Arome, avenir de la prévision régionale

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Résumé

Le système de prévision Arome regroupe les meilleurs composants des modèles Méso-NH Aladin, et de l'assimilation de données IFS/Arpège. Son premier objectif est la prévision numérique, dès 2008, des phénomènes de convection intense sur la France métropolitaine. Sa haute résolution spatiale, de l'ordre du kilomètre, lui permettra de modéliser de nombreux phénomènes importants jusqu'alors inaccessibles à la prévision numérique, grâce à une description détaillée des lois physiques en jeu, et une utilisation intensive des réseaux d'observation à l'échelle régionale. Sa conception originale l'ouvre à une large communauté de chercheurs.

Abstract

The forthcoming Arome regional forecasting system

The Arome forecasting system is a blend of the best components from the Méso-NH model, the Aladin model, and the IFS/Arpège data assimilation software. Its focus is on the numerical

prediction of intense convective systems over mainland France by 2008. Other important weather phenomena will also begin to be reliably forecast, thanks to a high (kilometric) spatial resolution and the use of regional observing systems. The Arome software is designed to be accessible to a wide research community.

The method of numerical weather prediction (NWP) founded modern meteorology. For a long time, it has relied on the software implementation of global models – with therefore rather coarse-resolution computation grids – and on a very simple representation of physical phenomena, because of the computing costs of forecasting software. At Météo-France, this was the case for the **Arpège** model, whose offshoot, the **Aladin** regional model, is almost identical, except for a horizontal geometry with a 10 km grid size over mainland France, better than the 25 km in Arpège (in the NWP scheme of early 2007). Aladin uses the large atmospheric scales from the Arpège forecasts to feed its lateral boundary conditions, with the idea in mind that local meteorological phenomena are generally determined by the large-scale atmosphere: depressions, jet streams, ridges, troughs.

Why a new model?

In this "hierarchical" vision of NWP, the global model closely controls the design as well as the coupling of the regional model, and neither could be used without the other. This method – which was supposed to give a strong advantage to those forecasting centres in control of both a global and a regional model – has been given a rough time in the 1990s by the community of cloud physics research. This community designed excellent and often freely usable regional models (MM5, Rams, WRF), widely used operationally by small meteorological centres or even by universities or private companies, without any help from a home-made global model, at kilometre-scale resolutions and with very good results. Another thing that happened was the success of experiments on local initialisation of convective clouds (see e.g. Sun et Crook, 2001; Ducrocq et al., 2000), proving that often assimilation of local data, and not large-scale atmospheric forcing, is decisive to make a good forecast.

In France, both of these aspects – kilometre-scale resolution and regional assimilation – are particularly crucial for forecasts of Cévenol floods and of severe thunderstorms. In 2000, it became clear that these phenomena, which are very important for the society, would not be forecast correctly before many years with the current strategy of continuous improvement of Arpège and Aladin (a strategy launched about 1990, which allowed for great progress in the forecasting of winter storms). So Météo-France abandoned its traditional ways and started a quick "jump" towards a new system, Arome, which would be a synthesis of the Arpège-Aladin software and of recent improvements in fine-mesh modelling.

The elaboration of Arome relies on the involvement of research teams (hence the acronym "Applications de la Recherche à l'Opérationnel à Méso-Echelle" = mesoscale applications of research for operational use) in order to create a third operational forecasting system, complementary to Arpège and Aladin, starting from 2008. Météo-France's purpose is a complementary relationship between three levels of modelling:

- Arpège, aiming at scales larger than about 20 km and forecast ranges of 1 to 3 days in 2008, combined with the **IFS** model of the European Centre for Medium-range Weather Forecasts (ECMWF),
- Aladin, dealing with regional forecasts at a scale of about 10 km, over Western Europe and other areas of the world,
- Arome, providing local forecasts and forecasts of dangerous phenomena, primarily over mainland France and for forecast ranges of 3 to 36 hours approximately.

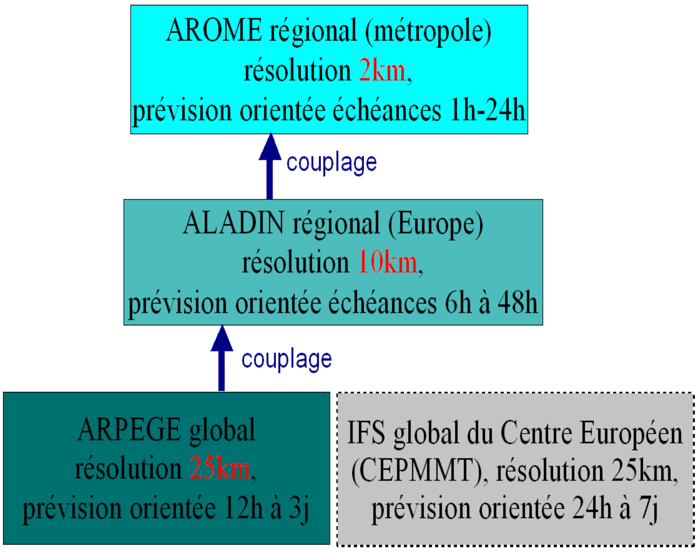


Figure 1 – Main operational NWP systems (models and data assimilation systems) used by Météo-France starting from 2008.

Each of these models will have its own *ad hoc* data assimilation. This choice of numerical systems (figure 1) will allow for the simulation of all significant meteorological phenomena, from winter storms to thunderstorms, except perhaps for very small-scale events, like local fog or some very local anomalies in urban or mountain environments.

The intention with Arome is indeed to complement IFS, Arpège and Aladin, and not to replace them. The development work on these forecast models is going on, with noticeable progress every year, which is important for the large-scale forcing that will feed Arome: a regional model can improve a good large-scale forecast, but can rarely correct a bad one. Among the most noteworthy developments, it can be remembered that:

- Arpège has recently acquired the ability to use most of the modern meteorological satellites, and is getting ready to use *Metop*,
- its physical parameterisations have recently begun including prognostic clouds and precipitation,
- its 4D-Var assimilation system is one of the most state-of-the-art in the world. Aladin has recently been given its own 3D-var data assimilation (Fischer et al., 2005 ; Fischer et al., 2006), with the same physics as Arpège.

The Arome model will have an even higher level of sophistication, in the spatial resolution of the computations and in the level of detail of the depicted physical processes.

A forecast system uses a numerical model of the evolution of the atmosphere, but is also a data assimilation system that initialises model forecasts with the newest possible and most accurate observations. A good large-scale forcing and a good model are not enough to forecast **Cévenol** precipitation, thunderstorms and fog: the atmosphere has a local-scale memory (figure 2), and in order to make good forecasts, it is essential to insert into the system the precursors of the phenomena, using a fine-scale assimilation of the determining parameters (see box below). In Arome, these are mainly the humidity field, and low-level structures like convergence lines. For that purpose, Arome will assimilate more exhaustively than Aladin the data from radars (Doppler winds, 3D reflectivities), satellites (clear-sky radiances, clouds) and national networks (mainly Radome ground stations). In this area, Meteo-France is at the cutting edge in the world, which will be the main asset of Arome as compared with foreign fine-mesh models.

