GENERAL INTRODUCTION

ECMWF organises regular workshops to consider the current state of knowledge on relevant topics and to assist in its programme of research. The workshop held on 16-18 September, 1991 considered the state of development of fine-scale (1 km) modelling and the prospects of such modelling aiding the development of physical parametrization schemes. Following more than two decades of progress and with the massive increases in computer power available (and projected), three-dimensional non-hydrostatic simulations of convective cloud fields, turbulence and flows over orography provide detailed four-dimensional 'datasets', the equivalent of which cannot be obtained from observational experiments.

The workshop was organised in the usual ECMWF pattern of 1 ½ days of lectures, followed by one day of working groups and a final general session to discuss conclusions and recommendations. The workshop was conveniently structured into lecture sessions on Orography, Turbulence and Convection; and working groups were similarly defined. Reports of each working group follow this short introduction.

The workshop demonstrated conclusively that there are many valuable model-generated datasets now available (and increasingly so in the near future). It also demonstrated the value and importance of closer contacts between fine-scale modellers of phenomena and the larger-scale modellers who have to parametrize such phenomena. In particular, it is hoped that more emphasis might be put on the design and interpretation of fine-scale modelling experiments in the parametrization context.

1. WORKING GROUP 1: CONVECTION

1.1 INTRODUCTION

There continues to be a number of outstanding problems associated with the representation of cloud and convective processes in large-scale models. As the horizontal resolution of these models is increased, the lack of clear separation of scales in convection is likely to make parametrization more difficult. Moreover, present parametrization schemes do not account for the inhomogeneities arising from the mesoscale circulations of organized convection. Even a T213 model cannot resolve the scales involved.

Diagnostic studies have now demonstrated that a major source of systematic error in General Circulation Models (GCMs) is the representation of the interaction between cloud and radiative transfer. These processes are particularly apparent for stratiform and cirrus cloud, which may or may not be associated with convective cloud. The interaction among all cloud processes needs to be recognised by the development of parametrizations that explicitly link deep and shallow convection with surface boundary-layer processes.

1.2 OUTSTANDING PROBLEMS

1.2.1 Cloud fields

Basic problems exist regarding scale selection, regime selection, convection initiation and life cycle of convection and this has implications for the criteria that determine the onset of convection in GCMs. This involves the simulation of cloud fields and the concurrent development of shallow and deep convection and has application to the partitioning between deep and shallow convection on a large-scale grid.

1.2.2 Comparisons with observations/observational needs

Concurrent with the use of fine-scale models to help the parametrization problem, an important step is to compare them with observations. A clear knowledge of when these models work well and what are the crucial problems implied is needed to build a strategy to improve existing or design new parametrizations, and also to improve the fine-scale models.

The comparisons should be performed at all scales and with different types of data, for instance large-scale effects of convection estimated from soundings (GATE, PRESTORM, EMEX, AMEX) are directly deduced from fine-scale Doppler radar analysis (COPT81, CCOPE, MFDP/FRONTS87). Some specific data are also needed to document some critical aspects e.g. rain evaporation, distribution and mass injection of different hydrometeors, especially at upper levels (anvils).

The need for appropriate field experiments should be stressed (TOGA/COARE, STORM), where the scale interaction between the surface fluxes, large scale flow and convection can be addressed, and appropriately documented. The use of new measurements during future experiments such as profilers, airborne Doppler will provide important data sets to also better compare fine-scale models with reality.

Fine-scale modelling and field experiments have mainly focused on Mesoscale Cloud Systems (MCSs), in particular fast moving squall-lines. This allowed basic progress in our understanding of organised convection during the mature stage to be made. Other questions must be addressed now, to document and understand the life scale of an MCS. In particular, the initial stage of an MCS is crucial for both forecast and parametrization.

1.2.3 Validation of convection schemes

Only a limited amount of observational data exists against which convection schemes can be validated. However, a wide range of convection is known to exist depending upon thermodynamic and dynamic fields. It is not clear whether present schemes can represent this variation.

