P4.13 THE IMPACT OF A NEW OROGRAPHIC GRAVITY WAVE DRAG SCHEME IN THE MET OFFICE UNIFIED MODEL.

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1. INTRODUCTION

At the Met Office, a single GCM known as the Unified Model (UM) is used for both numerical weather prediction (NWP) and climate research (CR). For NWP the horizontal grid has a resolution of $0.55^{\circ}\times0.83^{\circ}$ and forecasts are run out to 6 days ahead, whilst for CR the grid resolution is $2.5^{\circ}\times3.75^{\circ}$ and simulations are typically of several years duration. Thus the UM is run over a wide range of spatial and temporal scales and, clearly, a desirable property of all the dynamical and physical schemes employed is that their behaviour is robust over all of these scales.

Over the past couple of years a completely new version of the UM has been developed. This new version is built around a completely new dynamical core and hence is commonly referred to as the New Dynamics (ND). The changes made to the dynamical core include moving to a 'C' horizontal grid from a 'B' grid, changing the vertical grid to a Charney-Phillips staggering from the very widely used Lorenz grid, moving to a height based vertical coordinate from a hybrid σ-p coordinate, moving to semi-Lagrangian advection from Eulerian advection and moving to a semi-implicit treatment of gravity waves from a split-explicit treatment.

Several major improvements to the model physics have also been incorporated into the ND. Of particular relevance to this paper is the implementation of a new boundary layer scheme which is able to diagnose and represent up to 7 different boundary layer regimes. In order that this scheme can work effectively, the vertical resolution near the ground has been more than doubled, so that the boundary layer may now span 14 levels rather than the previous 6. The ND thus has 38 levels (L38) whereas the current UM has 30 levels (L30).

This change in vertical resolution has revealed a number of level dependencies in the current (hereafter referred to as OLD) orographic gravity wave drag (GWD) scheme. This scheme, together with an orographic roughness scheme, was implemented in the UM about 6 years ago. Together these schemes led to very significant improvements in model performance in both CR and NWP (especially). However, the level dependent behaviour of the OLD scheme is clearly undesirable since it implies a lack of robustness and thus any tuning of the scheme (within the bounds of uncertainty) is likely to be grid-dependent to some degree. Indeed, moving from L30 to L38 led to a significant reduction in GWD and thus a retuning of the OLD scheme would be necessary to recover the previous performance of the scheme. A more desirable solution, and the one we have adopted, is to eliminate the level dependencies in the GWD scheme. In seeking this solution a completely NEW GWD scheme has been developed that is both level independent and incorporates improved GWD physics.

In this paper, the main weaknesses of the OLD GWD scheme will be briefly described. The NEW scheme will then be briefly described and the resulting improvements in performance illustrated.

2. THE OLD GWD SCHEME

The OLD GWD scheme has been documented by Gregory et al. (1998) and Milton and Wilson (1996), who describe the impact of the scheme in CR and NWP modes respectively. The scheme represents the effect of 'the usual' linear hydrostatic waves that were typically the only gravity waves parametrized in the first generation of GWD schemes developed in the mid-late 1980's. This scheme also captures the low level wave-breaking associated with the non-linear hydraulic jump type of response and that associated with non-hydrostatic trapped lee waves. The scheme also accounts for the anisotropy of the sub-grid orography.

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One weakness of the OLD scheme is that it switches abruptly between the different regimes that it represents. When the Froude number, F_r [1], is large (≥ 1.5) the scheme assumes that linear hydrostatic waves are generated. Additionally, if the vertical profile of the Scorer parameter is found be favourable to the existence of trapped lee waves, then these waves will also be represented. When F_r is small ($\prec 1.5$), the GWD is based on the hydraulic jump type of response. Thus, when F_r is close to 1.5, very small changes in the low level U and N can lead to large changes in the parametrized GWD.

