1. Introduction

The organisation of symposia and workshops is a part of the Centre's research activity. The following publication contains the proceedings of a workshop on Mountains and Numerical Weather Prediction which was held at the ECMWF, Shinfield Park, Reading, from 20 to 22 June 1979.

It is well known that the earth's orography plays a very important role in forcing atmospheric motion on all scales, from the planetary to the sub-grid scale (defined, in this context, as less than order 100 km). It is therefore evident that a clear understanding of the interaction of the atmospheric flow with orography is a pre-requisite for successful medium-range weather forecasting.

This workshop was organised with a two-fold purpose : to assess the current state of knowledge on some topics of direct relevance to the Centre's objectives, and to generate discussion about possible areas of future research and relative priorities for the Centre.

The executive bodies of ICSU and WMO have approved a GARP Mountain Sub-programme, and this Sub-programme includes a major Alpine Experiment (ALPEX) . The coincidence of some of ECMWF's own research interests and the aims of the GARP Sub-programme was pointed out during the workshop. The possible role that the Centre could play in the numerical experimentation activity associated with the sub-programme was particularly stressed.

The following two sections summarise the results of the work of four subgroups formed by the workshop participants on the following broad subjects :

a) Problems related to analysis and initialisation
(Baede, Janjić, Sundqvist, Talagrand)

b) Mountains and long-wave numerical weather prediction
(Egger, Hills, Jarraud, Jonas, Källén, Keeping, Simmons)

c) Mountains and synoptic scale numerical weather prediction
(Bleck, Capaldo, Mesinger, Pümpel, Tibaldi)

d) The parameterisation of sub-grid scale mountain-induced processes. (Dell'Osso, Louis, Mason, Økland)

The first of these sections is devoted to a review of problems of relevance to medium-range numerical forecasts, while the second presents the recommendations that emerged from the work of the subgroups. All the contributed lectures are then included in this report as appendices.

2. Review of problems

2.1 Analysis and initialisation

There exists a variety of possibilities for choosing the vertical coordinate, and each is associated with its own problems of representing topography. The most frequent choice is the so-called sigma system. A number of other "transformed" sigma type coordinate systems, i.e. with coordinate surfaces following the ground surface, can be designed. However, the problems appearing in the sigma system are common to all of them.

Both for practical and historical reasons it is a commonly accepted practice to perform the analysis of relevant meteorological parameters on pressure surfaces. At present, the "optimum interpolation" technique is generally considered to be the most satisfactory from both mathematical and physical points of view. However, in practice, there are still some problems which require further clarification. As far as mountains are concerned, a very important point is how the mountains affect the relevant structure functions as well as the interpolation process itself. In particular, there is reason to believe that local effects are more pronounced in mountainous regions.

The problem of conversion from pressure to sigma coordinates and vice versa is by no means trivial in the presence of mountains. When calculating the surface pressure, p_s, it seems desirable to try to reduce as much as possible the effect of fictitious subterranean values defined on pressure surfaces intersecting the ground surface.
Because of this inaccuracy in the surface pressure calculation, p_s should perhaps be allowed to change in the initialisation procedure.

The retrieval of the mass field in the sigma system from that in the pressure system can be performed in accordance with either a static or a dynamic constraint. Usually, it is done via the hydrostatic equation, i.e. a static approach. However, this may result in serious errors in the initial pressure gradient force in the sigma system. On the other hand, the dynamic approach, such as retrieval of temperature from the interpolated pressure gradient force, may be advantageous in the sense that better forecasts may be obtained. However, certain mathematical difficulties arise that make further studies of such a method necessary, before it may be adopted operationally.

For the vertical interpolation of the wind field a physical criterion instead of a purely mathematical one may be desirable.

Problems related to vertical interpolation of humidity are also present. It may appear preferable to interpolate relative rather than specific humidity because of a less pronounced variation in the vertical, but this makes the application of integral constraints more difficult. Taking statistical properties of the field into account may improve the interpolation procedure.

Non-linear normal mode techniques at present seem to be the most promising method for initialising the large-scale flow in numerical forecast models. There are, however, some problems which require further investigation. For example, it is not quite clear if the effect of real mountain-induced gravity waves is important. Also the pressure gradient force error acts as a forcing in the non-linear normal mode initialisation. Generally it is desirable to require that the results of the initialisation deviate as little as possible from the observed data. This requirement for minimisation is felt to have the highest priority in the case of the pressure gradient force. Practically this requires a variational approach.

