Barotropic Impacts of Surface Friction on Eddy Kinetic Energy and Momentum Fluxes: An Alternative to the Barotropic Governor

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ABSTRACT
As the surface drag is increased in a comprehensive general circulation model (GCM), the upper-level zonal winds decrease and eddy momentum flux convergence into the jet core increases. Globally averaged eddy kinetic energy decreases, a response that is inconsistent with the conventional barotropic governor mechanism whereby decreased barotropic shears encourage baroclinic wave growth. As the conventional barotropic governor appears insufficient to explain the entire response in the comprehensive GCM, the nondivergent barotropic model on the sphere is used to demonstrate an additional mechanism for the effect of surface drag on eddy momentum fluxes and eddy kinetic energy. Analysis of the pseudomomentum budget shows that increased drag modifies the background meridional vorticity gradient, which allows for enhanced eddy momentum flux convergence and decreased eddy kinetic energy in the presence of a constant eddy source. This additional feedback may explain the changes in eddy momentum fluxes observed in the comprehensive GCM and was likely present in previous work on the barotropic governor.

1. Introduction
Surface friction plays a crucial role in the formation and maintenance of the eddy-driven jet. The midlatitude surface westerlies are maintained against drag by upper-level eddy momentum fluxes that grow via baroclinic instability (Held 1975; Edmon et al. 1980). Surface drag is necessary for the enhanced persistence of north–south shifts of the zonal flow due to its role in balancing the meridional circulation induced by the upper-level eddies (Robinson 2000). In addition, changes in surface drag can itself cause meridional shifts of the midlatitude, eddy-driven jet (Robinson 1997; Chen et al. 2007).

It has long been recognized that as one changes the surface drag in a general circulation model (GCM), the properties of tropospheric, midlatitude eddies will change as well. James and Gray (1986) and James (1987) first showed that stronger meridional shears in the zonal mean flow can actually reduce the conversion from potential energy to eddy kinetic energy (baroclinic eddy growth) by restricting the structure of the normal modes. This effect was termed the “barotropic governor” by James (1987), whereby increased barotropic shear modifies the baroclinic growth rates and thus reduces the eddy kinetic energy.

More recently, Chen et al. (2007) separated the impacts of linear friction on the mean flow from its impact on the eddies. In a GCM, decreased friction on the mean flow leads to a stronger eddy-driven jet and a reduction in eddy kinetic energy, as expected from the barotropic governor (BG) argument. In contrast, in a shallow-water model of the upper-troposphere coupled through thermal wind to a surface layer, reduced drag does not lead to such a change in eddy kinetic energy. They argue that baroclinic wave growth through the coupling of the upper and lower levels of the atmosphere is a crucial process for the tropospheric response to surface friction.

In this paper, we provide an additional mechanism for the effect of barotropic jet structure on eddy activity. As

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the drag is increased in a comprehensive atmospheric GCM, the upper-level eddy momentum flux convergence into the jet core increases, while the jet stays fixed in latitude. At first glance, these results appear to directly support the barotropic governor mechanism, with increased drag causing the zonal mean winds to decrease, decreasing the barotropic shear and thus increasing the baroclinicity. However, one aspect of the response does not fit with previous work on the barotropic governor: globally averaged eddy kinetic energy decreases with increased drag [opposite to the increase found by James and Gray (1986)]. We therefore seek an alternative explanation for these effects of drag on the eddy fluxes. Specifically, the barotropic model on the sphere is used to demonstrate an additional mechanism for the effect of barotropic jet structure on eddy activity. Section 2 provides additional motivation. Section 3 describes the barotropic model. Sections 4–7 describe the barotropic experiments, results, and supporting theory, and section 8 summarizes this study.

2. Motivation from GEOS-5

Garfinkel et al. (2011) update the air–sea roughness parameterization in the NASA Goddard Earth Observing System version 5 (GEOS-5) general circulation model and show that increased surface friction decreases the winds over the Southern Ocean by over 1 m s$^{-1}$. The changes made to the model parameterization scheme are explained in Garfinkel et al., but we briefly discuss them here for completeness. The model uses Monin–Obhukov similarity theory (MOST) to compute the surface wind stress based on the bulk wind, temperature, and humidity. However, the coefficients underlying MOST are empirically derived, and Garfinkel et al. (2011) find that using the most recently available observational data to update these coefficients leads to increased surface layer drag in the model. This new parameterization results in improved surface winds, surface stresses, and momentum fluxes aloft. Improvements in stratospheric heat flux, ozone, and forecast skill are currently being documented by C. I. Garfinkel et al. (2012, unpublished manuscript). Before these changes in forecasting skill and stratospheric flow can be fully understood, however, a better understanding of the dynamics in the troposphere must be provided.

