Influence of eddy-driven jet latitude on North Atlantic jet persistence and blocking frequency in CMIP3 integrations

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[1] The distribution of daily North Atlantic jet latitude is analyzed in 45 CMIP3 integrations. It is demonstrated that models that place the jet equatorward of its observed position have more positively skewed jet latitude distributions, while models that correctly place the jet have symmetric distributions like that of the observations. The jet is shown to be more persistent at equatorward latitudes compared to poleward latitudes, consistent with previous findings in the Southern Hemisphere. There is a robust decrease in annual blocking frequency as the jet shifts poleward with global warming, with larger decreases seen for models with larger jet shifts, consistent with the effect of latitude on jet persistence. These results imply that model biases of jet latitude of 1°–2° could result in large differences in jet variability and frequency of extreme events predicted for the future. **Citation:** Barnes, E. A., and D. L. Hartmann (2010), Influence of eddy-driven jet latitude on North Atlantic jet persistence and blocking frequency in CMIP3 integrations, *Geophys. Res. Lett.*, *37*, L23802, doi:10.1029/2010GL045700.

1. Introduction

[2] It was recently demonstrated that the persistence of the midlatitude jet decreases as the jet is found closer to the pole [*Kidston and Gerber*, 2010; *Barnes and Hartmann*, 2010b]. *Barnes et al.* [2010] demonstrated that the presence of a turning latitude near the pole reduces polar eddy-wave breaking and decreases the strength of the positive eddy-feedback between the eddies and the jet, reducing the persistence of the jet in its poleward state. *Barnes and Hartmann* [2010b] showed that general circulation models (GCMs) tend to place the Southern Hemisphere midlatitude jet too far equatorward compared to observations, accounting for the over-prediction of the annular mode timescale [*Gerber et al.*, 2008]. In addition, they confirmed that the Southern Annular Mode exhibits an asymmetry, whereby the equatorward-shifted jet exhibits a stronger eddy feedback and is more persistent than the poleward-shifted jet.

[3] The North Atlantic Oscillation (NAO) describes the meridional shift of the North Atlantic eddy-driven jet, and it also exhibits an asymmetry in the persistence of its phases [*Barnes and Hartmann*, 2010a]. We suggest that the effects of latitude on the eddy-driven jet persistence are also present in the North Atlantic, and the work here addresses the question of whether GCM biases in the latitude of the Atlantic jet affect the persistence of the jet.

[4] Blocking anticyclones are strongly linked to the low-phase NAO, or equivalently, an equatorward shift of the midlatitude-tropospheric jet [*Shabbar et al.*, 2001; *Barriopedro et al.*, 2006; *Luo et al.*, 2007; *Croci-Maspoli et al.*, 2007; *Woollings et al.*, 2008]. We hypothesize that GCMs that place the Atlantic jet closer to the equator will have more Atlantic blocking events, consistent with *Scaife et al.* [2010] who found that blocking frequency among climate models is strongly dependent on the biases of the model's mean state. We address this question by comparing blocking frequency of 45 GCM integrations and relating it to the latitude of the eddy-driven jet.

2. Data and Methods

[5] The reanalysis dataset spans 1958–2001 (44 years) and was obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-40) [*Uppala et al.*, 2005]. This work uses model output from the WCRP's CMIP3 dataset [*Meehl et al.*, 2007]. We present three scenarios (four time periods) over 14 models when available: pre-industrial control (40 years), 20C3M (1961–2000; 40 years), A2 (2046–2065; 20 years) and A2 (2081–2100; 20 years), which together comprise 45 model integrations.

[6] We define a "jet latitude index" as the daily latitude of maximum low-level (mass-averaged 925–700 mb) zonal winds zonally averaged over the Atlantic sector (0°–60°W, 15°–75°N), as done by *Woollings et al.* [2010a] and we refer the reader there for more details. We focus on the wintertime (DJFM) North Atlantic jet (unless otherwise noted), and the resulting daily jet latitude time series will be denoted Z_{jet}. For the Southern Hemisphere analysis, a similar calculation is performed except winds at all longitudes are averaged and only 37 integrations are analyzed (see *Barnes and Hartmann* [2010b] for details). Jet variability is diagnosed using this jet latitude index rather than an annular mode index since jet latitude is consistent across models and climate scenarios while an annular mode index derived from empirical orthogonal functions can describe different variability in different models [*Miller et al.*, 2006].

