Some informal news from the AROME project

F. Bouttier, G. Hello, S. Malardel, Y. Seity,

with help from many others.

CNRM/GMAP, Toulouse, 1 March 2005

This paper presents an overview of the design choices of AROME and an update on the status of its development.

1. OBJECTIVES

The basic reason for making AROME is to get ready for the next generation of computers, observations and users' requirements, by taking the best of what is already available – ALADIN-NH dynamics and software basis, some physics that are guaranteed to work well at kilometric scales, the IFS/ARPEGE/ALADIN variational analysis – and putting it together as a newer, better operational system. Over ten years of experimentation in the mesoscale research communities have given strong indications that it is a realistic goal, at least, for the most important aspects: much improved precipitation forecasts than in ALADIN. The choice of ALADIN-NH dynamics and ALADIN-3DVar to do AROME is a tribute to the excellent work of many ALADIN scientists who contributed to these projects, as confirmed by the many peer-reviewed publications on their scientific content.

The same software basis in AROME as in ALADIN – the IFS/ARPEGE library – is used, which provides a guarantee that there will only be minimal disturbances to the partners' operational practices. Only a small amount of technical adaptation will be required on the partner NWP services to switch to AROME when they want to start using it. In the meantime, ALADIN will keep running (and improving through the work done on improving its big brother ARPEGE), and ALARO will provide a much improved alternative to ALADIN for those who cannot switch to AROME.

2. USING THE MÉSO-NH PHYSICS

The choice of the complex Méso-NH physics (compared to the ARPEGE/ALADIN physics) was driven by the user requirements to improve products such as quantitative precipitations, small-scale convective rain and gusts, 3D distribution of cloud ice and water, aircraft icing and turbulence risk, urban weather and air quality, accidental pollutant dispersion, road conditions, coastal weather, fluxes for ocean models. Since the Méso-NH physics already are in a usable state, the priority of AROME is the software engineering and qualification for NWP applications, to be done in a fixed time.

As models go to higher resolutions, more subgrid-scale processes are explicitly resolved on the model grid. The AROME physics only borrows from Méso-NH the parametrizations that have been proved to be of significant importance at 2.5km resolution in Méso-NH experiments (the choice is confirmed by other NWP groups):

- a 1-D (i.e. vertical) prognostic turbulent mixing scheme
- a 1-D state-of-the-art radiation scheme
- a cloud micro-physics scheme that separates at least between liquid water and ice, and between small cloudy particles and bigger hydro-meteors
- the best affordable surface scheme, consistent with the available physiographic databases
- a shallow convection scheme

The schemes have been thoroughly validated in a large number of Méso-NH tests: convective storms, hurricanes, synoptic storms, PBL city weather, field experiments such as PYREX and MAP, and many more. There are some changes with respect to the ALADIN philosophy: the surface scheme has explicit time-stepping (not a problem with the AROME time-step, which is much shorter than in ALADIN), the vertical discretization is different, the surface scheme is externalised, and the coding rules, but are a bit different from the ALADIN ones. It was found more efficient to adapt to this new physics software than to rewrite it; an abundance of documentation, peer-reviewed publications and scientific experts is available on the Méso-NH physics.

The vertical turbulent scheme is based on a turbulent kinetic energy closure. It is prognostic, which should help with the depiction of the evolution of boundary layers and clouds. It is scientifically very close to what is being implemented in ARPEGE/ALADIN in 2005 at GMAP (although the code itself is still different). For very high resolutions, theory tells that the turbulent scheme should be a 3D one (i.e. elaborate horizontal mixing), however this effect seems to be significant only at resolutions higher than 1km, 3D turbulence is very complex and expensive, and the parametrization is still far from being in a satisfactory state, so it was decided to stick with a 1D scheme for the next few years.

The radiation scheme is very important for cloud/radiation interaction, and for the production of accurate fluxes at the surface (which is critical for some users). Since it is a lot of work to develop a competitive radiation scheme, it was decided in Méso-NH (and hence in AROME) to use a recent version of ECMWF's radiation scheme, RRTM, which happens to be already conveniently installed in the ARPEGE/ALADIN code.

The cloud micro-physics scheme (called ICE3, because it has three prognostic icy variables, on top of 2 liquid water ones) is scientifically very complex, and deals separately with the conversion («slow») processes, and the ones related to precipitation and saturation («fast» and adjustment). Condensed water species do not have special prognostic temperature or speed, but they interact with the gaseous thermodynamics in complex ways.

