12.2 A NEW SUB-GRIDSCALE OROGRAPHIC DRAG PARAMETRIZATION FOR THE MET OFFICE UNIFIED MODEL

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1. INTRODUCTION

For a number of years now sub-gridscale orographic effects have been incorporated into the global version of the Met Office Unified Model (UM) via an orographic form drag scheme and a gravity wave drag (GWD) scheme (Gregory et al., 1998). For high Froude number flows the GWD scheme represents the effects of linear hydrostatic gravity waves and, for suitable Scorer parameter profiles, the effects of trapped lee waves. (Here, the Froude number, $F = U/Nh$, where U is the low level wind speed, N is the low-level Brunt-Vaisala frequency and h the sub-grid mountain height). For low Froude number flows the response is modelled on the low-level non-linear gravity wave breaking associated with the hydraulic jump response. The introduction of these two schemes led to a very significant improvement in global numerical weather prediction (NWP) performance, especially in northern hemisphere mid-latitudes in wintertime.

However, a number weaknesses have been identified with the current GWD scheme. The most striking scientific weakness is the triggering of the hydraulic jump response; typically it is invoked at about 50% of land grid-points every timestep. This rate of occurrence is clearly excessive but equally it is inevitable given that it is the only process that the scheme can invoke at low Froude number. Coupled to the above problem is the lack of an explicit representation of low level flow-blocking. This process has been shown to be very important to the performance of global circulation models by both Lott and Miller (1997) and Scinocca and McFarlane (2000).

The current GWD scheme also has a number of numerical weaknesses. The first is that the switching between high and low Froude number regimes is very abrupt, occurring at $F = 1.5$. Thus, when F is close to 1.5, a small change in the low-level flow characteristics may result in a large change in the parametrized response. A second weakness is that the scheme is model level dependent. Thus, an increase in low-level vertical resolution led to a systematic decrease in the parametrized drag. Clearly, both these numerical weaknesses are undesirable; they imply that the current GWD scheme is not robust.

In this paper a new SSO scheme is presented which addresses the weaknesses of the current scheme and improves the performance of the UM. Thus, in section 2 some additional motivation for the new scheme is given before the new scheme is briefly described. Section 3 describes the impact on the modelled SSO response of the new scheme and also illustrates its beneficial impact on forecast skill in the UM. Finally, concluding remarks are given in section 4.

2. THE NEW SSO SCHEME

2.1 Motivation

The motivation behind the new SSO scheme is provided by the modelling study of Olaffson and Bougeault (1997) who performed a series of experiments of flow over an elliptical mountain. Figure 2 (adapted from their Fig. 4) summarises the main result of their study. This figure shows the pressure drag for three of their experiments (non-rotating, rotating, and rotating with friction). The drag in all these experiments was normalised by that predicted for linear two dimensional non-rotating frictionless flow. The non-rotating runs exhibit the well known variation in drag as the inverse Froude number is varied with, for example, the high drag hydraulic jump state evident when the inverse Froude number is of order unity. These results provided some of the motivation for the current GWD scheme.

The motivation for the new SSO scheme is drawn from the results for more realistic flow conditions, i.e. from the simulations with both friction and rotation. In these runs the pressure drag is much less dependent on the low level Froude number, deviating by no more than about 30% from the normalising value. Olaffson and Bougeault themselves commented on this result and suggested that it might help to explain why observed pressure drags agreed remarkably

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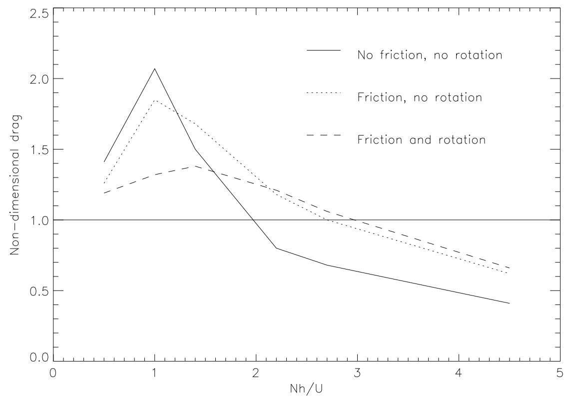

Figure 1: Simulated non-dimensional pressure drag on an elliptical mountain from Olaffson and Bougeault (1997). The drag is normalised by that predicted by the analytical expression for linear two dimensional non-rotating frictionless flow.

well with that predicted by the expression for linear two dimensional non-rotating frictionless flow.