[7] We identify blocking using the methodology introduced by E. A. Barnes et al. (A methodology for the comparison of blocking climatologies across indices, models and climate scenarios, manuscript in preparation, 2010), because it accounts for meridional displacements of the jet by searching for reversals of the geopotential height gradient near the latitude of seasonal maximum eddy kinetic energy. They demonstrate that proper comparison of blocking statistics across climate models and scenarios requires that the identified blocking location move with the jet stream, as the jet is known

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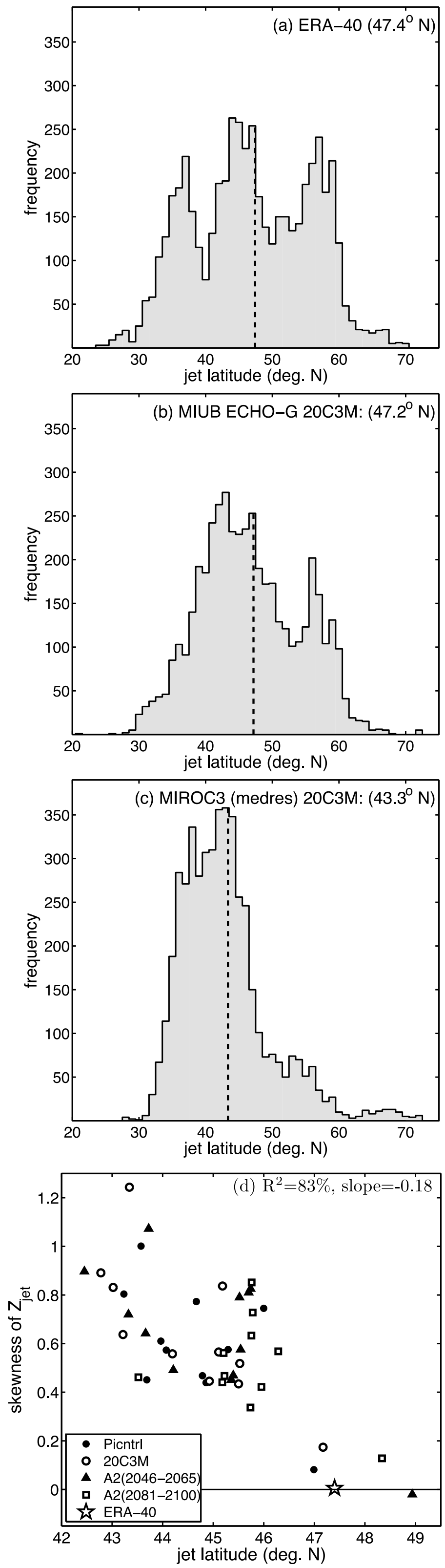

Figure 1. Histograms of Z_{jet} in the winter-time (DJFM) North Atlantic (0°–60°W, 15°N–75°N) for (a) the reanalysis (44 winters) and (b, c) two 20C3M integrations (40 winters) with different mean jet locations. Mean jet latitudes are denoted in the title of each panel and are plotted as dashed vertical lines. (d) Skewness of Z_{jet} for 45 GCM integrations versus the mean jet latitude.

to shift poleward with increased CO_2 forcing [*Miller et al.*, 2006; *Meehl et al.*, 2007].

[8] Due to data availability in the CMIP3 integrations, we use the 500 mb zonal wind instead of geopotential height to diagnose blocking. This variable was incorporated into the blocking definition by following *Scaife et al.* [2010] and converting the criteria for geopotential height to zonal wind using geostrophic and hydrostatic relationships and integrating between latitudes (see *Scaife et al.*'s [2010] Appendix for details).

[9] Lastly, to 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 is not included in the OLS fit, and the percentage of total variance explained by the OLS fit (R^2) and its slope are displayed in each figure.

3. Results

3.1. Distribution of Jet Latitude

[10] Figure 1a displays the histogram of Z_{jet} for the reanalysis, with mean jet at 47.4°N. As observed by *Woollings et al.* [2010a], the distribution of the observed eddy-driven jet latitude in the Atlantic displays a triple-peaked structure. They suggest that the equatorward peak is associated with the low-phase NAO, while the other two peaks are described by a superposition of the high-phase NAO and the East Atlantic pattern (elongation of the Atlantic jet stream).

