INTRODUCTION

ECMWF organizes regular workshops to assess the current state of knowledge on topics of direct relevance to its objectives and to provide guidance for its programme of research. The workshop held on 2-4 November 1987 considered techniques for the horizontal discretization in NWP models, including discussion of the performance of some of these techniques at resolutions finer than that currently used operationally at the Centre. Time-stepping aspects, which are intimately linked with the horizontal discretization, in particular semi-Lagrangian techniques, were also considered. The question of the vertical discretization was not directly addressed, but presentations and discussions included reference to problems such as the appropriate vertical resolution, the representation of orography, and the upper boundary condition for resolved, vertically propagating gravity waves, which are closely related to the topic of the performance of numerical schemes as horizontal resolution is increased. The relationship between parametrization schemes and numerical techniques and resolution was also discussed.

The workshop followed the usual ECMWF pattern of 1½ days of lectures, followed by one day of discussion within smaller groups, and a final general session to discuss the conclusions of the working groups. Two main groups were set up. The first considered numerical techniques per se, and its discussions were split into two parts. One was concerned with general consideration of aspects such as geometry, computational efficiency and the requirements placed on schemes by the need to simulate particular physical processes. The second dealt with both the use of semi-Lagrangian techniques, whereby computational efficiency is enhanced by the use of longer timesteps, and the general question of transport schemes for rapidly varying fields, where a promising approach is also based on a semi-Lagrangian scheme. The discussions and recommendations were particularly useful as they came at a time when the Centre is preparing to begin active work in this area.

The second working group discussed increased resolution and its implications. Current experience was reviewed, and guidelines laid down for future experimentation. Consideration was given to the possible need for methods of filtering, as models begin partially to resolve a number of mesoscale phenomena. Related problems in parametrization were also discussed. The resolution of the forecast model also has implications for data assimilation, and aspects of this received attention.

The reports of both working groups can be found in these proceedings. After these reports follow the lecture notes. ECMWF wishes to thank all lecturers for their efforts to prepare the lecture notes and for their contributions to a successful workshop.

ECMWF WORKSHOP ON TECHNIQUES FOR HORIZONTAL DISCRETIZATION IN NWP MODELS
2 - 4 NOVEMBER 1987

Report of Working Group 1

1. NUMERICAL TECHNIQUES

1.1 Introduction

Many of the current operational medium-range models use the spectral method for horizontal discretization. Centres that have adopted this method for medium-range forecasting based their decision on properties such as accuracy, economy of representation (computer memory), stability and efficiency of integration (accuracy in relation to computer-time expended) at resolutions that current computers can operationally achieve. In general, it appears that the spectral method is acceptably accurate, stable and computationally efficient for resolutions as high as at least of the order of T200. However, as the resolution is increased beyond this in spectral models, the relative computational cost of the Legendre transforms will increase to the point where it ultimately will dominate the computational cost of the numerical model (since it increases as the cube of the horizontal resolution rather than the square). This therefore motivates a reexamination of the computational properties of the method with respect to competing techniques (e.g. finite differences and finite elements) at resolutions of this order and higher.

This is not however the only motivation for such a reexamination. Increased resolution and increased knowledge have broadened the set of criteria that a medium-range numerical model should meet. In the not too-distant past phase errors associated with advection were significant, and less attention was paid to other properties of numerical schemes such as shape preservation and conservation of higher order moments of the equations. The choice of the representation of meteorological fields is still an open question particularly with respect to fields exhibiting sharp jumps. Furthermore the parametrization of sub-grid scale processes has become significantly more sophisticated and strongly interacts with the "dynamics". New prognostic equations may be considered (for example equations for turbulent kinetic energy and cloud quantities), which have their own characteristic space and time scales which should interact correctly with those of the larger-scale dynamics.

Looking towards the future, a reevaluation of the relative merits of spectral, finite difference, finite element (and possibly other) techniques for the horizontal and vertical discretization as a function of increasing resolution is thus warranted, bearing in mind the possible need to run models over a range of resolutions. Reevaluation should be made after establishing criteria that schemes for horizontal and vertical discretization should satisfy. First we will discuss these criteria, and then we will discuss three promising new techniques. Areas which are not discussed, but which may also be of importance in the future are the use of isentropic coordinates, and the use of adaptive grids. Work elsewhere in these areas should be closely monitored.

