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REDISTRIBUTION OF ANGULAR MOMENTUM IN A GLOBAL FORECAST MODEL DUE TO CHANGE IN DRAG PARAMETERIZATIONS

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1. INTRODUCTION

Contemporary numerical models of the global atmosphere include parameterizations of various drag mechanisms, e.g., orographic and convective gravity wave drag (GWD), mountain drag, surface friction drag, and artificial model top drag. These mechanisms, except for friction drag, directly affect the magnitude of the polar night jet, whose variation significantly affects the tropospheric circulation (e.g., Boville 1984; Kodera et al. 1990; Kuroda 2002). Moreover, these mechanisms in the model induce indirect secondary circulations that significantly affect the troposphere through the “downward control (Haynes et al. 1991)”.

Validation of these drag mechanisms in a global model can be done by comparing simulations or forecasts with observations or analyses of such first-order variables as the zonal wind and temperature, sea-level pressure and/or such derived quantities as the Eliassen-Palm (E-P) flux (e.g., Andrews et al. 1987) and the atmospheric angular momentum (AAM). In particular, the AAM is a globally conserved quantity and its global imbalance in an atmospheric model is considered to produce systematic errors in short-term forecasts as well as climate drift in long-term simulations (Huang et al. 1999). It is regarded as a useful diagnostic quantity for evaluating global numerical weather prediction models (Bell et al. 1991; Salstein et al. 1993). The budget of the AAM calculated from analyses can be indirectly compared with the model-simulated torques due to various drag parameterizations as an attempt to validate the parameterizations and also to understand the redistribution of the AAM due to the parameterizations (e.g., Swinbank 1985; Boer and Lazare 1988; Boer 1990; Lejenäs et al. 1997).

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In this study, we investigate the response of a global spectral weather forecast model to various parameterized drag mechanisms, such as orographic and convective GWD, mountain drag, surface friction drag, and artificial model top drag, in terms of the AAM redistribution. We discuss the usefulness of the AAM as a measure to diagnose the impact of parameterized drag mechanisms.

2. THE MODEL AND EXPERIMENTS

A series of ensemble simulations corresponding to January 2000 have been performed using the forecast model of an extended-top version (Kim and Hogan 2003) of Navy Operational Global Atmospheric Prediction System, NOGAPS (Hogan and Rosmond 1991) with its top around 0.1 hPa or 60 km and the resolution of T63L36. This version of the model parameterizes stationary “orographic GWD” based on Kim and Arakawa (1995) and Kim (1996), which takes into account selective enhancement of low-level drag due to resonant amplification of nonlinear / nonhydrostatic gravity waves (see also Alpert et al. 1996). The model also parameterizes stationary “convective GWD” based on Chun and Baik (1998) and Chun et al. (2001), which treats cumulus clouds as obstacles to the background wind for stationary heat sources that distort the flow and generate convective gravity waves. The enhancement of the surface friction drag is made through a crude “form drag” parameterization by which the surface roughness is systematically increased over orography, following Hogan et al. (1999). The “model top drag” is represented by a Newtonian cooling formulation for the topmost 2 levels with a damping coefficient that depends on the wavenumber in such as a way that more damping is imposed on higher wavenumbers. The “mountain drag” is represented by resolved model orography.

The rate of change of the AAM plus the divergence of the meridional AAM transport should balance the sum of various torques due to the irregularity of the Earth's surface, e.g., the "mountain torque" and the "friction torque" (Swinbank, 1985; Boer and Lazare, 1988) as well as the "gravity wave torque" due to subgrid-scale gravity waves (e.g., Huang et al., 1999). On vertically integrating and taking zonal and temporal averages, the following equation results (Swinbank, 1985; Boer and Lazare, 1988) with the terms we added due to gravity waves:

$$\frac{\partial}{\partial t}\left[\int_0^{p_s} m\frac{dp}{g}\right] + \frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}\left\{\left[\int_0^{p_s} mv\frac{dp}{g}\right]\cos\varphi\right\} \qquad \textbf{(1)}$$