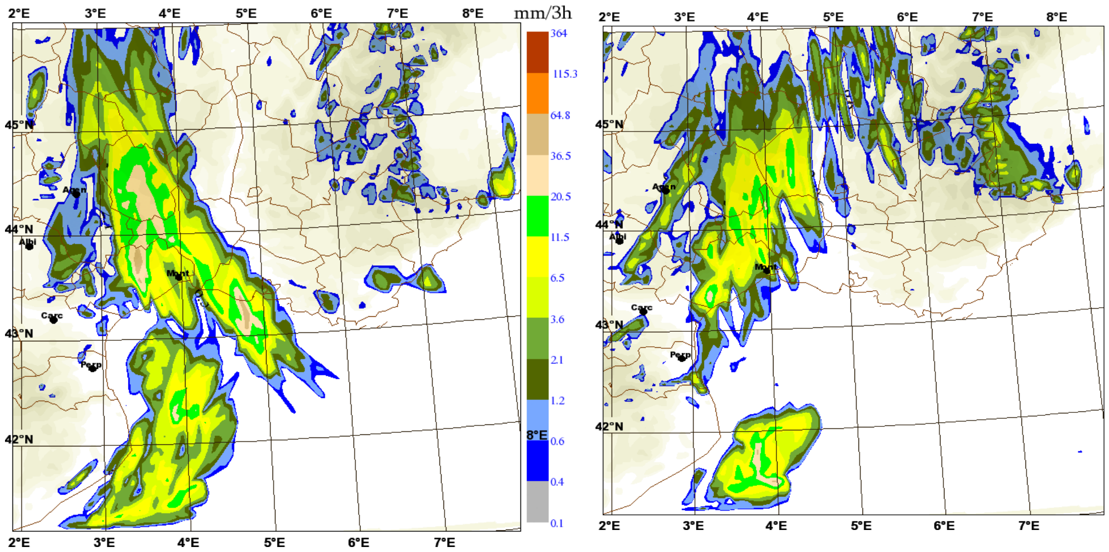
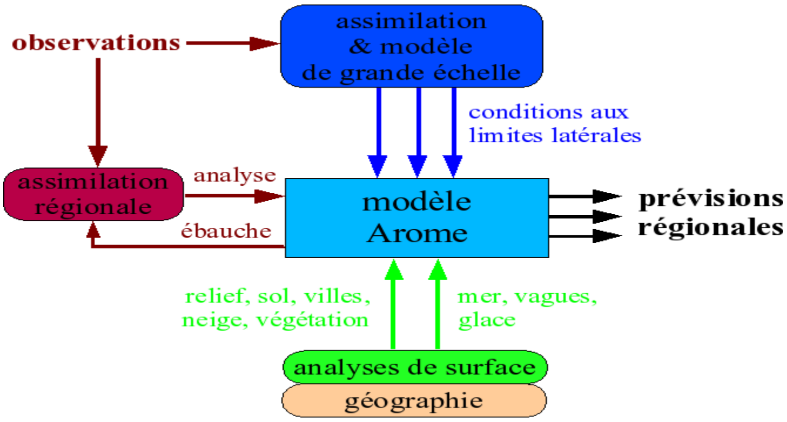


Figure 2 – Example of the impact of assimilation on rainfall forecast during a Cévenol precipitation event, at short range (accumulated rainfall between terms 3 h and 6 h): on the left, Arome forecast from a low-resolution (10 km) Aladin analysis; on the right, Arome

forecast after 3 h of 3D-Var assimilation in Arome (2.5 km resolution). Green and beige areas are intense rainfall areas. Differences are mainly due to Radome observations of low-level temperature and humidity; the forecast using the Arome assimilation is better.

Coupling between models

Like the local atmosphere, a regional model reacts to a set of factors, which should all be carefully modelled in order to produce good forecasts. The diagram aside summarises the main information sources needed for Arome forecasts:
– lateral forcing by the numerical forecast from a larger-scale atmospheric model (Arpège, Aladin or IFS),
– forcing from below by surface conditions on continents and oceans, whose non-constant parameters (snow, pack ice, vegetation, ground moisture…) have to be initialised adequately,
– initial state of the atmosphere in the Arome model, to be created by a data assimilation which is itself coupled with a large-scale assimilation.
Optionally, the model can be interactively coupled with the evolution of models of upper ocean, dust, chemistry and/or aerosols, in addition to its internal physical parameterisations (radiation, turbulence, surface fluxes, cloud microphysics, subgrid convection).



Components of Arome

The Arome project has been drafted with specific objectives: improving the forecasting of dangerous convective phenomena (thunderstorms, sudden floods, gust wind, intense precipitation), of local events and of low-level meteorology (wind, temperature, state of the ground, turbulence, visibility…). The base of this development is the Arome software, a brand new model with its own data assimilation (Ducrocq et al., 2005).

The novelty of the model is first and foremost the horizontal fineness of the computations (2 to 3 km horizontal grid in the 2008 version of Arome), a more realistic modelling of clouds (prognostic hydrometeors, with an ice phase and graupel) and of turbulence (prognostic turbulent kinetic energy), and also a detailed description of surfaces (mountains, cities, coasts, lakes, snow…). The orography of the Arpège, Aladin and Arome models is shown in figure 3, centred on the Alps. The contribution of assimilation is the use of satellites, radars and regional meteorological networks, in a system similar to Aladin (3D-Var method) but with a stronger spatial resolution, which will mainly improve very short-term forecasts (less than 12 hours).

The calendar for Arome is made of a period of real-time testing at Météo-France since June 2005, the implementation of the system on a powerful supercomputer in 2007, and the production of real-time Arome analyses and forecasts starting from 2008.

The ancestry of the Arome software is interesting. In order to share the research and development with the communities of numerical prediction and atmospheric scientific research, while maintaining our many cooperations (national cooperation with CNRS, international cooperation within Aladin, Hirlam and ECMWF, and cooperations between CNRM teams on Arpège, Aladin, Arome and Méso-NH), Arome is a hybrid between the Aladin software, bringing the dynamical kernel and the assimilation (Bénard et al., 2005 ; Fischer et al., 2005), and the Méso-NH software, bringing the physical parameterisations which are still being improved by the research teams (Lafore et al., 1998). In spite of the unwieldy character of this software mechanism, Arome is a powerful "pipe", which is fed by the best developments of IFS, Arpège, Aladin, Méso-NH, and puts them at everybody's disposal in its operational use. It is an opportunity for researchers outside numerical prediction teams to use a powerful prediction and assimilation software in their experiences, and to have their work valued directly in an operational department. Such advantages did not escape the attention of our European and North African partners from the Aladin and Hirlam consortiums, among which many are preparing to use the Arome software themselves, at the price of a few modifications (for instance the Alaro-0 model software, which is Arome with different physical parameterisations).

Later on in the process, Arome is assigned the task to supply numerical products to Météo-France forecasters for supervised production, and also to application models sensitive to small-scale meteorology, like the Cobel fog model (Bergot et al., 2005), which will benefit from better forcing from Arome in comparison with the presently used Aladin.

The surface physics module in Arome is particularly remarkable: Surfex, as it is called, uses a very high-resolution geographical database over Europe (Champeaux et al., 2005) to represent a great cartographic richness: vegetation cover, soil types, oceans, lakes, ice and snow, cities. The meteorological effects can be locally important, for instance on urban heat islands, breezes, or emission of desert dust. Surfex also plays a role in the coupling of Arome with models of hydrology and atmospheric chemistry, which enables it, among other things, to model the cycle of the carbon dioxide.

