

## Relationship between eddy-driven jet latitude and width

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[1] The relationship between the latitude and the width of the eddy-driven jet is examined. We find that there is strong correlation between jet latitude and jet width, with jets located towards the pole being broader. The broadening of the jet with increased latitude appears to be a consequence of increased barotropic instability. When the jet is located towards the pole, the reduced planetary vorticity gradient is more easily overwhelmed by the negative relative vorticity gradient on the flanks of the jet, and this allows a horizontal shear instability to occur. Enstrophy diagnostics show that when the condition of a negative vorticity gradient is met, the effects of barotropic instability are indeed more prevalent. **Citation:** Kidston, J., and G. K. Vallis (2010), Relationship between eddy-driven jet latitude and width, *Geophys. Res. Lett.*, 37, L21809, doi:10.1029/2010GL044849.

### 1. Introduction

[2] In the mid-latitudes of both hemispheres there are equivalent-barotropic eddy-driven jets associated with surface westerly winds. The location of these westerlies is important for regional climate because they are associated with mid-latitude eddies, which dictate regional weather. The westerlies are also important for global climate in that they drive the currents and vertical motion in the ocean.

[3] The surface westerlies arise because of the convergence of westerly momentum aloft. Eddies transport zonal momentum in the opposite meridional direction to their propagation and so westerly momentum converges into latitudes that are a net source of eddies. Baroclinic instability is the primary source of eddy activity in the atmosphere [Vallis, 2006], and so to first order the location of the westerlies is determined by the location of baroclinic instability.

[4] Here we show that there is a strong correlation between the latitude and the width of the eddy-driven jet stream, and we argue that barotropic instability becomes an increasingly important source of eddy activity as the jet moves poleward, and this broadens the jet. Previous studies have considered barotropic instability of the zonal-mean flow in the winter stratosphere [e.g., Hartmann, 1983; Randel and Lait, 1991] and concluded that it is important. Here we suggest that similar processes may be important for the tropospheric jet stream when it is located towards the pole.

### 2. Data and Methods

[5] In order to assess the generality of the results, output from three different classes of model is used, so providing a hierarchy of complexity. In decreasing order of complexity,

the three classes of models are: (i) comprehensive general circulation models, (ii) a primitive equation dynamical core with simplified forcing, and (iii) an incompressible barotropic model on the sphere. We now describe these in a little more detail.

[6] For the comprehensive general circulation models (GCMs) we use those in the World Climate Research Programme's (WCRP's) CMIP3 multi-model dataset [Meehl *et al.*, 2007]; these represent a near state of the art in climate modeling, and are the models that most closely approximating reality. Only data for the Southern Hemisphere (SH), where zonal averages are most physically meaningful, are analyzed.

[7] The dry dynamical core developed at the Geophysical Fluid Dynamics Laboratory is used as a simplified GCM. This is a spectral model run with T42 horizontal resolution and twenty vertical levels evenly separated in fraction of surface pressure ( $\sigma$ ). The only forcings are Newtonian thermal damping; Rayleigh friction below  $\sigma = 0.7$ ; and hyperviscosity to remove energy at small scales. The control experiment was set up as was done by Held and Suarez [1994]. The control values of the e-folding time for the frictional time scale at the surface ( $k_f$ ) and the thermal damping time scale ( $k_T$ ) were 1 and 40 days respectively. Twenty eight further experiments were conducted where the only changes were to either the  $k_f$  or  $k_T$ . In fifteen of the experiments  $k_f$  was set between 0.5 and 2.0 days, and in thirteen of the experiments  $k_T$  was set between 20 and 80 days.