Convection models seem able to represent ensembles of clouds with some realism, even two dimensional models. Greater details of fluxes can be obtained from these models than is available directly from observations, especially in the case of momentum. These models could be used to supplement the observed data by providing proxy data over convective regions. Hence a more detailed validation of convection schemes would be possible.

1.2.4 Organised convection

It is becoming clear that more attention has to be focused on the representation of distinct types of convection, and the use of dynamical cloud models in addition to the entraining plume models currently used in many parametrization schemes. This is particularly pertinent to the momentum transport problem which is highly dependent on the convective regime and thereby on the environmental shear and convective life cycle.

Fine-scale modelling has had excellent success in the simulation of travelling convective systems and satisfactory verification against observations has been achieved. Analytic models can provide consistent mass and momentum flux formulae that verify against observations and models, although more research is required. However, despite field experiments having demonstrated the ubiquity of these phenomena it is not known what proportion of the mass, energy and momentum fluxes are contributed by these systems on a global scale. Certain geographical regions are prone to organised convection of this type e.g. central USA or tropical Western Pacific, among others. The treatment of (parametrized) convection in these regions by (say) the T213 model should be analysed on a case study basis to determine if the Q_1, Q_2 and Q_3 profiles (apparent heat, moisture and momentum sources due to convection, respectively) and other properties verify against fine-scale models. The treatment of Q_3 is especially important, since this is expected to be the most poorly represented quantity. The precipitation forecast should also be critically examined.

More attention should be paid to the fine-scale modelling of less well organised convective systems, because their mesoscale interaction and large scale feedback and forcing is quite different from that associated with isolated clouds or travelling systems.

1.2.5 Mesoscale circulation

The role of mesoscale convective circulations in the parametrization problem needs to be better understood because it is a fundamental problem that has previously received little attention. Convective effects, in more than one grid square consecutively may have to be implemented in high resolution GCMs. For example, the role of anvils and boundary layer wakes by travelling convective systems involves this problem. In this regard, the use of high-resolution simulations (including nested simulations) in a large domain is an important utility.

1.2.6 Surface fluxes and downdraughts

Downdraughts are known to be an important part of convective systems, injecting cold dry air into the boundary layer and thus enhancing surface fluxes. Fine-scale models can provide information regarding this interaction which would improve representation in large-scale models.

However, in reality only part of grid square is stabilised by downdraughts, the remainder being able to support convection. The averaging of downdraught fluxes over the grid will underestimate instability and hence convective activity. Fine-scale models provide information regarding the fraction of modified air within a grid box which would enable, at least, some correction to made. A more complex treatment would be to build a history of convection into large-scale models, using fine-scale models to estimate the convective life cycle.

1.2.7 Radiative interaction with stratiform outflows

Recent fine-scale model simulations indicated that the longwave-radiation transfer processes can enhance the total surface precipitation by about 15-50% over a 16-24h time period. The net condensation in the upper troposphere within the stratiform (anvil) region is therefore increased significantly. A positive feedback between cloud-radiation processes occurs in the formation of the large-horizontal extent of the anvil. This implies that the micro-physical and radiation processes need to be more closely coupled in the GCM. The first step may be to include an explicit cloud water and cloud ice equation in the GCM. This is particularly important when the horizontal resolution of GCM reaches 40-80km.

A combination of an implicit (parametrized) and a prognostic (grid-resolved) scheme in a regional (meso-ß-scale) model has shown to reproduce the basic sequence of convective and stratiform rainfall associated with a midlatitude MCS. This is because the combination of implicit and prognostic schemes can handle several types and scales of precipitation, and consequently, allow a broader scale interaction. The prognostic scheme can be further closely coupled with radiation transfer processes. Results from meso-ß-scale numerical models may imply that a GCM can adopt a similar approach by including a prognostic microphysical scheme (such as cloud water/cloud ice).