The surface scheme is derived from the ISBA we know in ALADIN, but now, with many more processes, since it now includes tiling (i.e. several different surfaces may coexist in each model column, each with their own surface temperature), prognostic models for towns (with a special geometry for walls, roofs and streets, to represent urban heat island effects in particular), lakes, snow, and soon superficial ocean layers (so-called 1D «pseudo-3D» mixed layer). Technically, the really difficult issue is that it means dozens of new surface fields (physiographic and prognostic) in the system. It is no longer necessary to allocate them inside the ALADIN software (because they belong to the surface software, called SURFEX**)** but plugging these new fields inside our NWP technical environments is going to be a significant challenge: one will need, either to manage the model history as two files (one for the ALADIN atmosphere, one for the SURFEX state), or to define, allocate and maintain all these new 2D fields (as well as some non-2D data, there are coefficients and matrices) into the FA files. Fortunately, SURFEX already has a complete environment for computing climate files from high-resolution physiographic databases (the ECOCLIMAP database), doing I/O on SURFEX files and producing diagnostics.

The shallow convection scheme is not yet finalized, and work will be done on this topic in 2005.

This physics package will have its own problems. All convection is not resolved horizontally nor vertically at a resolution of 2.5km and L41 levels. Some of the turbulent eddies are partly resolved, which may cause problems akin to the subgrid convection issue in 10-km resolution models. Some of the cloud physics are missing, which may hurt the description of some cloud types. They may not be serious issues in practice, but they need to be carefully monitored on a good enough sample of real test cases, because they might lead to an evolution of the scientific strategy. The Méso-NH group keeps working in this field, on chosen test cases to target specific processes, it is necessary to complement this effort by looking at NWP-style validation, with lots of unselected cases, and a global view of the performance of the AROME model.

3. THE STATE OF THE PROTOTYPE

Upon examination, it turned out not to be too complicated to plug the Méso-NH physics into AROME. Yann Seity and Sylvie Malardel produced a first working version of the so-called AROME prototype in just a few months (the word "prototype" means that it is a bread-board testbed that needs to evolve into a clean and efficient configuration). Basically, the relevant Méso-NH and SURFEX source code has been extracted as libraries, and linked with the ALADIN-NH code through a specific physics interface (APLAROME) beside APLPAR. Although the timetable of the AROME project will not allow too ambitious plans for redesigning the physics interfacing from a theoretical and technical point of view, significant improvements can and will be done under the constraint of the available workforce.

The first step for AROME was to prove that it could compete with Méso-NH in terms of quality and cost. This required some Méso-NH-style testing on simplified cases: the dry ALADIN-NH dynamics on low-level orographic waves (already presented a few years ago), 1D simulation of convective and stratiform clouds (using the 1D model with physics), 2D vertical plane simulation of a convective system (an idealized African squall line), 3D simulation of an idealized convective cloud. All these tests revealed differences between AROME and Méso-NH, but no spurious behaviour of AROME.

The first real test cases were run in 2004. Each one required some considerable manual work, due to the technical nature of the prototype. There has been one famous convective flood event in the SE of France (the "Gard case"), and a thunderstorm system on the plains around Paris. On both cases, it was demonstrated that the AROME prototype was

1. performing at least as well as Méso-NH (although there is room for improvement of AROME),
2. sensitive, in a positive sense, to the assimilation, by checking that an AROME run started from a mesoscale analysis does indeed perform much better than one in purely dynamical adaptation mode (which justifies the current effort on developing mesoscale data assimilation).
3. much more efficient than Méso-NH in a CPU sense (by a factor 10 or so), thanks to its longer feasible time-step (which could be stretched to 1 minute, which remains to be confirmed on a wider panel of cases), and not more expensive than what is affordable, computerwise, at Météo-France in 2008 (which looks like a realistic goal so far).

To obtain these results was a huge relief. Although they do not prove that AROME is mature enough to be safely used in operations, they go a long way towards proving that, even though unexpected problems with probably be discovered in AROME in the future, they will be tractable. It also proved that it was feasible to work in a mutually beneficial cooperation between the Méso-NH research groups and the NWP community.

The work on the «old» ALARO model concept (i.e. AROME + convection scheme running at 5, 7 or 10km resolution) has been interesting for the comparison with AROME, too. It was mainly done by G. Hello, T. Kovacic, L. Kullmann, who ran the Gard case (and a «Czech front» case) at various resolutions. It showed that the Méso-NH physics can work at larger scales and longer time-steps, although it has not been proven to beat the ALADIN physics at low resolutions.

