INTRODUCTION

The representation of orography including the parametrization of subgrid-scale orographic processes is recognized as crucial to numerical weather prediction at all time ranges. For seasonal forecasting and climate simulation accurate modelling of orographic forcing is essential for the maintenance of the largescale circulations and statistics of lower frequency variability. The recent introduction of new subgrid orography parametrizations, the availability of high resolution global orography datasets, and the growing ability of LES and cloudresolving models to address key issues related to flow over and round orography, all supported the timeliness of a workshop on the subject.

The workshop followed the usual format of invited lectures and discussions in working groups and concluded with a plenary session. Groups were set up to consider the issues of turbulence and the boundary layer, waves and stability, and mesoscale dynamics and physics. The discussions and recommendations of these groups are summarized in the following three reports. The texts of the invited lecturers are also included. ECMWF thanks all the participants for their contributions to a successful and stimulating workshop.

Working Group 1 - Turbulence and boundary layer

1.1 Introduction

Before going into the details of turbulence and boundary-layer parametrization, it is appropriate to start with a few general remarks:

i) When we say Froude number we mean, $F_L = 2\pi U/NL$ where L is a length characteristic of the wavelength of the topography. This is in accord with the remarks in section 1.4 of *Baines* (1995) although in fact he tends to avoid the use of the nomenclature, Froude number, in the context of unbounded flow over orography.

ii) We assume that we are dealing with relatively homogeneous rolling or hilly or mountainous terrain rather than isolated mountains. We assume that the flow above the boundary layer can be characterized by constant U (for example 10 ms^{-1}) and constant N (say $10^{-2}\mathrm{s}^{-1}$). Absorption and reflection of gravity waves above the boundary layer were not considered by this working group.

iii) In this scenario we can divide topographic drag effects into a) wave drag with $F_L < 1$ ($L > 2\pi$ km in the sample case) and b) boundary layer drag, effective for all F_L but possibly dependent on F_L. For steep topography and strong stability there may also be a need to consider the effects of blocking/2D-wake effects á la *Lott & Miller* (1997).

iv) Boundary layer topographic drag becomes significant (roughly equivalent to surface shear stress caused by vegetation and other roughness elements) for terrain with $H/L > 0.1$ (maximum slope > 0.4). Wave drag is significant for $H/L > 0.01$ (maximum slope 0.04).

1.2 Gravity wave drag

When $F_L < 1$, two equivalent formulae for gravity wave drag per unit area in a constant U, constant N environment, both based on, for example, equation (6.8.11) of *Gill* (1982), are

$$\mathrm{DRAG} = A\rho U^2\left(\frac{H}{L}\right)^2 (F_L^{-2} - 1)^{1/2} \qquad (1a)$$

$$\mathrm{DRAG} = A\rho\frac{UNH}{2\pi}\left(\frac{H}{L}\right)(1 - F_L^2)^{1/2} \qquad (1b)$$

Here A is a constant dependent on the topographic shape and the definitions of H and L. They lead to different viewpoints. If equation (1a) is used the emphasis is on the slope of the terrain (H/L), squared, and the square of the velocity U^2. Note however that the limit as $F_L \rightarrow 0$ is singular. Equation (1b) emphasises terrain height, H. It is often (e.g. *Palmer et al*, 1986) given in the limit with $F_L = 0$ in the form

$$\mathrm{DRAG} = Ck\rho UNH^2$$

which emphasises H still further. Additional parametrization by *Palmer et al* (their equation 8) and by *Baines* (1995, equation 7.2.18) buries the wavenumber k (and hence the slope) in the dimensional constant k (*Palmer*) or C (*Baines*) which in the Palmer et al model becomes a tuning parameter.

There is increasing evidence to suggest a sensitivity of gravity wave fields to the presence of the boundary layer. At present the basic ECMWF gravity-wave scheme (neglecting the nonlinear components such as low-level flow blocking) scales the momentum flux profile on:

$$U_H^2 \frac{H^2}{L^2} \left| \frac{LN_H}{U_H} \right|$$

This formula assumes $F_L^{-1} \gg 1$ (i.e. hydrostatic limit) due primarily to limitations in the original orographic data set. With improved higher resolution data sets such an assumption no longer seems necessary. Use of the more correct $(F_L^{-1} - 1)^{1/2}$ term for $|F_L^{-1}|$ may lead to a more realistic reduction of gravity-wave drag as $F_L^{-1} \to 1$. This may well provide a more appealing parallel with the boundary-layer drag associated with evanescent waves, which *Belcher and Wood* (1996) argue should scale as $1 - F_L^{-2}$.