1.2.8 Closure

The detailed description of convection afforded by fine-scale models, provides an opportunity to validate the closure assumptions presently in use over a wider range of conditions than is possible with the limited amount of observational data. Many schemes use some form of quasi-equilibrium between the large-scale forcing and convective activity. However, observational data show that such equilibria do not always exist. Convective scale models suggest that this is due to a modulation of the "efficiency" of convective activity by the thermodynamic structure, especially the humidity fields. Data from these models might be used to develop more comprehensive closure schemes with this modulation taken into account. The inclusion of momentum transport in sub-grid scale parametrization may necessitate the revision of present closures to include additional dynamical constraints.

The concept of quasi-equilibrium has been used for some 20 years, but studies which explore the convective response to changes in large-scale forcing are still required. Fine-scale models could be used to determine the time scale of adjustment of the convective atmosphere for different convective regimes, for example in the tropics, where the thermal structure is quasi-neutral, in comparison with the severe storm environment where a sudden non-equilibrium adjustment takes place once a stable capping layer is penetrated. Several important questions arise: when and on what scales is the quasi-equilibrium concept useful? Do different convective regimes have different quasi-equilibrium states? Can we characterize convective overturning as an adjustment towards a new equilibrium state, for example characteristic of the outflow circulation, and if so on what space and time scales? Can we develop parametrizations which include the subgrid-scale inhomogeneity produced by mesoscale convective systems, where for example boundary layer inflow and outflow are thermodynamically very different? Many of these questions could be addressed by fine-scale models and the varying of the boundary conditions in these models.

1.3 RECOMMENDATIONS

- The representation of convective momentum transport in GCMs needs to be refined. Profiles of Q_1, Q_2 and, particularly, Q_3 from the T213 model, need to be verified against observations and fine-scale modelling data sets on a case study basis, including strong and weak shear environments. The effects of unresolved mesoscale circulations may be significant.

- The representation of multi-phase cloud physical processes in GCMs needs to be improved not least for improved radiation parametrization. For example, the effect of ice/water production in updraught and stratiform anvils could be developed including a prognostic microphysical scheme like those developed for certain regional (meso-β) scale models.

- Convective and mesoscale downdraughts are known to have an important interaction with surface fluxes and the boundary layer. Fine-scale models should be used to improve the representation of these processes.

- Co-operation between large-scale and fine-scale modellers should be enhanced through
  (i) the definition of internal statistics of convection needed to improve parametrization in large-scale models
  (ii) the development of diagnostic quantities to estimate these statistics from fine-scale models; for example, the relationship between the downdraught and updraught mass fluxes, and the ratios of convective to stratiform precipitation, and the radiative impact of stratiform anvils.

2. WORKING GROUP 2: TURBULENCE

2.1 INTRODUCTION

The present workshop takes place at a time when several fine-scale models, in particular Large Eddy Simulation (LES), have reached a state where one could start to ask questions of relevance to numerical weather prediction. In comparison to the Workshop on "Planetary Boundary Layer Parametrization" which took place at ECMWF, 25-27 November, 1981, the LES provide a new source of data and insight.

Comparisons of LES model output with observations have shown that they give results which are a valuable adjoint to field measurements at least under dry convective conditions in the PBL. Neutral and stable layers are more difficult. Here, new important aspects come from backscatter of kinetic energy and variances from small to large scales and from interaction between turbulence and internal gravity waves. Flow over orography still provides large challenges to LES, in particular for non-convective situations. There is also considerable progress in treating inhomogeneous land surface properties.

The complexity of cloud-turbulence interaction has limited progress. Significant developments have, however, recently been made with regard to cloud-top entrainment instability.