Two ensembles of 30-yr “control” and “updated” model integrations were performed with each ensemble pair having slightly different gravity wave parameterizations. Since there is no a priori reason to believe that these different model configurations should influence the results, we have chosen to average the ensembles together, resulting in 60 years of the control run and 60 years of the updated drag run. We note that the changes found between the control and updated runs are present for each of the two pairs of ensembles individually, giving confidence in the robustness of the GEOS-5 response.

Figures 1a,b show the change in 900-hPa and 200-hPa zonal-mean zonal winds for the control and updated drag parameterization of GEOS-5. The updated friction scheme shows decreased low-level and upper-level winds, consistent with the barotropic nature of the eddy-driven jet. Figure 1c shows the 200-hPa eddy momentum flux convergence $-\mathbf{\omega} \cdot \mathbf{v}' \partial y$, where we define eddy quantities as differences from both the zonal and temporal averages (transient eddies). The updated scheme shows increased eddy momentum flux convergence in the midlatitudes, so, although the zonal wind is decreasing, the momentum flux into the region is increasing, suggesting that the eddies partially act to compensate for the enhanced drag on the zonal wind. Although small, this increase is present in both of the GEOS-5 ensembles and appears in the 60-yr average.
In GEOS-5, the vertically integrated eddy kinetic energy (EKE) does not change appreciably with increased surface drag, as shown in Fig. 1d, although it does decrease slightly near the jet core. This response is opposite to what might be predicted by the barotropic governor mechanism. Furthermore, the globally averaged EKE defined as done by James and Gray (1986) decreases with increased drag from 5.65 \times 10^5 to 5.63 \times 10^5 J m^{-2}. One might think that the mid-to-lower tropospheric heat flux might explain the changes in EKE in GEOS-5. In contrast, we find that the response of the heat flux is opposite between the two hemispheres, while vertically integrated EKE decreases at the jet core in both hemispheres individually (not shown). Changes in heat flux therefore are likely not responsible for the lack of change of EKE. Many previous authors have used globally averaged EKE to diagnose the presence of the barotropic governor feedback between the eddies and the mean shear (James and Gray 1986; Robinson 1997; Chen et al. 2007b), so the effect of drag on the EKE in the GEOS-5 model integrations suggests that perhaps a mechanism exists other than the conventional barotropic governor that explains this response of the eddies to drag.

Finally, we note that the jet latitude does not change appreciably as the drag is increased in GEOS-5. While this appears contrary to Robinson (1997) and Chen et al. (2007), it may arise because of the smaller variations in surface drag invoked here as compared to the study by Chen et al. In the GEOS-5 model, the changes to the drag parameterization yield changes in the zonal wind on the order of 1 m s^{-1}, while the surface winds change from about 3 to 14 m s^{-1} in the experiments performed by Chen et al. (2007). While preliminary results indicate that larger changes to the drag parameterization in GEOS-5 yield a meridional shift of the jet, the focus of this paper is to explain the differences in eddy kinetic energy and momentum fluxes that cannot be explained by the conventional barotropic governor mechanism.

In this paper, we investigate the effect of enhanced drag on the eddy momentum fluxes in a barotropic model and utilize the pseudomomentum budget to explain the eddy response. We will show that increased drag modifies the background vorticity, thereby allowing for enhanced eddy momentum flux even as eddy kinetic energy decreases.

3. Barotropic model setup

We integrate the nondivergent barotropic vorticity equation on the sphere. The eddy-driven jet is simulated by forcing the vorticity field with stochastic stirring following Vallis et al. (2004) and allowing Rossby wave dynamics to produce westerlies. Specifically,

\[ \frac{\partial \zeta}{\partial t} + \frac{u}{a \cos \theta} \frac{\partial \zeta}{\partial \lambda} + \frac{v}{a \partial \theta} \frac{\partial \zeta}{\partial \lambda} + \nu \frac{\partial^2 \zeta}{\partial \lambda^2} + \nu \frac{\partial^2 \zeta}{\partial \theta^2} = F_{\zeta} - D_{\zeta} - \kappa \nabla^4 \zeta, \]