1.2 Computational properties

1.2.1 Simulation of physical processes

a) Atmospheric equilibria

Much attention has already been paid to the problem of geostrophic adjustment, and existing techniques for horizontal discretization appear to treat this process acceptably well when applied appropriately. More generally, both the representation of the fields and the discretization of the differential operators should respect properties of the governing equations which lead to atmospheric equilibria. Maintenance of structures such as modons is a particular example.

b) Advection

This process has several important aspects including those of non-linear energy cascade, stability, phase, amplitude and dispersion errors and conservation problems. Much progress has been achieved, although questions still remain.

c) Orography

Terrain-following coordinates have met with almost universal acceptance for the representation of orography, of which the sigma coordinate is the most popular. However, increased resolution leads to better resolved orography and large-amplitude forcing at small scales, and terrain following coordinates may not be the most appropriate way of handling orography.

Further aspects of orography are addressed in the proceedings of the 1986 ECMWF Workshop on Orography.

d) Forcing

There may be horizontal ramifications of vertical discretization. For example, when the forcing due to various physical processes is parametrized column by column, does this give rise to an appropriate spectrum in the horizontal? Other important issues that may affect the horizontal include the choice of technique for vertical discretization, variable staggering and vertical boundary conditions.

e) Spurious solutions

Care must be taken to avoid generating spurious solutions due to the choice of discretization technique.

1.2.2 Geometry and computational considerations

One reason for the success of the spectral method for global forecasting is its suitability for spherical geometry. It should be noted however that workable techniques for the treatment of the pole problems are available in both finite difference and finite element discretizations.

1.2.3 Efficiency

A serious drawback of the spectral method for the future appears to be asymptotic cost as a function of increasing resolution. In the short term, some economies might be achieved by :

i) reducing the number of spectral collocation points in polar regions;

ii) computing the physical processes on a coarser grid (at the expense of increased aliasing);

iii) using a variable resolution over the sphere.

However a "fast Legendre transform" would be the most effective way of eliminating this drawback (at least for a long time to come). It is important to discover how to do it, if it is possible, or to demonstrate that it is impossible.

Other alternatives to address this drawback include the use of other globally defined basis functions (e.g. double Fourier series, Chebyshev polynomials high-order splines) or locally defined basis functions (e.g. finite elements or finite differences) or mixed methods (e.g. Fourier series in E-W and finite differences or finite elements in the N-S).

A new technique for increasing computational efficiency has emerged in recent years (semi-Lagrangian advection) which when coupled to other techniques potentially leads to significant efficiency advantages with respect to schemes having an Eulerian treatment of advection.

If the four-dimensional variational approach becomes the established method of data assimilation in the future, considerations of efficiency will also have to take into account the requirements for the integration of the adjoint model, including the storage needed for the history of the forward time integration.

1.3 New techniques

1.3.1 Semi-Lagrangian Techniques

It has been demonstrated that semi-Lagrangian techniques can be used successfully to integrate barotropic models over both limited areas and the entire globe, in conjunction with the finite difference, finite element and spectral approaches. Some multi-level models on limited areas have also been developed. All these models permit the use of long time steps with no detectable loss of accuracy in the experimentation to date, and hence provide a gain in efficiency of integration compared to Eulerian models, despite some overheads associated with semi-Lagrangian schemes.

The method can preserve the monotonicity of the fields in principle. The properties of the interpolator are essential in this regard.

Both three- and two-timelevel approaches have been used. The former result in Helmholtz equations to be solved, while the latter leads to more complicated types of elliptic equations (due to the implicit treatment of the Coriolis terms), unless a two-step strategy is used. By using such a two-step strategy, it is possible to arrive at either a tridiagonal set of equations or again at a Helmholtz equation. The emergence of more complicated types of elliptic equations has generally been regarded as a deterrent to developing centred two timelevel schemes, though recent progress in methods of solving such equations has tended to reduce the time penalty involved. Such work with elliptic equations would anyway be needed if evidence for the use of a filtered model (as discussed in section 2) becomes firmly established.

In the context of three-timelevel schemes, both interpolating and non-interpolating variants have been proposed. At first sight, some non-interpolating schemes appear to have an advantage in terms of cost per time step, although futher investigation of the relative accuracies of the two variants needs to be made.