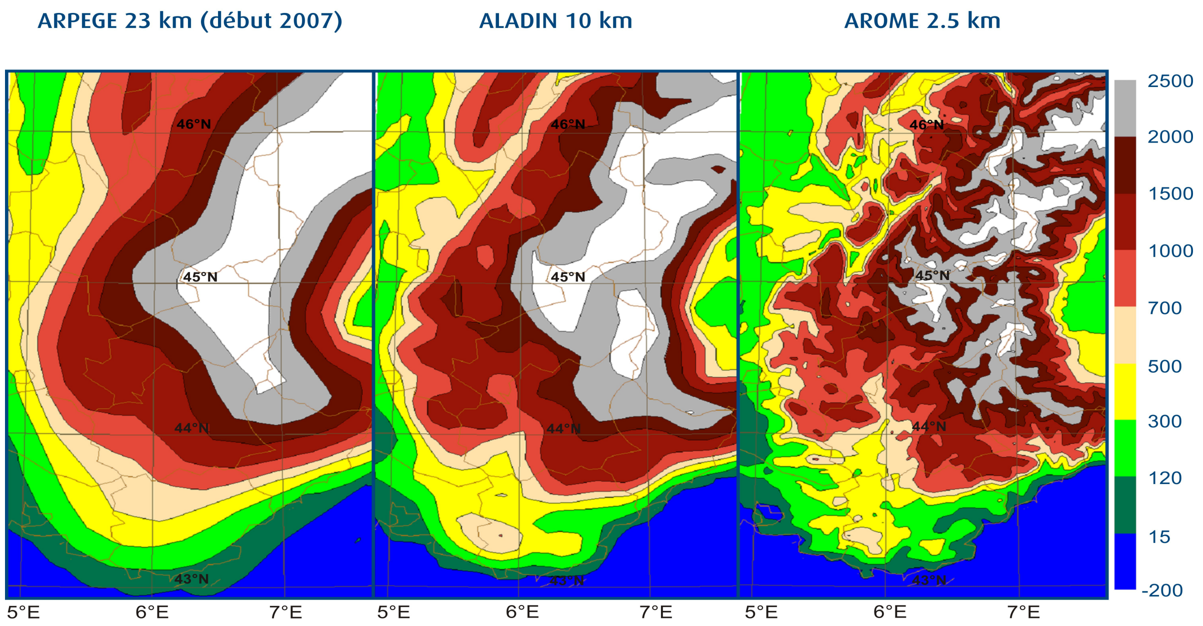


Figure 3 – Respective orographies of the models Arpège (left), Aladin (middle) and Arome (right) in the Alpine region.

Assimilation

Data assimilation is a method of using observations so as to optimise the initial state of forecasts. Observed data are inserted into the model in real time, in order to have it stick better to reality. Small initial errors can make a forecast fail if they happen to be in sensitive areas, which accounts for the fact that about half of failed forecasts can be explained by such errors. They can be improved by refining the mathematical methods for assimilation and by developing observation networks.

Several steps

Assimilation consists in several steps: first, useful data have to be received in time in the databases of the forecast centre. This is relatively easy for ground observations, but is sometimes problematic for moving satellites, which are not always above the area of interest of the model or within reach of a receiving antenna. Because of the very high number of spatial agencies and meteorological satellites and because of their relatively short lifetime, it may happen that data fluxes from some satellites cannot be used at once after their launch. New radars also experience such mishaps. At the end of the day, only a fraction of the measurements carried out can be used for numerical prediction.

The second step in the assimilation is sorting out the data, which is also called “quality control”. Each use of a measurement in the assimilation has a computing cost, and bears a risk of degrading the forecast if the data is affected by errors. A filtering software is able to only keep the data that almost certainly improve the forecast, which represents about 10% of the data received(1).

(1) Rejected data are for the most part satellite radiances which cannot be used, because they are affected by clouds or surfaces in a way that we are still unable to model. It may also be data of too high density locally (e.g. most aircraft measurements in the vicinity of airports) as compared with the numerical resolution of the models. But these data are still precious, either for future versions of the modelling system or for other applications, like nowcasting.

The third step is analysis, which serves to insert the measured information into the model grid. It is the computation of a weighted average between the most recent model forecast and the corrections suggested by the measurements, which are spatially smoothed so as to comply with the properties of the meteorological fluid: hydrostatic and geostrophic quasi-equilibrium, Ekman pumping, positivity and absence of supersaturation for humidity, for instance. In Arome, acquisition and sorting out of observations are similar to the Arpège and Aladin systems, using a higher density of data over France, since Arome has a stronger resolution there. Analysis is realised by the variational technique 3D-Var, refined in order to properly take into account the temporal distribution of observations. In Arome, each observation is used to correct the atmosphere inside an area of about 30 km in radius and 2,000 m in altitude.

Various observation classes

Among the observation classes most important for Arome, we can note measurements of precipitation systems (radars, microwave satellite radiances), of low-level humidity (today Radome automatic stations and GPS, tomorrow maybe lidars and radars), of low-level wind (Radome stations, Doppler radars and satellite scatterometers), of upper-level wind and temperature (Cris and Iasi satellite radiances, aircraft wind profiles, radiosoundings and profiling radars). The amount of effort assigned to the use of each observation type depends on the quality of the measurement, on how informative it is about the state of the atmosphere, and on the quality of the network coverage: for instance, a measuring device, even an excellent one, with only few measurement points over France is interesting for scientific studies, but is rarely useful for weather prediction…

The use of satellite radiances and of conventional in-situ observations, in spite of its importance, does not fundamentally differ between Arome and larger-scale systems like IFS, Arpège and Aladin. The main thing to note about it is that the better spatial resolution enables Arome to use high-density observations, partially getting rid of representativeness problems due to local disturbances in the measurements, such as mountains and clouds. On the other hand, the use of radars will be radically new. It is particularly fortunate that its development coincides with the renewal of the radar network in mainland France (Panthere project at Météo-France, which includes equipping several radars with measurements of Doppler wind and polarimetric reflectivity performing a three-dimensional scan of the troposphere). Doppler winds are wind measurements restricted to certain directions, in lower layers and clouds, in the vicinity of French radars (figure 4); their relevance to prediction consists mainly in the description of the convergence lines associated with the birth and evolution of large convective clouds, which is important for forecasting isolated thunderstorms and for aeronautical assistance. Arpège and Aladin take into account convective systems mainly in an implicit form called **parameterisation** of subgrid convection (see box on page 15): these models describe the net effect of convection, rather than the often complex three-dimensional wind circulation associated with cloud cells. The use of Doppler radar winds in Arome will be much more efficient than in these older models. The synergy between the model and the Doppler radars will probably be the most impressive contribution of Arome to regional numerical prediction, and also in a more distant future to nowcasting, that is, forecasting for up to a few hours, which has been so far quite dependant on the extrapolation of radar and satellite images. These developments are presently studied in the framework of the Flysafe European project for improvement of air traffic security.

