Group 1: Experiences with High Resolution Models

Chaired by Radmila Bubnova; Secretary Mariano Hortal

Others: Ulf Andræ, Anton Beljaars, Jean Côté, Terry Davies, Jean-Philippe Lafore, Martin Miller, Piotr Smolarkiewicz, Agathe Untch

1. Problem of validation

An important question when considering what advantages can be gained by increasing the horizontal resolution of a forecast model is the problem of proper validation at small scales (below ~20 km grid-length). The experience from the users of high-resolution models (for example ALADIN) is that almost no improvement in the traditional scores (root mean square error, bias, ...) is achievable by increasing the horizontal resolution. Hence, the forecasters' opinion becomes quite helpful to distinguish between realistic or unrealistic small-scale features. To compare with remotely-sensed data (radar, satellites) would be desirable for verification purposes but it is difficult to achieve in practice. Field campaigns are very useful in this context, e.g. MAP'99. The amount of precipitation is probably the most difficult of the weather parameters to forecast (and verify) properly at all scales. By contrast the fields of 10m wind or 2m temperature are more likely to benefit from an increase in the resolution of the forecast model (quick adaptation to the orography which is more realistic when using higher horizontal resolutions).

Verification of precipitation is carried out in research mode in France, using a dense network of automatic stations reporting precipitation every hour. Another possible way of verifying precipitation forecasts is to compute monthly climatologies from the model and compare them with the monthly means computed from measurements (e.g., the HERA project prior to the MAP field campaign). DWD currently compares the precipitation forecasts of several global models, but only with respect to the station network in Germany. It would be useful to enlarge the verification area in this study.

2. Intercomparisons

The working group agreed that a more controlled intercomparison between models, performed by running a set of common or simplified quasi-academic cases, would be welcome. However, this requires a proper setting of such tests and we probably cannot expect to find answers to our problems immediately. After some experience is gained with an initial set of cases we may be able to improve the settings for further experiments.

This set of intercomparison cases should address not only the differences in behaviour of the different models but also what are our common problems, despite differences in our schemes. Concerning the definition of common problems for comparison, some suggestions were:

- Behaviour of a single-point tropical island;
- Study of the rainfall over the equatorial Andes;
- Scandinavian mountain problem (uniform flow impinging on the Scandinavian mountain range from the north-west) including moisture.

UKMO will propose a set of intercomparison cases based on these ideas. Nevertheless it was stressed that ultimately we cannot look at the dynamics/numerics problems independently of the data assimilation and the physical parametrizations. Our aim should be to describe as well as possible the slow manifold in order to allow the model to benefit from the information brought by the observations.

3. Conservation properties

The group considered the possible benefits of using the flux-form of the evolution equations, which ensure local conservation of conservative quantities (using an Eulerian flux-form scheme). However, with this class of scheme it becomes more difficult to understand the systematic errors of the model. The conservation problem in semi-Lagrangian schemes, according to some studies, comes mainly from the boundary conditions and only the flux form of the equations (solved with an Eulerian scheme) can ensure local conservation by employing proper boundary conditions (zero normal flux at the boundary). Relating to this issue, a problem of conservation of humidity in the ECMWF model was mentioned and attributed to the shorter scales induced by the physics in the humidity field rather than to improper specification of boundary conditions. No consensus was reached on whether the conservation is important for medium-range forecasting, nor whether giving up the efficiency advantage of the semi-Lagrangian schemes in favour of conservation is worthwhile.

4. Validity of the hydrostatic assumption and the shallow atmosphere approximation

There was a lively discussion about the threshold scale where the hydrostatic assumption is still valid. This threshold is related also to the problem of parametrizations (when to stop parametrizing the convection, for example). The most difficult scales are the ones at which the convection starts being resolved and a problem of double counting appears. Due to this fact, the meso-NH group avoids working at resolutions between 10 and 5 kilometres. Experience so far indicates that hydrostatic models give very similar results to non-hydrostatic ones at scales down to 10km (evidence in the ALADIN group, and some other meso-scale community groups). The HIRLAM group considers that using the hydrostatic primitive equations at 10km gives perfectly acceptable results over flat terrain but they see problems over orography. The ALADIN group considers switching to the NH version at about 5km grid-length.

The problem of relaxing the shallow atmosphere hypothesis was broadly discussed. This relaxation would mean introducing the full 3D Coriolis force and taking into account the distance from Earth's centre in order to keep the conservation of angular momentum. According to some papers, 3D Coriolis is important in the boundary layer. Differing views were expressed as to whether this relaxation is more important than abandoning the hydrostatic approximation and should be done first on the hydrostatic set of equations, or whether the hydrostatic assumption should be relaxed first while still keeping the shallow atmosphere. It seems that just including the vertical acceleration and using hydrostatic pressure as the vertical coordinate is not so demanding for code development. It was suggested to evaluate the magnitudes of the terms neglected in the shallow atmosphere in a perturbative way in order to estimate their importance. It was also stressed that the relaxation of the shallow atmosphere approximation may be tested even at lower resolutions.