1.3.2 Transport schemes for rapidly varying fields

The spectral technique has serious deficiencies in representing the advection of fields with large horizontal gradients. Water vapour - usually expressed as a mixing ratio or specific humidity - is such a field. Similar problems undoubtedly occur with cloud liquid water and turbulent kinetic energy which have sharp gradients in 3 dimensions. For water vapour the most noticeable symptoms are regions of negative mixing ratio. Various ad hoc computational devices have been included in most models to eliminate this undershoot but they either imply or actually result in significant computational transport or production. Less noticeable, but equally serious, are regions of overshoot. Unlike undershooting, it is not obvious from the field itself when overshooting has occurred and generally if the overshooting results in super-saturation then irreversible physical parametrizations are invoked producing for example spurious precipitation.

The over/undershoot can be attributed to problems directly associated with the truncated spectral representation of fields, and to dispersion errors.

Additionally, in the spectral transform approach the model's number of degrees of freedom (spectral coefficients) is considerably less than in the associated collocation grid on which the physical parametrizations are computed. It should also be noted that many finite difference schemes have similar problems arising from dispersion errors.

Although problems are seen most clearly for the moisture variable, it is likely to be important to ensure a consistent treatment of variables that are closely related physically, such as temperature and specific humidity. The appropriate choice of prognostic variables also requires further attention.

Meteorologists are only now coming to grips with the fundamental numerical problems involved. Techniques that have met with success in other areas of computational fluid dynamics are flux correction techniques, flux limiting techniques, and piecewise parabolic methods.

For meteorological problems the approach outlined by Williamson and Rasch (in this volume) has promise. Their approach is based on shape preserving interpolation schemes combined with a semi-Lagrangian stepping scheme. Indeed, the Lagrangian techniques appear to provide a natural approach to the problem of maintaining monotonicity of fields under advection processes.

1.3.3 The step-mountain technique

The step-mountain technique has been applied in a fine-mesh grid point model with comprehensive physical package. The preliminary results presented by Janjic at this workshop indicate that a dramatic reduction of the mean height error can be achieved by switching from the sigma to the step-mountain eta coordinate. The question remains, however, as to whether this technique can be applied in spectral models.

1.4 Recommendations

(i) The results which have already been achieved indicate that efforts to develop multi-level semi-Lagrangian models are well justified, and should be continued. It should be investigated how well these schemes perform for medium and long range integrations and how they influence conserved quantities. The other factors limiting the timestep in comprehensive numerical models should also be investigated in order to assess the overall gain in efficiency offered by the semi-Lagrangian technique.

(ii) The use of higher order spatial differencing should be investigated in conjunction with semi-Lagrangian treatments of advection.

(iii) Two-time level schemes should be further investigated since they offer the potential of a two-fold increase in efficiency over three-time level semi-Lagrangian schemes. In addition to this they offer the advantage of smaller memory requirements.

(iv) More sophisticated methods of estimating trajectories should be developed. In particular, attention should be devoted to the question of whether vorticity and divergence fields could be used to improve these estimates. In this respect, spectral models may have some advantage, as derivatives are available to a high order of accuracy at the grid-points.

(v) Attention should be given to the use of 3-dimensional semi-Lagrangian approaches. Problems near the upper and lower boundaries, where computed trajectories may go outside the domain of integration, need to be investigated. It also needs to be investigated how successful these schemes are in handling vertical advection and whether it is necessary that they do so.

(vi) Possible problems in the use of semi-Lagrangian schemes near steep orography need to be investigated.

(vii) The use of semi-Lagrangian techniques in meso-scale models, with particular reference to gravity waves and frontogenesis, should be investigated.

(viii) Semi-Lagrangian techniques should be compared with Eulerian schemes in severe tests for which analytical solutions are available.

(ix) Generalization of the semi-Lagrangian technique to characteristics of more general hyperbolic operators should be explored.

(x) Approaches such as those proposed by Williamson and Rasch should be evaluated within the context of the spectral model paying particular attention to pole problems, conservation where appropriate, and long-term stability of the schemes.

(xi) Shape-preserving schemes suitable for use in both finite-difference and finite-element schemes should also be developed.

(xii) The alternatives to terrain-following vertical coordinates should be examined together with the implications of such coordinates for horizontal discretization. In particular the possibility of applying the step-mountain η coordinate in spectral models should be investigated.

