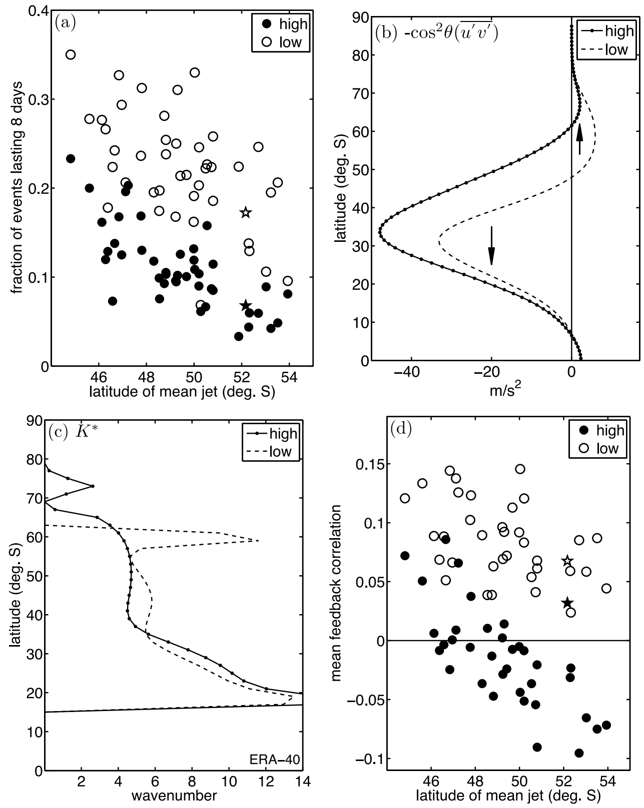

Figure 3. (a) The frequency of high- and low-phase events persisting for at least 8 days versus the latitude of the mean jet. (b) High- and low-phase meridional wave propagation at 300 mb averaged over all integrations. (c) K^* times the radius of the earth for the reanalysis at 300 mb for phase speed 11 m/s. Only real values are plotted. (d) The average cross-correlation over lags 0 to +20 days between Z and the eddy-forcing time series M for high- and low-phase events vs the latitude of the mean jet. In Figures 3a and 3d the star denotes reanalysis.

events is wider than that of low-phase events, and the widths of both increase as the mean jet moves poleward (not shown). Figure 3c plots the real part of K^* as defined in (1) for the wind profiles of the high- and low-phase SAM at 300 mb for a phase speeds of 11 m/s in the reanalysis. Plots are similar for the GCM integrations. Figure 3c shows that during low phase events, waves propagating from the center of the jet see a poleward critical latitude, and thus propagate poleward and break there. However, poleward of the jet during high-phase events, waves see only a decreasing K^* and turning latitude for all wavenumbers, so that all wavenumbers eventually turn equatorward without breaking. Consistent with this mechanism, high-phase SAM events exhibit a weaker eddy feedback that is strongly latitude dependent, as shown in Figure 3d, due the high-phase jet's proximity to the pole.

[20] In this section, we have demonstrated an asymmetry in the annular mode, whereby poleward-shifted jet events are less persistent than equatorward-shifted jet events and exhibit a weaker eddy feedback. Additionally, we have demonstrated that waves propagate preferentially equatorward during poleward-shifted events due to a turning latitude on the poleward flank of the jet. Thus, the effect of latitude on the eddy-mean flow interaction of the annular mode that can be seen by comparing integrations is also evident in the annular mode of a single integration, which gives rise to the asymmetry in the persistence of high- and low-phase events.

4. Conclusions

[21] This work analyzes the Southern Annular Mode (SAM) of 37 CMIP3 model integrations to demonstrate that when the eddy-driven jet is located closer to the pole, the positive feedback between the eddies and the mean-flow is reduced. This phenomena is due to the sphericity of the earth, which inhibits poleward wave breaking, consistent with the results of *Barnes et al.* [2010]. These results are presented in two contexts: (1) comparing mean states of each integration and (2) comparing poleward- and equatorward-shifted SAM events in a given integration. The main results of this study are as follows:

[22] 1. The positive feedback between the eddies and the mean-flow is reduced as the jet is found closer to the pole. This is consistent with a lack of polar wave breaking and a broader mean jet for integrations with more poleward jet locations.

[23] 2. In all integrations and the ERA-40 Reanalysis, equatorward-shifted annular mode events are more persistent than poleward-shifted events, consistent with the conclusions of the mean-state analysis.

[24] 3. Comparisons among forcing scenarios suggest a decrease in SAM e-folding time of approximately 3 days per degree of poleward shift of the jet.

[25] 4. The wave breaking and turning latitude mechanism described here also explains why models with mean jets too far equatorward relative to observations have unrealistically large persistences of their annular modes and also show larger poleward jet shifts in global warming scenarios.

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