SENSITIVITY OF OROGRAPHIC DRAG TO MODEL RESOLUTION.

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Samantha Smith[1] *, Andrew Brown[2], James D. Doyle[3], Stuart Webster[1],
[1] Met Office, Exeter, Devon, U.K.
[2] ECMWF, Reading, Berkshire, U.K.,
[3] Naval Research Laboratory, Monterey, CA 93943-5502

1. INTRODUCTION

Numerical models are used at a wide range of horizontal resolutions from several hundred kilometers for climate simulations to several kilometers for NWP forecast simulations. Therefore sub-grid scale orography (SSO) parametrisations play a very important role in the correct prediction of total drag and therefore of the large-scale winds over a wide range of resolutions. The Alps are highly complex and 3-dimensional, being made up of individual mountains up to 5km high and only a few kilometers wide so they are not resolved on the global model grid. The drag responsible for decelerating the large scale flow is produced by flow splitting and/or mountain waves which can not be resolved or even forced by the model orography and therefore must be represented in the SSO scheme.

As the horizontal resolution is increased, the orography becomes more complex and more of the atmospheric processes responsible for the drag are explicitly resolved. The resolved drag should converge towards its real value. Correspondingly, a smaller proportion of the total drag needs to be parametrized. Very few studies have been carried on the behaviour of resolved and parametrized drag with resolution. Clark and Miller (1991) investigated the variation of simulated orographic pressure drag and wave momentum fluxes over the Alps with horizontal model resolution (between 80km and 5km) for the strong south foehn case of 8 November 1982. They found that convergence in the resolved surface pressure drag was achieved at a horizontal resolution of 10km, but this was perhaps inevitable given that their orography data only had a resolution of about 10km.

The 8 November 1999 northerly foehn case (Smith, 2004) which occurred during MAP involved flow-splitting around the Alps as a whole and around individual peaks, with mountain waves forced aloft at horizontal scales as small as 6km, making this a perfect testbed for model drag behaviour. Simulations of the 8 November 1999 MAP case study have been produced using three different numerical models: the Met Office Unified Model (UM), the Naval Research Laboratory's COAMPS^{TM} and the ECMWF's Integrated Forecast System (IFS) in order to asses model drag behaviour. The IFS is a global spectral model, while the UM and COAMPs mesoscale simulations were run using 1-way nested domains. The UM and COAMPs simulations were initialised from the operational 8 November 0z analysis produced by each centre. The IFS simulations were initialised from the operational ECMWF analysis for 12z on 7 November. The work has so far focused on the behaviour of the explicitly resolved drag. The parametrised drag will be investigated later.

2. SURFACE PRESSURE DRAG CALCULATIONS

The calculation of the surface pressure drag on a mountain range is complicated by the use of a limited area domain where the average slope of the surface is non-zero. In particular, the surface elevation of the northern domain boundary is higher than the southern domain boundary by up to 300m for the Alpine region, depending on their exact location. This results in a non-zero drag due to the horizontal component of the force resulting from the weight of the atmosphere on a sloping domain, which is much larger than the mountain drag produced by flow past the Alps. The method described by Carissimo et al (1988) has therefore been used, whereby the hydrostatic pressure due to the elevation of the surface above mean sea level is subtracted from the surface pressure. At grid-box (i,j) the surface height is given by h(i,j) and the surface pressure by p_*(i,j). The hydrostatic pressure due to the surface height at each grid-point, P(i,j), is approximated using the standard atmospheric pressure assuming a constant temperature lapse rate in the troposphere $\gamma = 0.0065$ K m^{-1}.

$$P(i,j) = P_0(1 - \frac{\gamma \, h(i,j)}{T_0})^{\frac{g}{R\gamma}}$$

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*Corresponding author address: Samantha Smith, Met Office, Fitzroy Road, Exeter, Devon, EX1 3PB, U.K.; email:samantha.smith@metoffice.com where P_0 is the standard atmospheric pressure at mean sea level (101324.4 Pa), T_0 is the temperature at mean sea level (288.15 K), g is the acceleration due to gravity (9.80665 m s^{-2} at 45.5° latitude) and R is the gas constant for air (287.05). The following analysis is then performed on the surface pressure deviation from its hydrostatic value, $p = p_* - P$. The final drag calculation is also corrected for the deviation of the hydrostatic pressure from the standard atmosphere as shown below.

$$D_y \;=\; \sum p\,\frac{dh}{dy} dx\,dy - \frac{\sum\, p\,dx\,dy \;\; \sum \frac{dh}{dy}\,dx\,dy}{\sum dx\,dy}$$

where dx and dy are the resolution in the x and y directions. It has been found that the results are insensitive to the finite difference calculation approximations in the calculation of dh/dx. The correction for the average surface slope across the domain was tested by extending the averaging area by 1° north and south, which was found to make little difference to the drag values.

3. VARIATION OF RESOLVED SURFACE PRESSURE DRAG WITH RESOLUTION

For each simulation the drags were calculated over the region with its bottom left corner at (5°E, 43°N) and its top right corner at (17°E, 49°N). This region contains the whole of the Alps but does not contain the Massif Central to the west. The UM model orography within this region is shown for the 60km LAM in figure 1(a). Comparing this with the orography from the 4km LAM in figure 1(b) shows how little of the orographic detail is captured at the scale of the global NWP model.

