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Effect of latitude on the persistence of eddy-driven jets

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[1] An asymmetry in the persistence of the eddy-driven jet is demonstrated, whereby the equatorward-shifted (low-phase) jet is more persistent than the poleward-shifted (high-phase) jet. The asymmetry is investigated by stirring the non-divergent vorticity equation on the sphere and is shown to arise due to the sphericity of the earth, which inhibits poleward wave breaking when the jet is at high latitudes. This spherical effect becomes increasingly important as the mean jet is positioned at higher latitudes. The persistence of the annular mode decreases as the mean jet moves closer to the pole due to the decreased persistence of the high-phase state, while the low-phase state exhibits similar persistence regardless of the jet position. These results suggest that with the expected poleward shift of the jet due to increasing greenhouse gases, the annular mode's total persistence will decrease due to a decrease in the persistence of the high-phase. **Citation:** Barnes, E. A., D. L. Hartmann, D. M. W. Frierson, and J. Kidston (2010), Effect of latitude on the persistence of eddy-driven jets, *Geophys. Res. Lett.*, *37*, L11804, doi:10.1029/2010GL043199.

1. Introduction

[2] The annular modes are found in both hemispheres and exhibit variability associated with a meridional shift of the eddy-driven jet [*Hartmann and Lo*, 1998; *Thompson and Wallace*, 2000]. The North Atlantic Oscillation (NAO) is a local manifestation of the Northern Annular Mode over the North Atlantic, and recent work has documented an asymmetry in the persistence of its phases, with the equatorward-shifted jet (low-phase) being more persistent than the poleward-shifted jet (high-phase) [*Barnes and Hartmann*, 2010a; *Woollings et al.*, 2010]. *Barnes and Hartmann* [2010b] showed that the Southern Annular Mode (SAM) behaves similarly to the NAO during austral summer, and more recent work has confirmed that the SAM also exhibits an asymmetry in the persistence of its phases. *Gerber and Vallis* [2007] and *Kidston and Gerber* [2010] demonstrated that the persistence of the annular modes in both idealized and CMIP3 general circulation models (GCMs) is linearly related to the latitude of the mean jet. In this work, we stir the vorticity in a non-divergent barotropic model on the sphere and investigate the persistence and asymmetry of the resulting annular mode of the jet to study mechanisms for these observed and modeled features.

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2. Model and Parameters

[3] *Vallis et al.* [2004] showed that stochastic stirring in a barotropic model can produce a jet that exhibits the variability of an annular mode. We discuss the important parameters and equations for the model setup but refer readers to *Vallis et al.* [2004] for details.

[4] The non-divergent vorticity equation is integrated on the sphere,

$$\frac{\partial \zeta}{\partial t} + J(\psi, \zeta + f) = \mathcal{S} - r\zeta - \kappa\nabla^4\zeta, \tag{1}$$

where $\mathcal{S}$ denotes the parameterized eddy stirring, r is the damping parameter and κ is the diffusion coefficient for parameterizing the removal of enstrophy at small scales. We stir the vorticity field over a range of wavenumbers by modeling the stirring as an Ornstein-Uhlenbeck stochastic process to represent baroclinic eddies in the real atmosphere. For each combination of total spectral wavenumber n and zonal spectral wavenumber m, the stirring $\mathcal{S}_{mn}$ at each time step is calculated using the recursive relationship

$$\mathcal{S}_{mn} = \left(1 - e^{-2dt/\tau}\right)^{1/2} Q^i + e^{-dt/\tau}\mathcal{S}_{mn}^{i-1}, \tag{2}$$

where Q^i is a real number chosen uniformly between $(-\mathcal{A}, \mathcal{A}) \times 10^{-11}$, where $\mathcal{A}$ is termed the stirring strength and τ denotes the decorrelation time of the stirring.

[5] We define the parameters of the model similarly to *Vallis et al.* [2004], but state the values here for reference. The model is run at a resolution of T42, with a time step of 3600 seconds; the diffusion coefficient κ is chosen such that the highest resolved wavenumber is damped at 1/10th of a day. The memory of the stirring is set to $\tau = 2$ days. The runs presented here have a damping coefficient $r = 1/6$ day^{-1}.

[6] We stir the model over a range of total wavenumber n, with $8 \leq n \leq 12$. Like *Vallis et al.* [2004], zonal wavenumbers less than 4 are not forced. The results are qualitatively unchanged with $4 \leq n \leq 14$ (not shown). Finally, to mimic meridionally-confined storm tracks in the real atmosphere, a spatial mask is applied to the stirring field by multiplying the global stirring field by a Gaussian curve in the meridional direction centered at latitude θ_0 with standard deviation σ_θ, such that the resulting stirring is strongest at θ_0 and decreases toward the equator and pole.