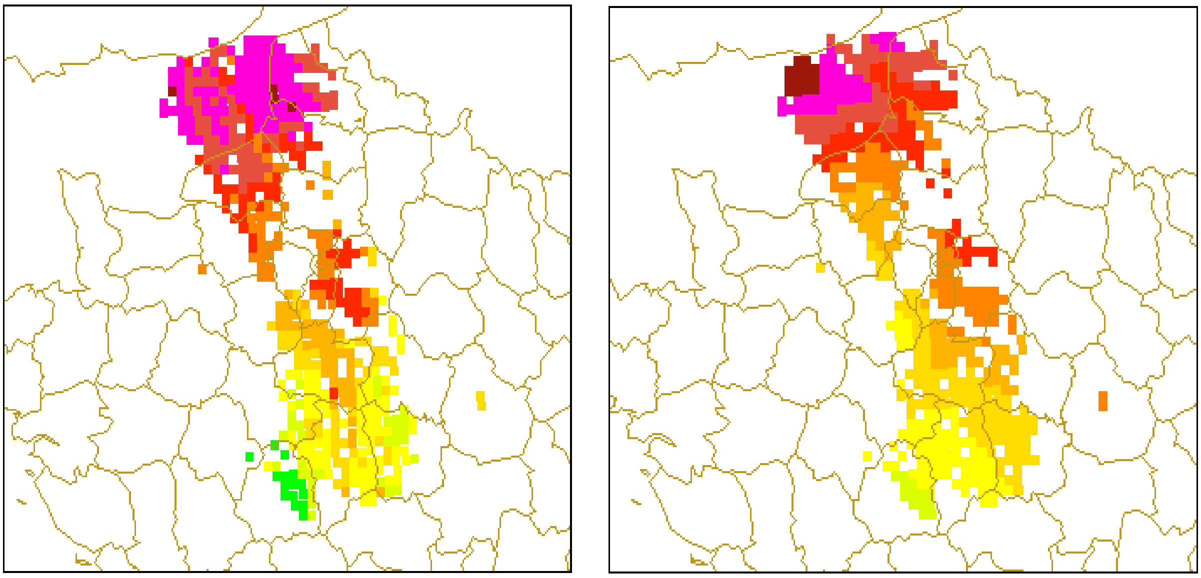


Figure 4 – Low-level radial Doppler wind observed by the Trappes radar (top) and simulated by a model (bottom). Colours represent different values of the radial component of the wind relative to the radar antenna (located in the Paris area). Data are interpolated at the same spatial resolution (10 km). White zones are unobserved. This ambiguous information is difficult to visualise, but is easily used in the 3D-Var assimilation to improve the initialisation of wind in Arome forecasts.

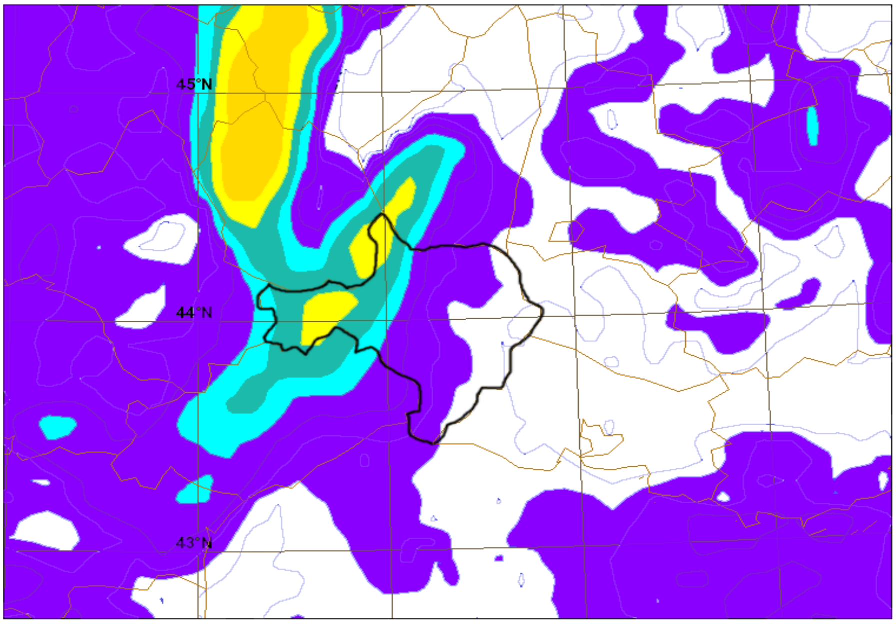
The convection “grey zone”

The size of the smallest phenomena described by a numerical model is about twice the size of the computation grid. In Arome, this mesh size is 2.5 km horizontally and about 300 m vertically (17 m near the ground). Mesh fineness is constrained by the processing power of the computer used for the forecast. This mesh allows explicit calculation of the structure of large convective clouds such as cumulonimbus clouds, which are controlled by air circulations represented rather well on the Arome grid. These circulations produce three-dimensional cloud structures which are important to forecast certain physical processes (hail, gust winds, anvils, rain-snow limit, transportation of a cloud far from its formation area, diurnal cycle…). In a lower resolution model such as Arpège or Aladin, but also in Arome for small clouds, the calculation grid is too coarse, and the idea of simulating the details of these clouds was given up; only the net effect is represented at grid scale (production of rain, of turbulent mixing, of partial cloud coverage, of latent heat…), which is a stopgap measure for forecasting the cloud-affected meteorological parameters. This net effect is calculated by rather empirical formulas, called parameterisations, which deduce them from characteristics of the atmosphere at grid scale (proximity of the air to moist saturation, vertical thermal instability, occurrence of conditions often associated with a given cloud type…).

Radar reflectivity data and precipitation

Another challenge in radar data assimilation is the use of reflectivity data, which give information on the distribution and intensity of upper-level precipitation. This idea is particularly difficult to work out, because precipitation is the result, rather than the cause, of the cloud mechanics: the assimilation of reflectivity data should ideally figure out three-dimensional structures for wind, temperature and humidity from precipitation images, which is generally out of reach of all known assimilation methods, for various reasons (starting with non-linearity of small-scale cloud microphysics, which precludes, at first sight, the use of classical algorithms like 4D-Var). In the Arome project, the effort now focuses on Bayesian non-linear assimilation techniques, which can provide a rather simple repositioning of convective columns in favourable meteorological situations. To make further progress, an ambitious research programme is preparing to be developed at Météo-France, based on the automatic identification of coherent structures in the atmosphere and on an intelligent method to take into account moist processes in data assimilation.

The biggest challenges for the future of assimilation will be realistic assimilation of precipitation, use of cloud observations, and taking account of the spatio-temporal variations in the radius of influence of observations, for instance across inversions at the top of the boundary layer (which are absolutely necessary for the analysis of fog and low clouds), near mountains and coasts. However, the value of Arome forecasts will not only stem from its assimilation. Large-scale assimilations (such as Arpège) will still dominate the forecasting of dynamical phenomena like winter storms, which come from over the borders of the Arome domain. Modelling the surfaces will still be essential to predict phenomena forced by lower layers: coastal breezes, fog formation, urban heat islands, effects of snow on the ground and of frost. Assimilation will thus concentrate on precursors of the changing phenomena which have a strong regional memory: formation and propagation of the convective systems and their gust fronts, arrangement of precipitation systems in cells and bands, evolution of inversions, of fog banks and of low clouds.