2.2 The representation of orography in numerical models

It is not clear how to represent accurately mountains in numerical models. The effective shape and size of a mountain complex may well differ from the physical shape and size of the complex. In particular flow separation occurs with steep slopes, and a possible approach might be to "fill in" valleys, etc., so as to limit slopes to some specific value.

The extent to which a model orography field should be smoothed to remove scales close to the smallest resolved by the numerical scheme is uncertain. Suggestions that scales less than 4 or even 6 grid lengths be removed appear in disagreement with some practical experience with grid-point models. Further controlled experiments are required in this area.

There are additional problems specific to spectral models. Such models suffer from errors similar to those of grid-point models in computation of the pressure gradient in sigma-coordinates, but due to the nature of the spectral method these are not strictly confined to the proximity of steep slopes but tend to spread over the globe. Truncation of the slowly converging spectral expansion of the earth's orography introduces the so-called Gibbs phenomenon near steep slopes, i.e. short waves of sometimes considerable height on both sides of the slope. A quantitative assessment of the practical effect of these possible problems seems desirable.

2.3 Mountains and long-wave NWP

The linear theory of stationary planetary waves forced by orography has proved to be successful in giving a representation of the time-averaged 500 mb mid-latitude flow in winter using as simple a formulation as a barotropic channel model. The comparison with observation is less conclusive in summer. Such steady linear theory breaks down, in the absence of dissipation, in tropical or stratospheric regions where the zonal-mean flow changes from westerly to easterly, and an outstanding theoretical problem is the relative importance of transience, non-linearity and dissipation in such a situation. Simple numerical models generally require a fine resolution in this case - the implications for numerical prediction models are unclear.

Theory has not completely clarified the relative roles of orography and thermal contrast in forcing planetary waves, but there are indications that the thermal forcing is particularly important for the low-level standing waves, while the orographically forced component may be the more important one in the upper troposphere and stratosphere. It should be noted that it is difficult to separate completely orographic and thermal forcing as orography provides elevated surface fluxes and triggers latent heat release.

Observation and linear theory show that in winter there is a significant planetary-wave propagation from the troposphere into the stratosphere. Linear models suggest that for vertical resolutions commonly used in prediction (or general circulation) models the upper boundary condition $\omega = 0$ at $p = 0$ may lead to serious errors in the behaviour of ultra-long waves in the troposphere. It is not at all clear that in practice the upper boundary condition generally gives rise to a problem in forecast or climate models, and some clarification of this apparent discrepancy between theory and practice is desirable.

The role of mountain complexes in influencing non-linear transfers between various scales is not well understood. Some numerical experiments indicate that orography can influence the level of transient eddy energy since weaker transients are found when standing waves are larger, but there are theoretical indications that mountain-induced standing waves may enhance instability, at least locally. Smaller-scale orographically forced perturbations, such as cyclones in the lee of the Alps, have an impact on the larger scales of motion.

There are indications from barotropic models that mountains may induce blocking-type flow patterns, but the role of smaller-scale eddies in maintaining a block has yet to be determined. Thermal forcing may also be important both in setting up and maintaining a block.

2.4 Synoptic scale numerical prediction

Mountains are directly or indirectly responsible for several synoptic-scale meteorological phenomena. Elevated plateaux, such as the Tibetan plateau, act as high level thermal sources due to the comparatively high amount of solar radiation they convert into sensible heat;the northward displacement of the "thermal equator" in the Himalayan region and its climatic consequences on the exchange of mass between the two hemispheres is well known.

From a more directly dynamic point of view, large-scale and synoptic-scale mountain barriers and massifs (such as Greenland and the Rocky Mountains) are known to be responsible for quasi-standing pressure (and therefore vorticity) perturbations of the "upwind high, lee trough" kind, and are also preferred areas of extratropical cyclogenesis.

The ability, however, of large-scale numerical weather prediction models to reproduce successfully all these effects has never been systematically investigated.

Lee cyclogenesis in the western Mediterranean (Alps and Pyrenees region) is still one of the major unsolved forecast problems in the European region. Some hypotheses have been put forward about the most favourable synoptic situations for cyclogenesis in the lee of the Alpine mountain range and about the major mechanisms responsible for its initiation (e.g. interaction between a low-troposphere cold front and the mountain, intensification of an upper-level trough).