5. Vertical coordinate and staggering in the vertical

The group considered the Lorenz vs the Charney-Phillips staggering and also no staggering at all in the vertical. It was not clear how much these choices actually matter, since each choice has some advantages and disadvantages. One can always use the non-staggered grid if the operators and boundary conditions are properly defined to avoid splitting of the solutions. It is felt that in non-hydrostatic flows where the pressure is not uniquely determined by the surface pressure the question of the staggering becomes more important. One can also use different staggering for different processes and this will eliminate the difficulty of performing semi-Lagrangian advection on staggered grids. The difficulty in this case is to define an accurate and reversible operator to go from one set of points to the other. In Canada experiments are being conducted to compare the different staggerings in both free and forced runs.

The choice of vertical coordinate (pressure type vs height type) to be used when going to the full Navier-Stokes equations was discussed. There was no real preference between the two, the real problem being the formulation of the top boundary condition..

Summary

The importance of 3D Coriolis terms and relaxation of the shallow atmosphere hypothesis should be tested in quasi-academic cases even at lower resolutions, looking mainly at the boundary layer.

- Introduction of hydrostatic pressure as the vertical coordinate and vertical acceleration is a first step towards a fully compressible model.
- Whether to use pressure or height based vertical coordinate is an open issue.
- Tests of staggering versus non-staggering in the vertical are being done in Canada. At the present moment it is not clear whether this is an important issue.
- Validation of results will become more and more difficult when going to finer scales.
- More work and collaboration on testing is needed.

Group 2: New Techniques for Horizontal Discretization

Chaired by Andrew Staniforth; Secretary Clive Temperton

Others: Detlev Majewski, William F Spotz, John Thuburn, Andy Wathen

Horizontal discretisation is an important consideration when designing an atmospheric data-assimilation and forecast system. There are a number of alternatives, with associated pros and cons, and despite (or possibly because of) much research in their development over the past several decades, a clear "winner" has not as yet emerged. Because of the diversity of approach at national European meteorological centres and at ECMWF, and good communication between them, Europe is well placed to objectively compare and evaluate the advantages and disadvantages of different discretisations as they are developed and improved.

Although it is likely that the Centre can meet its 2008 goal of an operational global system with 15-km horizontal resolution by further developing its current hydrostatic primitive equations/ spectral-based system, during the next several years it should nevertheless review the options for developing a system based on a more general, fully compressible, non-hydrostatic equations set. The simplest such option would be to adopt Laprise's "hydrostatic-pressure" vertical coordinate, e.g. as in models at Météo France and CMC, and to include the vertical acceleration term Dw/Dt. This option would nevertheless suffer from any limitations of the shallow-atmosphere assumption, and the associated neglect, for conservation and consistency reasons, of several metric terms and the $2*\Omega*\cos(\phi)$ terms. Although scaling arguments suggest that these terms may be of some importance in certain situations, particularly the $2*\Omega*\cos(\phi)$ ones which are not only arguably as important as the Dw/Dt term but may have an impact on the large-scale atmospheric circulation, this has not as yet been quantified via controlled experimentation. The second option is thus to not make the shallow-atmosphere assumption but to retain the missing terms, as in e.g. the new dynamics of The Met. Office's model. The ongoing development and performance of this latter model should be monitored by the Centre for evidence of any demonstrated advantage of its more complete equation set. If it were deemed desirable for the Centre to develop a model based on this more general equation set, then thought would need to be given to whether the vertical coordinate should be scaled geometric height, as in The Met Office's new dynamics, or something else, e.g. hydrostatic pressure. Note also that there may be implications for the relative cost of the spectral method with respect to alternative methods of horizontal discretisation, and these would need to be examined.

We agree that the spectral transform method should remain a viable and competitive forecast model until the stated goal of 15 km resolution is obtained. Of course, the $O(N^3)$ associated Legendre transforms will continue to increase in percentage of execution time relative to the other components of the model. This percentage can be reduced by adoption of the double Fourier method coupled with an associated Legendre projection.

This approach has been demonstrated to give the same stability and accuracy as the spherical harmonic method in an Eulerian context, while reducing the associated Legendre transform operation count by roughly half. Theoretically, semi-Lagrangian savings should be even greater, and it is conceivable that fewer (or even no) associated Legendre projections would be required in a semi-Lagrangian framework.