The new scheme thus uses this simple normalising value as its prediction of the surface pressure drag. The use of this prediction ensures that the surface pressure drag will be within 30% of the correct value irrespective of the Froude number of the incident flow.

The surface pressure drag is then partitioned into a blocked flow component and a GWD component. This is done by diagnosing the depth of the blocked layer, *i.e.* the depth of air diagnosed to be flowing around rather than over the sub-grid mountains. Linear hydrostatic gravity waves are then launched with an amplitude proportional to the depth of the sub-grid mountains above the blocked layer. The remainder of the surface pressure drag is attributed to flow-blocking.

The new scheme is thus a simple empirical fit to the most realistic simulations of Olaffson and Bougeault, i.e. the simulations including both friction and rotation. The novel feature of the new scheme is that it accounts for the effects of rotation although, admittedly, this is an implicit rather than explicit feature of the scheme. The new scheme also addresses the weaknesses of the current scheme identified in the previous section.

2.2 Description

We now give a more precise description of the new scheme. The total surface stress is given by the well known expression for linear two dimensional non-rotating frictionless flow. Following Gregory et al.(1998), the expression is modified to account for the anisotropy of the sub-grid orography and it thus becomes

$$\tau_{sx} = \rho U N \hat{K}^{-1}(\sigma_{xx}^2 \cos\chi + \sigma_{xy}^2 \sin\chi) \quad (1)$$
$$\tau_{sy} = \rho V N \hat{K}^{-1}(\sigma_{xy}^2 \cos\chi + \sigma_{yy}^2 \sin\chi) \quad (2)$$

where τ_{sx} and τ_{sy} are the zonal and meridional components of the surface stress, ρ is the low level density, U, V are the components of the low level wind speed, χ is the direction of the low level wind relative to westerly, $\hat{K}$ is a "tuneable" wavenumber constant, and the σ_{ij} are the grid-box average squared gradients of the source dataset (e.g. $\sigma_{xx} = (\partial h(x,y)/\partial x)^2$). Here, "low level" is the depth of the sub-grid mountains, and is taken to be the average from the ground up to the 2.5σ level, where σ is the standard deviation of the sub-grid orography. 2.5σ is slightly deeper than the generally accepted 2σ value for the tops of the sub-grid mountains. However, the impact of the exact choice of sub-grid mountain height on the performance of the new scheme is in fact very small.

The partitioning of the drag into blocked flow and gravity wave components depends on the low level Froude number and, more precisely on the depth of any blocked layer. The blocked layer depth, d, is diagnosed as

$$d = 2.5\sigma - \frac{U}{F_c N} \quad (3)$$

where F_c is the Froude number at which flow blocking is deemed to first occur. This should be of order unity, but there is some scope for "tuning" the scheme with this constant, since the Froude number diagnosis is not guaranteed to be completely correct.

Once the blocked layer depth is known, the gravity wave component of the surface stress can be evaluated. Only linear hydrostatic waves are considered and the surface stress is predicted using a modified version of the expression used to predict the total surface stress. The modification to that expression is to set the amplitude of the gravity waves to be proportional to the depth of air flowing over the sub-grid mountains. The gravity wave surface stress is given by

$$\tau_s(gwd) = \tau_s \cdot \left(\frac{2.5\sigma - d}{2.5\sigma}\right)^2 \quad (4)$$

where $\tau_s = (\tau_{sx}, \tau_{sy})$. The remainder of the surface stress is assumed to be due to flow-blocking. Here, flow-blocking is more a generic than a precise term;

we actually make no attempt to attribute the low-level drag to any specific mechanism or mechanisms. Rather, the low-level drag is a consequence of our empirical fit to the results of Olaffson and Bougeault (1997).