2.2 WHAT HAS BEEN ACHIEVED USING FINE-SCALE MODELS

By means of LES the following prototype flow configurations have been investigated:

- CBL (Convective Boundary Layer)
  - with mean wind from 0 to order 10 w_* (w_* is the convective velocity scale)
  - over homogeneous flat, dry surfaces with prescribed surface heat flux, uniform surface roughness
  - over certain types of inhomogeneous surfaces (variable surface heat flux, wavy surface of small to moderate surface amplitude and varying surface wavelengths), mainly for zero mean wind; cases with non zero mean wind are under investigation
  - stratus-topped convective boundary layers
  - upslope boundary layer over an inclined plane

- NBL (Neutral Boundary Layer)

  barotropic Ekman layer (this case has been selected for an ongoing comparison between various LES codes)

- SBL (Stable Boundary Layer)

- Homogeneous turbulence without and with shear and with neutral or stable stratification (results from direct simulation are published; LES studies are underway).

The LES studies have provided:

- information on the flow structure (e.g. polygonal convection pattern in the CBL for weak mean wind, rolls oriented downstream for cases with strong mean wind, structural impact of surface inhomogeneities)

- information on first, second and third order moments; budgets of kinetic energy, vertical heat flux, vertical velocity variance, temperature variance; entrainment fluxes, pressure fluctuations

- structural properties like
    - updraught/downdraught area fractions and mean properties versus height
    - velocity skewness
    - spatial cross-correlation (e.g. showing longer persistence of flow structures over inhomogeneous surfaces)
    - plume budgets
    - composite structure of updraughts and downdraughts

- vertical and horizontal diffusivities, showing differences for bottom-up and top-down diffusion, diffusivity depending on chemical reactions, impact of surface inhomogeneities, diffusion tensor for sheared/stratified homogeneous turbulence, information on the effective turbulent Prandtl number as a function of Richardson number.

- information on open parameters in second-order closure models, in particular for pressure-correlation with velocity and temperature and their gradients; mixing and dissipation length scales.

However, overall, the LES studies (and others) have shown that second-order modelling might not provide the ultimate solution. It fails to account for coherent motion structures (plumes, rolls, waves). It is believed that the use of a predictive equation for turbulent kinetic energy and dissipation (so-called 1 ½ order closure) might be useful once enough vertical resolution has been established. It has been suggested that so-called VLES (Very Large Eddy Simulation), which resolves at least the dominant mode of energetic motion might provide better insight and basis for parametrization, at least under special conditions.

Simulations of a large-eddy model can also be used to evaluate the heat and scalar flux equations. By introducing parametrizations for some of the terms in the flux equations it can be shown that the vertical diffusion process in the convective boundary layer is well described with a modified flux-gradient approach (*Holtslag and Moeng*, 1991). In the latter approach the non-local vertical exchange is accounted for by a so-called counter gradient correction term and a non-local eddy diffusivity. The impact of such an approach on the vertical temperature and moisture profiles of a global climate model appears to be quite significant (*Holtslag and Boville*, 1992).

Only a very limited number of Large Eddy Simulations of the cloud-capped boundary layer have been carried out. In no sense can it be claimed that an adequate study of the parameters influencing the development of the cloud (e.g. surface fluxes, wind shear, radiation, entrainment) have been carried out. The scale of variation across the capping inversion may be as small as 1 m or so, while the scale of long-wave radiative cooling at cloud-top is of order 10 m. It is currently only feasible to carry out three-dimensional large-eddy simulations of the cloud-capped boundary layer with resolutions of a few tens of metres. It is difficult to adequately resolve processes near cloud-top and such simulations are so expensive that a proper exploration of parameter space is not practical. Two-dimensional simulations can be carried out with resolutions of a few metres and are economical enough that a fairly wide range of parameters can be examined. However, limitations imposed by the geometry must always be borne in mind. Such simulations have provided support for the criterion for cloud-top entrainment instability $R = c_p \Delta\theta_e / L \Delta q_t > k_m \sim 0.70$ proposed by *MacVean and Mason* (1990). Here $\Delta\theta_e$ and Δq_t are the jumps across cloud-top of equivalent potential temperature and total water mixing ratio, respectively. These integrations suggest that if the criterion is satisfied, then entrainment is likely to be so strong that it is implausible that stratocumulus will persist. One cannot, however, conclude that if the criterion is not satisfied, then the cloud will persist - other processes could still lead to break-up. Mixing across cloud-top may lead to buoyancy reversal which could be a significant source of in-cloud mixing when $R > 0.23$. A subgrid model which embodies this entrainment instability criterion but not the buoyancy reversal criterion has been developed and has, in fact, been implemented in the UKMO GCM.