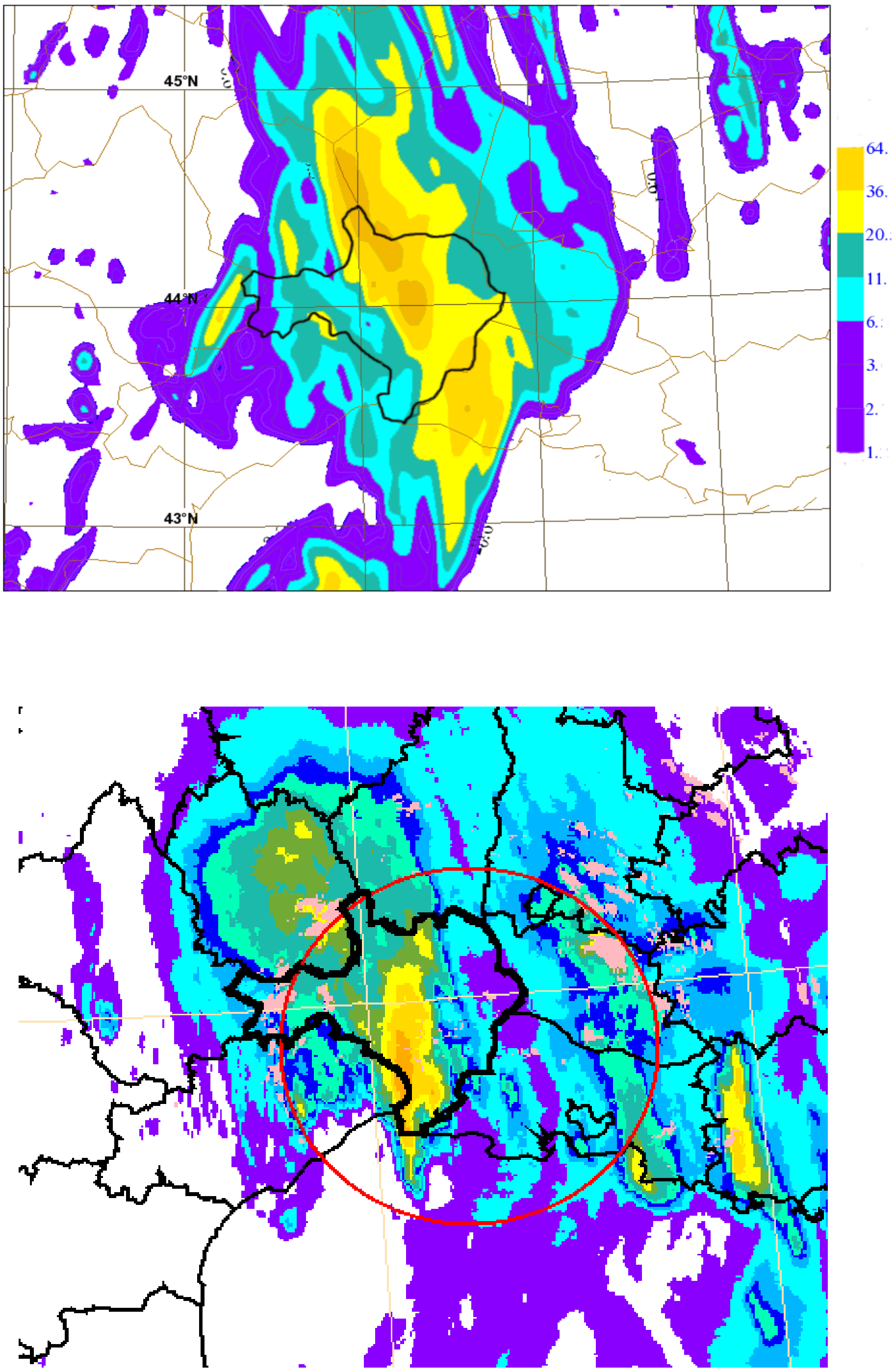


Figure 5 – Accumulated rainfall over three hours during the Cévenol flood event of 6 September 2005. Top: Aladin forecast; middle: Arome forecast without own assimilation; bottom: observations (radar data with rain gauge correction) of actual rainfall. The crucial zone (most intense rain) is in yellow and orange. The Arome model performs better than Aladin, though the latter gives the former its initial conditions and lateral boundary conditions.

First results

The most awaited contribution of Arome is the ability to properly forecast Cévenol-type intense Mediterranean precipitation. The first evaluations made in 2005 and 2006 naturally focused on recent Cévenol events most present in the media. Although the system is still incomplete (the synergy between radars, assimilation and high-resolution model has not yet been tested), these tests confirmed that Arome is clearly more realistic than its predecessors (IFS, Arpège and Aladin) when forecasting Cévenol precipitation 6 to 24 hours in advance, particularly concerning intensity distribution, timing and location of the most intense precipitation, which are the most important criteria to anticipate flood risks. The positive contribution of Arome (figure 5) is clear, both for the direct use of forecast maps and for the subjective interpretation of the risk of intense precipitation: other models only describe the risk areas, leaving the forecaster with the heavy responsibility of correcting their tendencies to under- or over-predict the accumulated intense precipitation, depending on the case. Arome provides precipitation structures with intensities closer to reality, so that the residual error left for the forecaster to correct mainly consists in the exact location of the event.

These conclusions cannot be generalised to all Cévenol events, which have varying mechanisms: some can be easily predicted by all models; others are entirely determined by local orographic forcing and do not need any particular effort on assimilation; some do not produce significant precipitation in spite of the misleadingly alarming meteorological context; and still others produce impressive and unexpected showers which still elude all modelling efforts, in spite of the research studies to understand their causes.

The tests available today have for the most part been achieved using a direct coupling of Arome with Aladin, without high-resolution assimilation. The first experiments with assimilation of Cévenol events in Arome show en extra improvement of forecasts at the regional scale. The future use of radars and satellites on the western Mediterranean will probably make it possible to get even more predictability at the small scale and at very short range.

Numerical systems are nowadays the “handmaidens” of meteorological prediction: besides tests of Cévenol events, Arome forecasts still had to be evaluated in a large range of atmospheric conditions, and with several evaluation criteria. Since the summer of 2005, two Arome forecasts a day have been run at Météo-France, over various areas, and have been compared to Aladin. The high spatial resolution of the model dramatically improves the geographical detail of low-level forecasts, as illustrated in the figures. They display the meteorological effects of towns, coasts, or large valleys: urban heat islands (figure 6) over large cities, diurnal cycle of coastal and valley breezes, local orographic winds, shelter effect in the vicinity of mountain ranges (figure 7), fog banks in basins, frost areas (figure 6). In some situations, Arome builds atmospheric structures which were so far inaccessible to operational models, such as thunderstorm gust fronts (figure 8), cumulonimbus anvils, multi-layer clouds, turbulent areas of Autan and Mistral winds (figure 7), sudden showers (figure 9), cumulus streets.