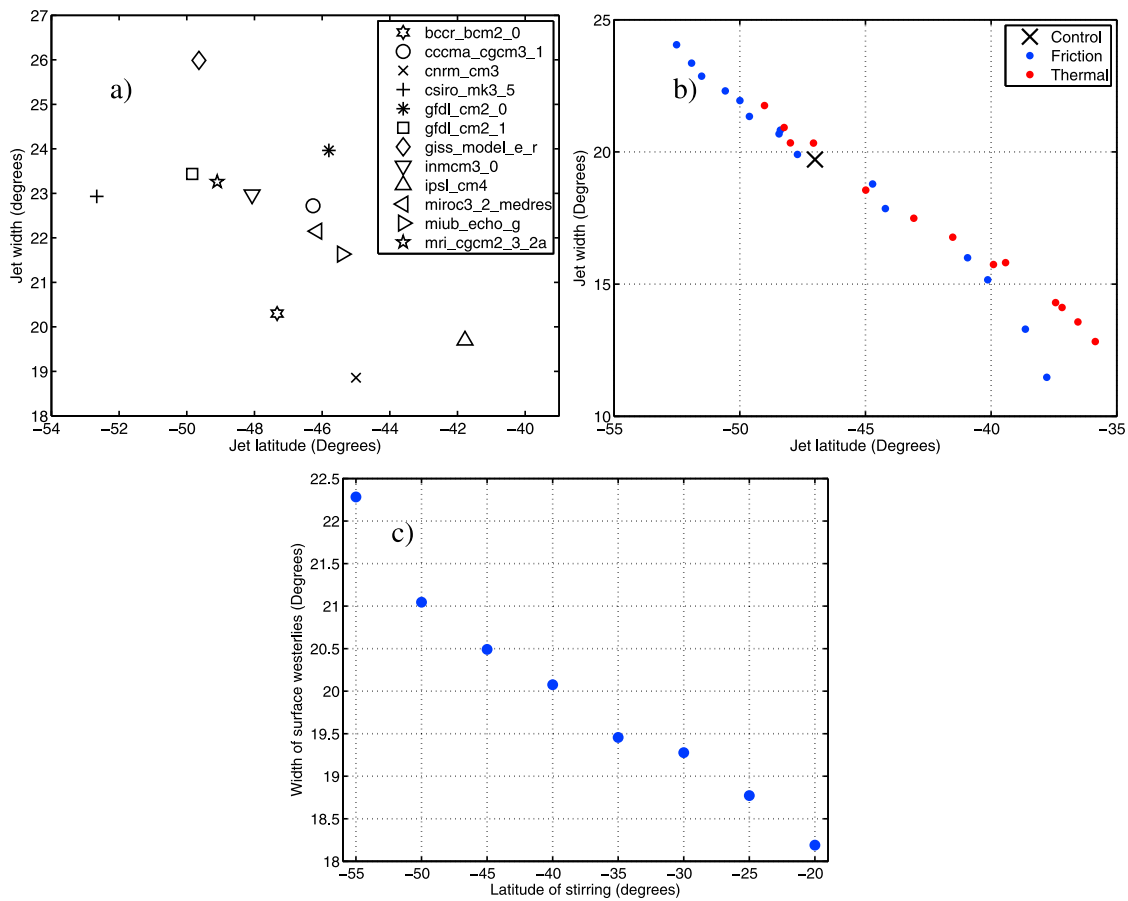
[8] A barotropic model on a sphere is our third class of model. The equation that is integrated is

$$\zeta_t + J(\psi, f + \zeta) = S - r\zeta - \kappa\nabla^4\zeta \quad (1)$$

The left-hand side gives the material derivative of the absolute vorticity (the notation is standard). The first term on the right-hand side is the stochastically stirred vorticity source, and is the same as that of Vallis *et al.* [2004]; only wavenumbers 4-12 were stirred, and waves with zonal wavenumber ( $k$ ) less than 4 were not stirred. A Gaussian mask with a half-width of 12 degrees was applied to meridionally localize the stirring. The sink terms on the R.H.S represent hyperviscosity and linear damping, necessary to produce a statistically steady state.

[9] The latitude of the eddy-driven jet stream ( $\Phi$ ) is taken as the latitude of the maximum surface (near-surface for the GCMs) time-mean zonal-mean zonal wind ( $\bar{u}$ ). The value of  $\Phi$  is calculated by fitting a quadratic to  $\bar{u}$  between the two latitudes either side of the maximum. The width of the jet is the separation between the latitudes at which  $\bar{u} = \max(\bar{u})/2$ . These latitudes are calculated by evaluating a 3rd order polynomial that is fitted to  $\bar{u}$  at all latitudes on the appropriate side of the maximum where  $\bar{u}$  is above zero. Although they are written in Cartesian coordinates, all diagnostics are calculated taking full account of the Earth's sphericity. For the

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**Figure 1.** The relationship between jet latitude and jet width for a range of models (see text). (a) Inter-model variability of the pre-industrial control runs for the GCMs submitted to the CMIP3 report (see text). (b) Output from the simplified baroclinic GCM (see text) for the control (cross), and runs where the strength of the surface friction or thermal damping were altered (blue and red, respectively). (c) Runs of the stirred-barotropic model where the stirring latitude was altered.

simplified GCM, diagnostics are presented for the pressure-weighted vertical average, where vertical braces ( $\dots$ ) denote vertical averaging.