where \( D_{\zeta} \) represents drag and \( \kappa \) is the diffusion coefficient for parameterizing the removal of enstrophy at small scales; \( F_{\zeta} \) denotes the stirring of the vorticity field and represents the forcing of the barotropic flow by baroclinic wave growth (Vallis et al. 2004; Vallis 2006; Hartmann 2007). This stirring is modeled as an Ornstein–Uhlenbeck stochastic process (\( F_{\zeta} \)) defined for each combination of total wavenumber \( l \) and zonal wavenumber \( m \):

\[ F_{\zeta,lm} = (1 - e^{-2dt_{stir}})^{1/2} Q^l + e^{-dt_{stir}} F_{\zeta,lm}^{stir}, \]

where \( t_{stir} \) denotes the decorrelation time of the stirring (2 days) and \( dt \) is the model time step (3600 s); \( Q^l \) is a real number chosen uniformly between \((-A, A) \times 10^{-11}\), where \( A \) is the stirring strength (see Vallis et al. 2004 for details). The model is stirred over total wavenumbers from 8 to 12 with the zonal wavenumber required to be larger than 3. We have tested the sensitivity of the results to the stirring scale range and find them to be robust. Finally, to mimic a meridionally confined "storm track," the gridded stirring field is windowed in the meridional direction with a Gaussian spatial mask centered at latitude \( \theta_{stir} \) and having a halfwidth of 12°. The model is spectral, and each integration is spun up at least 500 days and then integrated an additional 8000 days for analysis.

Chen et al. (2007) focus on the changes in jet latitude due to changes in surface drag and, while they do plot eddy momentum flux convergence, the changes associated with the shift of the jet make it difficult to determine the extent to which the magnitudes change as well. The aim of this paper is to investigate the asymmetric response of the eddies to varying drag, and thus we limit our focus to jets centered on the equator (\( \theta_{stir} = 0^\circ \)) to remove the shifting response. We have studied cases where the jet is located off of the equator and find qualitatively similar results to those presented here, although an equatorward shift of the jet with increasing drag is also evident.

4. Linear zonal mean and eddy drag

We stir the barotropic vorticity equation on the sphere and parameterize the model’s friction [\( D_{\zeta} \) in (1)] with linear drag,

\[ D_{\zeta} = \frac{\zeta}{\tau}, \]

where \( \tau \) is the damping parameter with units of time; so, as drag increases, the time scale \( \tau \) decreases. If we split the drag on the zonal mean winds into an eddy part and a zonal mean part, we get
where overbars denote the zonal mean and primes denote departures from it. Here $\tau_z$ and $\tau_e$ denote the damping time scales of the zonal and eddy components of the flow, which can be varied separately; we will use $\tau$ to denote when $\tau_z = \tau_e$. In the barotropic model, we damp vorticity and not the zonal wind explicitly; however, formulation of the linear drag on zonal wind is very similar:

$$D_z = \frac{\tau}{\tau_z} + \frac{\zeta'}{\tau_e},$$

$$D_u = \frac{\tau}{\tau_z} + \frac{u'}{\tau_e}.$$  \hspace{0.5cm} (4)

The zonal-mean barotropic zonal momentum equation with no direct forcing of the mean flow states that

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial (\overline{u'u'})}{\partial y} - \frac{\overline{u}}{\tau_z},$$

where we have modeled friction with linear drag; assuming steady-state leads to

$$\overline{u} = -\tau_z \frac{\partial \overline{u'u'}}{\partial y}. \hspace{0.5cm} (6)$$

This equation states that, as $\tau_z$ decreases, the resulting zonal mean winds will decrease if the eddy momentum flux convergence stays constant. In the rest of this section, we present the changes in zonal wind, momentum flux, and kinetic energy as we vary the zonal mean drag and the eddy drag.

\textit{a. Varying zonal mean drag}

We first vary the drag on the mean flow by varying $\tau_z$ between 8 and 4 days while keeping $\tau_e$ fixed at 6 days. The results are plotted in Figs. 2a,b. The zonal mean winds decrease as friction on the zonal mean winds increases; however, the response of the eddy momentum flux convergence is opposite to that of the jet. Namely, as friction increases from 8 to 4 days, the eddy momentum flux convergence increases, suggesting that the eddies are acting to compensate for the enhanced zonal mean drag. In terms of (7), while the eddy forcing increases with increasing zonal mean drag, the changes in $\tau_z$ are large enough to compensate and still cause an overall reduction of the jet strength with increased drag.