At present there is a sensitivity of the gravity wave scheme to the boundary layer but it is ad hoc and depends on the choice of the height H at which the velocity and buoyancy frequency scales are calculated. Linear analysis suggests a scaling height that is related to the horizontal scale of the forcing orography rather than the vertical scale, as currently used. For hills of scales longer than 10 km this would lead to a “launching” height above the boundary layer. Use of such height would circumvent problems with an underlying convective boundary layer which would suggest no gravity waves when in practice it seems likely that such waves could be forced by variations in height of the top of the boundary layer, rather than the topography directly. Then of course the problem would be to characterise the appropriate “slope” to use and such improvement must await the results of further research.

A desirable goal for the future might be the unification of the turbulent orographic drag scheme and the orography induced gravity wave scheme. Such unification may well be aided by the explicit representation of boundary layer drag as an imposed momentum flux (most likely as $C_D U^2$ multiplied by stability corrections), possibly having a significant divergence within the boundary layer, rather than via a derived or effective roughness length. Such an approach would also complement the low-level blocking scheme. Noting the apparent opposite stability dependence of these mechanisms it is tempting to speculate that future work may suggest the single addition of the two contributions.

1.3 Effective roughness length

“Effective roughness length” is believed to be a useful practical concept to represent the effects of drag of subgrid orography through the vertical diffusion parametrization. Support can be found in observational and model studies. They show for neutral stratification that far away from the orography the pressure drag caused by the orography is merged with the turbulent stress and that a logarithmic wind profile exists as if there is an underlying surface with a high roughness length.

Important questions related to the parametrization of effective roughness length are: i) How should orographic roughness be derived from fine scale orographic data sets? ii) What are the contributing orographic scales? and iii) Does stability interact with orographic roughness length?

Orographic roughness parametrizations for gentle topography are fairly well documented on the basis of fine scale models. However, the enhancement factors are rather small (factor 2 to 3). For real terrain in large scale models, steep orography effects are more important. Steep topography results in flow separation and the so-called silhouette parameter ($\Sigma A/S$, where ΣA is the total silhouette area and S the horizontal area) is believed to be the best parameter to represent the steep orography bluff body drag.

Parameter $\Sigma A/S$ is a slope parameter and therefore dominated by small scale features. Horizontal scales between 100 m and 5 km should be included to compute $\Sigma A/S$ from orographic data sets.

Effective roughness lengths for orography can be large. However, Monin Obukhov similarity assumes a scale separation between Obukhov length and surface roughness and is therefore not necessarily applicable over orography. Preliminary studies for idealized cases suggest that the orographic roughness should depend on boundary-layer stability and also that the stability functions (closure functions dependent on Richardson number) for the entire boundary layer should depend on orographic roughness. A practical compromise could be to implement the orographic component of the surface drag with help of a drag coefficient on the lowest model level without any stability effects. In contrast to the reference height for the gravity waves, the reference height for the orographic drag should be of the order of the height of the subgrid orography (H). Whether the orographic roughness length has an anisotropic component is not clear from existing data sets and needs further study.

A mechanism like orographic form drag does not exist for heat and moisture transfer and therefore special attention has to be paid to the transfer of heat and moisture. This can be done by reducing the roughness lengths for heat and moisture in such a way that, in neutral cases, the transfer coefficients for heat and moisture are not affected by orography. It can also be achieved by parametrizing orographic form drag separately from the vegetation roughness and by using the vegetation roughness only for the transfer of heat and moisture. These considerations apply to gentle topography; very little is known about the subgrid parametrization of heat and moisture transfer above steep orography. Also little is known about the effects of subgrid katabatic flow on heat and moisture transfer, although it can be anticipated that these effects are substantial.