A second weakness of the OLD scheme is that the hydraulic jump response is invoked much too readily since, typically, it is invoked at over half of the points at which GWD is occurring. Whilst such a GWD response undoubtedly occasionally occurs, and when it does it can have significant near surface effects (see e.g. Lilly, 1978), the rate of occurrence as diagnosed by this scheme would seem to be excessive. Moreover, the low level U and N are taken as averages from the top of any diagnosed blocked layer up to min($\sqrt{2}\sigma$, 750m), where σ is the standard deviation of the sub-grid orography. Over regions of significant orography, where σ may reach 1500m, the 750m limit prevents near jet level winds entering the surface stress equation, and hence prevents excessive surface stresses being diagnosed. However, over major orography, the combination of overly small U (the average does not extend high enough) and large h leads to $F_r < 1.5$ and hydraulic jumps being diagnosed virtually 100% of the time. In summary, therefore, for most of the time over high orography, it would appear that the wrong U and N are being used to calculate a surface stress in the incorrect GWD regime.

As mentioned in the introduction, a third weakness of the current GWD scheme is its level dependent behaviour. This is due to a number of reasons. For example, the low level U and N averages extend up to and including the model level in which the min($\sqrt{2}\sigma$, 750m) lies. The thickness of that level will obviously change when the vertical resolution changes and so the depth over which the average actually extends also changes. However, the primary level dependency is in the calculation of the vertical profile of the Scorer parameter. This calculation involves finding two layers of equal thickness, where their interface is the optimum level for the existence of lee waves. In the current scheme, the two layers of equal 'thickness' contain equal numbers of model levels, rather than being of equal thickness. This leads to an erroneous and level dependent diagnosis of lee waves. Moreover, the associated drag is applied over too shallow a near surface layer, and hence the scheme acts as an erroneous source of low level (below mountain top) drag. This behaviour of the OLD scheme, to a large extent, masks the need to explicitly parametrize the blocked flow drag.

3. THE NEW GWD SCHEME

The NEW scheme is built on the framework of the OLD scheme, but includes a number of improvements that have been made to address the problems highlighted in section 2. The outline of the scheme is as follows:-

1) Diagnose the depth, d, of any blocked layer. Thus, $d = 2\sigma - \boldsymbol{U}_s / N_s$, where 2σ is used to define the top of the highest sub-grid mountains and $\boldsymbol{U}_s$ and N_s are the average wind speed and buoyancy frequency from the ground up to 2σ. Note that the anisotropy of the sub-grid orography is accounted for by taking $\boldsymbol{U}_s$ to be the component of the low level wind perpendicular to the major axis of the sub-grid orography.

2) Apply a blocked layer drag uniformly through the depth of the blocked layer. There are two components to the blocked layer drag. The first represents flow blocking and wake vortices on scales where rotation effects are not important and is based on the scheme implemented by Scinnoca and McFarlane (2000). The second component represents flow blocking at longer length-scales and hence represents flow blocking when rotation effects are important. This scheme is based on the idealised modelling study of cold air damming by Shutts (1998). The blocked layer surface stress, τ_s, is based on equation 23 of Scinocca and McFarlane and on equation 3.20 of Shutts and is thus given by

$$\tau_s = -\frac{\rho_s d l \boldsymbol{U}_s |\boldsymbol{U}_s|}{2L^2} - \frac{2}{3L^2}\frac{(\rho_s f \boldsymbol{U}_s d l^2)}{1 + (f\boldsymbol{U}_s l/(Nd)^2)}$$

[1] $F_r = U / Nh$, where U is the low level wind speed, N is the low level buoyancy frequency and h is the height of the sub-grid orography. h is taken to be proportional to the standard deviation, σ, of the sub-grid orography.

where ρ_s is the 0 to 2σ average density, l is the length of the sub-grid ridge (currently taken to be the length of a grid-box edge), L^2 is the model grid-box area and f is the Coriolis parameter. The cold air damming parametrization is most effective at very low Froude numbers and appears able to account for much of the "missing" drag at low Froude numbers that both the Scinocca and McFarlane and the Lott and Miller (1996) GWD schemes suffered from.

