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DOES THE EFFECT OF ROTATION NEED TO BE ACCOUNTED FOR WHEN PARAMETRIZING SUB-GRID OROGRAPHY?

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1. INTRODUCTION

The parametrization of the effects of sub-gridscale orography (SSO) used in the Met Office Unified Model (Webster *et al.*, 2003) is very simple, using linear theory and ignoring rotation to predict the SSO drag. The use of such a simple prediction for the SSO drag was encouraged by the idealised experiments of Olafsson and Bougeault (1997, hereafter OB97) who found that when rotation was included the drag on an elongated mesoscale ridge (normalised by the prediction from linear theory ignoring rotation) depended only weakly on the low-level Froude number ($F_r = U/Nh_m$, where U is the low level wind speed, N is the buoyancy frequency and h_m is the height of the mountain), i.e. depended only weakly on the non-linearity of the flow. As illustrated in Webster *et al.*, even though the parametrization ignores rotation, it performs well in the UM with most of the drag being attributed to flow blocking, i.e. usually $F_r < 1$.

Shutts (1998, hereafter S98), however, has suggested that the drag on a mesoscale mountain ridge should, in fact, include a dependence on rotation, i.e. on f, the Coriolis parameter. This suggestion was based on a simple idealised model of the cold-air damming mechanism, which is the flow-blocking process captured by OB97 at low F_r, and is arguably also the dominant drag process over real mesoscale orography. See our Fig. 2 for an illustration of the low-level flow typical in this situation. Essentially, the effect of rotation is to divert preferentially the air to the left of a ridge (in the Northern Hemisphere) and to form a barrier jet adjacent to the ridge. Ultimately, S98 deduced an expression for the drag (F_{m^*}, again normalised by the prediction from linear theory ignoring rotation) as follows:-

$$F_{m^*} = \frac{4\gamma h_{m^*}}{3\left(h_{m^*}^2 + \gamma\right)} \qquad (1)$$

where $\gamma = fL/U_g$ and $h_{m^*} = Nh_m/U_g$. Here, L is the length of the mountain ridge and U_g is the geostrophic wind speed perpendicular to the ridge. This model assumes that $L >> L_R$, where $L_R = Nh_m/f$ is the Rossby radius of deformation and hence also assumes that the Rossby number, $R_0 = U_g/(fW)$, based on the mountain width, W, is greater than unity, whilst the Lagrangian Rossby number $R_{0L} = V_b/fL$, where V_b is the barrier jet wind speed, is less than unity.

For typical values of L, U_g and h_{m^*}, Eq. (1) indicates that the normalised drag, F_{m^*}, may reach a maximum value of 3. S98 therefore implies that the drag predicted by the current UM SSO parametrization may, in certain situations, be up to a factor of 3 too small.

The aim of this study, therefore, is to extend the work of OB97 to clarify whether f should in fact be accounted for when parametrizing the drag due to SSO. Thus, whereas the results of OB97 were based on a single ridge of half-length 200 km, here we investigate how the normalised drag varies as the ridge length, L, varies. In particular, we have varied R_{0L} by varying L and f and hence, for longer L or bigger f, have extended the modelled parameter space to be more in keeping with the assumptions of S98.

2. RESULTS

Five simulations have been performed using the Met Office BLASIUS code. The model solves the time-dependent Boussinesq equations in a terrain-following coordinate system and utilizes a finite-difference discretization and an explicit time integration scheme. Four different ridges have been used and, in each case, they are “witch of Agnesi” shaped at each end, with a half-width of 40km. This circular hill is then elongated in the y-direction by the addition of a flat ridge of length 160km, 240km, 320km and 480km respectively. The height of the ridge is 2700m and so, with the mean wind speed, $U = 10ms^{-1}$, and buoyancy frequency, $N = 0.01s^{-1}$, $F_r = 0.37$. In the first 4 simulations the ridge length

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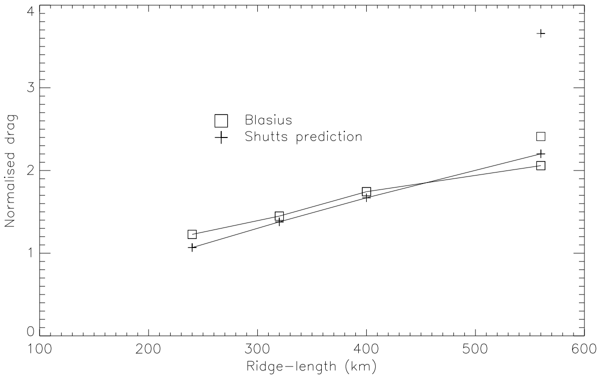