### 3. Results

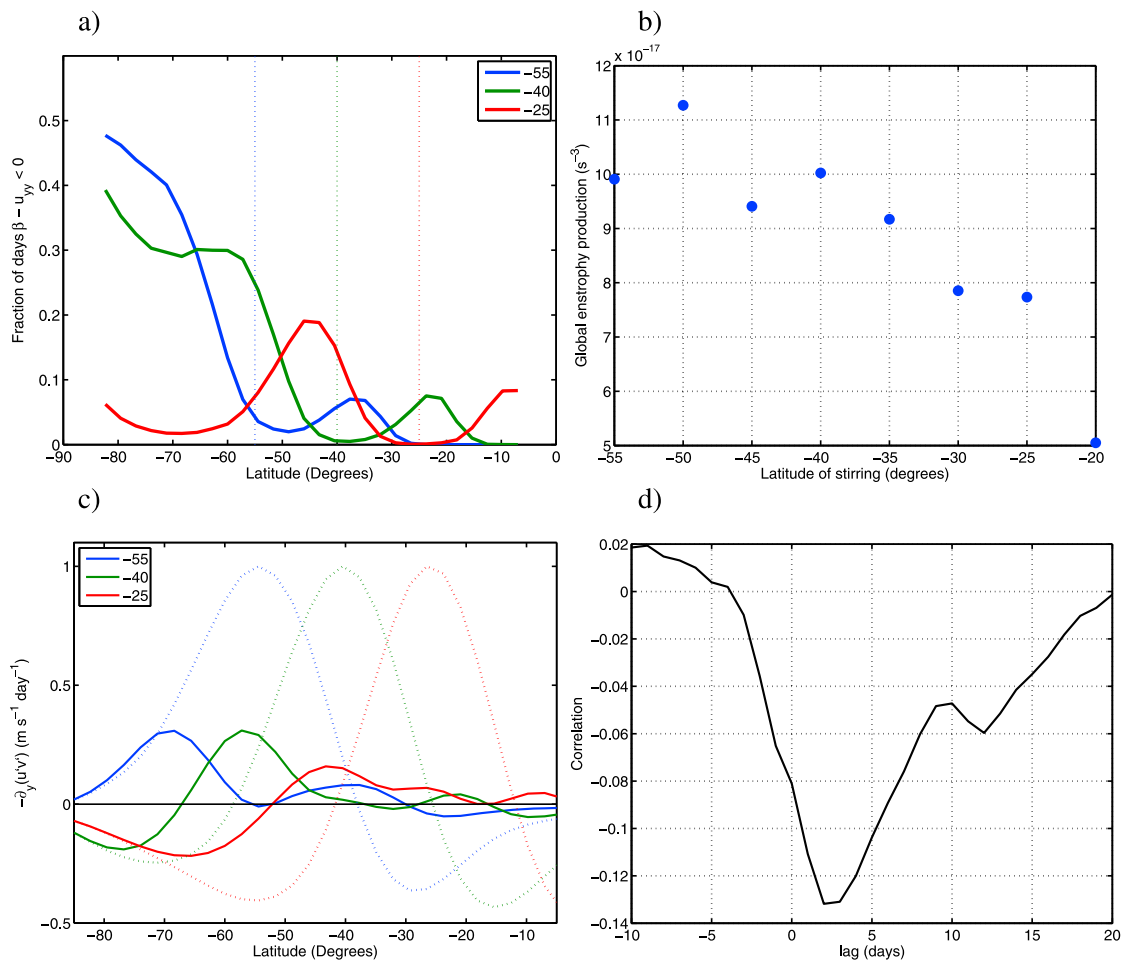
[10] The relationship between the latitude and the width of the jet is shown in Figure 1. For all of the models, there is a negative correlation; when the westerlies are further poleward the jet is broader. The fact that the relationship is manifest across the broad range of models suggests that it is robust, although as we might expect the relationship is less clean in comprehensive GCMs. The relationship has been implicitly noted by *Kidston et al.* [2010], who found that the latitudinal width of the momentum flux convergence was broader for jets located towards the pole in the simplified GCM, and by *Barnes et al.* [2010] who found similar results in a stirred-barotropic model. The response is noticeably weaker in the barotropic model than the GCMs. The reason for this is discussed in the final section. Given the degree of similarity between the different datasets, the underlying dynamics in the relatively simple stirred-barotropic model will first be investigated.