The calculation of gravity wave breaking uses the same saturation hypothesis as in Gregory et al.(1998). The blocked flow drag is applied uniformly from the ground up to 2.5σ.

The new scheme is thus very simple, and has only two free parameters ($\hat{K}$ and F_c). The simplicity of the scheme makes interpreting its behaviour simple, and also makes implementing it in a numerically robustness way simple.

3. THE NEW SCHEME IN THE GLOBAL FORECAST MODEL

In this section a pair of one month (December 1999) forecast trials will be described which illustrate the impact of the new SSO scheme on the performance of the UM. Each trial had an independent data assimilation cycle and 5 day forecasts were made once per day from the 1200 UTC analysis. The horizontal resolution was $0.83^o \times 1.25^o$ whilst 38 levels were employed in the vertical, with the lowest 10 levels concentrated in the lowest 2000 metres of the atmosphere. The NEW trial uses the new SSO scheme, whilst the CONTROL trial uses the current GWD scheme.

In the NEW trial, the free parameters ($\hat{K}$ and F_c) were set to $1 \times 10^{-5} m^{-1}$ and 2 respectively. These "optimum" values were the ones which showed greatest skill in a series of forecast only tests run from operational analyses.

3.1 Impact on the modelled orography response

Figure 2 shows the zonal mean drag on the zonal wind for the two trials. The main features to notice are the increase in drag at all latitudes with the new SSO scheme, and also the increase in the proportion of the drag being applied at low levels. With the new SSO scheme, in fact, about 80% of the total surface stress is attributed to low level flow blocking. Thus there are clearly large changes in the modelled orographic response with the new SSO scheme.

3.2 Impact on forecast skill

The forecast skill of these two trials has been assessed by objectively verification against surface and radiosonde observations and also against each trial's

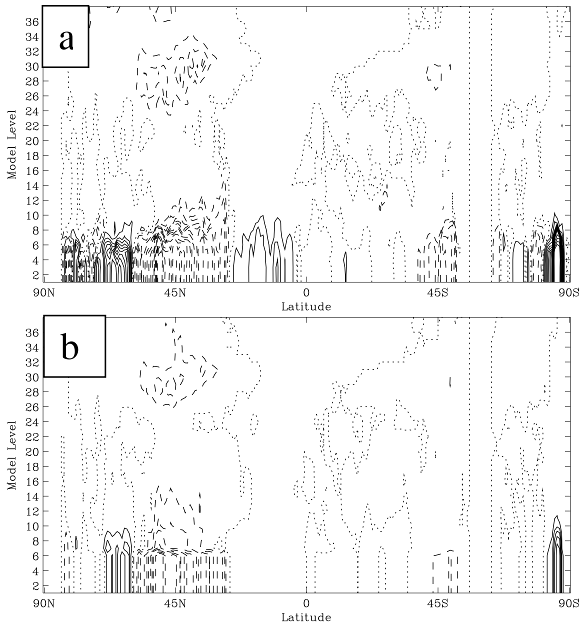

Figure 2: The average day 1 zonal mean zonal wind acceleration for (a) the NEW trial and (b) the CONTROL trial. Solid lines denote positive values, dashed lines denote negative values whilst the dotted line denotes the zero contour. The contour interval is $0.5 m s^{-1} d^{-1}$.

own analysis. Mean sea level pressure (MSLP), 500hPa heights and 250hPa winds are verified in the extra-tropics ($> 20^o$N and $< 20^o$S), whilst 850hPa and 250hPa winds are verified in the tropics ($< 20^o$). Differences in root-mean-square (RMS) errors of 2% are statistically significant for this length of forecast trial.

The largest improvements are in the Northern Hemisphere in both MSLP and 500hPa height, especially at early forecast ranges. For instance, day 1 MSLP RMS errors are 3.4% improved when verified against observations and 4.6% improved when verified against analyses. Low level tropical winds are also significantly improved, most notably when verified against observations. The impact on all other fields verified was not significant.