1.4 Flow splitting

On the PBL scale, the majority of terrain features are highly three-dimensional, and therefore it is expected that for stably stratified boundary layers, wave generation by the flow over topography, as well as flow blocking and splitting are an important part of the PBL dynamics. Depending on the stability of the boundary layer, as well as wind speed, some of the subgrid-scale orographic features will cause strong blocking and flow splitting upwind, leading to downstream separation and quasi two-dimensional wakes. The current approach of the subgrid-scale orographic drag parametrization is to distribute the drag due to these effects at model levels beneath the height of the separation streamlines.

It is unclear what effect this representation of the low-level gravity wave drag has on the rest of the boundary layer and how it interacts with the current PBL parametrization scheme which applies the neutral concept of effective roughness along mean topography.

The impact of the turbulent wakes behind orographic features on the simulated mean flow is usually neglected in NWP models. However, the importance of this process and its parametrization are unknown and need study. Most of this turbulence is generated by small scale orography and probably does not affect the large scale flow. The same might not be true for mountain ranges like the Alps or the Rockies where the turbulent wake may have an non-negligible impact.

1.5 Topographic data

For effective roughness length parametrization and for the gravity wave drag scheme (GWD), subgrid-scale information is needed. For an adequate representation of orography we need global elevation data sets at the highest resolution. From elevation data, ECMWF calculates the Subgrid scale Orography (SO) parameters for standard deviation (μ), RMS slope (σ) and silhouette slope ($\Sigma A/S$), angle of principal ridges (Θ) and anisotropy (γ). Due to the fact, that the currently used data set USNAVY is noisy and on a coarse resolution of 10' x 10', it is necessary to replace it, in particular if we want to use higher target grid resolutions.

Available alternatives are:

GLOBAL DTM5 (GETECH): Global Digital Terrain Model on a 5' x 5' resolution, which is factor 2 better than the USNAVY data currently used.

D2M30: A 2'30" x 2'30" data set with land sea mask created by G. Jaubert and E. Legrand of Meteo-France. The main inputs of the data set are: GLOBE mean, maximum and minimum orography at a resolution corresponding roughly to 1 km x 1 km, but covering only 60% of the land points and DTM5 for the missing points.

GTOPO30: A global digital elevation model (DEM) developed as the result of a collaborative effort led by the U.S. Geological Survey's EROS Data Centre in Sioux Falls, South Dakota. Elevations in GTOPO30 are regularly spaced at 30-arc seconds (approx. 1 km). The main sources of this data set are digital terrain elevation data (50%), digital chart of the world (29.9%) and USGS 1-degree DEM's (6.7%).

Different studies show that SO Parameters on a chosen target grid, depend strongly on the resolution of the original data set. In particular slope parameters σ and $\Sigma A/S$ increase with finer resolutions. When we use higher and higher resolutions we hope to get convergence for σ, $\Sigma A/S$ and the other parameters. Therefore these parameters should be validated for areas where data bases are available on a resolution of 3-arc seconds (approx. 90 meters) or better. In this way calibration factors might be applied to parameters computed from GTOPO30-data.

Given the availability of high resolution data sets it may be useful to use spectral information in the parametrization of gravity waves (e.g. 4x4 wave components).

1.6 Observations

There are relatively few observations of the stable boundary layer in complex terrain and such data as there are should be extensively used. The largest deficiency in data is observations of the overall boundary-layer structure. Recent observations of flow in and above a ridge- valley system have been made by MORU (Met. Office Research Unit) in Wales and this provides valuable data on the flow structure through a considerable proportion of the boundary layer. Even here though no estimate of the boundary-layer depth is available and what is ideally required is a mapping of the variation of boundary-layer depth above surface height variations. For example a key question is whether the boundary layer follows the underlying terrain or smooths out such variations and is essentially flat. The answer to these questions will have bearing on our view of gravity-wave boundary-layer interaction. Such observations may be or become possible with advanced remote sensing techniques.

1.7 Recommendations

1) Present gravity wave drag schemes should be re-evaluated in the light of high resolution data sets. Aspects to consider are the Froude number dependence and the reference height for velocity and buoyancy frequency scales.

2) Boundary-layer and possibly LES modelling of stratified flow over 3D terrain should be used more extensively to tune GWD and surface drag schemes.

3) More observations of gravity wave spectra, boundary-layer structure and N(z), U(z) above the boundary layer are needed. A climatology of N(z) and U(z) based e.g. on radio sonde data would be very useful.