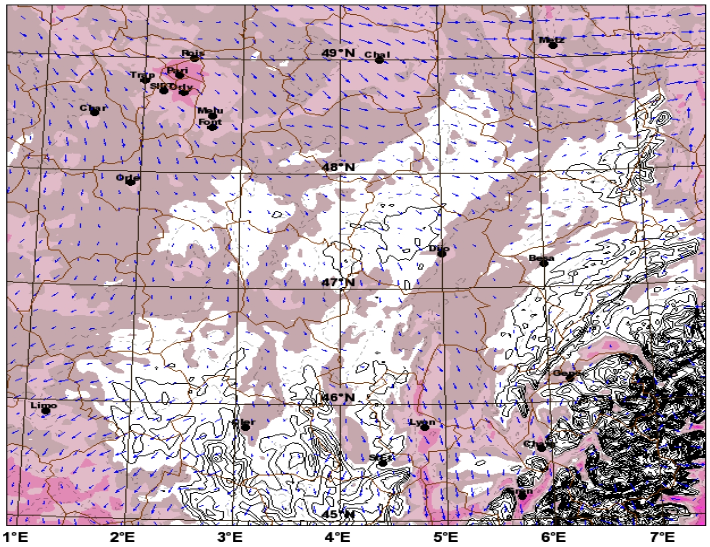


Figure 6 – Arome simulation of low-level temperatures (coloured, frost areas in white) and wind (blue arrows) over north-eastern France on 10 February 2006. Arome shows the urban heat islands (dark pink) in Paris, Lyon, Grenoble, Genève, the relative mildness of Lake Léman, and the frost areas on the Langres plateau and in mountain ranges.

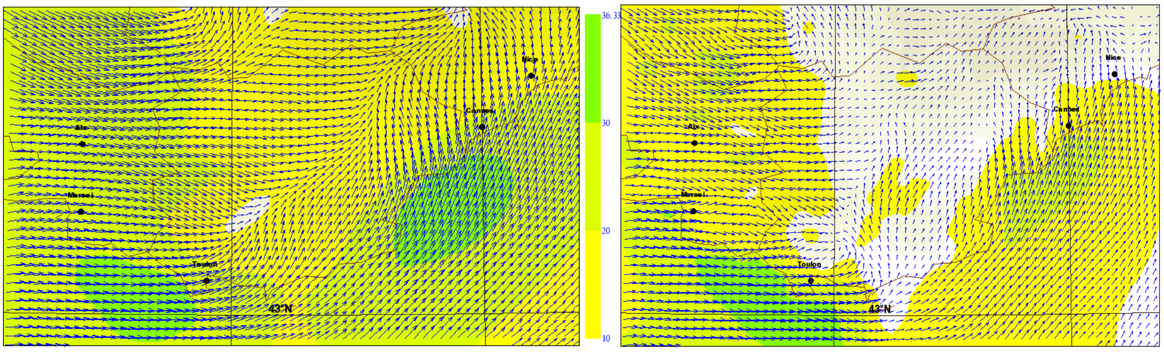


Figure 7 – Aladin (left) and Arome (right) simulations of low-level wind over the Var department during a Mistral event. Colours represent the strength of the wind, white areas are places of relative calm. Arome shows more clearly than Aladin the area of influence of the Mistral, the shelter and rotation effects in the vicinity of the mountains, the wind gradient on the coasts.

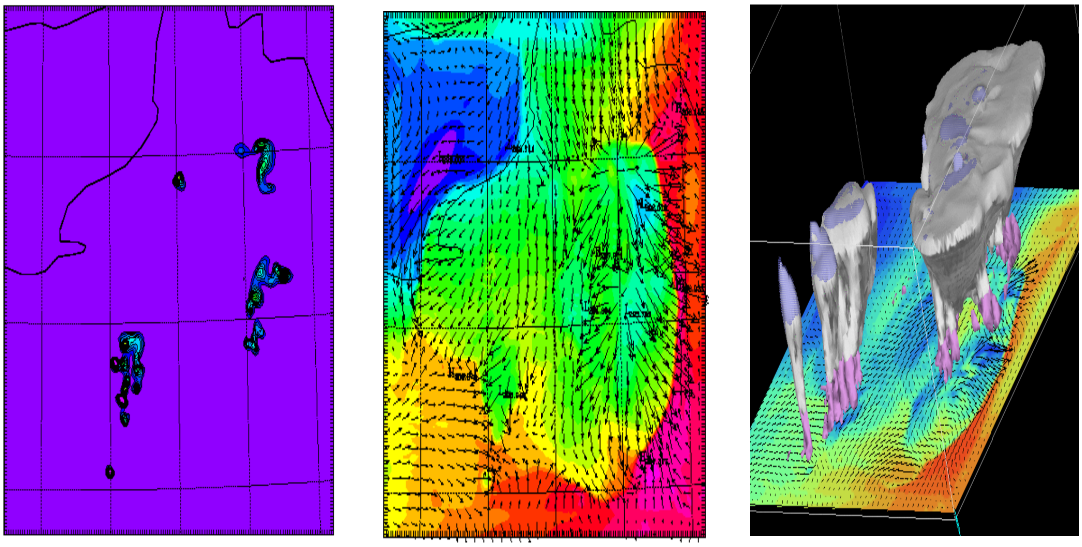


Figure 8 – Arome simulation of a group of thunderstorms in the Paris area on 4 August 1994 at 18:00. Left: patches of rain on the ground; middle: potential temperature (coloured zones, cool air in blue and green, warm air in red and magenta) and low-level wind vector (black arrows); right: perspective visualisation of the associated cloud volume (grey: cloud liquid water, blue: cloud ice, magenta: rain). Notice the inflow of cool air from the English Channel, the cooling under the thunderstorm, the divergent gust fronts associated with density currents, the characteristic tower and anvil shape of cumulonimbus clouds.

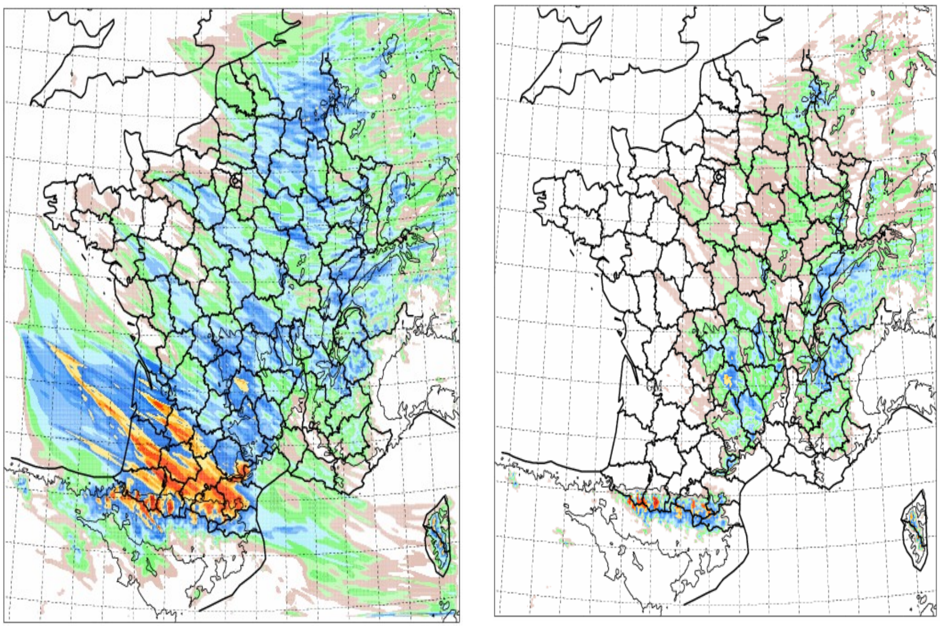


Figure 9 – Accumulated rainfall (top) and snow (bottom) during 24 hours in one of the first tests of Arome over the whole of mainland France, on 10 March 2006, a winter storm day. Red areas indicate the strongest precipitation. Notice strong accumulations on the Pyrenees range and upstream (orographic blocking). The striated appearance of the fields is due to the sudden showers.