In GEOS-5, the eddy momentum flux convergence increased and the vertically integrated eddy kinetic energy (EKE) decreased near the jet. A similar response is found in the barotropic model simulations when the mean drag is varied. Figure 3a shows that, although the eddy momentum flux increases with increased mean drag, the EKE near the jet decreases, as shown by the decrease in $u'^2$ and $v'^2$ separately (Figs. 3b,c). Figure 3 demonstrates that, while the magnitude of the zonal and meridional eddy winds near the jet decreases with increased mean drag, the correlation between the two increases, resulting in an increase in the eddy momentum flux.

Figure 4a shows that the globally averaged zonal kinetic energy (ZKE) decreases as the drag on the mean flow increases, as one would expect. We quantify the eddy activity in two different ways—globally averaged EKE and the maximum eddy momentum flux convergence (EMFC). As already shown, the eddy momentum flux convergence increases as drag increases (Fig. 4c); however, the globally averaged EKE stays constant (Fig. 4b). Note that, although Figs. 3b,c show a slight decrease in EKE at the jet core, the globally averaged EKE remains constant with varying $\tau_z$.

One might argue that the eddy fluxes in the barotropic model may be varying due to changes in the eddy source, so, to confirm that the stirring strength itself is not changing between the runs, the mean stirring strength magnitude is plotted in Fig. 4d (defined as the mean absolute value of $F_z$ at the equator). Section 5 offers dynamical insight as to why these eddy diagnostics change even when stirring is constant.

\textit{b. Varying eddy drag $\tau_e$}

Before attempting to find an explanation for the behavior of the eddies, we show results from another experiment when $\tau_z$ is held fixed at 6 days and the drag on the eddies $\tau_e$ is varied. Figure 5 shows that both the zonal-mean zonal winds and the eddy momentum flux convergence decrease with increased drag, unlike the case of varying $\tau_z$. When the eddy drag is increased, it is perhaps not surprising that the total eddy momentum flux convergence decreases, and that, as a result of (7), $\overline{u}$ also decreases since both terms on the right-hand-side decrease.

Figure 4 summarizes these results and demonstrates that the eddy momentum flux convergence and the eddy kinetic energy decrease with decreasing $\tau_e$ but not for decreasing $\tau_z$. For additional clarity, Table 1 summarizes Figs. 4a–c and diagrams the response of the eddies and mean flow to increased drag for the experiments presented here and in the following sections. We refer the reader to the table for additional reference.

\textbf{5. Pseudomomentum budget}

To understand the response of the eddies to varying the zonal mean drag, we use the pseudomomentum budget and refer the reader to section 12.1 in Vallis (2006) for additional background.
nondivergent barotropic eddy vorticity tendency equation can be written as

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial (\zeta u')}{\partial x} + \gamma u' = F_\zeta' - D_\zeta', \tag{8}
\]

where the rhs denotes the stirring and dissipation of vorticity, and \( \gamma \) denotes the background vorticity gradient:

\[
\gamma = \beta - \frac{\partial^2 \Pi}{\partial y^2}. \tag{9}
\]

Multiplying by \( \zeta'/\gamma \) and taking the zonal average leads to the pseudomomentum equation:

\[
\frac{\partial}{\partial t} \left( \frac{1}{\gamma} \zeta'^2 \right) + \bar{u'} \zeta' = \frac{1}{\gamma} \left( \zeta' \bar{F}_\zeta' - \zeta' \bar{D}_\zeta' \right). \tag{10}
\]

If once again steady state is assumed, we see that the zonal-mean vorticity flux is given by the sum of the pseudomomentum source and sink terms:

\[
\bar{u'} \zeta' = \frac{1}{\gamma} \left( \zeta' \bar{F}_\zeta' - \zeta' \bar{D}_\zeta' \right). \tag{11}
\]
Assuming linear drag, we can explicitly write an equation for the eddy momentum flux convergence as a function of the eddy vorticity and dissipation time scales:

\[
\frac{\partial \bar{u}'v'}{\partial y} = \frac{1}{\gamma} \left( \frac{\bar{v}'F'_\zeta \frac{\bar{\zeta}^2}{\tau_e}}\right),
\] (12)

where we have used the fact that \( \bar{\zeta}'^2 = -\frac{\partial \bar{u}'v'/\partial y} \) for nondivergent, two-dimensional flow. Furthermore, if we combine (7) with (12), we obtain an equation for the mean flow:

\[
\bar{u} = \frac{\tau_z}{\gamma} \left( \frac{\bar{v}'F'_\zeta \frac{\bar{\zeta}^2}{\tau_e}}\right),
\] (13)

keeping in mind that \( \gamma \) is also a function of \( \bar{u} \). Noting that the eddy stirring \( F'_\zeta \) is held fixed for all integrations, we now use (12) and (13) to understand the response of the mean flow and the eddies to changes in linear drag.