2.3 CURRENT PARAMETRIZATION PROBLEMS THAT CAN BE ADDRESSED BY MEANS OF FINE-SCALE MODELS

2.3.1 Stably stratified shear flow

Numerical weather prediction models are very sensitive to the formulation of vertical diffusion in the stably stratified free atmosphere. This sensitivity is in the Richardson number range of 0.2 to 1., where intermittency and wave-turbulence interaction are important factors. The existing experimental data is very limited and inconsistent. Although large eddy simulation of stably stratified shear flow is known to be difficult, it could provide valuable data even if the models treat idealized cases. A particular problem arises because the dominant length and time-scales for turbulence in the free atmosphere are not well known.

Also issues like the interaction with orographically induced gravity waves, breaking waves and exchange at the tropopause could possibly be addressed with fine-scale modelling.

2.3.2 Entrainment

The current vertical diffusion scheme (in the ECMWF model) with local closure, gives negligible entrainment at the top of the convective boundary layer. The non-local eddy diffusivity approach has potential to cure this, but an entrainment parametrization has to be specified. Most data (including LES data) imply an entrainment constant (ratio of buoyancy flux at the top of the boundary layer and the surface flux) between 0.15 and 0.25. The value derived from recent FIFE data is much larger (about 0.4). This constant can be derived from LES simulations, but so far only a very limited range of parameters has been covered. A more extensive LES study covering a wider range of parameters (e.g. different values of shear in the inversion, different lapse rates above the boundary layer) seems necessary.

2.3.3 Momentum transfer in the convective boundary layer

The diffusion of quantities which are not well mixed in the convective boundary layer has received much less attention than the diffusion of heat. An example of a deficiency in the momentum transfer parametrization in the ECMWF model is found during cold air advection (cold air over a warm sea). Observations in the Northern Hemisphere often show a backing of wind with height whereas the model gives virtually no wind turning. In general the model tends to underestimate the ageostrophic angle of the surface wind, in cases with backing as well as cases with veering. Detailed data on the momentum and thermodynamic budgets of strongly baroclinic boundary layers is virtually non-existent and LES appears an obvious tool to provide such data.

2.3.4 Boundary layer clouds

The coupling of boundary layer processes to the cloud parametrization is an area where current models have difficulties. LES can provide useful data here.

2.3.5 Coupling of the PBL with deep convection

This is very much an open question and fine-scale modelling could provide guidance.

2.3.6 Coupling of cloud and surface processes

For typical cloudy conditions in a mid-latitude forest, the modelling of the following feedback loop has to be assessed. PBL clouds are crucial for determining the net radiation available at the surface, the stress from the underlying vegetation determines the magnitude of the latent heat fluxes, which in turn can change the boundary layer cloudiness. Large eddy simulation needs to be coupled to a realistic land surface parametrization to obtain the proper feedbacks and compared to observations such as from BOREAS.

2.3.7 Land surface processes

It has been shown that detailed modelling of the effects of inhomogeneous land surfaces can provide "effective surface parameters" in certain cases, but can be quite difficult for strongly heterogeneous terrain. In the latter case it might be beneficial to adopt the blending height concept whereby different land types in a single grid box are treated separately.

2.3.8 Cloud physics

The small scale interaction between turbulence and the microphysics of cloud and rain water is not well understood. Large eddy simulation could be a useful tool here.