$$= -\left[\int_0^{p_s}\frac{\partial\Phi}{\partial\lambda}\frac{dp}{g}\right] - a\cos\varphi\left\{[\tau_{Fr}]+[\tau_{OGW}]+[\tau_{CGW}]\right\},$$

where t is time, m (= $\Omega a^2 \cos^2\varphi + u\, a \cos\varphi$) is the (absolute) AAM per unit mass, Ω is the angular velocity of the Earth's rotation, φ is the latitude, u and v denote, respectively, the zonal and meridional winds, p is the atmospheric pressure, g is the gravity, Φ is the geopotential, λ is the longitude, and τ_{Fr}, τ_{OGW} and τ_{CGW} are the zonal stresses due, respectively, to surface friction and subgrid-scale orographic and convective GWD. The subscript "s" denotes surface values and the square bracket represents the zonal average. By evaluating each term on the right hand side and comparing their sum with the second term of the left hand side (neglecting the first term based on the assumption that the monthly local tendency of integrated and averaged m can be neglected), one can check the adequacy of the collective monthly magnitude of the right hand side terms represented in the model. This equation forms the main basis for the design of our experiments.

The control experiment (CTRL) includes all the drag mechanisms and uses the NIMA (National Imagery and Mapping Agency) silhouette orography. Experiment NoOG is without the orographic GWD parameterization; NoCG is without the convective GWD parameterization; NoGD is without both the orographic and convective GWD parameterizations; NoND is without Newtonian damping; NoFD is without the "form drag"; and XORO is with the previous version of orography used for NOGAPS derived from the 10-min US Navy data. (The control silhouette orography is overall significantly higher than the Navy silhouette orography.) Each experiment is an ensemble of 5 model simulations initialized at 20 Dec. 1999 with different startup procedures and is an average of the last 31 days (i.e., January 2000) out of the 41-day runs.

3. THE RESULTS AND DISCUSSIONS

The total and individual components of the zonally averaged and vertically integrated torque calculated from the CTRL experiment are shown in **Fig. 1a**.

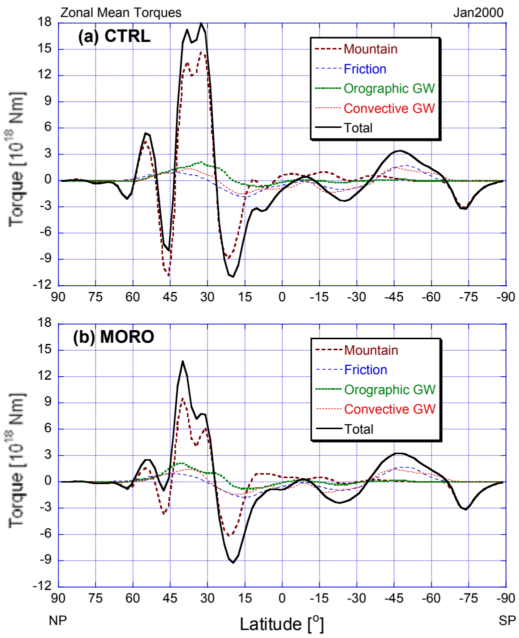
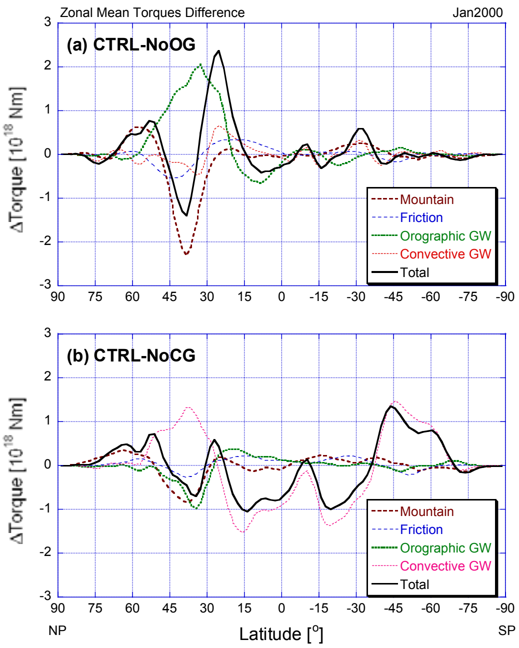