a. Varying \( \tau_z \)

First, we interpret the experiment where only \( \tau_z \) is varied. Figure 6 shows the terms in the pseudomomentum budget for this experiment and the three rows correspond to the pseudomomentum source and sink terms, eddy momentum flux convergence (12), and zonal wind (13), respectively. The left-hand panels denote the source and sink terms, and the right-hand panels denote their sum. Note that these equations were derived by linearizing about the mean flow, so the predicted \( \bar{u} \) and eddy momentum flux convergence curves are larger in magnitude than those output by the model since we have neglected small-scale diffusion and the nonlinear terms in the pseudomomentum budget.

Figure 6a shows that the eddy sink term is nearly constant with \( \tau_z \) (as expected) since the sink term is a strong function of \( \tau_e \), which is constant among these integrations. The source terms are also very similar. Dividing by \( \gamma \) leads to the plots of the eddy momentum flux source and sink terms in Fig. 6b, and it is clear that the background vorticity gradient causes the eddy momentum flux convergence to increase with increased drag. As the drag is increased, the zonal mean winds decrease, causing \( \gamma \) to decrease, resulting in an increase in the eddy momentum flux convergence. Finally, although the eddy momentum flux convergence increases with increased drag, the resulting zonal mean flow still decreases due to \( \tau_z \), as seen in Fig. 6c.

The pseudomomentum budget can describe how increased zonal mean drag can lead to an increase in eddy momentum flux convergence even with a constant eddy source. Intuitively, one can understand this result by considering the case where the zonal mean and eddy drag are equal and the eddies and the mean flow coexist to give an equilibrium jet profile. If the zonal mean drag is suddenly increased, the jet will weaken. Since the eddies do not explicitly feel the change in the mean drag, one might expect the eddy fluxes to continue to try bringing the zonal winds back to their initial equilibrium profile. In the process, the eddy momentum flux convergence will increase, although not by enough to completely counteract the decrease in the zonal winds due to the change in mean drag.

b. Varying \( \tau_e \)

Figure 7 displays the pseudomomentum budget terms for the experiment where only \( \tau_e \) is varied while \( \tau_z \) is held constant. The largest difference among integrations is the dissipation of vorticity due to the change in \( \tau_e \). Figures 7b,c show the eddy momentum flux convergence and zonal-mean zonal wind as a function of the pseudomomentum terms. As the drag is increased, the resulting eddy momentum flux convergence decreases in Fig. 7b, since the dissipation is directly a function of \( \tau_e \)
and $\tau_z$ is constant across the integrations. In both Figs. 7b and 7c, we see that the source term is constant with varying $\tau_z$, and it is the dissipation that varies among the integrations. It is likely that the source term ($\gamma^{-1}\frac{\partial}{\partial \xi} F^2_\xi$) stays constant since increased eddy drag causes a decrease in both $\zeta'$ and $\gamma$, so their net effect is to cancel each other.

6. Barotropic governor feedback with linear drag

Thus far our results suggest that even with constant eddy kinetic energy generation, the eddy forcing of the mean flow still increases with increasing drag because the background vorticity gradient changes and modifies the wave propagation. However, James (1987) suggests that in a baroclinic atmosphere, if the barotropic winds and jet shear decrease, the eddy kinetic energy and baroclinic wave growth (or eddy source) will increase, which they term the “barotropic governor effect.” It is conceivable that such a process is present in GEOS-5 as well. Therefore, we implement a barotropic governor (BG) feedback in the barotropic model so that we can contrast the effect of such a process to the pseudomomentum mechanism of the previous section. Specifically, the eddy source (or wave generation) is made a function of the background meridional zonal-wind
shear. By comparing the effect of drag on eddies both in the presence and absence of the BG feedback, we can qualitatively evaluate the relative importance of the two mechanisms for the response to surface friction in GEOS-5.