A more detailed analysis of the improvement in NH MSLP pressure has been carried out. Figure 3a shows the region of largest day 1 RMS reductions in the Northern Hemisphere, which is over Alaska. The largest reduction (1.5hPa) equates to a 50% reduction in the RMS error in that region. Figure 3b shows the change in the mean error in MSLP in this region. The change evident in this plot actually equates to a large reduction in mean error in the NEW trial. Thus

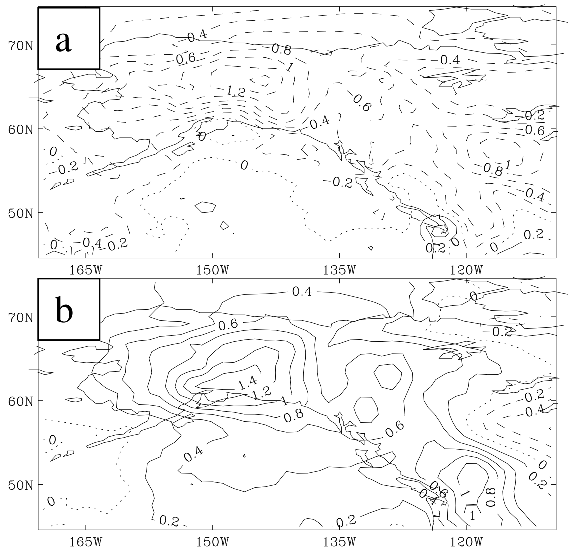

Figure 3: Latitude-longitude sections of mean sea level pressure (MSLP) over north west North America, the region where the reduction in day 1 rms errors was greatest. (a) The difference in root mean square MSLP error between the two trials (NEW - CONTROL). (b) The difference in mean MSLP error between the two trials. The contour interval is 0.2hPa. Solid lines denote positive values, dashed lines denote negative values whilst the dotted line denotes the zero contour.

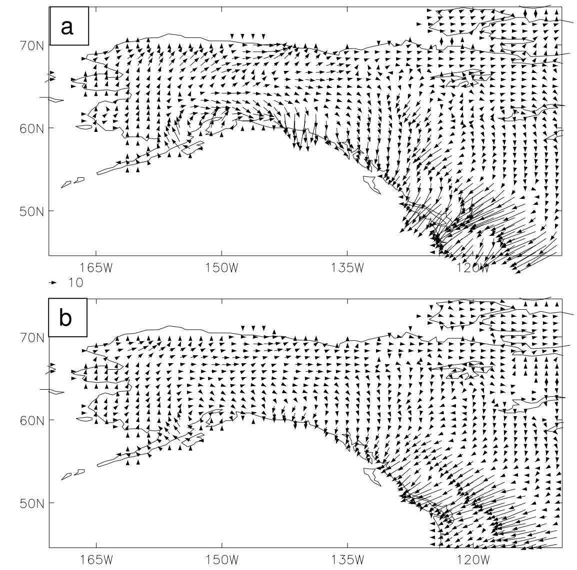

Figure 4: The low level (lowest 2.5 kilometres of the atmosphere) deceleration of the large-scale flow in the (a) NEW trial and (b) in the CONTROL trial. The units are $ms^{-1}d^{-1}$, with the size of the deceleration being proportional to the arrow length, and the arrow length being normalised by the $10ms^{-1}d^{-1}$ arrow shown between the two panels.

the change in mean error would appear to be significantly contributing to the reduction in RMS error.

Figure 4 shows that the improved mean MSLP error in figure 3b is being forced by a big increase in the low level drag along the eastern flank of the mean MSLP error. Thus, the biggest improvement in MSLP forecast skill appears to be due to the new SSO scheme capturing the flow blocking effect of the mountains in South East Alaska.

4. SUMMARY

A new SSO scheme has been implemented in the Unified Model. The new scheme gives an approximately correct prediction of both the surface pressure drag and the vertical distribution of the drag on the atmosphere, whilst at the same time being very simple and numerically robust. The new scheme significantly improves the forecast performance of the UM, especially at low levels.

5. REFERENCES

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