Fig. 1. The zonally and vertically averaged individual torques [10^{18} Nm] due to resolved mountain, surface friction, orographic / convective gravity wave drag and also the total torque for January 2000 simulated by NOGAPS T63L36 from (a) the CTRL (with silhouette orography) and (b) the MORO (with mean orography) experiments.

Swinbank (1985) earlier inferred the meridional momentum flux divergence, i.e., the second term in the left hand side of Eq. (1), from January 1979 FGGE IIIa data for 2° latitude bands (his Fig. 7), which is comparable to our model resolution of T63 (= 1.875°). He used the inferred torque to validate the mountain and friction torques calculated from his model simulation, i.e., the first two terms in the right hand side of Eq. (1).

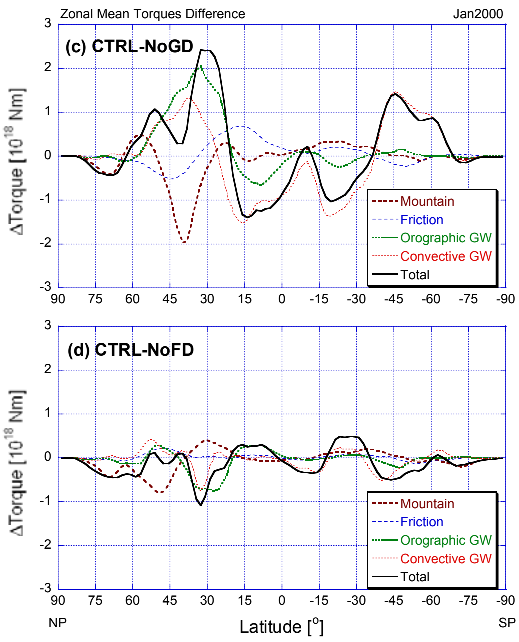
Swinbank's curves are in qualitative agreement with ours (note that the torque due to gravity waves was not included in his calculations). However, over the northern mid-latitudes our mountain torque is about seven times larger than his values whereas our friction torque is roughly about a half of his. Our simulated maximum total torque is about three times larger than his torque inferred from the momentum flux divergence. This is due mainly to our much larger mountain torque, which alone is about two times larger than his inferred torque.

We investigate the impact of orographic and convective GWD in view of the difference in the torque from the control experiment. The difference due to orographic GWD is the largest over the northern mid-latitudes as expected (**Fig. 2a**). It should be noted here that other torque terms also change significantly in response to the omission of orographic GWD; especially the mountain torque, which seems to try to balance the gravity wave torque of opposite sign in the northern mid-latitudes.



Figs. 2a, 2b. As in Fig. 1, but of the difference between the control simulation and the simulation performed without the (a) orographic or (b) convective GWD.

In experiment NoCG (**Fig. 2b**), double region of large convective gravity wave torque is found in the subtropics as well as in the mid-latitudes, and orographic gravity wave torque change is as large as that of mountain torque in the mid-latitudes. The convective gravity wave torque plays a role similar to the orographic gravity wave torque in the northern mid-latitudes in that the mountain torque is balanced by convective gravity wave torque although the change in mountain torque is smaller than that of NoOG. The combined impact of NoOG and NoCG seems to be fairly linear (**Fig. 2c**), i.e., it is roughly the linear sum of the two cases, which suggests that zonally averaged and vertically integrated torque is an effective measure to investigate the impact of model physics changes in contrast to the monthly zonal means of the basic variables such as the zonal wind, temperature and sea-level pressure, which reveal nonlinear responses (Kim and Hogan 2003).