Some numerical experiments have shown that it is at least possible to simulate some of these "phenomena" separately, provided numerical models are able to reproduce successfully some of the relevant physical mechanisms. It is not clear, though, how advanced is the incorporation of these features in an operational global numerical model like that of ECMWF, and how feasible improvements in this direction might be.

Regarding the numerical problems related to mountain-generated disturbances on the synoptic scale, it is worth pointing out that the effects of varying the horizontal to vertical grid aspect ratio in relation to the maximum steepness of the sigma surfaces, although theoretically investigated, have not been satisfactorily explored with the aid of numerical case studies, and, therefore, their practical impact has not been precisely assessed.

2.5 The parameterisation of sub-grid scale mountain-induced processes.

On small scales the parameterisation of aerodynamic drag is accomplished through a roughness length Z_0, and on these scales it has a sound basis. Its use on larger scales is uncertain, but owing to the lack of reliable alternatives it may be the best approach for the moment. Techniques for deducing such Z_0 fields exist and have already been used at ECMWF. The question again arises as to the extent to which these fields should be smoothed.

Measurements show horizontal diffusion to be enhanced by mountains, and some representation of this effect in models may be desirable. Some assessment of the common practice of performing diffusion on sloping sigma-surfaces is also required.

Gravity wave drag is a significant process often giving drag at high levels. Work on this subject is in hand elsewhere and its progress should be reviewed.

Mountains affect precipitation both by "large-scale" lifting and by the triggering of convective rain. The peak heights of the barrier which the sub-grid scales present to the flow are probably significant. A number of approaches are possible : one suggestion is discussed in the following section.

3. Recommendations for ECMWF's Research Programme

ECMWF can play a useful role in helping to solve some of the outstanding problems noted in the preceding section. Some of the research involved may lead to an immediate improvement in the quality of forecasts, while some results may enhance our general understanding of orographically-forced motion. Specific areas of research are summarised below. These are given in approximate order of priority, but it should be noted that some work is already underway in areas (c) and (e), while plans have already been made for the diagnostics required for (d).

(a) Study of the sensitivity of 10-day forecasts to the prescription of orography and the related surface stress. Experiments could include smoothing of small-scale features, for instance topography and Z_0, and the use of an upper envelope to the orography or use of barriers. Attention should be focussed on the ability of the model to simulate known synoptic and planetary-scale phenomena directly or indirectly produced by the influence of mountains. Some experiments specific to the problems of representing orography in the spectral model are desirable. In the longer term, experiments to isolate the influence of particular mountain complexes might be useful.

(b) Model studies of lee cyclogenesis. The ability of the EC global model to simulate cyclogenesis in the lee of the Alps should be investigated. Concurrently, the Limited Area Model should be used to study the requirements for a successful forecast of lee cyclogenesis in a number of typical synoptic situations, varying among other parameters, horizontal resolution, the definition of model mountains, and the physical parameterisations.

The sensitivity of these forecasts to the representation of sub-synoptic features (location and intensity of jet streaks, upper and lower level fronts) in the initial conditions should be assessed. This should include variations arising from different versions of the analysis and initialisation schemes.

Efforts should be made towards improving the observational description of synoptic features associated with mountain related processes, including Alpine lee cyclogenesis, with the purpose of gaining insight into these physical processes, as well as improving the verification methods.

(c) Diagnosis of blocking in the model. Study of the ability of the model to simulate the development, maintenance and decay of blocks may give information on the relative roles of orography, thermal forcing and smaller-scale eddy motion. Controlled numerical experimentation in cases of particularly successful and/or unsuccessful forecasts should be performed.

(d) Establishment of the long-wave statistics of the model. In the first instance this will involve evaluation of the climatology of the forecast for day 1, day 2, etc. up to day 10, but longer term integrations are also to be recommended in order to establish the time-average climatology and compare it with the trend of the long-wave error deduced from the 10-day forecast. Establishment of the climatology will help the interpretation of forecast errors, and with reference to the specific problems mentioned in the preceding section :

   (i) Examination of phase tilts may indicate whether there is any particular long-wave problem associated with the upper boundary condition. If so, experiments involving prescription of analysed stratospheric variables should be performed. Development of simpler stratospheric representations may follow.

   (ii) It may illustrate whether or not the model represents the inhibition of inter-hemispheric energy propagation due to tropical easterlies suggested by simple theory.