4) More analysis of existing micro-barograph data would be useful.

5) Careful evaluation of the statistics of new and existing orographic data sets should be carried out, in particular for selected areas where high and low resolution data sets can be compared.

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Working Group 2: Waves and stability

2.1 INTRODUCTION

The orographic drag scheme used at ECMWF provides a representation of the drag on the large-scale flow due to nonlinear stratified flow over and around 3-dimensional anisotropic orography. Low level flow drag and gravity wave drag are combined in a ratio that depends on the Subgrid Scale Orography (SSO) elevation and the incident flow characteristics. At low level the drag is applied directly into the flow at the levels which are diagnosed to intersect the SSO. A gravity wave drag is applied aloft where the waves are believed to break, depositing momentum on to the large-scale flow. For large mountains the addition of low level drag and of gravity wave drag reproduces quite realistically the so-called "high-drag" states found in the theoretical simulations of mesoscale stratified flows over/around 3-D orography. The scheme also partly includes 3-D anisotropic effects, the drag orientation being between the direction of the largest mountain slope and the incident flow direction. The scheme has been validated systematically against the PYREX data for flow configurations in which the component of the incident flow perpendicular to the Pyrenees is large.

The working group discussed various aspects of this scheme, and possible improvements to it. Various physical aspects of flow past orography were discussed, as outlined below. Aspects of diagnostics and means of estimating errors were also considered.

2.2 OROGRAPHIC PROCESSES

2.2.1 Gravity waves, boundary layer turbulence and clouds

Experience with GCMs suggests that there is a large interaction between the representation of boundary layer processes and the estimation of orographic drag. Use of measures of wind strength and stability too close to the surface may result in reductions in orographic drag when boundary layer turbulence is enhanced. It is currently unclear at what levels quantities used to characterise the flow over orography should be estimated. However, recent studies of the effects of boundary layer turbulence on gravity wave response to topography have suggested that gravity wave stress is reduced by the presence of a boundary layer. Such links need to be investigated further and feedbacks incorporated into parametrization schemes. The presence of stagnant valley flows may also change the shape and variability of the orography seen by the large-scale flow and so change the gravity wave response.

A further complication, little explored, is the effect of clouds and moist stability upon the estimation of gravity wave activity. Clouds are often present when air flows over orography and the lower stability of the saturated atmosphere may affect the amplitude of the gravity waves. Gravity wave activity is also a source of cloud generation. This is not currently accounted for in large-scale models but will have an impact upon the radiation budget in mountainous regions.

2.2.2 High drag states

Several studies of idealized mesoscale flows past isolated mountains have shown the importance of three-dimensional effects in both sheared and unsheared environments. These numerical studies have shown, in particular, the possibility of high drag regimes associated with wave breaking aloft, where three-dimensional effects also come into play. Present feeling, though, is that there is no observational evidence that these high drag effects are sufficiently important in terms of momentum balance to be considered for more direct parametrization. Observational data coming from future experiments, like MAP, may allow for a better evaluation of the importance and effect of these wave breaking episodes.

2.2.3 Wave propagation and the middle atmosphere.

In the current scheme the gravity wave momentum flux is tacitly assumed to be carried by a single plane two-dimensional wave orientated in the direction of the surface stress vector. However, the surface stress vector calculation incorporates the anisotropy of the SSO orography, and thus it makes some allowance for the three-dimensional nature of the gravity wave field.

For a three-dimensional gravity wave field in directional wind shear, each level in the atmosphere will act as a critical level for those waves orientated perpendicular to the local flow direction. Thus the spectrum of waves will be selectively absorbed and, in contrast to the current scheme, the stress vector may turn with height. However, at this stage it is not obvious how important this process is and whether it should be explicitly included in the model. Indeed, the current scheme implicitly accounts for two-dimensional critical level effects and this may yet prove to be the most pragmatic solution. However, some of the implications from considering three-dimensional critical level effects are worth bearing in mind. For example, the wave pseudo-momentum may be advected considerable horizontal distances before being absorbed by the mean flow. Thus, the drag on the atmosphere should be felt in a grid box far displaced from where the surface pressure drag was exerted. Currently it would appear that the consideration of three-dimensional critical level effects may have greatest relevance to the treatment of gravity waves in the middle atmosphere.