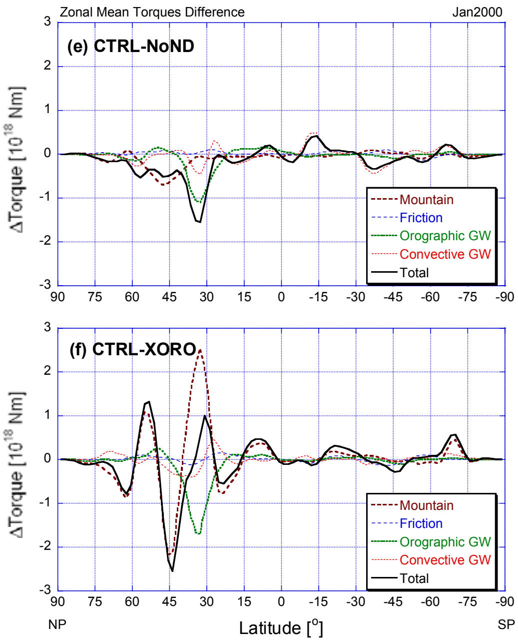
Figs. 2c, 2d. As in Fig. 2, but of the difference between the control simulation and the simulation performed (c) without both the orographic and convective GWD, or (d) without the form drag.

These results demonstrate that the magnitudes of drag mechanisms in the model are determined not only by the individual parameterizations but also by their balance with other mechanisms, thus advising caution in the interpretation of addition or removal of any drag mechanism in the model. Boer and Lazare (1988) reported that when GWD parameterization was removed in their model the surface torque was unexpectedly increased, interpreting their results as "paradoxical" since they expected decrease of surface torque. However, their results can be understood in terms of the momentum balance discussed in our study. When GWD is removed, the model tries to conserve the total amount of the stress by increasing the magnitude of other drag mechanisms. If GWD were considered in the budget, therefore, their results would not be paradoxical but in fact would be quite expected.

The impact on the torques of the form drag parameterization implemented through systematic enhancement of the roughness length is shown in **Fig. 2d**. The surface drag enhancement does not significantly change the balance of the momentum compared with GWD although it is still non-negligible. This may look rather surprising considering the extent of the enhancement in the surface roughness (as large as 99 m), but is understandable in that the effect of form drag is mostly confined near the surface and suppressed by the stronger static stability in the northern winter.

The impact of Newtonian damping is shown in **Fig. 2e**. In the northern hemisphere, the torque is almost uniformly greater in NoND, resulting in an imbalance in the AAM redistribution. In principle, the positive and negative differences of the AAM should approximately be in global balance (i.e., zero sum) as roughly shown in other sensitivity experiments presented in **Fig. 2**. In other words, the AAM redistribution due to any change in drag is made while conserving the total amount (the global average should be zero in a perfect model). As we discussed in the introduction, several studies (e.g., Boer, 1990; Klinker and Sardeshmukh, 1992; Lejenäs et al., 1997; Huang et al., 1999) suspected GWD as a source of "imbalance" in the vertically averaged AAM budget. In our case, the Newtonian damping generates a clear response of such kind. This may be due to its scale-dependent damping nature of our Newtonian damping, but may also be due to the lack of a constraint that the net drag over the sphere on a given level must vanish (Shepherd et al. 1996).

The impact of the change in the resolved orography due to direct differences in the orographic heights is significant (**Fig. 2f**). The mountain torque is significantly different over the northern mid-latitudes (with different signs depending on the signs of the orographic slopes and the winds). It is interesting that orographic gravity wave torque also responds strongly to this change in orographic height. This is due partly to the direct changes in the wind speed and static stability, associated with elevated or lowered surface, which are inputs for the GWD parameterization. It is noteworthy again that mountain torque and gravity wave torque try to cancel each other (**Fig. 2f** compared with **Fig. 2a**), i.e., the removal of gravity wave torque results in an increase of mountain torque. These results underscore the fact that an increase / decrease in drag through one drag mechanism is compensated for by a decrease / increase through another mechanism to maintain the overall balance of the momentum budget.