   (iii) It can give evidence of the direction of non-linear transfers in the model, and useful comparisons can be made with the climatology deduced from the Centre's analysis system and from other independent sources.

   (iv) Comparison of the model climatology with orographically and thermally forced stationary waves computed using linear theory should help both the diagnosis of model error and the development of the theory of standing waves.

(e) Study of numerical accuracy. Expressions used in the EC model for the Pressure Gradient Force (PGF), the hydrostatic equation and the $\omega\alpha$ term in the thermodynamic equation in the presence of mountains should be re-examined through accuracy and consistency tests and compared against the performance of possible alternative schemes, including hybrid models. Possible deficiencies due to convergence problems in the PGF finite difference scheme should be investigated in relation to the vertical and horizontal grid resolution and to the steepness of mountains.

Tests might include experiments in which different versions of the model are started from a hydrostatically balanced state of rest. In these cases, motions generated by the model would be entirely due to errors of differencing schemes for the PGF in mountainous regions. Furthermore, errors in representing hydrostatic states defined by different observed temperature profiles could be calculated. Parallel runs with the LAM and/or the global model varying in turn mountain steepness and horizontal to vertical grid aspect ratio could be performed.

(f) Study of problems related to analysis and initialisation. A careful comparison of the current analysis scheme with the scheme in which only increments (observed minus first-guess values) are interpolated from pressure to sigma surfaces should be made. The possibility of analysing completely on sigma-surfaces should be investigated, as should the use of anisotropic structure functions in the vicinity of mountains. Some indication of errors in the sigma-coordinate pressure gradient may be given by a comparative experiment with and without normal-mode initialisation starting from an atmosphere at rest with a temperature distribution dependent only on pressure.

(g) Study of problems related to sub-grid scale parameterisation. The results of ALPEX should be examined for further information on the sub-grid scale mountain-induced drag. The sensitivity of forecasts to enhanced horizontal diffusion and precipitation in the vicinity of mountains should be determined. This may be achieved by setting the

(g) (continued)

diffusion coefficient proportional to the neutral boundary layer drag coefficient (for a derivation of such a formula, see Annex I) and by lowering the critical relative humidity in proportion to the difference between peak heights and the smooth orography of the resolved scale. The work of Bretherton (1969, Quart. J. Roy. Met. Soc.) may be used as the basis of a parameterisation for mountain-induced gravity-wave drag.

(h) Comparison with known solutions. The ability of numerical models using currently-feasible resolutions to reproduce either known analytical solutions for flow over isolated obstacles, or very high resolution numerical solutions, should be investigated.

(i) Diagnosis of the EC model's diabatic heating and mechanical forcing. This is necessary for point (iv) of recommendation d), and is of general theoretical interest. The associated use of linear standing-wave models for studies of long-wave sensitivity to physical parameterisation and numerical representation, for example to the representation of the upper boundary condition, is computationally efficient and potentially beneficial.

ANNEX I: On the Magnitude of Horizontal Diffusion in the Atmosphere

We note the following observations:-

1. Under conditions of neutral stability, all components of the Reynolds stress tensor are comparable in magnitude. In particular in the boundary layer

   $\overline{uu} \sim \overline{vv} \sim 2\cdot\overline{uw}$

   (In fact observations in hilly terrain suggest $\overline{uu}$ and $\overline{vv}$ increase in relative magnitude)

2. In other stability conditions, the low frequency contributions to $\overline{uu}$ and $\overline{vv}$, etc., are not much changed and form a large part of the total variance.

3. These low frequency contributions to the horizontal variance extend throughout the troposphere

   In the numerical model we represent the Reynolds stresses by an eddy viscosity. Thus we have:

   $K_H \frac{\partial u}{\partial x} \sim \overline{uu}$

   Now in a neutral boundary layer

   $\overline{uw} \sim C_{DN}|U_g|^2$ thus $\overline{uu} \sim 2\ C_{DN}|U_g|^2$

   and

   $K_H \sim 2\ C_{DN}|U_g|^2/\frac{\partial u}{\partial x}$

   Thus we may note that values of $\frac{\partial u}{\partial x}$ are about 5 to 10 $|U_g|/\Delta$ assuming reasonable scale of resolution (Δ = grid length)

   and

   $K_H \sim (10 \text{ to } 20)\cdot C_{DN}|U_g|\Delta.$