MEDIUM-RANGE FORECASTING: APPLICATIONS AT DMN

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Abstract

Several applications in the domain of medium-range forecasting have been developed in recent years at the French Met-Office D.M.N (Direction de la Météorologie Nationale). Most of them are a normal follow-up of short-range applications and make use of the numerical products received from ECMWF. In this paper some of them are presented which illustrate the DMN activity in various fields such as the conventional meteorological forecasting, ship routeing, environmental issues, decision processes and applied research.

1. INTRODUCTION

Fifteen years ago, medium-range forecasting appeared as a fantastic challenge to the meteorological community. After ten years of operational medium-range forecasting using deterministic numerical models of the atmosphere, it is clear that useful information can be provided one week in advance, and that further progress can come from improvements of the quality of the observation network and analysis-assimilation techniques and the realism of the parametrization of diabatic processes in the atmosphere.

The policy at D.M.N has always been to rely on ECMWF to provide the basic source of information for medium-range forecasting. Both the organization of and the applications at the Division Prévision (PREVI) have been very much influenced by this. As a consequence, DMN is very attentive to the efforts and the progress made at ECMWF and has tried to exploit the ECMWF products in various domains.

In this paper, several examples are given to illustrate the use of such products for conventional meteorological forecasting, ship routeing, environmental issues, decision processes and applied research.

2. ORGANIZATION OF THE FORECASTING SERVICE AT D.M.N.

Weather forecasting is the main task of DMN. Its success results from the coordinated efforts of several services within the SCEM (Service Central d'Exploitation de la Météorologie) in charge of various activities: data collection, analysis-assimilation, study of NWP products, information to the public.

The division SCEM/PREVI is responsible for the technical and some scientific part required to produce forecasts. It is divided into 5 sections:

- PREVI/PGA (Prévision Générale et Aéronautique) receives raw data (observation reports, etc...) and elaborated products. It generates meteorological maps and general directives, basis of the meteorological bulletins.

- PREVI/R (Renseignements) answers the outside demands of meteorological information.

- PREVI/DEV (Développement) is in charge of the preprocessing of the observations and the development of dedicated tools (plotting programmes, telematic assistance for instance).

- PREVI/MAR (Maritime) focuses on marine applications: forecast over and assistance for the oceans and for the coastal areas. It runs specific programs like a wave model over the Atlantic VAGATLA (Guillaume, 1987). Another one over the Mediterranean sea is under development.

- PREVI/NUM (Numérique) is responsible for the analysis and carries out some research activities (3-D variational analysis, predictability) in close relationship with the Research Department.

The policy of DMN is clear and simple as far as the medium range is concerned: ECMWF products are the main source of information used at DMN, the numerical models EMERAUDE (spectral T79, global) (Coiffier et al., 1987) being run up to 72 hour and PERIDOT (35 km, limited area) (Imbard et al., 1987) up to 60 hour. EMERAUDE is run both to obtain numerical guidance and numerical outputs for feeding other applications and to provide the lateral boundary conditions to the PERIDOT system. Both models will be replaced by the unique ARPEGE model (global, variable mesh, semi-lagrangian advection scheme, unified physics) in 1991 (Geleyn et al., 1988).

As a consequence, every application existing at the short range and based on EMERAUDE and/or PERIDOT products can in principle be extended to the medium range. The realization of this extension largely depends on the required accuracy of the meteorological products for each specific application.

The following sections give an overview of the use of ECMWF products at DMN. The accent is drawn preferably on the activities which have required specific developments to be initiated.

3. CONVENTIONAL APPLICATIONS

As most meteorological services, D.M.N issues forecast bulletins both for the general public and dedicated users. A wide sample of ECMWF model output is at the disposal of the forecasters for the range D+1 to D+6. Up to 72 hours, these products can be compared with the analogous EMERAUDE results which benefit from more recent data. This is the basis for making the medium range forecast in which the experience of the forecaster is useful in appreciating the most plausible causes of errors depending on the weather regime and his knowledge of the main models defects.

3.1 Routine products

In the past years, DMN has invested much effort in giving the general public direct access to the meteorological information by means of messages and images available via the telephone network. This goes as a complementary channel to the now well established newspapers and television bulletins. This telephonic information concerning the medium-range is updated once a day. An example of the telematic product on the MINITEL system is given in fig.1. Currently, this product is very simple, but foreseeable improvements in the transfer rate on telecommunication lines and the quality of the screens will make this information vector very powerful in a very proximate future (D.M.N has its own telematic system METEOTEL which already offers the possibilities expected from the future national network). Interesting enough, it is worth noticing that the number of calls to this specific item (medium-range weather forecast) of a list referring to other meteorological products is very much more dependent on its labelling within the list than the a priori quality of the consulted product!

3.2 A specific case: the 15/10/87 storm

The most violent storm to hit France in recent history, with wind gusts of 50m/s, occurred during the night 15-16 October 1987. The way the French forecasters handled the case is extensively described in Jarraud et al. (1989) who discuss the synoptic situation and its evolution, the NWP products available to the forecasters and the role of human experience for the period 11 to 15 October. For the sake of this paper, it is just worth concentrating on the specific role of the ECMWF forecasts at the earliest stage of this episode, that is on Monday 12 and Tuesday 13 October.