There has also been encouraging progress lately towards developing the elusive fast Legendre transform with a low break-even resolution. This would be directly applicable to making not only the current ECMWF forecast model more computationally efficient, but a future double Fourier model as well, by using a projection composed of the new fast Legendre transforms.

Adoption of the double Fourier method should extend the usefulness of the spectral dynamical model beyond that of the standard spherical harmonic model, but not indefinitely. The development of fast Legendre transforms would also extend the spectral method's lifetime, perhaps indefinitely. But the successful development of such a transform algorithm is not guaranteed, and the Centre should be evaluating other discretization techniques for global dynamics for possible adoption beyond the current goal of 15 km resolution.

Latitude-longitude grids have the advantages of a long proven track record and convenient structure (ease of coding, suitability for direct solvers and for cascade interpolation). It is also relatively easy to convert the grid data to spherical harmonics if needed (archiving, variational data assimilation). On the other hand, the clustering of grid points near the pole results in difficulties (CFL criterion) for Eulerian models, potential problems for semi-Lagrangian models, difficulties with iterative solvers and wasted calculation.

Numerical methods based on the icosahedral and conformal cubic grids have been gaining renewed interest in recent years. The first attempts to use the icosahedral grid in 1968 were unsuccessful because of the so-called "wave number five problem" which was due to a discretization error arising from the slight grid non-uniformities. Recently developed spatial discretization schemes that achieve second-order accuracy seem to show no significant wave number five error any more.

The numerical methods based on the new grids offer the following advantages:

- The group of problems (no coordinate singularity; no very small grid cells which might restrict the time step; no wasteful clustering of grid cells in polar regions; no highly anisotropic grid cells with attendant problems, e. g. for elliptic solvers) collectively known as the "pole problem" which exists in latitude-longitude grids are eliminated; this is especially important at high horizontal resolutions.
- Near homogenous resolution, thus fewer problems if parametrizations require resolution dependent tunings.
- There is a natural hierarchy of grids which can be used in conjunction with multigrid elliptic solvers or at inner/outer loop calculations of 4D-Var.
- The data structure is quite regular, i.e. 10 square matrices for the icosahedral grid or 6 ones for the cubic conformal grid. Thus 2-d domain decomposition on MPP systems can be easily implemented.

The following disadvantages have to be noted:

- For Courant numbers greater than 1, finding the departure point in a semi-Lagrangian scheme is more complicated than in regular latitude-longitude grids.
- Few discretization schemes have been tested so far on icosahedral grids; it is not clear if staggering of variables (e.g. C-grid) will work.
- The grid does not map neatly onto a single rectangular array. Thus special code may be needed to join the patches and more communication may be required on MPP systems.
- Not much experience has been gained so far in operational NWP models using the new grid methods.

Group 3: Alternative Approaches and More Implicit Schemes

Chaired by Jim Purser; Secretary Mike Cullen

Others: Chris Budd, David Dritschel, Ali Mohebalhojeh, Nils Wedi

The eleven topics listed below range from aspects of spatial representation, through questions concerned with implicitness to processes at or near the resolution limits.

1. The appropriate vertical discretization and choice of variables

Studies such as *Johnson et al* (1993) and *Konor and Arakawa* (1997) have shown the benefits of adopting θ-σ (potential temperature-σ) hybrid terrain-following coordinates in improving long range transport of advected quantities, such as humidity fields. However, it is recognised that pure θ coordinates impose undue limitations on the range of atmospheric states that can be represented, and can lead to deficiencies of vertical resolution in regions of low static stability. While the working group endorses efforts aimed to exploit θ-σ hybrid coordinates in future ECMWF forecast models, we recommend that the construction of such coordinates contain safeguards against the potential problems. It is suggested that variational "grid generation" methods be investigated as a class of techniques for the construction of the vertical coordinates.

The present Lorenz vertical grid staggering is considered unsatisfactory for the representation of fine scale vertical structures. From this perspective, a Charney-Phillips vertical staggering, *Arakawa and Konor* (1996) is regarded as more desirable, although it is recognised that **any** grid staggering poses an inconvenience for a model whose advection is treated in the semi-Lagrangian way.

The group considered the adoption of variables more directly associated with identifiable conservation laws. For example, *Ooyama* (1990) discusses how, under moist adiabatic conditions, involving changes of water phase, the 'forcing' terms of moisture and thermodynamic variables can be eliminated by choosing model variables that are a pair of independently conserved quantities (e.g. total water substance, total entropy). However, in view of the trend towards separate treatments of various types of liquid and frozen hydrometeors in physics packages, the group came to no consensus about recommending this approach. The choice of potential vorticity as one of the dynamical variables might be advantageous for ensuring its long-term numerical conservation where such conservation is valid.