Report of Working Group 2

2. INCREASED RESOLUTION AND ITS IMPLICATIONS

2.1 Introduction

Experience with global and limited-area modelling at ECMWF, and with fine-mesh short-range forecasting systems elsewhere, points to some distinct potential advantages of increasing horizontal resolution beyond the T106 resolution of the Centre's operational spectral model. This is particularly evident in the short and early medium range, where improvements in synoptic-scale accuracy and local detail (particularly associated with orographic or coastal resolution) have been demonstrated in experimental medium-range forecasts and in operational as well as experimental short-range models. Use of higher resolution (vertical as well as horizontal) may not only bring about improvements due to better model performance during the production of the medium-range forecast itself, but should also improve initial analyses by enabling better use to be made of observed data in the assimilation process. Further benefit to the user should also arise from the availability of the wider range of forecast products that increased resolution allows. It is difficult to assess at present the scope for improvement later in the medium range, when forecasts are much more prone to error on the synoptic scale, but the impact of increased resolution can be expected to become increasingly important as major components of forecast error are reduced by the development of improved parametrizations, numerical methods and assimilation techniques.

Other developments of the forecasting system will influence the resolution, or resolutions, that are expected to be used operationally in coming years. The development of Monte Carlo techniques for provision of supplementary probabilistic medium-range forecast information is likely to require the use of resolutions lower than T106. Conversely, the use of variable resolution in the horizontal, either through the Schmidt transform or more locally (near significant orography say) in a finite-difference or finite-element technique, would require that the model performs well at a finer scale than would be possible in a global model of uniform resolution. The choice of resolution(s) may also be influenced by the implementation of a variational assimilation scheme requiring repeated integration of the forecast model and the adjoint of its tangent linear form. Overall, taking into account the likely developments in computer power, it appears that over the coming 10 years there will be a requirement for a medium-range forecast model or models which can perform well over a resolution range of around 300 to 30 km in the horizontal.

Increased horizontal resolution is likely to be accompanied, or even preceded, by increased vertical resolution. An important component of the Centre's research work will thus be the determination of the appropriate combination of horizontal and vertical resolution for future use. The study of increased vertical resolution should include not only higher resolution in the free troposphere and lower stratosphere, where benefit is expected to arise from better data assimilation as well as directly from improved model performance, but also increased low-level resolution to facilitate the parametrization of boundary-layer processes, and increased stratospheric resolution to improve the simulation of the mean circulation and the treatment of upward propagating waves, including the dissipation of gravity-wave motion, which may become increasingly important as horizontal resolution is refined.

Although a number of benefits are expected to arise from the use of increased resolution, problems may also result as models begin partially to resolve mesoscale processes that were hitherto unresolved. In addition, known problems of the forecasting system may be exacerbated as resolution is refined; several examples for the ECMWF system have been presented at this workshop. Some of these problems are related to the fact that gradients sharpen as resolution increases. The tendencies due to the parametrized processes will thus have a natural tendency to become larger (even though a resolution might eventualy be reached beyond which processes would have to switch off smoothly with further increases in resolution). Consistency between physical and dynamical formulations may become increasingly important, and care may have in particular to be taken if spectral decomposition remains as the basic representation of upper-air fields. These considerations have important implications for the development of parametrization schemes and perhaps more fundamentally for the choice of dynamical equations.

The following section discusses specific questions relating to parametrization and the appropriate system of dynamical equations. The implications of increased model resolution for data assimilation are discussed in Section 2.3. Recommendations are summarized in Section 2.4.

2.2 Modelling techniques

2.2.1 Effect of higher resolution

As the resolution of models in space and time is increased, it becomes possible to resolve a wider range of atmospheric phenomena. These include frontal rainbands, orographically generated gravity waves, convective systems and thermally driven circulations such as sea-breezes and drainage flows. None of these will be completely resolved by global models on the computers likely to be available in the next 20 years. It is therefore necessary to make a choice about which processes should be explicitly resolved and which parametrized. If this is not done effectively, there are dangers of misrepresenting such circulations in the explicit solutions, and of spurious interactions between the dynamics and the parametrization schemes, such as grid-point storms. In addition there is a danger of confusion between dissipation introduced for numerical reasons and that representing a true physical mechanism.

A similar problem arises with respect to resolved time scales. For instance convective clouds are presently assumed to form, develop and precipitate in one time-step (15 minutes in the current ECMWF T106 model), which obviously is unrelated to their own time-scale.

These difficulties need to be assessed first by using limited area models with much higher horizontal and vertical resolution. Use should be made of experience at other centres which use high resolution models not only for weather forecasting but, for instance, for cloud and boundary layer modelling.

These problems can have an impact on medium-range forecasting because of incorrect feedbacks of mesoscale circulations onto the large-scale flow, or the draining of excessive energy from the system into such circulations which may then have to be smoothed out.