[7] Each run is spun up for 500 days and then integrated an additional 8000 days for analysis. This paper focuses on runs where all parameters are held fixed except the latitude of the center of stirring θ_0, which is varied every 2.5° between 20° and 47.5° with a fixed σ_θ = 12°. The stirring strength $\mathcal{A}$ is

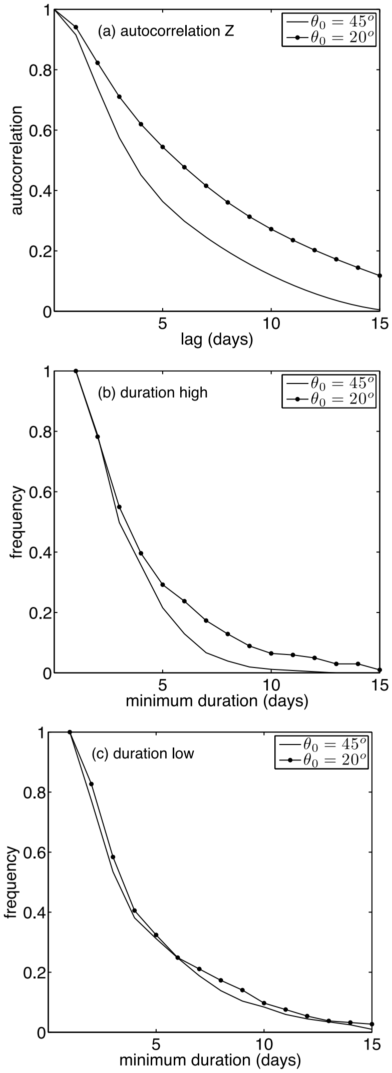

Figure 1. (a) The autocorrelation of the annular mode time series Z for two runs of varying stirring latitude θ_0. (b and c) Frequency of high- and low-phase events that persist for at least a certain number of days, where a high- (low-) phase event is defined for values in the top (bottom) 10% of Z.

fixed at 7.0; however, we will discuss the results and implications of varying this parameter in section 5.

3. Asymmetry in the Barotropic Model

[8] To first order, the jet follows the eddy-stirring such that the mean jet for each run is found within 1–4.5 degrees of θ_0, with maximum zonal-mean zonal winds of about 11 m/s. The annular mode of each run is defined as the leading EOF of the daily zonally-averaged zonal winds, which in every case represents a 3°–5° meridional shift of the jet, and in runs with more poleward jets, a strengthening as well. The normalized principal component time series of the annular mode is denoted by Z and has a mean of zero and a standard deviation of one.

[9] Figure 1a shows the autocorrelation of Z for two of the runs, which we define throughout the text as the "NO ASYM" run (θ_0 = 20°) and the "ASYM" run (θ_0 = 45°). We find that the annular mode of ASYM is significantly less persistent than that of the NO ASYM run. Figures 1b and 1c show the frequency of high- and low-phase events that persist for a minimum duration, where the duration of a high- (low-) phase event is defined as the number of consecutive days Z is in its top (bottom) 10%. (Results are qualitatively similar for 20%). This duration statistic defines the persistence of the jet during extreme annular mode events. We see that the persistence of the high-phase jet varies between the two runs while the persistence of the low-phase is similar in both.

[10] To show this is true for all 12 runs, Figure 2a plots the autocorrelation of Z at 7 days (ϕ_{7Z}) against the frequency of minimum duration at 7 days of the high (ϕ_{7h}) and low (ϕ_{7l}) phases (values are obtained from Figure 1). The persistence of the low-phase changes little with variations in ϕ_{7Z}, and we see that the differences in the persistence of Z are mainly due to differences in the persistence of the high-phase, poleward-shifted jet. Figure 2b plots the ratio of ϕ_{7h} to ϕ_{7l} against the latitude of the mean jet, with ϕ_{7Z} denoted in parenthesis. When the jet is closest to the equator, the high- and low-phases of the annular mode persist for similar lengths of time (ratio close to one). However, when the jet is in the midlatitudes, the high-phase is less persistent than the low-phase, consistent with the decrease in the persistence of Z.