With plans to enhance the vertical resolution in the stratosphere, an alternative approach to representing gravity waves may be necessary. For instance an approach commonly adopted in middle atmosphere climate models is to assume that the spectrum of gravity waves reaching the lower stratosphere is a random ensemble with the waves having no preferred orientation or phase speed; there is no attempt to identify the gravity waves with a particular tropospheric source. The spectrum of waves is launched upwards in the lower stratosphere and allowed to propagate and/or dissipate in the usual way.

2.2.4 Wakes

Existing SSO parametrization schemes make no allowance for the effects of wakes, or more generally, of the effect of neighbouring topography on flow past orography. Several types of wakes have been observed in the atmosphere and laboratory:

i) long straight wakes with reduced momentum attributed to hydraulic transitions over and near the topography,

ii) quasi-steady symmetric lee-side eddies,

iii) a time-dependent stratified vortex-street type wake.

Wakes are attenuated on a length scale that depends on the diffusion of momentum from above and mixing at the sides, so that their extent is limited. None-the-less, these wakes may extend downstream for distances exceeding many obstacle widths.

2.3 NUMERICAL CONSIDERATIONS

The numerical treatment of the atmospheric equations may affect the accurate representation of orographic drag on atmospheric flow in the following two ways:

a) Processes such as gravity wave drag act on a relatively short time scale and are therefore treated in a semi-implicit way. The same applies to the turbulent processes in the boundary layer. Most weather prediction models (including the ECMWF model) use a split scheme whereby increments from different processes are simply added. The addition of increments obtained from two different semi-implicit schemes may result in a time step dependency. Normally, different resolutions of an atmospheric model are run with different time steps and as a consequence orographic drag will be represented differently in these models apart from the obvious dependence on the different representations of orography.

b) In order to prevent numerical instability in weather prediction models it is common practice to introduce horizontal numerical diffusion. Although the ECMWF model has only a relatively mild type of horizontal diffusion, the latter nevertheless imposes a severe restriction on the effective number of degrees of freedom of the model. For example, in the T213 version of the atmospheric model the surface kinetic energy spectrum starts to deviate from the k^{-3} law at wave number 100. Since there is little energy in the small scales, atmospheric flow near topography is not well represented by weather prediction models. This is not desirable and needs further attention. A solution will probably require readjustment of the SSO scheme.

2.4 DIAGNOSTIC STUDIES

2.4.1 Observational studies

Greater comparison is required between the overall response of the model to orography and direct measurements. Comparison to PYREX data was a positive step in this direction, although the results obtained for the Pyrenees may not be simply transferrable to other large-scale mountain ranges, like the Rockies and the Himalayas. In this context use of data from the MAP experiment would be useful. Direct observations of the momentum flux carried by internal waves in the atmosphere is very difficult, and no (remotely sensed) techniques for substantial aerial coverage on a continuous basis are available or in prospect.

Another useful mode of observational study would be to compare the impact of SSO representations on the overall atmospheric angular momentum budget, comparing fluctuations in this to those of the length of the day.

2.4.2 Modelling studies

Detailed process models (both Large Eddy Simulation (LES) and mesoscale models) provide a valuable tool for understanding the processes which parametrization schemes aim to represent. Although there are uncertainties with the results of such models, together with observational studies they have provided ideas which have been included into the latest generation of orographic drag schemes. However these studies often involve very simplistic and small topographic elements, with idealised wind profiles and thermodynamic structures. Also, for the most part there seems to be a separation of modelling into those groups concerned with purely "boundary layer turbulence" or "gravity wave" effects; the real atmosphere knows no such distinction.

Greater efforts should be made to introduce more realism into the flow used in such simulations (for example increasing wind across the boundary layer, changes between dry and moist stabilities at the top of the boundary layer). An important question which could be addressed by such models is: at what level are gravity waves initiated, and what levels of the flow should be used to characterise the response of the flow to orography (see 2.2.1 above)? A further difficulty in the use of current LES and mesoscale modelling studies in deriving orographic drag schemes is the question of how to scale from a single orographic element to the many elements within a grid box of a large-scale model. Efforts should also be made to investigate the flow regimes (for example different wind directions and strengths) with more realistic orography. Previous work done on PYREX Intensive Observation Periods (IOPs) by several groups is an example of this. Such simulations could be compared against the performance of orographic drag schemes in one column models. However, it is uncertain at what resolution such models would provide a sufficiently accurate description of flow over complex orography.