2. Compact and finite element methods

Compact difference schemes were considered for the vertical and horizontal directions. While it was recognised that compact schemes could play a useful role in conservative "compact" semi-Lagrangian interpolation schemes, it is not so clear that the horizontal application of compact schemes in other areas of the model would be so useful, given the present reduced-grid geometry. In the vertical, it was felt that the choice of vertical grid was more significant than the choice of compact or finite element schemes.

3. Conservative advection in the semi-Lagrangian approach

Attention should be paid to achieving proper conservation of first order quantities (such as mass, moisture, tracers, possibly momentum or zonal angular momentum) but should **not** extend to second order quantities (such as energy, potential enstrophy). In the semi-Lagrangian scheme, consideration should be given to exact conservation methods, such as the conservative "cascade" (*Leslie and Purser*, 1995) or constraint restoration (*Priestley*, 1993).

4. The extent to which the model formulation should approach a fully implicit scheme

The group recommends that efforts be made to make the physics and dynamics more intimately connected and more fully implicit. It would be desirable to investigate the importance of small-scale gravity waves and the significance of their distortion by implicit numerics. Idealized tests of the role of "implicitness" need to be carried out both with idealized models and full GCM simulations. Among the most basic consistency checks are those that compare solutions at different settings of the time and space steps.

5. Elliptic solvers and preconditioning

Anticipating a trend towards increasing implicitness in future numerical formulations, the group suggest that an emphasis be given to research into preconditioning techniques for elliptic/algebraic solvers. The elliptic problems that arise in more fully implicit methods tend to be fully three-dimensional and non-separable. However, it is recognised that existing spectral methods, for semi-implicit adjustment, can serve as good large-scale preconditioners, possibly in combination with vertically-direct line solvers to handle the vertical "stiffness" characterizing these elliptic problems. Research is particularly required to address the problem of stiffness in the horizontal where it is localised near orography. Multi-grid preconditioners deserve consideration.

6. Adequacy of interfaces between physics and dynamics, the appropriateness of the present modularity and the improvement of the matching of space and time scales among processes

An adaptive vertical grid geometry should be designed with the benefits to the physics in mind, and the physics schemes should be adapted to take advantage of the adaptive vertical levels. The main terms of the physics and dynamics should be written as a combined set of equations and the best techniques for solving the combined set should be identified. Both these developments will break the existing modularity of the code and there will have to be general agreement amongst groups about how new forms of modularity can satisfy each group. The key time and space scales should be identified and appropriate treatments designed for their adjustment.

7. Should special consideration be accorded to reconciling conflicting requirements of ensemble and deterministic forecasts, regarding their treatment of uncertain physical and dynamical processes?

The present stochastic perturbations to the physics forcings in the ensemble members should be more intelligently constructed, reflecting the relative degrees of uncertainty according to the meteorological circumstances. However, the uniformity of the model formulation itself should be preserved.

8. Should under-resolved motions be excluded from the model?

Experience with idealised models suggests that inaccuracies of gravity waves can contaminate the large-scale field. There is a need to assess possible alternatives to present treatments of under-resolved motions. Options include: a change of prognostic variables to reduce spurious interactions among under-resolved motions; selective filtering (e.g. de-centring); use something closer to a filtered model; design better sub-grid models for parametrization.

There was a debate about the need to retain the tail end in the spectrum of motions. This is not possible in a purely deterministic way, but it should be investigated whether a stochastic restoration of spectral power could be beneficial in deterministic models and in ensemble-forecast members.

9. The reduction of artificial small-scale viscosity

The group agreed, as reflected in previous sections, that it was desirable to use numerical methods that did not produce grid-scale noise unnecessarily.

10. The role of grid adaptivity and the relative importance of horizontal, vertical and temporal resolution

The identification of horizontal scale ratios should dictate the relative grid scales (including time). We previously mentioned the ability of hybrid vertical coordinate based on θ to achieve appropriate vertical grid scaling. To improve beyond this would require more complex grid adaptivity, which we do not see as a short-term practical possibility. There may be a longer-term pay-off after experience has been gained in sufficiently realistic idealised studies, and benefits demonstrated.

11. The need for 'difficult' test problems including forcing- with well-defined solutions

A recommendation was made that the IFS code be made more modular with clearly defined interfaces to facilitate experiments by outside users. It would be desirable to have versions of future model codes that do not require full spherical geometry in order to perform idealised experiments. Such codes might allow comparisons with experimental data for special dynamical flows. We noted the existence of several suites of test problems available on the web and encourage the more widespread use of such test problems in future code developments.

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