4. Two Runs in Detail

[11] We explore the reason for the asymmetry in persistence by focusing on the NO ASYM and ASYM integrations. The results described here are consistent with all integrations where the stirring latitude is varied; for brevity we choose to show only these two cases. For all plots, high- (low-) phase composites are defined as averages over days when Z is in its top (bottom) 10%. The zonal wind profiles for NO ASYM and ASYM are plotted in Figure 3a and 3b. We define the location of the mean jet as the latitude of mean maximum zonal-mean zonal winds, and the jet is located at 22° for NO ASYM and 49° for the ASYM case. For both NO ASYM and ASYM, the low-phase jet exhibits easterlies in both the low and high latitudes while the high-phase jet lacks easterlies toward the pole in the ASYM run. In addition, for ASYM the high-phase jet represents a poleward shift similar to that of the low-phase (4°), but also a strengthening of the jet by 5 m/s.

[12] The convergence of eddy-momentum flux will be termed the "eddy forcing", and its composites exhibit profiles (not shown) nearly identical to the wind profiles in Figures 3a and 3b as expected since the momentum fluxes drive the wind. From Figures 3a and 3b we see that for NO ASYM, the wind profiles are very similar, implying divergence of eddy-momentum flux on the flanks of the jets and convergence at the jet core. However, the wind profiles vary significantly between the two modes of the ASYM run. The low-phase profile looks similar to that found in NO ASYM, just shifted poleward. For the high-phase jet in the ASYM run we see the wind anomaly spread over a wide latitudinal range, with no easterlies on the poleward flank, implying a broad region of eastward zonal wind acceleration by the eddies, with no region of deceleration poleward of the jet maximum.

[13] Figure 2c shows the width of the eddy forcing (full-width at half-maximum) for the time-mean, high- and low-phase events. It is clear that the forcing during high-phase events is broader than during low-phase events and the width increases as the mean-jet moves polewards. Note that as the time-mean jet moves poleward it and its associated wave

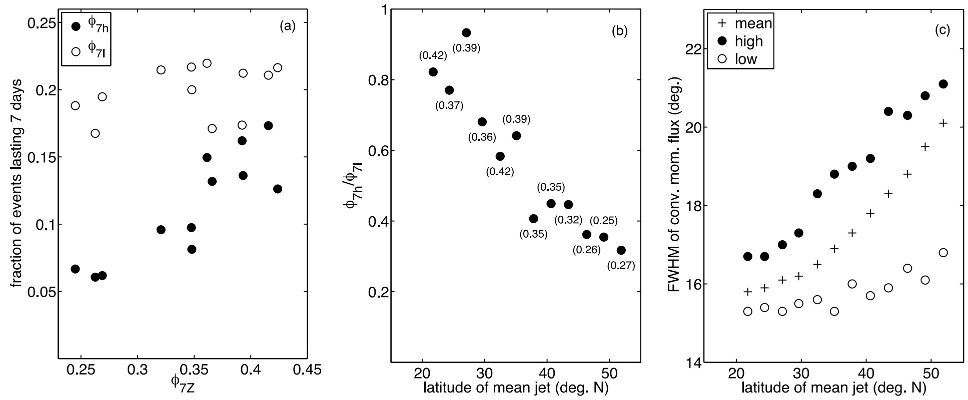

Figure 2. Results for 12 runs with varying stirring latitudes. (a) The frequency of high- (ϕ_{7h}) and low-phase (ϕ_{7l}) events persisting for at least 7 days versus the autocorrelation of the run's annular mode time series Z at a lag of 7 days (ϕ_{7Z}). (b) The ratio of ϕ_{7h} and ϕ_{7l} versus the latitude of the mean jet, with ϕ_{7Z} plotted adjacent to each point. (c) The full-width at half-maximum (FWHM) of the eddy forcing for the time mean and composites of the top (high) and bottom (low) 10% of annular mode events.

driving also broaden, so that the differences exhibited between the high and low phases are completely consistent with the changing structure of the mean jet as it moves poleward. We will next show that the broad profile of eddy forcing and lack of easterly winds poleward of the ASYM high-phase jet are due to a lack of poleward wave-breaking.

[14] We plot the meridional propagation of the waves defined by the y-component of the EP-flux vector ($-\overline{u'v'}$) in Figures 3c and 3d during each phase. Positive (negative) values denote poleward (equatorward) wave-propagation, and thus equatorward (poleward) momentum flux. Waves in NO ASYM propagate both equatorward and poleward during both phases of the jet, the profiles appearing as meridional shifts of one another. However, in the ASYM integration, no net poleward wave propagation occurs during the mean or high-phase states, and it is only when the jet is shifted equatorward that poleward wave propagation is observed.