Although these structures are not always judiciously created, comparison with observations shows that they are improvements in most cases. Research teams are presently correcting the identified weaknesses of the model: priority is given to stratiform clouds and light precipitation. Today, the most impressive recognised strengths of Arome are intense Mediterranean convective precipitation and orographically forced precipitation structures (figure 10), sometimes very far downstream from the mountains. It is a safe bet that there will be many other such strengths over time, with the growing power of the Arome assimilation and of the tools for objective verification of small-scale forecasts.

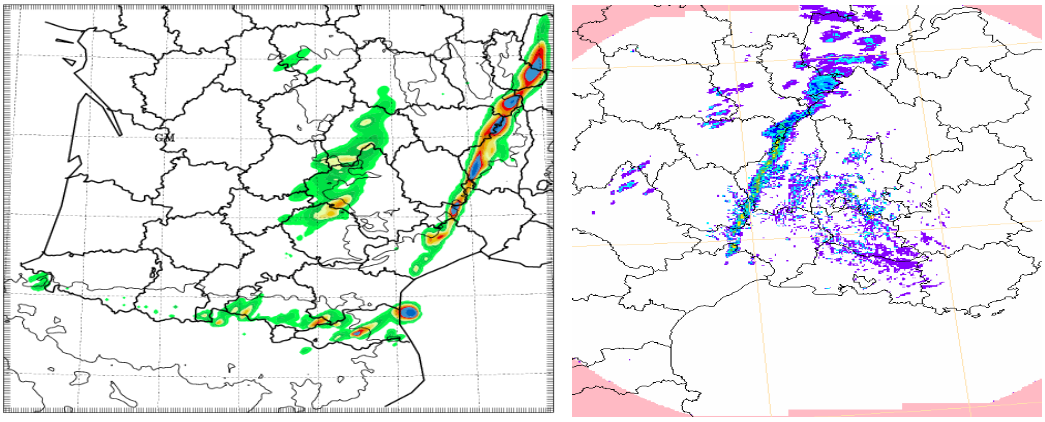


Figure 10 – Example of an orographically forced precipitation structure.
It is a rain band related to a convergence zone downstream the Pyrenees,
extending until Lyon in a south-western flow.
Left: rainfall from Arome simulation; right: rainfall from radar observations. (Note that colour ranges are different.)

What is the contribution for the user of the model?

It was mentioned above that Arome contributes to the anticipation of dangerous Cévenol-type convective events. Experimentation on other kinds of phenomena that need a special vigilance has made less progress, but first results are promising. The high resolution of the model ensures better relevance and improved fineness for the local forecasts of storms, snowfalls, frost, heat waves, strong winds. First evaluations of the forecasts of low-level temperatures (figure 11) and wind suggest that Arome, in extreme cases but also on average, will noticeably improve derived products: air quality, aeronautics, road conditions, pollutant dispersion, hydrology, oceanography and coastal or mountain meteorology, just to quote a few applications.

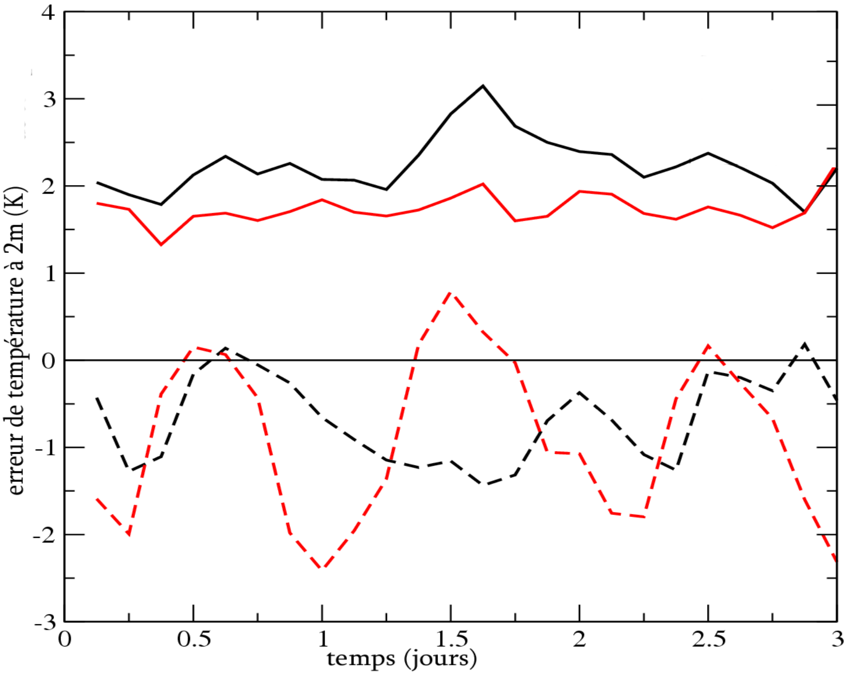


Figure 11 – Objective comparison of Arome (red) and operational Aladin (black) forecasts of temperature, over three days in August 2006 in south-eastern France. Forecasts are launched every day at midnight and are evaluated over the first twenty-four hours. Continuous lines are mean-square forecast errors, dashed lines are errors averaged over all of the Radome observation network. This graph shows that, in spite of strong mean errors (related to a teething problem of Arome which is being corrected), the Arome model, in the evaluated preliminary version, is already better than Aladin.

Like its elder brother Aladin, Arome will be a transferable system. Except for assimilation of the observations specific to mainland France, the whole system can be easily cloned to any area of the world, by coupling it with Arpège and Aladin and, if necessary, with the help of the IFS model for the most remote areas. These distant applications will be limited only by the allocated computing power. Already now, interesting tests have been performed by Météo-France over Northern Africa, Equatorial Africa and Turkey, and also in Central Europe and Scandinavia in the countries of our foreign partners from the Aladin and Hirlam consortiums. These partners will help us optimise Arome for a rich diversity of climates: Arctic, Nordic, continental, dry Mediterranean, Middle-East, Sahara. A particular effort will be made for future use in the French overseas departments and territories.

Fog forecasting is a crucial stake at institutional level for Météo-France. It almost totally eludes current numerical models. Study of about ten fog-prone cases in the winter of 2005-2006 (figure 12) showed that Arome already brings a clear added value, which is still being optimised by improving its initialisation, its modelling, and the coupling with the local fog model Cobel. During the winter of 2006-2007, Arome has been involved in the experimental measurement campaign Parisfog, which is devoted to understanding and forecasting fog in the Paris area. The ability of Arome to model three-dimensional boundary layer forcing, local orography and lakes, and to finely analyse low-level humidity, opens exciting perspectives for the improvement of fog formation and dissipation in the next years.