The barotropic governor effect is included in the barotropic model by making the stirring strength $A$ a function of the meridional-average zonal-mean zonal wind shear $\alpha$ according to the following equation:

$$A = A_0 \left(2 - \frac{\alpha}{\alpha_0}\right), \quad \text{(14)}$$

where $A_0$ is the baseline stirring strength and $\alpha_0$ is the average wind shear from the control integration. Thus, when the daily wind shear $\alpha = \alpha_0$, the stirring strength $A = A_0$. When the wind shear is larger than $\alpha_0$, the stirring strength decreases and, when the wind shear is smaller than $\alpha_0$, the stirring strength increases.

We equilibrate each integration by running it for 500 days without the barotropic governor feedback present and then spinning up 100 days with the feedback present before integrating an additional 8000 days for analysis: $\alpha_0$ is the same for all integrations and is defined as the time-mean, zonal-mean, meridionally averaged wind shear of the $t = 6$ case without a feedback.

We focus on the effects of a barotropic-governor-type feedback on the experiment where $\tau_e$ is varied since these integrations show similar eddy momentum flux behavior to what is seen in the GCM. The zonal-mean zonal wind and the eddy momentum flux convergence profiles for the runs with a barotropic governor feedback are displayed in Figs. 2c,d to more easily compare with the $\tau_e$ experiment without a BG feedback. To first order we see the same behavior as in Figs. 2a,b, namely, that, as drag is increased, the zonal winds decrease but the eddy momentum flux convergence increases. Figures 2e,f display the profile differences between the integrations with and without the barotropic governor feedback (Figs. 2c,d minus Figs. 2a, b). First, the difference plots show that the $\tau = 6$ control runs are very similar whether a barotropic governor feedback is present. This is because the $\tau = 6$ shear was used to define $\alpha_0$ for all barotropic governor integrations. Second, it is evident that the barotropic governor feedback enhances the eddy response to drag; namely, the eddy momentum flux convergence is even stronger for stronger drag with the BG feedback present, and thus the resulting zonal winds are stronger than without this feedback.

Figure 8a displays the source and sink terms in the pseudomomentum budget for the integrations with a BG feedback. The source increases with drag because of the feedback between the eddy strength and background shear, whereby the stirring strength increases as background shear decreases. Although $\tau_e$ does not change among the integrations, the sink term does change because of changes in $\tau_b$ brought about by changes in the strength of the stirring. Figure 8b displays the eddy momentum flux convergence terms. The BG feedback enhances the effects of mean drag on the eddies, and comparing to Fig. 6b we see that all terms are bigger due to the changes in the eddy source itself. Finally, the net differences between the integrations with and without the barotropic governor feedback (Figs. 2c,d minus Figs. 2a, b). First, the difference plots show that the $\tau = 6$ control runs are very similar whether a barotropic governor feedback is present. This is because the $\tau = 6$ shear was used to define $\alpha_0$ for all barotropic governor integrations. Second, it is evident that the barotropic governor feedback enhances the eddy response to drag; namely, the eddy momentum flux convergence is even stronger for stronger drag with the BG feedback present, and thus the resulting zonal winds are stronger than without this feedback.

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<th>Drag increases</th>
<th>$\bar{\tau}$</th>
<th>$\frac{\partial}{\partial \tau} (-\bar{u}'v')$</th>
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effect on the zonal-mean zonal winds is plotted in Fig. 8c and shows $u$ decreasing with drag, although the differences among integrations are smaller owing to the BG feedback. Figures 4a,b show that the BG feedback causes the zonal-mean kinetic energy to decrease less with increased drag compared to the integration without a BG feedback. However, the BG feedback leads to an increase in EKE (along with the eddy momentum flux convergence) with increased drag, an effect not seen in sections 4 or 5. This increase in EKE with drag is attributed to changes in the source of the eddies, not just their propagation, brought about by the changes in stirring strength.

These simulations show that the conventional barotropic governor mechanism and the mechanism due to wave propagation on a background vorticity gradient lead to similar signed changes of the eddy momentum fluxes. The differences in these two feedbacks can be seen by comparing the changes in eddy kinetic energy, where the barotropic governor feedback changes the eddy kinetic energy through changes in the eddy source, while the mechanism due to wave propagation has no effect on EKE when $\tau_c$ is fixed.
7. Quadratic drag

The simplified barotropic simulations presented thus far were parameterized with linear drag on the eddies and mean flow separately, but the drag parameterization in GEOS-5 is quadratic in wind speed and was changed simultaneously for the mean and eddy quantities. In this section, we show that the response of the eddies in the barotropic model to changes in quadratic drag is similar to the changes observed in GEOS-5. Namely, the eddy momentum flux convergence increases in the jet core and the globally averaged eddy kinetic energy decreases.