[15] The lack of poleward wave breaking when the jet is near the pole is consistent with basic linear wave propagation arguments [*Matsuno*, 1970; *Hoskins et al.*, 1977; *Hoskins and Karoly*, 1981; *Held*, 1983]. Barotropic waves on the sphere with zonal wavenumbers $k < K^*$ can freely propagate away from their source but cannot propagate for $k > K^*$, where

$$K^* = \left(\frac{\hat{\beta}}{\hat{u} - c_\omega}\right)^{1/2}, \qquad (3)$$

where $\hat{u}$ is the angular velocity $u/\cos\theta$, $\hat{\beta}$ is $\cos\theta$ times the meridional gradient of the absolute vorticity and c_ω is the angular phase speed of the wave. Waves propagate toward larger values of K^* and break near their critical latitude when $\hat{u} = c_\omega$ (K^* is large). In addition, the latitude at which $k = K^*$ acts as a turning point for the wave, such that the wave is refracted back toward larger K^* [*Hoskins and Karoly*, 1981; *Held*, 1983].

[16] We plot K^* averaged over phase speeds 0–4 m/s in Figures 3e and 3f. For NO ASYM, the profile of K^* is similar for both phases, with a local minimum centered at the jet and larger values of K^* on either side, indicative of wave propagation away from the jet maximum and wave-breaking on both flanks of the jet. Consistent with our previous diagnostics this is also true for K^* during ASYM low-phase events. However, during ASYM high-phase events K^* is zero at 70° N, and thus all wave numbers eventually turn back equatorward without breaking. A maximum of K^* occurs equatorward of the high-phase jet center, suggesting that waves propagate and break equatorward of the jet, consistent with Figure 3d.

[17] We can explain the effect of latitude on the K^* profiles by noting the importance of $\cos\theta$ in the definition of (3), mainly that it is the angular velocity and $\cos\theta$ times the meridional gradient of absolute vorticity that are important. K^* goes as the $\cos\theta$ and so decreases toward the pole, causing waves to turn equatorward when $k = K^*$. The importance of a turning latitude near the pole has been previously noted. [*Hoskins et al.*, 1977] use the linear barotropic vorticity equation on the sphere to show that on average, there is net equatorward wave propagation due to the decrease in β toward the pole. [*Hoskins and Karoly*, 1981] put a realistic Northern Hemisphere background flow into a five-layer baroclinic model and demonstrated that waves with zonal wavenumbers larger than 4 were trapped equatorward of the northern flank of the jet due to this spherical effect. What is new here is the importance of this geometric effect for eddy-zonal flow interaction in annular modes.

[18] In this simple barotropic model, the eddies force the mean flow, but the zonal winds determine where the waves break by setting the critical latitudes. Thus, a feedback is present whereby the zonal wind profile determines the location of momentum flux divergence. If wave breaking on the poleward flank of the jet is weakened, then the eddy forcing is broad like the source of eddy vorticity. In this instance, the eddy-momentum flux convergence is not concentrated in the jet core, and so the jet is not as efficiently reinforced in its shifted position, causing a weaker feedback and shorter decorrelation time of the jet excursion.

[19] Consistent with the results shown here, we find the same relationships between the asymmetry and total persistence of the annular mode when we vary the stirring strength $\mathcal{A}$ keeping the stirring latitude fixed at 45°. A larger $\mathcal{A}$ causes the asymmetry between the two phases of the annular mode to increase (and vice versa). In addition, varying the damping