2.2.2 Systems of equations

If problems caused by partial representation of some types of motion are found, it may be necessary to exclude those types of solution from the equations. Methods of filtering would be needed that are appropriate globally and describe the essential links between diabatic forcing and the dynamical response. It may become natural to use different variables in the models, such as potential vorticity, with attendant consequences concerning the choice of integration technique. Any method of dynamical filtering also has implications for data assimilation methods.

An alternative approach is to move to a nonhydrostatic system of equations. This has potential advantages in the treatment of the interaction between diabatic forcing and the dynamics even at resolutions when the hydrostatic approximation is still a reasonable one. Another approach which avoids the difficulties generated by increasing the resolution is to carry more information such as variances and higher order moments, at the same resolution. Predicting these quantities requires more elaborate systems of equations.

Whether or not the basic set of equations is changed, it is necessary to understand the convergence of the system as resolution is increased, taking account of the diffusion and parametrizations as well as the explicit dynamics. Differences between approaches may be best shown up by considering the energetics; for instance how diabatic inputs get into the large scale motion and how effectively dissipation removes energy from the system. The moist energetics may be an essential part of this. It may be necessary to use extra moist variables such as liquid water, or to change to conservative variables such as total water content. Appropriate numerical methods for treating them are also required.

2.2.3. Parametrization schemes

Presently the model physics is formulated at space and time scales which are the same for all processes and which are prescribed from non-physical considerations (the model grid and time step). However, the problems related to this space-time "truncation" will have to be reconsidered if the horizontal or vertical resolution is increased or if the time-step is modified by the use of alternative numerical techniques. This will involve mainly the following features.

a) Turbulent diffusion: Vertical diffusion will increase with vertical resolution (sharper gradients) and the present scheme may become unstable with larger time-steps used in conjunction with semi-Lagrangian techniques; steeper orographies associated with increased horizontal resolution may worsen the problem (associated with terrain-following coordinates) of horizontal diffusion in mountain areas. One approach to explore would be to compute a three-dimensional turbulent diffusion tensor based on physical considerations (simplified second order closure) and project on the model coordinate system. Any diffusion needed for purely numerical reasons should be distinguished from that determined by the physical considerations. Another approach is to abandon terrain following coordinates in favour of a representation such as with step-mountains.

b) Subgrid orography: Most important barrier effects should be resolved when the horizontal resolution is increased to the order of T213. However, there may still be a need to parametrize the effect of the local flows generated by both resolved and unresolved orography. A higher resolution model will also resolve a larger part of the gravity wave spectrum and the computation for momentum deposition is sensitive to the model's vertical resolution. Experimentation at various resolutions is needed and a resolution-dependent scheme may have to be worked out.

c) Cloud, meso-scale and convective systems: Possible ways to help overcome the arbitrary space-time truncation of these systems by the model is to allow their life cycle to be explicitly taken into account. This requires inclusion of prognostic water variables and a better consistency between resolved and non-resolved scales using a statistical estimate of subgrid cloud properties.

d) Radiation: At present complete radiative computations are made only once every 3 hours which is not adequate for representing the cloud-radiation interaction. Increases in vertical resolution will also have a large impact on how this is represented.

e) Choice of the space and time resolution: Some parts of the physics may have to be computed with different resolutions or time steps depending on the model representation and resolution, especially in the context of semi-Lagrangian techniques using fairly large time steps for the dynamics.

2.3 Data assimilation

The assimilation system updates a model prediction of the state variables by making adjustments (which are preferably small) to the predicted fields. The difference between observed and predicted values is spread out spatially and/or temporally by the analysis scheme. By improving the 4-dimensional (4-D) definition of the first-guess, one expects the increased accuracy to be transferred to the analysed state as a result of smaller adjustments being necessary. As more information is extracted from observations on finer scales, the accuracy and representativeness of the first-guess becomes increasingly important and should match the spatial and temporal sampling of a particular observation type. The exact time and 3-D spatial position of a radiosonde measurement may become important as we move towards higher resolution. On the other hand, satellite data represent the mean properties over a fairly substantial volume, and should be compared to the corresponding predicted volume averages. An increase of the model's horizontal or vertical resolution may not necessarily produce short-range forecasts with much greater skill than climatology on the finest scales. In such circumstances, we may need to filter the unwanted scales or to use alternative techniques to produce a balanced first-guess.