2.4 RECOMMENDATIONS

2.4.1 Effort should be put on a better description of the following processes in the ECMWF parametrization:

2.4.1.1 Representation of entrainment into the Boundary Layer (BL) and, more generally, all phenomena close to the top of the BL, is essential if a reliable forecast of boundary layer development is to be made. A proper description of the turbulent fluxes at the top will in turn improve the surface fluxes, at least in convective BL, where the two fluxes are related. This can be achieved in one of two ways:

i) Classical boundary layer parametrization is based on z (height above surface), z_0 (roughness length) and Monin-Obukhov length scale. Since *Deardorff* (1970) we know about the importance of convective scaling (z_i, the depth of the convective layer; θ_s, representing the surface buoyancy flux). These convective scales should enter the BL parametrization. An extra layer defining $z_i(x,y,t)$, along with the discontinuity of model variables across this interface, would allow convective mixing models to be used, and open the way to determine more precisely the depth of stratus clouds and consequent radiation properties. Such a parametrization would facilitate the explicit linking of the convective parametrization with the surface flux scheme.

ii) Another approach can be the increase of resolution close to the interface. It seems unlikely that an adequate parametrization can be achieved with the current grid space of 300 m or more. The increase in resolution which should be necessary to properly model the observed vertical scale of variation in the capping inversion is clearly not feasible, particularly in view of the temporal and spatial variation of the BL height. If the grid space could be decreased to about 100 m (which would mean 8 extra levels for the present 31 level ECMWF discretization) one might begin to see an improvement in the representation of jumps in discontinuities across the top of the BL. Parametrizations of cloud-top entrainment should then be evaluated in conjunction with a representation of in-cloud mixing resulting from buoyancy reversal.

2.4.1.2 Where the turbulent Prandtl number is a function of stability it should increase with the Richardson number.

2.4.1.3 The exchange coefficient for heat and moisture should have a minimum value accounting for convective turbulence at zero wind speed. This is already properly accounted for over sea, over land it should also be considered, although the problem is certainly less important due to the interactive characteristic of the land surface.

2.4.1.4 The non-local diffusion approach with counter-gradient correction should also be tested in the ECMWF model. This should relate to the determination of BL height and the prescription of entrainment.

2.4.1.5 Before increasing the complexity of the ECMWF land surface scheme, the current parametrization should be assessed over selected cases in a stand-alone mode. Although the number of soil and vegetation parameters of the scheme is limited, this would help understand the effective values of these parameters which would give fluxes in reasonable agreement with the observations.

Long time series of surface measurements may be used, representative of areas sufficiently large to be seen by the ECMWF model:

- Amazonian forest	ARME 84
- Tall grass	FIFE 87
- Crops in temperate regions	HAPEX 86
- a case of bare ground	EFEDA 91 (*Bolle et al.*, 1991)HAPEX-SAHEL 92

2.4.2 To future research with fine-scale models

- Critical cases where global atmospheric models have difficulties should be studied by LES models. These cases should be defined and documented by ECMWF (see section 2.3)

- One should intensify communication and cooperation between
  - field experiments
  - fine-scale modelling
  - ECMWF model development

Various field experiments in the past (e.g., MIZEX, LOTREX (*Jochum et al.*, 1990), FIRE, ...) have provided extensive data sets on the boundary layer turbulence, which should be used more for model development.

Data collectors and LES modellers should be encouraged to compare their data with the ECMWF model. ECMWF should provide support for such studies. For future field experiments, this interaction should be planned more carefully and in advance.

- It is recommended to develop more simple models which serve to explain basic turbulence and provide the basis for parametrization.
- The issue of spatial variability in land surface properties from spatial scales ranging from 10 to 100 km that has been investigated for HAPEX-MOBILHY should be addressed for other experiments in other areas.

2.4.3 General recommendation

It appears appropriate to review the recommendations of previous workshops and to see which aspects need more attention. Obviously, the present workshop repeats some of the older recommendations.