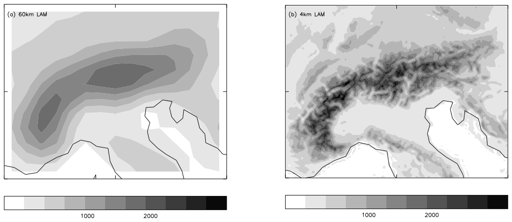

Figure 1: Orography over the drag averaging region from (a) the 60km LAM and (b) the 4km LAM.

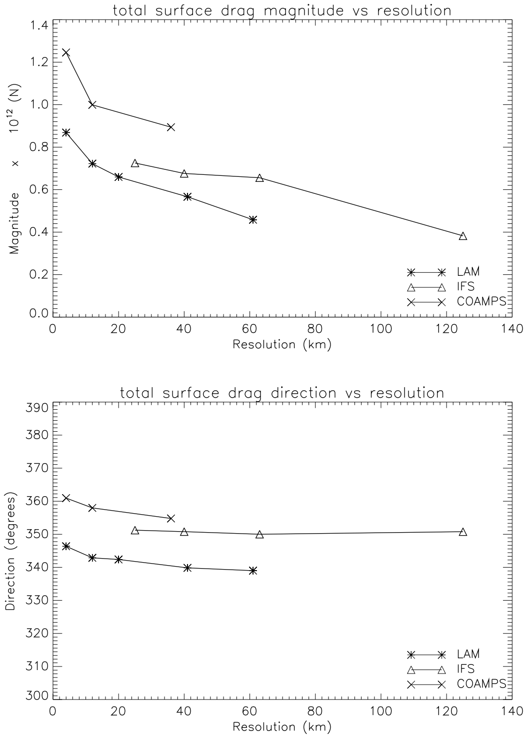

Figure 2: Total surface pressure drag acting on the mountain versus horizontal resolution: (a)drag magnitude and (b) drag direction.

For each model simulation, the total drag over the area shown in figure 1 was averaged between 0600 and 1500 UTC. Figure 2 shows how this time averaged surface pressure drag varies with model resolution for the UM (asterisks), the IFS (triangles) and COAMPS (crosses). For each model, the drag magnitude increases with horizontal resolution over the range included in this study, while the direction of the drag vector rotates towards a more northerly direction. There is no indication of any convergence in the drags for the range of resolutions in this study. In fact, the largest increase in drag is from a resolution of 12km to 4km in both the UM and COAMPS. A 4km grid can only properly resolve scales larger than 20km while a 12km grid can only resolve scales larger than 60km. (Smaller scales which cannot be well resolved are filtered from the mean orography in the UM , and must be represented using the SSO scheme). This suggests that dynamical processes between 60km and 20km in length make an important contribution to drag in this case (for example, mountain waves of about 25km to 35km wavelength were shown by Smith 2004). The lack of convergence suggests that the individual peaks and valleys which force the smaller scale waves and secondary PV banners may be as important as the large scale waves and Alpine flow splitting.

Although all three models predict drags which follow a similar trend with horizontal model resolution, the actual drag magnitudes vary by about 30%. The drag direction also varies by ±8°. Many factors may be responsible for these differences in the drag magnitudes and directions. Different analyses are used to initiate each model, but IFS simulations initialised by operational and era40 analyses showed relatively little sensitivity to a change in analysis. The high resolution UM and COAMPs mesoscale simulations are driven by lower resolution forecasts which may introduce errors in the large-scale flow fields. Smith (2004) verified that the 4km mesoscale simulation was correctly reproducing the large-scale flow past the Alps. The use of different orographic source datasets and varying methods of creating model orography may also be a source of discrepancy. This needs to be investigated further.

All three models predict a maximum drag at 06:00 after which the magnitude generally decreases with time, with some oscillations. The time-series of the drags predicted by the UM at the various resolutions are shown for in figure 3. The non-stationary conditions on this day will make the model intercomparison much more difficult.

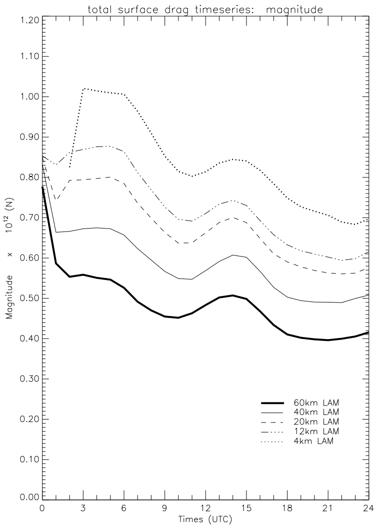

Figure 3: Time-series of the magnitude and direction of the total surface pressure drag acting on the Alps for the UM at various resolutions.

4. Future Work

The reasons for the different resolved drag prediction between the models will be further investigated, including the different representations of orography and different initial conditions. The study will also be extended to higher horizontal resolutions in an attempt to achieve convergence of the resolved drag and to achieve a high resolution "truth". The behaviour of the subgrid scale orography parametrisations will also be investigated to see if it correctly reduces to zero as the drag is fully resolved by the model. Ideally, the total (resolved plus parametrised) drag should be independent of resolution. How well or poorly the parametrizations behave will provide guidance for their future development.

5. Acknowledgements

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6. REFERENCES

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