[11] The reason for the triple-peaked structure of Z_{jet} is beyond the scope of this analysis. However, we analyzed the histograms of all 45 integrations (not shown) and found that GCM integrations with mean jets equatorward of observations have positively skewed jet distributions, while those with mean jets closer to the reanalysis exhibit a more symmetric structure. Two representative integrations (MIUB ECHO-G and MIROC3.2 (medres)) are shown in Figures 1b and 1c, and the results for all 45 integrations are summarized in Figure 1d where we plot the skewness of Z_{jet}. Here, we define the skewness of Z_{jet} as the statistical measure of asymmetry of the jet latitude time series about the mean jet latitude. All but one model (4 integrations) place the jet more than a degree equatorward of observations, and consistently, integrations with mean jets farther equatorward have a larger skewness of Z_{jet}. This implies that the variation of jet latitude becomes more symmetric as the mean jet moves away from the subtropics toward higher latitudes.

[12] We suggest that the distribution of jet latitude becomes less positively skewed for two possible reasons. 1) The subtropical jet on the equatorward flank prohibits the midlatitude jet from extending into the subtropics, so as the mean-jet shifts poleward, the distribution becomes more symmetric. 2) The poleward extent of the jet is limited by the reduction in eddy-feedback near the pole, caused by the lack of wave breaking there [*Barnes et al.*, 2010]. Thus, the poleward tail of the distribution grows around 57°N, but does not shift, as the mean-jet moves poleward.

[13] Comparing the distributions of jet latitude in the reanalysis with those of the CMIP3 integrations suggests that small deviations in the position of the mean jet are associated with significant changes in the day-to-day variability of the North Atlantic jet. In the next section we will

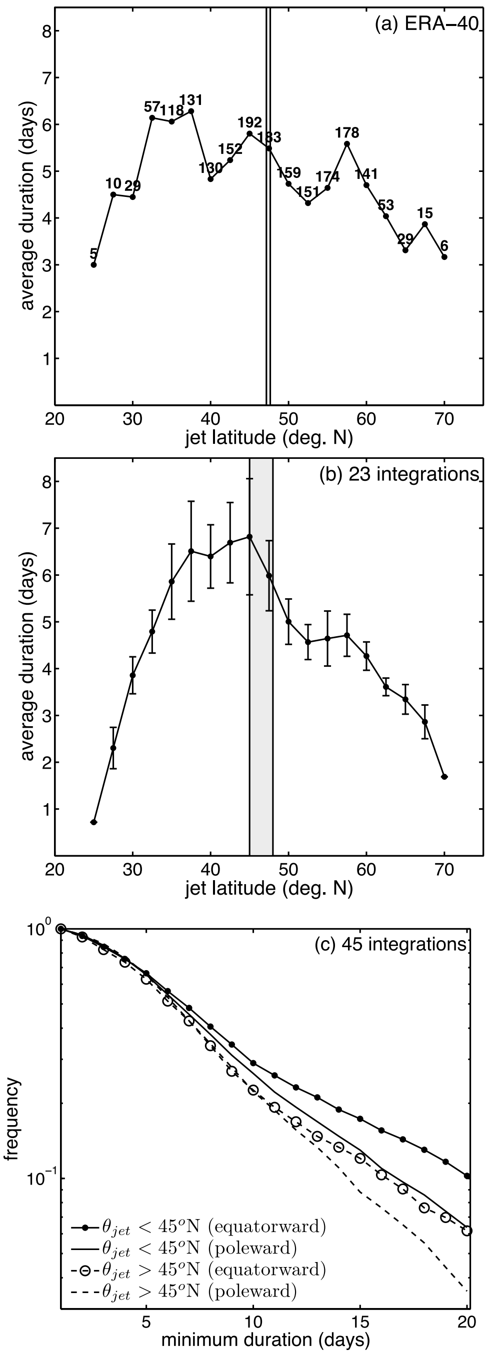

Figure 2. Average duration of Z_{jet} in a moving 5° latitude window for (a) the reanalysis with the number of events denoted above each point and (b) the average of 23 GCM integrations with mean jet latitudes between 45°–48°N. The latitude of the mean jet is denoted by gray shading. (c) The frequency of minimum duration of equatorward and poleward jet events in the GCMs defined for days when the jet is more than 5° from its mean latitude. The integrations are composited on whether the mean jet (θ_{jet}) is north (25 integrations) or south (20 integrations) of 45°N.

show that this is also true for the persistence of the jet at these latitudes.

3.2. Persistence of the Jet

[14] Here, we ask whether the North Atlantic jet is more persistent when found in the equatorward peak compared to the poleward peak of Figure 1a. We present a new duration statistic based solely on the daily position of the midlatitude jet. We calculate the average duration of the jet in a 5° latitude moving window, where the duration is defined by the number of consecutive days Z_{jet} is within the 5° bounds. An advantage of defining jet persistence in this way is that one does not rely on defining anomalies about a mean, which can give misleading results if the distribution is heavily skewed, as is the case in many of the model integrations.