3. WORKING GROUP 3: OROGRAPHY

3.1 FIELD EXPERIMENT REQUIREMENTS

3.1.1 Aerodynamic drag over orography

Current understanding of aerodynamic drag and scalar fluxes over orography is based upon a combination of field observations and numerical simulations. This work needs to progress to a more precise and detailed description through the continued application of both models and field studies to a more diverse range of conditions.

It is already clear that the roughness length z_0 description is an appropriate parametrization. Studies provide a basis for estimating z_0 and indicate large values (10 m for parts of Wales and 100 m for parts of Scotland). The roughness lengths for scalars (e.g. z_{0T} for temperature) should be reduced so as to maintain the fluxes unaffected by orography. It would be timely to derive interim fields of such values of z_0 and z_{0T}. These should be used to study the requirements for realistic inclusion in the models and to investigate the impact on model results.

In the implementation the key issue will be the ability of the boundary layer scheme to correctly deepen the boundary layer in correspondence with increased z_0's. Virtually all high resolution boundary models will achieve this result but the coarse resolution of the boundary layer in numerical weather prediction models is known to limit such growth. When obvious errors have been corrected, a comparison of model output with radiosonde profiles over hilly terrain should be sought.

3.1.2 Gravity wave drag

Current gravity wave drag parametrization schemes are usually based on an over-simplified view of the type of gravity wave existing in a grid box at any time. Only recently has there been any attempt to address the issue of wave trapping and the profile of wave stress associated with it. In fact, as discussed by *Bretherton* (1969), there are considerable conceptual difficulties in defining the vertical momentum flux in trapped lee wave situation. The theory of wave-mean flow interaction suggests that effect of the wave stress will be felt in the region in which the waves are dissipated. How trapped lee waves are dissipated is not known and would be worthy of observational study.

Another dynamical effect for which we have some theoretical insight but little observational guidance is the critical level where the intrinsic frequency goes to zero. There are certain regions of the world where the climatological mean winds are such that critical levels (for stationary gravity waves) are commonplace (e.g. in the subtropics, Alaska and Greenland). For parametrization schemes, the question that must be posed is, 'How much wave absorption takes place at the critical line?' It is common practice in parametrization schemes to ignore any partial internal reflection that might be implied by a height-varying Scorer parameter or critical level and treat the surface wave drag formula as independent. Wave reflection invalidates this assumption and in the extreme case permits resonance. An observational study of gravity wave structure in critical level conditions, when synoptic situation permits, would assist the choice of absorption coefficients.

Another area of great uncertainty is the magnitude and height distribution of diabatic heating arising from the passage of moist airstreams over mountainous terrain. Latent heat release is capable of exerting a direct influence on the structure and intensity of orographic gravity waves (e.g. trapped lee waves). Satellite imagery suggests that the abundance of ice crystals in frontal zones is greatly influenced by deep vertically-propagating gravity waves of wavelength greater than 50 km, causing evaporation zones over the orography and dense orographic cirrus downstream. The seeder/feeder mechanism causes substantial low-level latent heat release as saturated airstreams pass over elevated terrain. The bulk effect of these differing mechanisms for latent heat release has an unknown effect on wave drag and precipitation totals and deserves observational study.

As usual, it would be necessary to rely heavily on data collected with instrumented aircraft though radiosonde data could provide valuable information on vertical fine-structure and vertical velocity through the balloon rate of ascent. Mesosphere/Stratosphere/Troposphere (MST) radar and lidar is also capable of providing momentum flux information and should be exploited where available.

3.2 USE OF FINE MESH (FM) MODELS

The requirements of the FM model can be categorized as either mathematical, dynamical or physical. The FM model's coordinates should be logically similar to the T213 to allow reasonably accurate data exchange. The FM should also be able to attain high resolution down to scales of a few kilometers to assess a range of physical processes. The FM model could also be used to assess the importance of lee waves which requires the non-hydrostatic framework as a model option.