Figs. 2e, 2f. As in Fig. 2, but of the difference between the control simulation and the simulation performed (e) without the Newtonian damping, and (f) with the previous version of orography.

Partitioning the parameterizations of the effects of subgrid-scale gravity waves (through GWD) and resolved planetary waves (through mountain drag due to enhanced orography such as envelope or silhouette orography) has been a subject of debate since the introduction of the GWD parameterization in 1980s, although the enhanced orography technique is now fading out with the enhancement of model resolutions (some detailed thoughts on this issue are given in Kim et al., 2003). A comparison of the E-P flux vector differences (Kim and Hogan 2003) reveals that the directions of the flux vectors and divergences for NoOG and XORO are qualitatively similar in the northern polar stratosphere although XORO induces stronger vertical vectors. Thus, the impacts of orographic GWD and mountain drag are very similar even in terms of such derived quantity as the E-P flux as well as of such first-order field as the temperature (Kim and Hogan 2003). This implies that it is particularly difficult to properly partition through the parameterizations between the effects of subgrid-scale orography and resolved orography, or more specifically, the partition between parameterized drag (GWD) and resolved drag (mountain drag). This issue seems to be present in most (if not all) of the global atmospheric models and needs to be further explored.

Furthermore, in order to investigate how a systematic difference in resolved orographic height affects the magnitude of mountain torque, we have performed additional ensemble simulations with "mean orography (MORO)" derived without using the enhancement algorithm for the silhouette orography. The difference between the silhouette orography and the mean orography derived from NIMA data is as expected an order of magnitude larger than that between the two silhouette orographic datasets (i.e., NIMA and Navy). The impact on the torque (**Fig. 1b** in comparison with **Fig. 1a**) shows significantly reduced mountain torque and accordingly reduced total torque. The torque is virtually unchanged in the southern hemisphere, which is due mainly to the scarcity of major mountains and lower static stability in that hemisphere in January. The total torque in the northern hemisphere is still larger than Swinbank's inferred torque, but is much closer and overall more similar to it. If we assume that our model overestimates the mountain torque (and Swinbank's inferred torque is accurate), we can conjecture that the magnitude of the total drag with the silhouette orography in our model is already too large even without GWD and thus an addition of GWD results in degradation of the forecast through undesirable redistribution of the total drag. After extensive tests, the silhouette orography has been permanently replaced by a mean orography in all versions of the model.

4. CONCLUSION AND REMARKS

From the analyses of atmospheric angular momentum budget, it is found that the various drag mechanisms of the model - when modified - interact with one another by redistributing their drag while conserving the total amount. An overestimation of one drag mechanism, for example, can result in an under-estimation of others thereby breaking an optimal balance among the mechanisms. This has an important implications for numerical modeling of the atmosphere: when a drag parameterization or equivalent mechanism is added into (or removed from) a model, not only the amount of the new drag, but also its balance with existing mechanisms must be checked, which may require adjustment of the existing mechanisms.

The parameterization of GWD and use of enhanced orography such as envelope and silhouette have been popular in many global atmospheric models as an effective means to alleviate systematic model errors and have improved climate simulation and weather forecast. In some cases, however, it is possible that some improvement could have been due to concealment of systematic errors by fortuitously beneficial re-balancing of the drag mechanisms, especially between GWD and mountain drag, which is closely depending on the partition between them. As the models become more sophisticated and their resolutions are increased to resolve more explicit subgrid-scale processes, more careful validation of the models by a more refined measure, such as the AAM budget, is recommended.

The present study shows that the use of mean orography instead of silhouette orography improves the budget of mountain torque. It is in fact a general trend in the modeling community that mean orography is favored over enhanced orography (see Kim et al., 2003) involving, e.g., an undesirable rejection of valuable data near the surface in data assimilation and an unrealistic enhancement of orographic rainfall (Lott and Miller, 1997), which becomes more serious as the resolution increases. This trend is also true with the introduction of more physical representation of low-level flow-blocking parameterizations (Lott and Miller, 1997; Scinocca and McFarlane, 2000).

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