Comparison of mesoscale models of 10km resolution with PYREX IOPs (the COMPARE project) suggests the need to still include descriptions of SSO parametrizations such as those used in GCMs. Without such schemes these relatively (to GCMs) high resolution models imply that the deviation of the flow by the Pyrenees was weaker than observed. Simulated lee vortices were also too weak and not as horizontally extensive as observed. The amplitude of the mountain waves was also excessive. All these features suggest that the model topography is providing insufficient deceleration of the flow. However an objective tool for evaluating the magnitude of the underestimate of the mountain drag is not available, since the non-linear two dimensional pressure drag is controlled by low level features and the momentum flux cannot be calculated below the top of the orography.

2.4.3GCM budget studies and systematic errors

The fact that dynamical tendencies should balance diabatic tendencies when averaged over a long period of time has been used to estimate diabatic forcing from observed large-scale fields. In a similar way the performance of a large-scale model can be checked by comparing the output of the parametrization schemes with dynamical tendencies. This can be done simply by running the model for only one time step and averaging initial model tendencies over a long period of time (typically one month), and over 4 analysis times per day to cancel the diurnal cycle.

Analysis errors, or insufficient data density available to the analysis, impose limits on the usefulness of estimates of diabatic forcing for the evaluation of the model parametrization. However, experience at ECMWF and at the Met. Office has shown that the calculation of initial model tendency residuals can provide sufficient information on model problems associated with orography to improve the parametrization of SSO effects.

Running the model in a diagnostic mode that allows all dynamical tendencies and those from the various parametrization schemes to be saved increases the memory requirements to such an extent that normally only a lower resolution of T106 (compared to the operational T213) has been used. However, in order to avoid adjustment processes due to a resolution change in the region of orography, selected periods should be run with the resolution of the operational analysis. Alternatively, budget runs could be done from a period of re-analysis using a lower resolution.

The present SSO scheme has now been in operation for long enough to provide sufficient cases for a diagnostic study on flow dependence of systematic errors to mountains. The singular vector decomposition of analysis and forecast fields in the short range could give some indication of systematic errors related to orographic forcing.

2.4.4GCM seasonal simulations

The impact of the different representations of orography (explicit and parametrized) also needs to be addressed in the context of long GCM simulations. Indeed, these kinds of simulations allow evaluation of how the steady and quasi-steady features of the large-scale atmospheric circulation (planetary waves, storm tracks, weather regimes) are affected by orography, with a good degree of significance. GCM simulations have already shown that a good representation of the orientation of the mountain induced forces is important. This suggests that the variation of the wave drag force with altitude, found for three dimensional mountain waves propagating in a shear flow, may be an important issue. It should be noted that even when NWP models reach the stage of having sufficiently high resolution to resolve topographic effects explicitly, other lower resolution models such as climate models (that are used for long runs) will still depend on SSO parametrizations.

2.5 CONSIDERATION OF NEW TECHNIQUES

2.5.1Cellular Automata

It has been suggested that the formalism of cellular automata may be useful in providing the basis for parametrizing subgrid-scale effects that have complex behaviour on the small scale. In particular, it would appear that such a framework may readily and economically cope with the effects of wakes, of events outside the grid box, of uneven distributions of topography, and of variations in the large-scale flow within the grid box. It is recommended that ECMWF support work designed to evaluate this approach.

2.5.2High resolution nested grids

Use of high resolution nested grids, with horizontal resolutions of order 1km, over orographic regions may provide an alternative approach to SSO drag schemes in large-scale models, as computational power increases in the future.

2.6 RECOMMENDATIONS

1. Diagnostic budget studies for momentum at operational resolution and focused on orographic regions are recommended for:
   i) evaluation of subgrid-scale orography schemes
   ii) evaluation of the role of horizontal diffusion.

2. Studies of the interaction of the boundary-layer and subgrid-scale orography schemes should be pursued, with a view to determining appropriate means of amalgamating them.

3. Further use should be made of field experiment data (for example, the MAP experiment) for evaluation and improvement of subgrid-scale orography schemes.