The quadratic drag acting on zonal velocity \((u, v)\) is given by

\[ D_u = C_D |u| u \]

and

\[ D_v = C_D |u| v, \]

where \(u = (u, v)\). Following Grianik et al. (2004), one can easily show that this leads to

\[ D_\zeta = \frac{\partial}{\partial x} D_v - \frac{\partial}{\partial y} D_u \]

in the vorticity equation. Here we define three scenarios: the first setting \(C_D = 10 \times 10^{-9} \text{ m}^{-1}\) and the other two scenarios representing the control and updated drag coefficients used in GEOS-5. Curves showing the dependence of \(C_D\) on wind speed as implemented in the barotropic model are plotted in Fig. 9: similar curves for the GEOS-5 model can be found in Fig. 2 of Garfinkel et al. (2011). Note that the relationships shown here are not absolutely comparable to those of the GEOS-5 model since the GCM defines \(C_D\) as a function of additional bulk quantities (i.e., stability of the air column).

The changes in zonal kinetic energy and eddy kinetic energy from the quadratic drag simulations are plotted in Figs. 10a,b. As the quadratic drag increases, the zonal winds decrease (not shown) and the zonal kinetic energy decreases. The eddy kinetic energy also decreases since the drag felt by the eddies is not held constant but rather increases. The key result of this experiment is shown in Fig. 10c, where we see that the maximum eddy momentum flux convergence increases with increased quadratic drag, similar to what was seen when only \(\tau_z\) was varied. Thus, this experiment demonstrates a case where the eddy momentum fluxes increase with drag, but the EKE actually decreases, highlighting once again that these two measures of eddy activity do not necessarily vary together (cf. Table 1).
The full GCM shows a decrease in the globally averaged eddy kinetic energy, consistent with the barotropic model integrations with quadratic drag. Thus, in many ways, the full GCM appears to respond to increased drag similarly to the barotropic model with “baroclinicity” independent of shear, and no reference to the barotropic governor is necessary to explain the results. Future work will focus on the response to surface friction of a dry primitive equation model to further test this result.

8. Conclusions

We demonstrate in both the GEOS-5 GCM and a barotropic model that increasing zonal-mean surface drag leads to enhanced eddy momentum flux convergence into the jet core. In the comprehensive GCM, the globally averaged eddy kinetic energy decreases, contrary to what is predicted by the conventional barotropic governor feedback. This result can be obtained in the barotropic model, and analysis of the pseudomomentum budget suggests that changes in the background vorticity gradient along which the Rossby waves propagate can explain the eddy response without a change in the eddy source itself. However, when the eddy source is made to be a function of the background shear in the barotropic model, we find that the eddy kinetic energy can also increase with increased drag. These results illustrate that studies that find changes in eddy momentum fluxes with varying drag should not immediately conclude that the conventional barotropic governor mechanism is dominant, as this wave propagation mechanism may also be important.

The GEOS-5 model integrations with varying air–sea roughness parameterizations served as motivation to investigate additional mechanisms by which increasing zonal mean drag may increase upper-level eddy momentum fluxes. However, we acknowledge that additional work is certainly necessary before one can claim that the barotropic governor mechanism is not important in these GEOS-5 integrations. In particular, we note the caveat that upper-level eddy kinetic energy does increase in GEOS-5, and it is not clear whether this is the more relevant measure over the vertically integrated quantity. It is also likely that the relative roles of the barotropic governor and the propagation mechanism presented here may depend on the class of GCM examined (i.e., idealized vs comprehensive) and the magnitude of the surface drag perturbation imposed. In addition, the potential vorticity gradient, rather than the absolute vorticity gradient, is the more relevant quantity in a baroclinic atmosphere. Thus, further work is required to fully understand whether (and why) one effect might dominate over the other in the GCM. Nevertheless, the results presented here suggest that modulation of Rossby wave propagation by changes in the background vorticity gradient has the potential to explain the large-scale atmospheric GCM response to varying surface drag.

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