[15] We plot the results for the reanalysis in Figure 2a, where the number of events averaged are plotted above each point, and the mean jet latitude is denoted by the vertical bar. Consistent with the results of *Barnes and Hartmann* [2010b] in the Southern Hemisphere, the poleward jet appears to be slightly less persistent than the equatorward jet which can be seen by the small negative slope of the duration curve. The three duration peaks also align with the peaks in the distribution of Z_{jet} (Figure 1a), suggesting that the jet not only frequents these latitudes most often, but is also the most persistent there.

[16] We calculate the same duration statistic for all 45 integrations and average together the curves of integrations with mean jets located between 45°–48°N (23 integrations), although the conclusions are the same if other latitude ranges are used. The results are plotted in Figure 2b, where the error bars denote plus/minus one standard deviation of the distribution of model means. The asymmetric shape of jet duration about the mean jet latitude range (vertical bar) demonstrates that the jet persists approximately two days longer at 40°N compared to 55°N.

[17] Previous results of *Barnes et al.* [2010] and *Barnes and Hartmann* [2010b] also suggest that the total persistence of the midlatitude jet is latitude dependent, where a mean-jet closer to the equator has more persistent fluctuations than a mean-jet nearer to the pole. To confirm this, Figure 2c displays the frequency of minimum duration of poleward- (equatorward-) shifted jet events defined as consecutive days when the jet is greater (less) than 5°(−5°) from its mean position. To show the effect of mean jet latitude on this asymmetry, we have averaged duration curves for integrations with mean jets north (25 integrations) and south (20 integrations) of 45°N.

[18] Two main results are displayed in Figure 2c: 1) The equatorward-shifted jet (circles) is always more persistent than poleward-shifted jet (lines). 2) As the mean jet is located closer the pole, the persistence of the poleward-shifted jet decreases (compare solid line to dashed line) and the persistence of the equatorward-shifted jet decreases (compare solid circles to open circles). This implies that the effect of latitude on the North Atlantic eddy-driven jet is to decrease the persistence of the jet as it moves closer to the pole, both in the mean, and for deviations about the mean of a given integration.

3.3. Blocking Trends

[19] Previous studies have found evidence for blocking frequency to decrease with global warming, although they

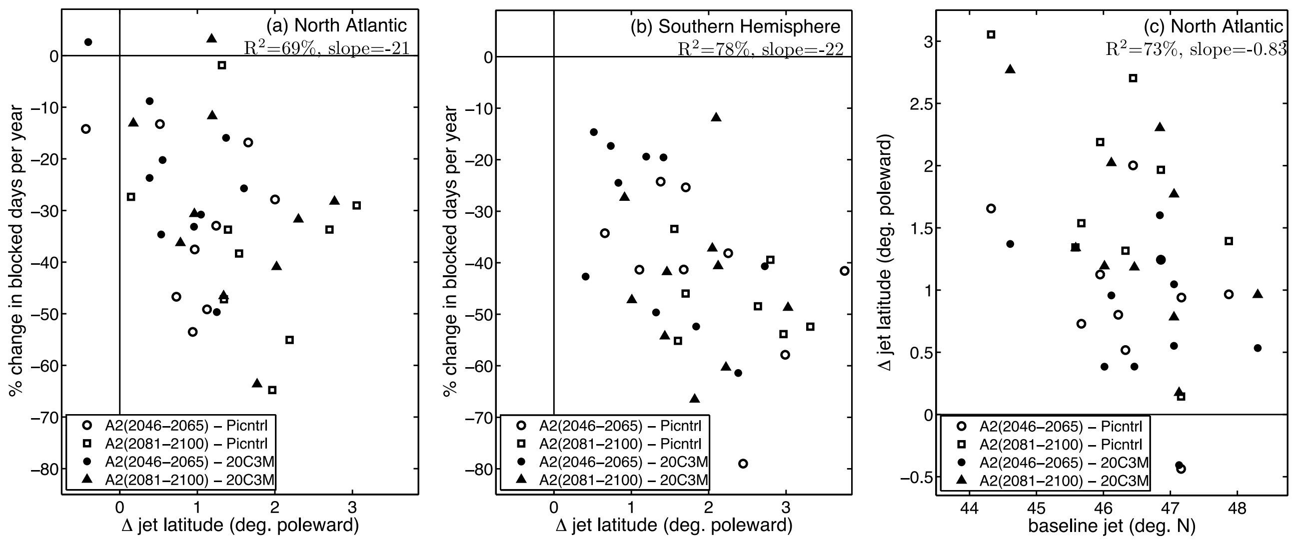

Figure 3. The percentage change between scenarios of the mean number of blocked days per year versus the poleward shift of the jet in the (a) North Atlantic (0°–60°W) and (b) Southern Hemisphere. (c) Annual change in jet latitude between global warming and baseline scenarios versus the latitude of the jet in the baseline scenario for the North Atlantic.