Assuming that the information on finer scales is not misrepresented in the short-range forecasts, many observations which would be redundant or even detrimental in the current ECMWF analysis scheme could become very useful. Very high-resolution orography and detailed delineation of land/sea boundaries would make large amounts of data potentially valuable for the analysis. Improved parametrization combined with increased horizontal and vertical resolution could make existing and planned observing systems very attractive in numerical weather prediction. Observations of precipitation, fog, cloud from the surface (both conventional and from radar) and space, wind observations from profilers and Doppler radar, and detailed measurements from aircraft during ascent and descent, may provide additional useful information. Some observing systems may be difficult to handle in a statistical interpolation environment, while 4-D variational techniques, provided the cost function and its derivative can be formulated, can exploit the high temporal resolution of some new observing systems much better than a static analysis scheme. The advantages of the 4-D variational approach will have to be weighed against its computational cost, and the cost of the forecast integration in choosing the optimal resolution(s) to be used for data assimilation and forecasting.

An increase in the analysis resolution leads to a reduction of the effective data density thereby reducing the capabilities of the analysis scheme to identify and reject erroneous observations. Conditional probability methods and time continuity checks may solve some of these quality control problems. Space based observing systems with complicated error characteristics present a much more complex quality control problem than conventional observations as we attempt to extract more information on fine scales from them.

High spatial analysis and model resolution increase the degrees of freedom the analysis scheme has in interpolating the analysis increments between data points through the structure functions. Orography and the planetary boundary layer pose particular problems in defining proper structure functions. Higher analysis resolution can be achieved, where data supports it, by widening the spectral window of the forecast error covariances and by relaxing the constraints currently imposed on the increments. By removing the requirement of non-divergence, separability in the horizontal and vertical, and near geostrophy on all scales, of the increments, it will be possible to analyse more complicated flows. However, too-sophisticated high-resolution structure functions may complicate the use of single-level data. Similarly, orography- and land/sea-dependent influence functions are needed for surface analyses. These analyses must be carried out in a way consistent with the model physics.

As more processes are explicitly resolved, more physical constraints need to be imposed in the analysis. Such constraints are naturally imposed in a variational 4-D analysis, while in statistical interpolation such constraints are difficult to formulate. Some of the "spin-up" problems may be alleviated by detailed physical forcing in the initialisation estimated from outgoing longwave radiation data and by adjusting the moisture distribution to give the necessary condensation.

2.4 Recommendations

2.4.1 General

(i) Efforts should continue to be devoted to determining more precisely the benefits and problems associated with increased horizontal resolution for the next generation of operational forecast system. Work on increased vertical resolution should be carried out in close conjunction with the work associated with the horizontal. The impact of increased resolution on the assimilation of observed data should be a significant part of this work. Verification should include conventional assessment of experimental medium-range forecasts, but increased emphasis should be paced on local verification against observed data and on diagnosis of the performance of the model on the shorter resolved space and time scales, including use of the tangent linear model to study initial error growth.

(ii) Perform experiments with much higher horizontal (30 km) and vertical (500 m) resolution to assess likely problems, using either the limited-area model or variable-mesh global model. This work should be carried out in close collaboration with groups within the Member States who are actively involved in modelling at this resolution, and make due use of data gathered in field experiments.

2.4.2 Model development

(i) Depending on the results of the above experimentation develop methods of dynamical filtering to avoid the need for large amounts of unphysical smoothing. Even if not necessary for the forecast itself, investigate implications for assimilation.

(ii) Consider methods other than increased resolution for increasing the information predicted by the model, through prediction of additional quantities describing sub-gridscale variability.

(iii) Develop parametrization schemes which take into account that some processes occur in nature on timescales slower than the model timestep, and that others occur much faster.

(iv) Give more consideration to the resolution-dependence of the parameterization, to enable schemes to be used effectively over a wide range of space and time scales.

(v) Reconsider the problem of dissipation in the framework of a three-dimensional diffusion operator.

(vi) Examine the implication of the step-mountain representation for the physical parametrization schemes.

2.4.3 Data assimilation

(i) Improve the 4-D generation of the analysis scheme's first-guess to match the sampling of observations. In addition to reducing the analysis error, this would increase the amount of observations that can be sensibly used in the analysis. It is practicable to use some of these observations only in a 4-D variational context.

(ii) Improve the quality control by time continuity checks and investigate the Bayesian (conditional probability) approach to quality control.

(iii) Relax the dynamical constraints imposed by the structure functions on the analysis increments to allow for more complex structures in the analysis.

(iv) Exchange and use for higher resolution analysis, nonconventional data such as winds, precipitation rates, temperatures and humidities, from (Doppler) radars and wind profilers.

(v) Improve the consistency between the analysis and model formulations wherever appropriate.