Further test-cases are being worked on. There has been a case on Romania, on the MAP field experiment (see figure), and more are planned, usually involving ALADIN partners or scientific visitors. The results will be shown to the ALADIN community, of course. But there is a limit to the usefulness of test-cases for NWP, and it will soon be time to start running AROME every day (on a small domain for computational reasons, until the next computer upgrade) in order to test what AROME is worth in terms of robustness (does it ever blow up or produce silly forecasts ?) and average NWP performance (we have worked a lot on convection in AROME, but what about the other kinds of weather ?).

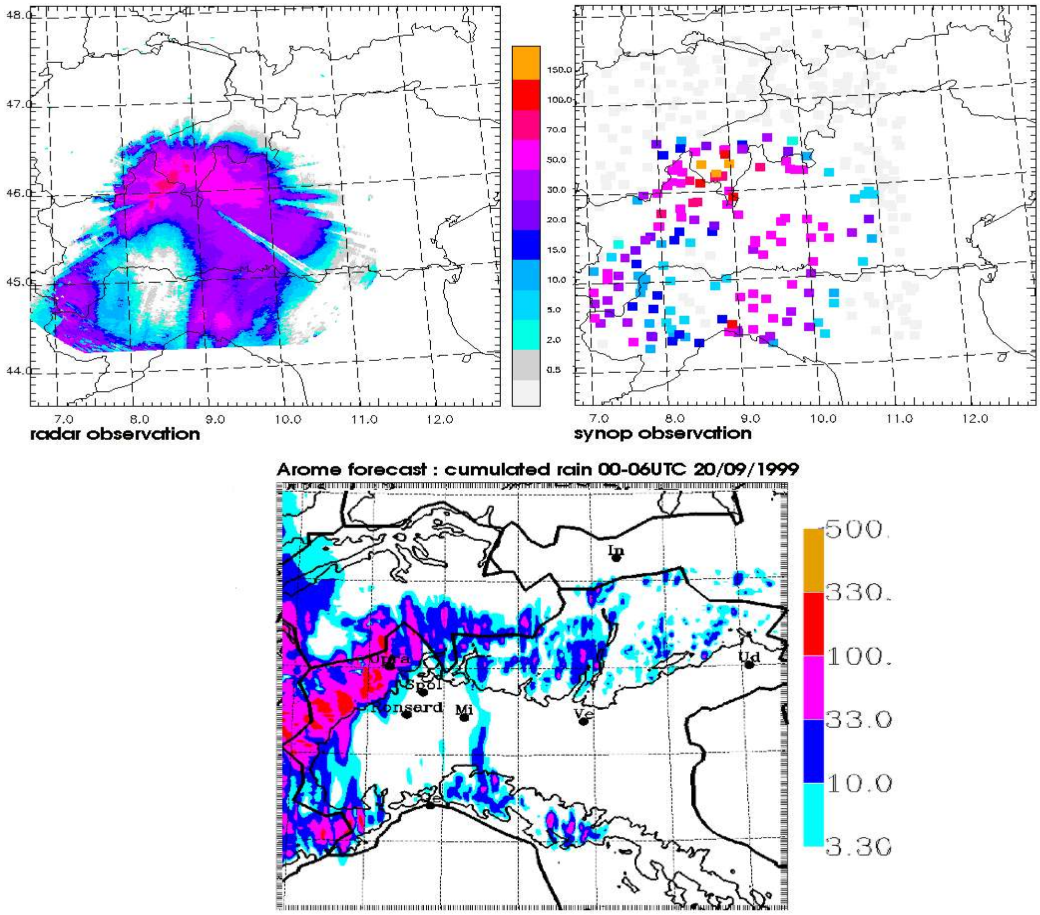

Figure : A rain forecast with the AROME model, started on 19/09/1999, 00UTC from a large-scale analysis(mm cumulated over 6 hours, MAP POI2B case), with radar estimates and SYNOP rain-gauge verification. The model was run by Y. Seity.