[11] If barotropic instability is more likely to occur when the jet is located towards the pole, the relationships in Figure 1 would be expected. It is well known that barotropic instability

acts to broaden a jet [e.g., *Pedlosky*, 1979]. A necessary condition for barotropic instability is that the absolute vorticity gradient ( $\beta^* = \beta - \bar{u}_{yy}$ , where the two terms on the R.H.S. are the planetary and relative vorticity gradients respectively) must change sign somewhere in the domain [*Kuo*, 1951]. On the flanks of a westerly jet,  $-\bar{u}_{yy}$  is negative. Thus on the flanks of a jet that is sufficiently sharp, it is possible that  $\beta^*$  be negative. The magnitude of  $\beta$  is smaller towards the pole, and so for a given jet profile it is more likely that the conditions for barotropic instability will be met when the jet is located towards the pole.

[12] To investigate whether this process is relevant, the probability of the daily-mean  $\beta^*$  being negative is shown in Figure 2a for three different runs with the stirred-barotropic model. The vertical dashed line shows the central latitude of the stirring and roughly corresponds to the jet latitude. In all of the runs there is a non-zero probability of  $\beta^*$  being less than zero on the flanks of the jet. However, the likelihood of  $\beta^*$  being negative increases as the stirring moves polewards.

[13] One way of confirming that barotropic instability is more prominent for jets located towards the pole is to consider the behavior of waves that were not stirred into existence. As noted above, a mask is applied to the stirring so that no enstrophy is imparted to waves with  $k = 1-3$ , and so they exist only because of a mean-flow instability or an inverse cascade. Barotropic instability can be diagnosed by consid-



**Figure 2.** Diagnostics of barotropic instability for the stirred-barotropic model: (a) the probability that the total vorticity gradient ( $\beta^*$ ) is negative for three different runs. The central latitude of the stirring is indicated the legend. (b) The globally averaged value of enstrophy production (see text) for waves with zonal wavenumber ( $k$ ) three. (c) The time-mean momentum flux convergence ( $-\partial_y(\overline{u'v'})$ ) for all wavenumbers (dashed lines), and  $-\partial_y(\overline{u'v'})$  for waves with  $k = 1-3$  (solid lines) for three different runs. (d) Correlation coefficient between the time-series of the domain-averaged eddy kinetic energy for waves with  $k = 1-3$  and  $\beta^*$  on the poleward-flank of the jet (see text) as a function of lead and lag.

ering the generation of enstrophy from the mean flow. The linear counterpart of equation (1) (ignoring the terms on the R.H.S.) can be manipulated to give  $\partial_t \zeta'^2 = 2\beta^* \partial_y(\overline{u'v'})$ , where the overbars denote zonal averages and the primes departures therefrom. If (in the global mean) momentum converges into regions of negative vorticity gradient then waves are growing at the expense of the mean flow, and are acting to broaden the jet. Figure 2b shows the globally averaged  $\beta^* \partial_y(\overline{u'v'})$  for  $k = 3$  as a function of the latitude of the stirring. For all of the runs  $\beta^* \partial_y(\overline{u'v'})$  is positive, indicating that there is a production of enstrophy from the mean flow. When the stirring is closer to the pole, the increase in enstrophy is more pronounced, indicating that the flow is more unstable to  $k = 3$  fluctuations.

[14] That waves with  $k = 1-3$  act to broaden the jet can be seen more clearly by considering the momentum flux convergence of these waves. Figure 2c shows  $-\partial_y(\overline{u'v'})$  as a function of latitude for all waves (dashed lines) and for waves with  $k = 1-3$  (solid lines), for three runs. For each run, waves with  $k = 1-3$  have a local maximum in  $-\partial_y(\overline{u'v'})$  on the flanks of the total  $-\partial_y(\overline{u'v'})$ . These local maxima act to broaden the jet, and have been used in previous studies to diagnose bar-

otropic instability [Randel and Lait, 1991]. They are coincident with the regions where  $\beta^*$  is most likely to become negative (Figure 2a). Relative to the total momentum flux convergence, the broadening of the jet due to waves with  $k = 1-3$  is stronger when the stirring is located towards the pole.