Figure 1: Normalised drag against ridge length for the BLASIUS simulations (open squares) and for the S98 prediction (crosses). The ridge length, L, is taken to be the length of the central flat ridge plus twice the half-width of the "witch of Agnesi". For the simulations joined together by the lines $f = 10^{-4}s^{-1}$, whilst for the other simulation $f = 2 \times 10^{-4}s^{-1}$.

is varied and $f = 10^{-4}s^{-1}$. The final simulation again used the longest ridge, but $f = 2 \times 10^{-4}s^{-1}$. All the simulations were run for 10^5s, i.e. until the area-averaged surface pressure drag was quasi-steady.

Figure 1 compares the normalised surface pressure drag on the ridge in these five simulations with that predicted by S98. Note that the ridge used in OB97 was of length $L = 400km$. There are three main points evident from this plot. Firstly, the variation in modelled drag is much less than the variation in the S98 prediction. This suggests that ignoring rotation when predicting the UM SSO drag is not unreasonable; the variation in drag from including f is only about half that predicted by S98.

Secondly, for those ridges less than or equal to the OB97 ridge length, the agreement between the modelled drag and predicted drag is very good. This is despite the fact that L in these runs is comparable to L_R and hence the S98 prediction is not strictly applicable.

Finally, for the two pairs of runs with the longest ridge, i.e. for the two runs where the S98 prediction should be most valid, the agreement appears to remain good for the $f = 10^{-4}s^{-1}$ run (hereafter the F1 run), but appears to significantly over estimate the drag for the $f = 2 \times 10^{-4}s^{-1}$ run (hereafter the F2 run). Thus, the S98 prediction breaks down in the region of parameter space ($L >> L_R$) where, *a priori*, it would appear to be most applicable.

We are not yet certain why the S98 prediction is in error for the F2 run. However, it would seem likely that the prediction error is associated with the very different low-level flow field in the two runs (Fig. 2). The flow in the F1 run is predominantly around the mountain, whilst the flow in the F2 run is much less around and much more over the mountain. Indeed, of all the five simulations performed, it is only in the F2 run that the along-ridge displacements are considerably less than the ridge length, L. Since the S98 prediction is proportional to L because the along-ridge displacement is assumed to be close to L, this would appear to be the most likely reason for the S98 prediction to be in error. However, further experiments are required to better understand why the along-ridge displacements are reduced in the F2 run.

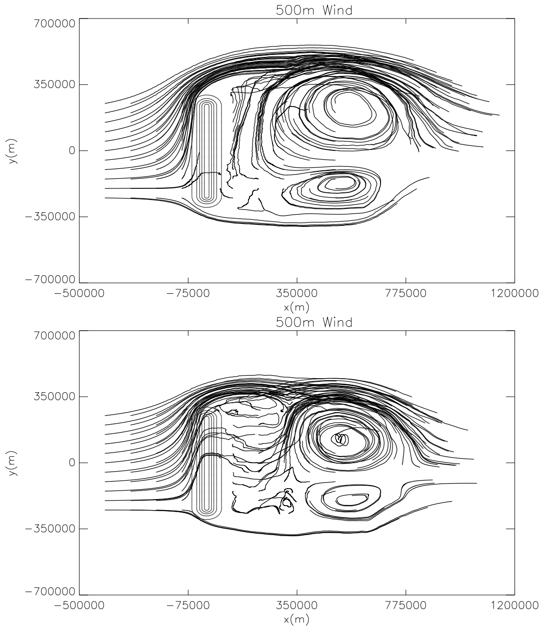

Figure 2: Trajectories initialised at $500m$ above the ground for the longest ridge ($L = 560km$). Top plot is for the simulation with $f = 10^{-4}s^{-1}$ (run F1) whilst the bottom plot is for the simulation with $f = 2 \times 10^{-4}s^{-1}$ (run F2). The trajectories are calculated assuming the flow has reached a steady state and thus use the winds output after 100,000s of integration.

3. SUMMARY

The current UM SSO parametrization ignores rotation when predicting the surface pressure drag. Shutts (1998) has suggested that this may not be justified, i.e. the effects of rotation may significantly affect the surface pressure drag on mesoscale mountain ridges. In this study we have presented a series of experiments to clarify the importance of rotation in diagnosing the surface pressure drag. The conclusion from the experiments performed is that rotation is not very important, but further experiments are required to confirm this conclusion.

4. REFERENCES

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