4. THE REMAINING WORK

As any good cook (French or not) will say, to make a good meal you not only need the best ingredients, you also need flawless preparation. The AROME model of 2004 is nothing like a ready-to-wear product. To prepare initial conditions is inefficient: one needs to run Méso-NH software every time there is a change to the model geometry. Post-processing is cumbersome, in order to plot most kinds of fields the AROME files have to be converted back into Méso-NH and then fed into a specific plotting package, some fields just cannot be post-processed at all because Full-Pos does not yet understand the AROME surface fields. There is no provision for deported AROME execution yet, for lack of e927 and ee927 coupling file processing jobs that can handle the externalised surface. And AROME has flaws in its parallelization and its computational optimisation. All this means that AROME can currently be used for scientific experimentation, but not for routine production.

It is not as bad as it sounds: only small software development is needed to recover in AROME all the functionalities that ALADIN offers, since the bulk of the software is essentially the same. The main annoyances come from the externalised surface (called SURFEX) and the presence of new 3D fields in the model. They can (and will) be cured with appropriate software developments which are not big, but must be done. The technical issues are as follows:

- the preparation of new domains is done in ALADIN by the 923 configuration, which cannot prepare surface fields for SURFEX. These fields can be prepared by a specific SURFEX tool called *prep_pgd*, on exactly the desired ALADIN domain. This is not a problem per se, but a change of habit: to prepare AROME "climate files", one will need to install and run *prep_pgd* at home beside 923.

- the change of geometry is done by Full-Pos, which needs to read and write the surface fields, currently it can do neither. In order to FullPos atmospheric fields, only a few surface fields need to be read, which can be done either by hacking a copy of the needed SURFEX fields into the FA file given to Full-Pos, or (better) to teach Full-Pos how to reach these fields in a SURFEX file directly. Producing surface fields at a new geometry can be done by *prep_pgd*, except the rapidly evolving ones, which we want to be able to update without rebuilding the complete climate files. They will come with the coupling files, we need to extend the SURFEX software of Full-Pos itself to interpolate these evolving fields efficiently.
- the post-processing has about the same problems to solve as the change of geometry feature above. Plotting of SURFEX fields can be done by tools provided with the SURFEX software itself. But to avoid too much disturbance to the operational systems, we need to keep a consistent interface the new system with the downstream NWP product generation. One solution can be to code into SURFEX the production of the required FA or GRIB fields, or we can send those fields to Full-Pos to post-process them just like in ALADIN. Both are feasible, and we will choose the solution that is easiest to develop, optimize and maintain.

In theory, we could have backward compatibility of the SURFEX I/Os with the old surface scheme, by developing appropriate conversion tools. In practice, it seems that we will try to make everyone (ARPEGE, ALADIN, ALARO, AROME) switch to SURFEX at the same time, which will save the development of conversion tools. This issue is broader than AROME, and relates to the surface work plan proposed by D. Giard.

There are other technical issues with AROME. One, is the coupling of the new 3D fields and their interfacing with the assimilation (discussed below). Obviously, ARPEGE and 3D/4D-Var are not going to have the same prognostic fields as AROME, so some conversion tools are going to be necessary (we already have some model state conversion for the incremental analysis and the launching of ALADIN-NH, and it works fine), as well as an extension of the capabilities of Full-Pos to deal in a basic way with the new fields, at least in order to help with diagnosing the new physics (which applies to DDH diagnostics too).

The computing cost of AROME (per time-step, per gridpoint) is currently in AROME close to 2.7 times the cost of ALADIN. Profiling of AROME reveals that the prototype software can be optimized with some technical work on the dynamics (probably unnecessary biperiodizations are done at every time-step) and the advection (probably not configured for so many prognostic 3D fields). There is work to do to improve the parallelization (some field slicing is missing at the interface with the surface, and it is being worked on). There may be some algorithmic work to do inside the parametrizations, too.

Last but not least, there are scientific issues in the AROME model. The ALADIN-NH dynamics are not completely finalized yet, and the presence of prognostic micro-physical fields imply changes in the philosophy of the dynamics/physics interface. And there are issues with the physics themselves; the Méso-NH community is working on most of them, but some effort in this field will be required. For instance, the behaviour of AROME has not yet been checked in the presence of stratiform clouds, fog or synoptic storms. The existing test cases show some suspicious elongation of the convective cells, and dilution of low-level cold pools below convective clouds. There is no clear methodology for tuning the diffusion of the cloud variables and hydro-meteors, or for optimizing the model vertical resolution. There is evidence that Méso-NH has a strong spin-up of micro-physical processes, and we should check for its existence in AROME as well. Without any doubt, we will discover many more issues with the AROME model as we run more and more test cases, and running the test cases themselves is a significant job.