4. The performance of subgrid-scale orography schemes should be re-assessed when model resolution is increased.

5. ECMWF should keep abreast of new techniques such as nested grids over topographic regions and cellular automata.

Working Group 3 - Mesoscale dynamics and physics

3.1 Introduction

Mountain environments host a range of mesoscale flow systems. Moreover a sub-set of these systems account for most of the extreme weather events in a mountain region and the net effects of others contribute significantly to the atmosphere's lateral and vertical flux of momentum and energy.

Thus in a forecasting context the existence of such phenomena should impact upon:

i) The design of observational networks in the vicinity of orography;
ii) The strategy for assimilating observational data, and;
iii) The formulation of NWP models.

Factors that influence all three of these considerations include: The scale and structure of both the orography and the mesoscale systems, the realisable space time resolution of the NWP model, and the predictability and perceived significance of the various systems. Scale and resolution factors relate to the issue of "representation versus parametrization", and predictability and significance will help determine the desirability of explicitly resolving the mesoscale features in the NWP model. Some aspects of these topics are discussed further in the following sections.

3.2 Predictability

The predictability of these orographic related phenomena is generally not well established. There are indications that an enhanced level of predictability exists for some phenomena when the forcing comes from the larger scale flows. Examples include trapped lee waves and even small-scale rotors with severe wind behind steep slopes. Likewise, mountains can increase the predictability compared to prediction over flat land, e.g. orographic precipitation in coastal areas. However the sensitivity of the threshold criteria for high-drag and low-drag states and the occurrence of flow bifurcation upstream of the mountains suggest that claims for enhanced predictability need to be further studied.

3.3 Orographic precipitation systems

Global scale climatological studies show there exists a strong correlation between precipitation and orography. Orographic lifting and seeder-feeder cloud mechanism are usually invoked to justify an increase of background stratiform precipitation in mountainous areas. Regional studies (e.g. the MAP Alpine Climatology, Frei) indicate that the alpine slopes are a preferred location for heavy convective precipitation. These strong convective systems, triggered, enhanced, or sustained by the orography constitute a major hydrological risk but are often mispredicted by operational NWP models. Accurate predictions of these systems requires a much higher resolution than the 10-20 km grids of present mesoscale models. Individual mountain elements often possess intrinsic scales of less than 1 km and influence the representation of orographic forcing. Heavy precipitation occurs mainly in vertical columns of 100 m within which there are complex dynamical, thermodynamical and microphysical interactions involving liquid and solid particles. Such motions are obviously not resolved by operational models that have to resort to heavily empirically-based parametrization schemes.

One possible solution is to adopt a multiply-nested simulation system (with the most refined grid capable of explicitly resolving convection and non-hydrostatic motion) which may allow to simultaneously account for the large scale forcing and most of the mesoscale unresolved phenomena.

3.4 Mesoscale aspects of orographic drag

Much of the Earth's orography can be conveniently described as either mesoscale mountain ridges or plateaus. Here 'mesoscale' is defined as the length scale at which Coriolis effects begin to be important, and in this context note that for mountain ridges of sufficient height the Lagrangian Rossby number of blocked flow (based on the length of the ridge) may be quite small. There are indications that the dominant function to the orographic form drag comes from the hydrostatic pressure differences across the mountains due to temperature contrast generated by flow blocking. However, the atmospheric mesoscale is only partly resolved at current global model resolutions and as a consequence, mountain ridges are often overly smoothed. This tends to allow more air to pass over the ridges rather than around leading to underestimated 'cold air damming' drag and overestimated hydrostatic gravity wave excitation.

The underestimation of cold air damming is clearly a resolution issue but not one that falls naturally into the parametrization category since its subgrid description is not that of a statistical process involving many parameterizable elements. Nevertheless, it would seem justifiable to introduce low-level drag forces into an operational forecast model that might correct the associated drag deficiency. This may not correct the tendency to overestimate the near-gridscale explicit gravity wave drag. The current ECMWF parametrization of low-level flow blocking (*Lott and Miller*, 1997) is based on the notions of flow splitting (in the high NH/U regime) around subgrid-scale orographic features and turbulent wake production. This may be associated with recent observational and numerical studies of 'PV banner' generation (*Schär*, 1997) when air flows through valleys transecting mountain ridges. The deficiency in low-level drag may, however, be due to the model's inability to accurately resolve the mesoscale cold air damming phenomenon and attendant mesoscale balanced jets on the upwind side of ridges. The Lott/Miller drag scheme may be playing the role of a stable boundary layer drag parametrization scheme albeit at horizontal scales for which gravity wave radiation occurs.