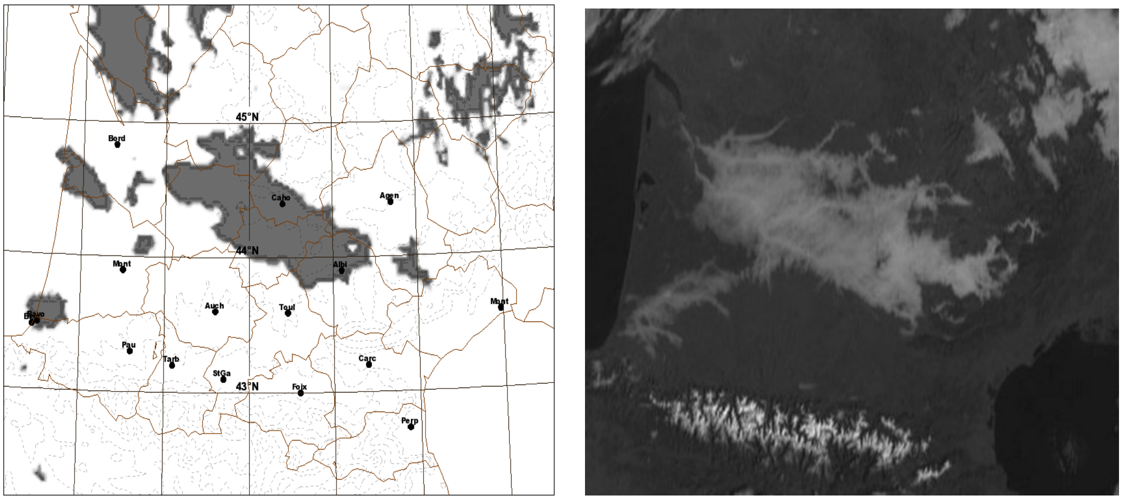


Figure 12 – Example of Arome forecast of fog (left, predicted fog is represented in grey) and the corresponding observation (right, Météosat satellite visible image, light grey areas are fog), over south-western France on 11 November 2005.

Arome, a tool for atmospheric research

The institutional and software structure of Arome is completely innovative, since a founding feature of the project is its openness to the research world. This fundamentally sets it apart from the Aladin system and from rival foreign models, which are usually characterised by complete control of the software by operational departments or research teams. Arome takes the bet that there is more to win than to lose by using a hybrid group of developers, based on the numerical forecasting community, but also on some of the research teams most competent to keep some state-of-the-art components of the system at the highest possible level. Indeed, with the growing sophistication of the processes and observations required for meteorological modelling (continental surfaces, oceans, aerosols, cloud microphysics, radars, hydrology…), it is becoming impossible for numerical prediction groups to meet all needs on their own. Involving specialised researchers means an increasing quality and quantity of available brains. This of course implies some clever organisation of the work. In practice, the Méso-NH model, which is better adapted to research laboratory methods, is preferentially used for the very high-resolution experiments needed to improve Arome. Modifications of the physical components of Méso-NH are introduced in Arome on a regular basis. Conversely, some computational optimisation techniques crucial to real-time numerical prediction are being developed in parallel in Méso-NH and in the IFS/Arpège/Aladin/Arome system, so as to ensure operational efficiency of the latter.

The Méso-NH/Arome couple is thus a convenient way for researchers to have their modelling developments valued quickly in an operational weather prediction system. And it is also an interesting tool for the upstream research, for two reasons. Firstly, the particular organisation of the computations in Arome enables it to make forecasts with a numerical cost 5 to 50 times lower than Méso-NH and other similar models. Although Arome does not offer all the freedom and flexibility of a research software, it makes it possible to carry out experiments that otherwise could not be made because they would be too costly. These are the experiments implying a great number of simulations (as opposed to case studies) or the handling of a great number of chemical species and aerosols; for this latter application, a research version with atmospheric chemistry has been created. Arome will become even more useful for research when it can carry out simulations with a horizontal grid finer than one kilometre, which is a development currently under study.

Another feature important for research is the ability of Arome to assimilate high-resolution data, with very good capabilities since it is based on the IFS software which has a very good reputation in this matter, particularly for its use of satellite data. Such assimilation software are often difficult to cope with for research laboratories, because of their complexity and their dependence on an operational observation database.

To solve this difficulty, Arome has been integrated into an experiment configuration system developed at Météo-France, called Olive. In its most classic use, Olive allows for recalculation of a forecast or of an operational assimilation period at a later time, after modifying some parameters (number of assimilated observations, model settings, software itself, etc.). An automatic comparison with the archive of operational observations and forecasts makes it possible to easily check whether the modifications tested in this "numerical experiment" would have benefited the operational production system or not. It is even possible to reproduce a colleague's experiment and then change the desired parameters. For a researcher, it is a convenient way to study the practical behaviour of the operational system and to carry out more theoretical studies, for instance on assimilation techniques.

Olive will also be a fantastic tool to add value to the measurement campaigns during which many experimental observations are made but are seldom assimilated by operational meteorological centres. Olive makes it possible for laboratories to insert their own standard or experimental observations (such as new GPS, radar and lidar instruments), study the value of these observations, and produce reference reanalyses for the measurement campaigns. When properly carried out, these reanalyses are better than the operational analyses and are ideal to study the phenomena covered by these campaigns, thanks to the spatialisation of observations that is brought by the data assimilation. Olive presently makes it possible to perform Arome forecasts and assimilations (and Aladin and Arpège as well) at the Météo-France computer centre via the Internet, using if necessary the ECMWF supercomputer. Porting to other computers, for instance PCs or clusters, is under way.

The use of Arome with a scientific purpose is firmly established at Météo-France, where research teams have been contributing to the Méso-NH and Arpège/Aladin systems for more than ten years, which directly benefits Arome. This use has recently spread to European and North African scientists from the Aladin and Hirlam consortiums. The Arome model has been deployed in quasi-real time, as a demonstration, for the measurement campaigns Amma (African monsoon, summer 2006) and Parisfog (fog in the Île-de-France region, winter 2006-2007). It has also been used for past situations from the MAP campaign (Mesoscale Alpine Experiment, 1999). During the summer of 2007, the full Arome system with data assimilation will be employed for the international campaigns Cops (Convective and Orographic Precipitation Study) and MAP D-phase, orientated towards forecasting of convective rain and hydrology in Europe, which are issues at the heart of the Arome project. These campaigns will include the study of new measuring instruments: GPS and lidars.

Prospects

In accordance with its institutional commitments, Météo-France will deploy Arome for real-time forecasting over the whole of mainland France in 2008. This system will complement Arpège and Aladin, it will be used by forecasters and for the elaboration of finalised products. So the year 2007 will be a phase of final integration and exhaustive evaluation of the quality of the system. Arome will not stop there, however: like any numerical prediction system, it is meant to improve, diversify towards new applications, and exchange software components with other numerical prediction centres. Likely evolutions include most notably:

– application to nowcasting using a frequent refresh of the model;
– application to climatology using reanalyses;
– design of a high-resolution probabilistic forecast system;
– growing use of the model outside mainland France;
– its evolution towards very high-resolution local modelling on interest sites, such as industrial sites, airports and large urban areas, for an integrated modelling of the environment.

Thanks

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