5. COMPUTATIONAL COST ISSUES

The debate about installing AROME in ALADIN countries is completely dependent on the speed of their future computers. *Assuming constant funding of NWP computers in each country*, it is a safe hypothesis that the power of affordable computing for regional modeling is going to increase at the same speed as in recent years: a doubling every 18 months. This is a result of current technology progress called Moore's law: one person's increase in affordable computing will be 60% in 1 year, a factor 4 in 3 years, 16 in 6 years. That is to be compared with the cost of AROME: dx=dy=2.5km, dt=7min, the cost per gridpoint per time-step is 3 times that of ALADIN (which is as much due to the extra 3D fields required by the micro-physics, TKE and the NH dynamics, as to the cost of the physics themselves, by the way). Bringing together Moore's law and the cost of AROME, there can be two extreme point of views (and of course an infinity of intermediate views):

- *The pessimistic view*: I have an ALADIN at 10-km resolution and 7-min time-step. And I will not use AROME until Moore's law gives me a computer to replace ALADIN with the same domain, forecast ranges, number of forecasts per days. That means AROME needs an (approximately) 4x4x7x3=300 computer increase, which Moore's law will give me in 12 years, that is, in 2012.
- *The optimistic view:* I have an ALADIN at 7-km resolution and 5-min time-step, runs to 48-h range, and I believe current optimization work on AROME will bring the per-gridpoint overhead from 3 to 2.5. My ALADIN domain and forecast ranges are ludicrously oversized for AROME which is going to be primarily useful in the 0-24h forecast range; for longer ranges I can keep running my good old ALADIN model or the brand-news ALARO model. So I can shrink the AROME area to 20% of my current ALADIN domain, which covers the important areas of my country, and to half of my previous range. That means a computer increase of 3x3x2.5x0.2x0.5=2.25; adding 1 to the cost to keep running ALADIN, the total power needed is 3.25. Applying Moore's law since the last time my boss bought me a new computer, say 2 years ago, means that AROME is affordable for me by the end of 2005.

As one can see, the key aspects fo the AROME expense are not the AROME physics cost, but the required domain size, useful forecast ranges, and current ALADIN resolution. Each partner should consider its own options carefully. To try to replace ALADIN completely with AROME to do the same thing will not be an optimal approach for short-range, regional modelling. ALARO will probably be more suited for NWP over wide areas.

6. ASSIMILATION, PREDICTABILITY AND COUPLING

The bulk of so-called AROME activities in Météo-France are on developing the model. However, data assimilation is very important, because it is known (from the mesoscale scientific literature of e.g. NCAR and from Méso-NH initialization impact studies since 1997) that data assimilation gets more and more important as the resolution increases. This is mainly because deep convective systems have interesting memory properties: the regional assimilation of low-level fields, cloud fields and humidity has a substantial beneficial impact on mesoscale forecasts for at least the first 12 hours, at constant large-scale forcing. Of course, it is important to improve the large-scale forcing too, but the novelty is that there is an enormous amount of unused mesoscale data in many regions, whereas all the easy large-scale data is already being used in the global data assimilation system. The other good news is that the most important part of the regional data assimilation system can be setup regardless of the model: the ALADIN 3D-Var can be applied with very few changes to ALADIN itself, to ALARO, AROME, or even Méso-NH. The important differences are in the computation of the background term Jb (it requires different ensembles and some fiddling of the variances), the data thinning (adapted to each model's resolution) and in the interface between 3DVar and the forecast model (using the incremental approach: 3DVar analyses wind, T and q, it is useful to correct them in all models). Thanks to the excellent work of the ALADIN scientists, Météo-France has been able to set up a pre-operational 3DVar for ALADIN and Méso-NH relatively quickly, and AROME and ALARO will follow soon.

To go to higher resolution, a few extras will need to be put into 3DVar, starting with those with the best cost/benefit ratio. Suggested ones are FGAT (First Guess at the Appropriate Time, which increases the use of frequently reporting data by several orders of magnitude), analysis of cloud humidity (mainly based on Meteosat data), use of radar Doppler winds and reflectivities (more difficult, so it was important to start early), and (later) initialization of micro-physical fields, on top of the already existing work plan activities: blending, Jk coupling, work on Jb, etc... More ambitious stuff like 4D-Var and adjoint physics will become important, but only later, since they will only be affordable several years after we have moved to AROME.