Accurate simulation of the large-scale flow requires that the representation of the total pressure force on mountains is correctly handled. Note that this pressure force will also involve components at right-angles to the incident (upstream) flow i.e. the 'lift' force. The exact nature of large- (or mesoscale) lift forces is controversial and the simplest quasi-geostrophic view suggests that they are currently handled (in a uniform geostrophic flow at least) if the mountain volume is correct.

3.5 Characteristics of subgrid-scale orography

Parametrization schemes used by large-scale models need input fields characterizing the grid scale and subgrid-scale orography, e.g. mean height, subgrid-scale variance, slope, orientation, and anisotropy. Those different statistics are derived at model resolution using as input a baseline orography. The baseline orography used by ECMWF at present has relatively coarse resolution (10'x10') and is known to suffer from serious regional errors (e.g., Antarctica). ECMWF efforts to replace it by a global 1x1 km should be pursued quickly and the subgrid-scale orography (SSO) parametrization scheme should be adjusted to the new subgrid-scale fields. Although the 1x1 km dataset allows for a much more accurate representation of statistics like characteristic slope, it also raises scale-related issues. We argue that the slope at the 1 km scale should be used for the parametrization of the drag via an effective roughness length, while the slope associated with the gravity wave scheme should be computed at scales that force trapped lee waves, e.g. order 5 km.

3.6 Validation datasets

There is an ongoing need for observational data or results from detailed numerical simulations that can be treated as a proxy for reality. They are essential for the: a) understanding of physical mechanisms involved in mesoscale phenomena; b) verification of model performance; c) validation of model parametrizations and identification of model strengths and deficiencies. The PYREX data was extensively used to develop and validate the *Lott and Miller* (1997) parametrization. Additional datasets of relevance for the mesoscale include:

a) The alpine precipitation data collected by MAP;

b) The precipitation dataset for the Baltic areas collected by the BALTEX group;

c) Direct measurements of total drag due to the mountains and its decomposition into small-scale and gravity wave drag (to be collected on the Isle of Arran).

d) Data assimilation issues

Currently not much remotely sensed or conventional data (e.g. radar, satellite and surface pressure data) are used in data assimilation over mountains areas at sub-synoptic scales. If such data were to be used with current data-assimilation schemes, they would generate vertical velocities and associated divergent circulations not necessarily in balance with the model dynamics and physics, exciting gravity modes in the subsequent model integration. There is a pressing need for an appropriate balance condition valid at the mesoscale in order that the relative wealth of information of remotely-sensed data available over orography can successfully used over orography.

3.7 Speculative comments

a) The validity of the assumption that a model's mountain surface is impervious to airflow (i.e. $\dot{\sigma} = 0$) can be questioned. Considering, for example, the representation of the Antarctic plateau in a forecast model we know that strong katabatic drainage currents transport mass through the lowest model level near the sea and that there must be a corresponding ingestion of mass on the plateau to feed this. Another example would be the 'porosity' of a mountain complex like the Alps resulting in air flows through valley transects.

b) There is a strong desirability for multiply-nested model systems (or very high-resolution models) to handle orographically related phenomena.

c) Many mesoscale phenomena have a rich vertical structure that demand very high vertical resolution.

3.8 Recommendations

1. The subgrid-scale orographic height statistics should be recomputed on currently available 1 km terrain height datasets and the algorithm used should take into account scale separation.

2. The ECMWF lowlevel flow blocking parametrization should be reviewed in the light of recent numerical modelling simulations of flow over mesoscale ridges (e.g. *Olafsson and Bougeault,* 1997).

3. Datasets obtained in MAP should be used to verify the ability of the ECMWF model to capture the flow blocking process and associated drag.

4. Detailed case studies of heavy precipitation events are highly desirable.

5. There is a need to use the available remotely sensed data in a more effective way to ensure a correct representation of the mesoscale in the model initial conditions.

References

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