[15] Another insight into whether the jet is unstable can be gained by considering the time-dependence of the flow. If waves with  $k = 1-3$  grow due to barotropic instability, it is expected that their eddy kinetic energy (EKE) would increase following a reversal of  $\beta^*$ . Figure 2d shows the correlation coefficient between the time-series of the domain-averaged EKE for waves with  $k = 1-3$  ( $T_{1-3}$ ), and  $\beta^*$  on the poleward flank of the jet, for the run with the stirring located at  $-55^\circ$ . The time-series of  $\beta^*$  ( $T_{\beta^*}$ ) was averaged from  $-56^\circ$  to  $-66^\circ$ . The most negative correlations occur when  $T_{1-3}$  lags  $T_{\beta^*}$  by 2–3 days. I.e. following a reduction in  $T_{\beta^*}$ ,  $T_{1-3}$  increases. This is what is expected if waves with  $k = 1-3$  grow due to barotropic instability.

[16] When the same set of experiments are run with weaker stirring, so that the jet is much weaker (with a maximum value of less than half a meter per second), the relationship between jet latitude and width is not observed (not shown). This

suggests the increase in jet width towards the pole (for realistic speeds) is not simply due to linear wave propagation characteristics on the sphere. Thus it appears that the reason that the jet is broader in this model when it is located towards the pole is that barotropic instability is more prevalent, as is expected due to the reduction in  $\beta$ .

[17] The question of whether the same dynamics are relevant to the simplified GCM is now addressed. Figure 3a shows the probability that the pressure-weighted vorticity gradient ( $|\beta^*|$ ) is negative. The metric is shown for the ensemble-mean of the 29 runs (black line), and those runs where the jet latitude was in the lowest/highest 50th percentile (blue/red line). The runs located towards the pole are generally those where frictional damping was reduced, or thermal damping was increased (not shown). In all of the ensemble-means there is non-zero probability that  $|\beta^*|$  is negative on the poleward flank of the jet, and the probability is higher for runs with the jet is located towards the pole. Some of the runs with the jet located further poleward have regions of  $\beta^* < 0$  in the time-mean in the upper troposphere (not shown).

[18] In the simplified GCM, similar enstrophy production analysis as shown in Figure 2b for the barotropic model has been conducted on the pressure-weighted, vertically averaged flow. As such the analogous enstrophy production equation for the simplified GCM is  $0.5|\zeta^2|_r = |\beta^*| \partial_y (\overline{u'v'})$ . The global-mean of this metric, summed over zonal wavenumbers 2–4 is shown in Figure 3b. (Barotropic instability tends to be dominated by low zonal wavenumber disturbances [Hartmann, 1983], with higher wavenumbers being baroclinically unstable). For both sets of runs there is more likely to be enstrophy production from the mean flow as the jet moves towards the pole. The correlation coefficient between jet latitude and global enstrophy production from the mean flow is  $-0.81$  and  $-0.86$  for the runs where  $k_T$  and  $k_F$  were altered respectively. Many of the runs show negative enstrophy production, which indicates that the dominant enstrophy transfer is not directly from the mean flow. Nonetheless, as the jet moves poleward, it is more likely that waves with  $k = 2-4$  grow at the expense of the mean flow and act to broaden the jet. For runs where the jet is very far poleward there is net enstrophy production from the mean flow, indicating that barotropic instability is dominant for these waves.

[19] Barotropic instability can also be inferred from the behavior of the climatology of  $-\partial_y (\overline{u'v'})$ , shown in Figure 3d for the control run. For the control run,  $-\partial_y (\overline{u'v'})$  due to  $k = 4$  and  $k = 5$  exhibit the double maximum characteristic of barotropic instability, with eddy source regions on the flanks of the jet. Waves with  $k = 6$  and higher (not shown) exhibit a single local maximum in the mid-latitudes, which suggests that their energy source is baroclinic instability.