Predictability is another fairly transversal activity, the basic techniques can be applied to all mesoscale models, so what is being done on ALADIN will be useful for the other models too. AROME is of course handicapped because of its high model cost that will limit the development of ensemble prediction for the next few years. But there is a significant demand for fine-scale probabilistic forecast, and what is done on ALADIN or ALARO is important. The current emphasis is on ensembles perturbed by changing the large-scale coupling (which suggests we will need a specific strategy for coupling file compression). Now that more attention is paid to the quality of short-term forecasts, it may be the time to think more seriously on strategies to perturb these short-range forecasts, which is likely to involve work on how regional data assimilation works, and how we can perturb precipitation forecasts.

Coupling is still a poorly understood issue, in the sense that we do not much know how much priority it should have. It is easy to anticipate that AROME will require bigger (and more frequent) coupling files to be transmitted, which shall be compared with the planned increases in telecommunication lines. It is less clear how much sense it makes to transmit full-domain files when the information inside the coupling frame is not really used at the end, or how serious it is to couple non-hydrostatic, micro-physical and TKE prognostic fields. Some experimentation is needed there, but it will require complete AROME (and ALARO) deported systems to be installed before it can start.

On the scientific side, there is work in Toulouse on improving the mathematical formulation of the coupling in the dynamical part of the model, so progress is expected soon. But if it does not seem possible to have a physically really accurate coupling strategy in spectral space, one must weigh the pros and cons of both aspects of the models.

7. CONCLUSION

Now the community is working is parallel on ALADIN, ALARO and AROME, it is important to ensure a correct allocation of workforce between these three models, if we want to keep all of them alive. This will be an important issue to discuss at the next ALADIN workshop, when preparing the next ALADIN work plan.

References on the ALADIN web:

- the ALADIN work plan (D. Giard et al)
- documents from the Split ALADIN Assembly, 2004
- the proposal for a CNRM work plan on the AROME and ALARO models in early 2005 (F. Bouttier)
- the proposal for a work plan on the externalised surface (D. Giard)
- other articles about AROME and ALARO in recent Newsletters including this one.

8. BASIC REFERENCES ON THE MÉSO-NH PHYSICS AND FINE-SCALE ASSIMILATION:

Caniaux, G., J.-L. Redelsperger and J.-P. Lafore, 1994: A numerical study of the stratiform region of a fast-moving squall line. Part I. General description, and water and heat budgets. *Journal of Atmospheric Sciences,* **51,** 2046-2074.

Cuxart, J., Bougeault, Ph. and Redelsperger, J.L., 2000: A turbulence scheme allowing for mesoscale and large-eddy simulations. *Q. J. R. Meteorol. Soc.,* **126,** 1-30.

Ducrocq, V., J.-P. Lafore, J.-L. Redelsperger and F. Orain, 2000: Initialisation of a fine scale model for convective system prediction: a case study. *Quart. J. Roy. Meteorol. Soc.,* **126,** 3041-3066.

Ducrocq, V., D. Ricard, J.-P. Lafore and F. Orain, 2002: Storm-scale numerical rainfall prediction for five precipitating events over France: on the importance of the initial humidity field. *Weather and Forecasting,* **17,** 1236-1256.

Lafore, J.-L., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, C. Fischer, P. Héreil, J.-L. Redelsperger, E. Richard and J. Vilà-Guerau de Arellano, 1998: The Meso-NH atmospheric simulation system. Part I: adiabatic formulation and control simulations. *Ann. Geophys.,* **16,** 90-109.

Masson V., 2000: A physically-based scheme for the urban energy budget in atmospheric models. *Bound. Layer Meteor,* **1994,** 357-397.

McPherson, B.: Operational experience with assimilation of rainfall data in the UK Met Office research model. *UKMO NWP forecasting research tech. report no.289.* December 1999.

Montmerle, T., A. Caya and Isztar Zawadski, 2002: Short-term numerical forecasting of a shallow storm complex using bistatic and single-Doppler radar data. *Wea. and Forec.,* **17,** 1211--1225.

Morcrette, J.-J., 1991: Radiation and cloud radiative properties in the European center for medium range weather forecasts forecasting system. *J. Geophys. Res.,* **96,** 9121-9132.

Pinty, J.-P. and P. Jabouille, 1998: A mixed-phase cloud parameterization for use in mesoscale non-hydrostatic model: simulations of a squall line and of orographic precipitations. Proc. Conf. of Cloud Physics, Everett, WA, USA, *Amer. Meteor. soc.,* Aug. 1999, 217 - 220.

CONTENTS