disagree on whether the duration of extreme blocking events will increase or decrease [*Sillmann and Croci-Maspoli*, 2009; *Matsueda et al.*, 2009]. In addition, *Scaife et al.* [2010] and *Woollings et al.* [2010b] demonstrated that the mean-state biases of the CMIP3 20C3M integrations were a main contributor to errors in blocking climatology when compared to the ERA-40 reanalysis. Figure 2c suggests that as the *mean jet* moves closer to the pole, equatorward-shifted jet events will be less persistent, and so, it is possible that blocking frequency and/or duration will also decrease, since Atlantic blocking events are strongly associated with an equatorward-shifted jet [*Shabbar et al.*, 2001; *Barriopedro et al.*, 2006; *Croci-Maspoli et al.*, 2007; *Woollings et al.*, 2008].

[20] We analyze blocking frequency in the CMIP3 integrations to show that differences in model blocking frequencies are a function of the mean jet, and are consistent with the dependence of jet persistence on jet latitude shown in the previous section. Only 14 days on average are blocked each winter, so to increase our sample, we analyze blocking frequency during all four seasons but note that the conclusions are the same if only the winter season is used.

[21] Figure 3a shows the percentage change between scenarios of the number of days there is a block in the Atlantic (0°–60°W) versus the poleward shift of the jet. All but three instances show a poleward shift of the jet and a decrease in the number of Atlantic blocking days, where the best fit line has a slope of −21% per degree shift of the jet.

[22] Analyzing the day-to-day variability of the North Atlantic jet offers some challenges due to the effects of nearby continents and the tilt of the midlatitude jet across the basin. To confirm that the blocking result is robust, we look at the Southern Hemisphere where the jet is more annular in structure and the effect of latitude on the persistence of the jet has been previously demonstrated [*Kidston and Gerber*, 2010; *Barnes and Hartmann*, 2010b]. Figure 3b shows that all integrations show a poleward shift of the Southern Hemisphere jet with increased CO_2 concentration, and that all models exhibit a decrease in blocking frequency of approximately 22% per degree shift of the jet, consistent with the North Atlantic.

[23] Since models with baseline jets closer to the equator tend to shift more with increased CO_2 concentration, as shown in Figure 3c, we suggest that these models will also exaggerate the change in Atlantic blocking frequency by about 20% per degree error in jet latitude.

[24] Interestingly, our hypothesis suggests that the reanalysis has fewer blocked days than most integrations, due to its poleward jet location. However, most studies have found that models consistently *underestimate* current blocking frequency, and we have found a similar result here (not shown) [*D'Andrea et al.*, 1998; *Scaife et al.*, 2010; *Woollings*, 2010]. This inconsistency suggests that although the dynamics of the jet are strongly linked to jet latitude, additional considerations are needed to fully explain the differences between the GCMs and the reanalysis.

[25] Our analysis did not find a significant change in mean blocking duration with jet latitude. However, our blocking definition requires a minimum duration of 5 days, and the average blocking duration is 8 days. Thus, the change in blocking duration is mainly seen as a change in blocking frequency, as events that last less than 5 days no longer contribute to the calculation of the average duration. We note that we do find a decrease in maximum blocking duration with jet latitude increase in future climates (not shown) similar to the findings of *Matsueda et al.* [2009].

4. Conclusions

[26] An analysis of North Atlantic jet latitude in 45 CMIP3 GCM integrations showed that models with mean jets equatorward of the reanalysis jet have positively skewed jet latitude distributions and more persistent jet-shifts than integrations with jets closer to the pole. In addition, nearly all models showed a decrease in blocked days per year with a poleward shift of the jet, consistent with the decrease in duration of equatorward-shifted jet events. These results stress the importance of models correctly positioning the

eddy-driven jet, since both day-to-day jet variability and extreme event frequency are highly sensitive to jet latitude.

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