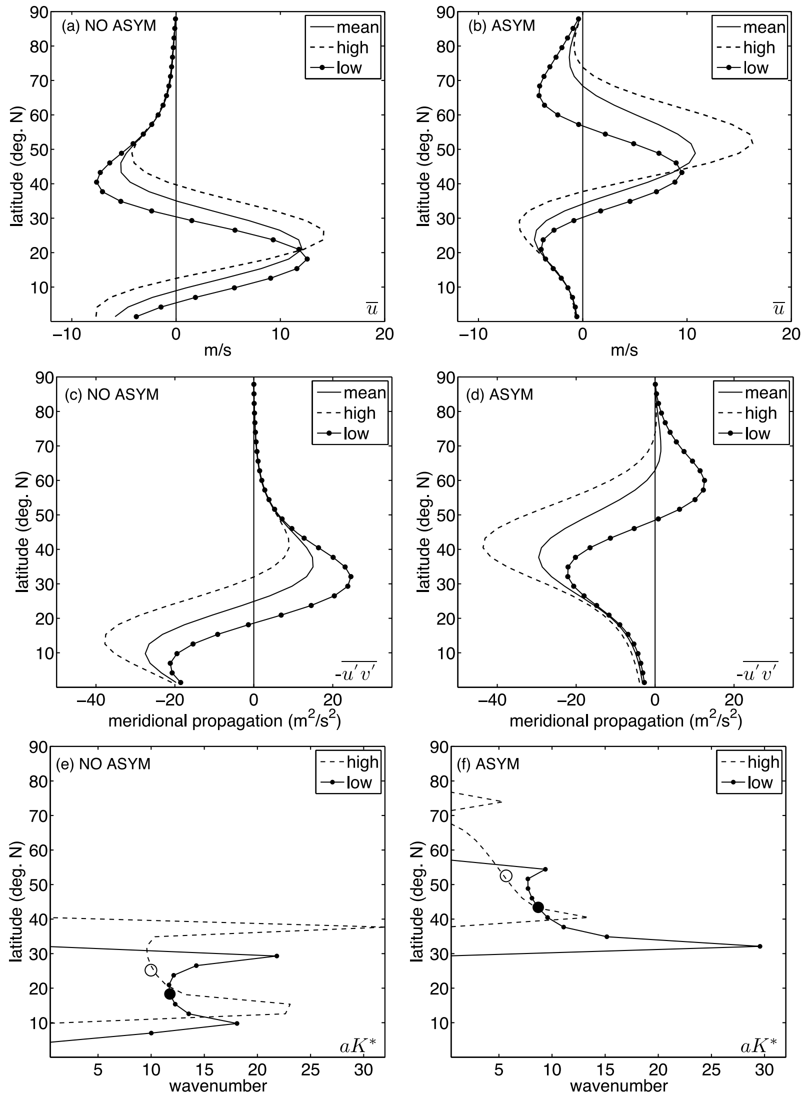

Figure 3. Results for the NO ASYM and ASYM free model runs, where the high- and low-phase are composites defined by the top and bottom 10% of the annular mode index *Z*. (a and b) Zonal-mean zonal wind profiles and (c and d) the meridional propagation of the eddies defined by the zonally averaged meridional flux of zonal momentum $(-\overline{u'v'})$. Positive (negative) values imply poleward (equatorward) wave propagation. (e,f) K^* defined in (3) times the radius of the earth *a* for the high- and low-phase zonal wind profiles averaged over phase speeds 0–4 m/s. The large open (filled) circle denotes the position of the high- (low-) phase jet where the calculation was centered.

parameter *r* produces similar relationships, since the forcing magnitude and damping parameter jointly determine the wave activity and the waves' ability to propagate.

5. Conclusions

[20] The non-divergent, fully non-linear, barotropic vorticity equation is integrated on the sphere. The vorticity field is stirred to produce a jet with variability associated with a meridional shift of the jet, and the persistence of this variability is investigated for stirring centered at different latitudes. The asymmetry in wave breaking and the presence of a poleward turning latitude become more pronounced as the stirring latitude is moved from the equator to the pole. The conclusions of this study are as follows.

[21] 1. The latitude of the jet strongly affects the persistence of the poleward-shifted phase of the annular mode: the closer the jet to the pole, the less persistent. The equatorward-shifted jet persists for similar timescales for a range of latitudes.

[22] 2. The asymmetry in phase persistence is due to the presence of a turning latitude near the pole brought about by the sphericity of Earth, which prevents waves from breaking there, inhibiting the positive eddy-mean flow feedback when the jet is shifted poleward.

[23] The results found in this simple case of the vorticity equation on the sphere are also seen in the observations. *Barnes and Hartmann* [2010a] found a lack of feedback between the eddies and the jet in the polar lobe of the North Atlantic Oscillation (NAO), consistent with a lack of wave-breaking there. In addition, they found that the equatorward-shifted jet of the NAO is significantly more persistent than the poleward-shifted jet, and plots of **E**-vectors [see *Barnes and Hartmann*, 2010a, Figure 9] show that the poleward-shifted jet lacks poleward wave propagation, while the equatorward-

shifted jet exhibits wave propagation in both meridional directions, consistent with a larger forcing of the shifted jet by the eddies during this phase [see *Barnes and Hartmann*, 2010a, Figure 10].

[24] The results presented have important implications for climate and climate change research, as shifts of the eddy-driven jet are associated with changes in weather and, if they persist, will affect the climate.

[25] 3. Climate models that disagree on the latitude of the mean jet will also disagree on the persistence of the annular modes as well as the amount of asymmetry between the two phases. This conclusion is supported by [*Kidston and Gerber*, 2010], who found that the e-folding times of the annular modes in 11 CMIP3 models were linearly related to the latitude at which each model positioned the 20th Century mean jet.

[26] 4. The expected poleward shift of the eddy-driven jet due to increasing greenhouse gases may cause the asymmetry between the two phases of the annular modes to increase. The extreme phases of the annular modes are associated with significant regional climate variability, and a change in the distributions of the annular mode phases could alter the nature of this variability. Current work aims to determine how important this might be.

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