3) Calculate a linear hydrostatic mountain top wave stress and deposit that stress according to the 'traditional' wave saturation hypothesis. The x-component of the mountain top wave stress is given by

$$\tau_{sx} = -\hat{K}^{-1}\rho_{2\sigma}U_{2\sigma}N_{2\sigma}\left(\frac{2\sigma - d}{2\sigma}\right)^2 \times (\sigma_{xx}\cos\chi + \sigma_{xy}\sin\chi)$$

where $\hat{K}^{-1}$ is a typical horizontal wavelength (though see Gregory et al. (1998) for a more precise definition), the subscript 2σ denotes quantities calculated at the 2σ height, σ_{xx} and σ_{xy} are sub-grid orographic gradients (again, see Gregory et al. for more details) and χ is the direction of the full vector wind, ***U*** at the 2σ level. For brevity, the analogous equation for the y-component of the stress is not shown here. Thus, when no blocked layer is present, the surface stress is the same as in the OLD scheme, except that point values at 2σ are used. This ensures that the flow characteristics are obtained from air flowing over the sub-grid orography. When a blocked layer is diagnosed, the wave stress reduces in a manner akin to the τ_{free} term in Scinocca and McFarlane. Thus the linear hydrostatic wave stress smoothly switches off as the flow blocking parametrization smoothly switches on.

4) Test for the existence of lee waves and calculate surface stresses and stress profiles as appropriate. The details of the scheme follow those in Gregory et al. However, as for the linear hydrostatic waves, we now use the *U* and *N* at 2σ to calculate the surface stress. Also, the weaknesses of the implementation in the OLD scheme discussed in section 2 have now been addressed. These changes lead to the lee wave drag being deposited over a much deeper layer.

4. IMPACT OF THE NEW SCHEME

The most easy to demonstrate feature of the NEW scheme is its improved robustness. An illustration of the improved performance with the NEW scheme is seen in Fig. 1, which shows a timeseries of the wave drag at model level 7 (~500m above the ground) for a point over the Rockies in a pair of simulations with the L38 version of the ND.

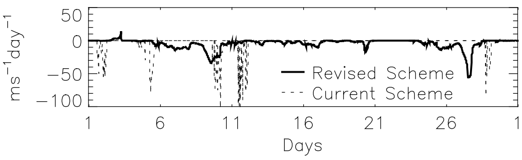

Figure 1. One month timeseries of the lee wave drag at model level 7 for a point in the central Rockies. The NEW scheme is denoted 'revised' whilst the OLD scheme is denoted 'current'.

The improved performance with the NEW scheme is evidenced here by the smooth changes in wind increments, with the lee waves appearing and disappearing over the course of a few hours or days (several to many timesteps). In contrast, the wind increments with the OLD scheme are much more intermittent and extreme, with several instances of large drags being applied for a single timestep only. A wind increment such as this indicates that the OLD scheme, in contrast to the NEW scheme, will not be temporally robust, i.e. its behaviour will change if the timestep length is changed.

The second way in which the NEW GWD scheme is more robust than the OLD one is that it is much less model level dependent. To illustrate this, 2 pairs of single timestep experiments have been performed using the forecast version of the ND. These experiments were all run from the same initial state. Each pair of runs used the NEW GWD scheme in one run and the OLD scheme in the other. The pairs of runs differed in the vertical levels used; the first pair used the L30 set of levels described in the introduction whilst the second pair used the L38 set of levels.