[20] For waves with  $k = 1-5$ ,  $-\partial_y (\overline{u'v'})$  is shown in Figures 3d and 3e for the ensemble-mean of the runs with the jet latitude in the lowest/highest 50th percentile ((e)/(f) respectively). The value of  $-\partial_y (\overline{u'v'})$  summed over all wavenumbers is also shown, and all values have been normalized to enable comparison between the individual wavenumbers and the total. Relative to the total, the acceleration due to waves with  $k = 1-5$  is more important for jets located towards the pole. These waves exhibit the profile of  $-\partial_y (\overline{u'v'})$  expected from barotropic instability, acting to broaden the jet. Thus it appears that barotropic instability does occur in this model, and it is more prominent when the

jet is located towards the pole, as is expected due to the reduction in  $\beta$ .

#### 4. Discussion and Conclusions

[21] It has been shown that there is a strong correlation between the latitude and the width of eddy-driven jets, with jets located towards the pole being broader. This relationship was manifest in a stirred-barotropic model, an idealized dry dynamical core, and in the inter-model variability across a range of state of the art GCMs used in the CMIP3. The underlying dynamics were investigated in the barotropic model and idealized GCM. The absolute vorticity gradient is more likely to reverse when the jet is located towards the pole, which is a necessary condition for barotropic instability. Furthermore there was more enstrophy production from the mean flow when the jet was located towards the pole for zonal wavenumbers relevant to barotropic instability. In the stirred-barotropic model, waves with zonal wavenumbers that were not stirred (and thus may indicate barotropic instability) acted to broaden the jet more effectively when the jet was located towards the pole. Time-series analysis of the EKE showed that long waves tend to increase in energy following a reduction in the vorticity gradient, as expected in barotropic instability. In the simplified GCM, the momentum flux convergence associated with zonal wavenumbers 1–5 exhibited the characteristic double maximum associated with barotropic instability, and these waves exerted more influence on the mean flow when the jet was located towards the pole. Thus it appears that enhanced barotropic instability broadens jets that are located towards the pole. Further work is needed to determine whether the same dynamics are quantitatively relevant to the same relationship observed in the CMIP3 intermodel variability.

[22] The variation of width with latitude was much greater in the full GCMs and the simplified GCM than in the stirred-barotropic model. In the barotropic model the primary cause of the change in jet latitude was the change in the prescribed stirring latitude, and the width of the prescribed stirring region was constant. Conversely, in the simplified GCM the primary cause of the change in jet latitude was a shift in the latitude of baroclinic instability due to wave-mean flow interaction. It is possible that there is a feedback between the jet latitude and the jet width, leading to a larger variation of jet width with latitude in the GCMs than the stirred-barotropic model. For example, following the onset of barotropic instability, which accelerates the poleward flank of the jet, there may be less dissipation on the poleward flank because waves are less likely to find their critical latitude there. This reduction in dissipation could cause the maximum surface winds to shift further poleward, and this hypothesis will be explored in future work.

[23] There is a strong relationship between the latitude of the jet and the time scale of the leading mode of variability, or the so called annular modes [Kidston and Gerber, 2010]. A number of authors [Gerber and Vallis, 2007; Kidston et al., 2010] have argued that the persistence of zonal index and the annular modes is due to the self-maintenance of eddy-driven jets. Because of this the time scale is enhanced for sharper jets. Thus, the enhanced barotropic instability of the jet as it moves poleward may explain the relationship between the time scale of the annular mode and jet latitude.



**Figure 3.** Diagnostics of barotropic instability for the simplified GCM: (a) the probability that the daily-mean vertical-mean zonal-mean total vorticity gradient ( $l\beta^*1$ ) is negative. The three lines are the ensemble-mean for all runs (black), runs with the jet latitude in the 50th percentile closest to the pole (blue line), and runs with the jet latitude in the 50th percentile closest to the equator (red line). (b) The globally averaged value of entrophy production (see text) summed over waves with  $k = 2-4$ . (c) The value of  $-\partial_y (lu'v')$  for waves with  $k = 4-6$  for the control run. (d) The value of  $-\partial_y (lu'v')$  for waves with  $k = 1-5$  and for all zonal wavenumbers, for runs where the jet latitude is in the 50th percentile closest to the pole. The values have been normalized by the maximum value of the total  $-\partial_y (lu'v')$ , and the values for the individual wavenumbers were further multiplied by 5, for comparison with the total. (e) The same as Figure 3d but for runs where the jet latitude is in the 50th percentile closest to the equator.

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