A problem which arises when attempting FM modelling of orographic flows over large sections of the globe is that there is no adequate high resolution dataset of the orography. The current standard is the 10′ US Navy. FM models run at much higher resolution than this and require datasets closer to 1′. Orographic height datasets of resolution ~ 200 m would also be required for determining z_0 and used in gravity wave drag schemes.

Matching of the orography between the FM and T213 requires some consideration. For nested type calculations it is probably best to have the coarse-mesh orography of the nested model correspond to that of the T213. At the same time this coarse mesh orography should be a logical average of any higher resolution orography used in the FM calculations. The averaging operator here would correspond to that used in the finer meshes. It seems impractical to expect the T213 to alter its orography to facilitate such fine mesh experiments. An alternative would be for the FM models to generate their higher resolution orography using a variational technique. For example, one could fit the US Navy data set in a least squares sense and satisfy the constraint that the appropriately averaged FM orography equals that of the T213. Without such a procedure it seems likely that the introduction of finer resolution orography could lead to excessive noise generation.

The FM models should of course be able to handle a broad range of physics such as surface roughness in either a z_0 formulation or simple drag formulation. Surface heat fluxes are necessary to simulated convective boundary layer processes. Precipitation physics should also be considered as part of the FM modelling strategy to assess moisture effects. Rainfall could also be used as a verification tool in the FM modelling. Is the model rainfall pattern consistent with observations? Does it conform on average with the orography as in the UK or does it conform more to a systematic gravity wave pattern as in Hawaii?

Recent model results for flow over the Alps suggest a significant over-prediction of gravity wave activity. Is this due to poor representation of the boundary layer physics which includes aerodynamic drag? Experimental data such as the PYREX data could be useful here. The FM models could be used to refine T213 forecasts to assess their accuracy, for example the existence of numerical reflections due to lack of upper level absorber or stretched vertical coordinate could be addressed. The T213 Gravity Wave Drag (GWD) parametrization could be assessed with the FM calculations. Also, the utility of any T213 proposed orographic representation could be addressed. FM models for such studies include the ECMWF Limited Area Model (LAM) and *Clark's* mesoscale model (see proceedings of this workshop).

3.3 RECOMMENDATIONS

- There is a need to obtain a high resolution global orographic dataset at a resolution of a few hundred metres.

- Fine mesh models should be validated against field observations and, in turn, used to validate the ECMWF model. Contributions to the pressure drag from all relevant mountain scales need to be quantified so that the apparent mismatch between measured vertical momentum flux and surface pressure drag can be rationalized.

- ECMWF should, separately or in collaboration with other Centres, seek to derive interim fields of z_0 and z_{0T}. Sensitivity studies are to be encouraged. Even over flat homogeneous vegetation, z_0 and z_{0T} differ by a factor of 10.

- Comparison of ECMWF model boundary layer output with observed profiles of wind and temperature in mountainous regions should be sought.

- Both fine mesh and ECMWF model output should be compared with specific (e.g. for Europe) rainfall datasets.

- Studies should be undertaken to assess the ability of the Centre's boundary layer scheme to respond to large values of z_0.

- Fine mesh models should be run on ECMWF forecasts to provide subgrid diagnostics.

- Nonlinear saturation needs to be considered for high drag state wave conditions.

ACRONYMS

AMEX	Australian Monsoon Experiment
BOREAS	Boreal Forest Study
COPT	Convection Profonde Tropicale
COOPE	Co-operative Precipitation Experiment
EFEDA	European Field Experiment in a Desertification - Threatened Area
EMEX	Equatorial Mesoscale Experiment
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
GATE	GARP Atlantic Tropical Experiment
LOTREX	Longitudinal Land-surface Traverse Experiment
MFDP	Mesoscale Frontal Dynamics Project
MIZEX	Marginal Ice Zone Experiment
PRESTORM	Preliminary Regional Experiment for Stormwide Operational and Research Meteorology
PYREX	Pyrenees Experiment
TOGA COARE	TOGA Coupled Ocean Atmosphere Experiment
UKMO	UK Meteorological Office

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