A number of features are evident from figure 2. Firstly, the change in GWD torque due to the change in vertical resolution is significantly reduced with the NEW scheme, i.e. the NEW scheme is much less vertical level dependent. This reduction is evident in each component of the scheme as well as in the total torque. Secondly, the total torques with each scheme are broadly similar. However, the interesting feature is that the two schemes achieve this

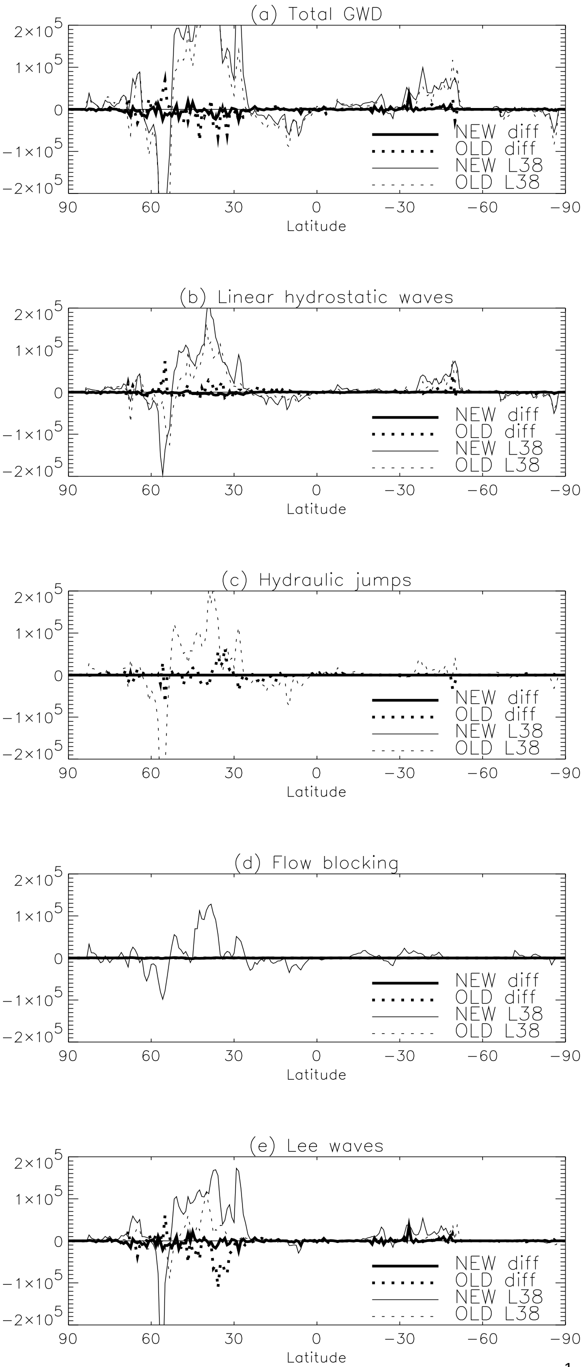

Figure 2. (a) The total zonal mean torques (Nm^{-1}) with the NEW and OLD schemes. The "NEW diff" line is the difference in torque with the NEW scheme at L38 minus that at L30. The "OLD diff" line is as per "NEW diff", but for the OLD scheme. The bottom two lines show the full zonal mean torques from the L38 runs with NEW and OLD schemes respectively. (b) As (a), but for the linear hydrostatic wave component only. (c) As (a), but for the hydraulic jump component only. (d) As (a), but for the flow blocking component only. (e) As (a), but for the lee wave component only.

result via very different mechanisms. Thus, the hydraulic jump response dominates the OLD scheme. In the NEW scheme, significant drag is attributed to flow blocking, whilst the importance of linear hydrostatic and trapped lee waves is increased compared to their importance in the OLD scheme. Thus both schemes produce similar torques, but the NEW scheme appeals to more believable processes and behaves in a more robust manner.

5. SUMMARY

A new parametrization of subgridscale orographic drag is in development at the Met Office. This scheme will replace the current (OLD) scheme which, when that scheme was introduced led to an almost 10% improvement in NWP performance. Here, we have identified a number of weaknesses with that scheme and presented a NEW scheme that is both more robust and is also built on a sounder scientific basis. More substantial results illustrating the impact of the scheme on NWP and CR systematic model errors will be presented in due course.

6. REFERENCES

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