The ECMWF products are the unique source of numerical guidance in the medium-range. Therefore, the forecasts issued those two days were mostly based on ECMWF runs from 12

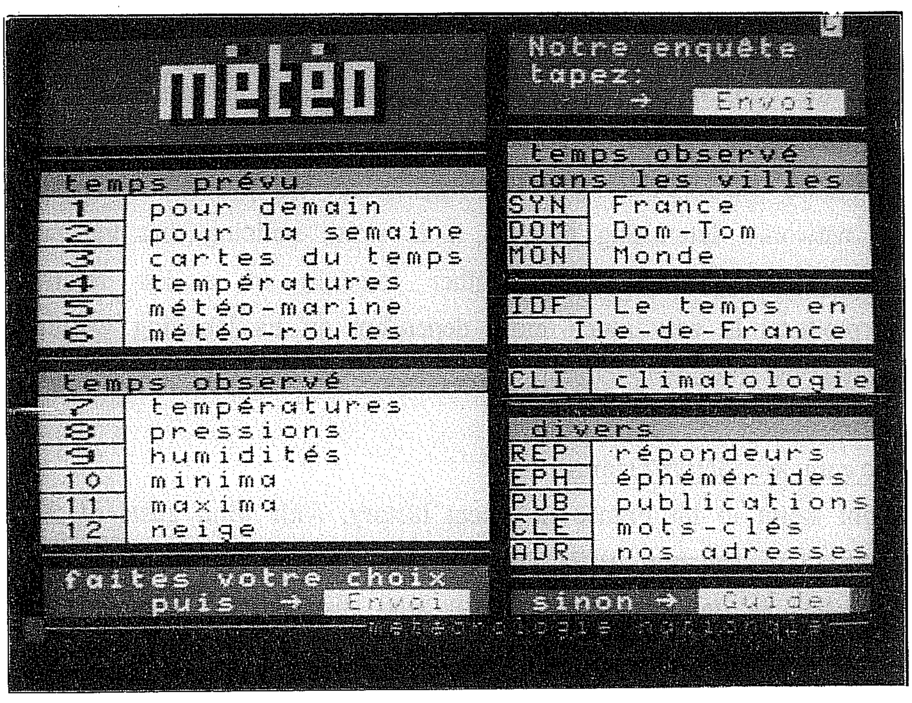


Fig. 1 The MINITEL system consists in a terminal connected to the French public telephone network (top) through which several data serving centres can be accessed.

The METEO menu is displayed (bottom). The medium range 5 day bulletin is under the item 2: "pour la semaine".

UTC 11 and 12 October. As shown in figs.2 and 3, both forecasts predicted the cyclone to the west of its observed position, the trajectory from the 12th being located more to the west and less accurate than the trajectory from the 11th, but with an indication of a stronger development. Both numerical predictions led to manual forecasts of strong winds over France with a generally correct southwesterly orientation. In fact as early as Monday 12 October, the 5 day bulletin, which is issued every morning to both the general public and a large number of specialised users, indicated that a "worsening of the situation....with very strong southwesterly winds" was likely on Thursday 15 October. On Tuesday 13 October, the 72 hour forecast valid at 00 UTC 16 October, issued by the senior forecaster at the central service in Paris, and used as the basic forecast in all local and regional offices, indicated a very deep low west of Ireland. This was sufficient to issue a more precise warning quoting "a considerable strengthening of the winds....reaching storm force over Brittany and the English Channel" during the second half of Thursday. In issuing these warnings, the human experience of the forecasters has been very important: their knowledge of model defects and of the strong possibility of local strengthenings of gradients in such synoptic conditions has been essential. It is evident that during this episode the early indication by the ECMWF products of a general worsening of the situation has considerably helped the French forecasters in being prepared to deal with a major meteorological event. This successful forecasting episode was due to a synergy between the numerical guidance and the forecasters experience.

4. USER ORIENTED APPLICATIONS

Whatever the intrinsic quality of a numerical forecast, the information provided requires a variable amount of interpretation before being usable by a specific user. For a majority of tasks, a human intervention (by a forecaster for instance) is sufficient: this is the case for conventional meteorological applications. However, many applications can only be set up through a further processing of the model output by other numerical models. The following sub-sections illustrate two applications which are available operationally at D.M.N on user requests.

4.1 Ship routeing

This application concerns the routeing of sailing ships during major sports events like the crossing of the Atlantic ocean. This activity was initiated in 1968, but was abandoned for a while. The routeing, as it exists now, started in 1984 with the development of microcomputers, and the possibility of rapid exchange of large amount of data like the 10m wind over an entire ocean and for several forecast ranges.

The routeing, stricto sensu, is the identification of an optimum route. It relies mainly on the results of a numerical program activated on a regular basis (typically twice a day)

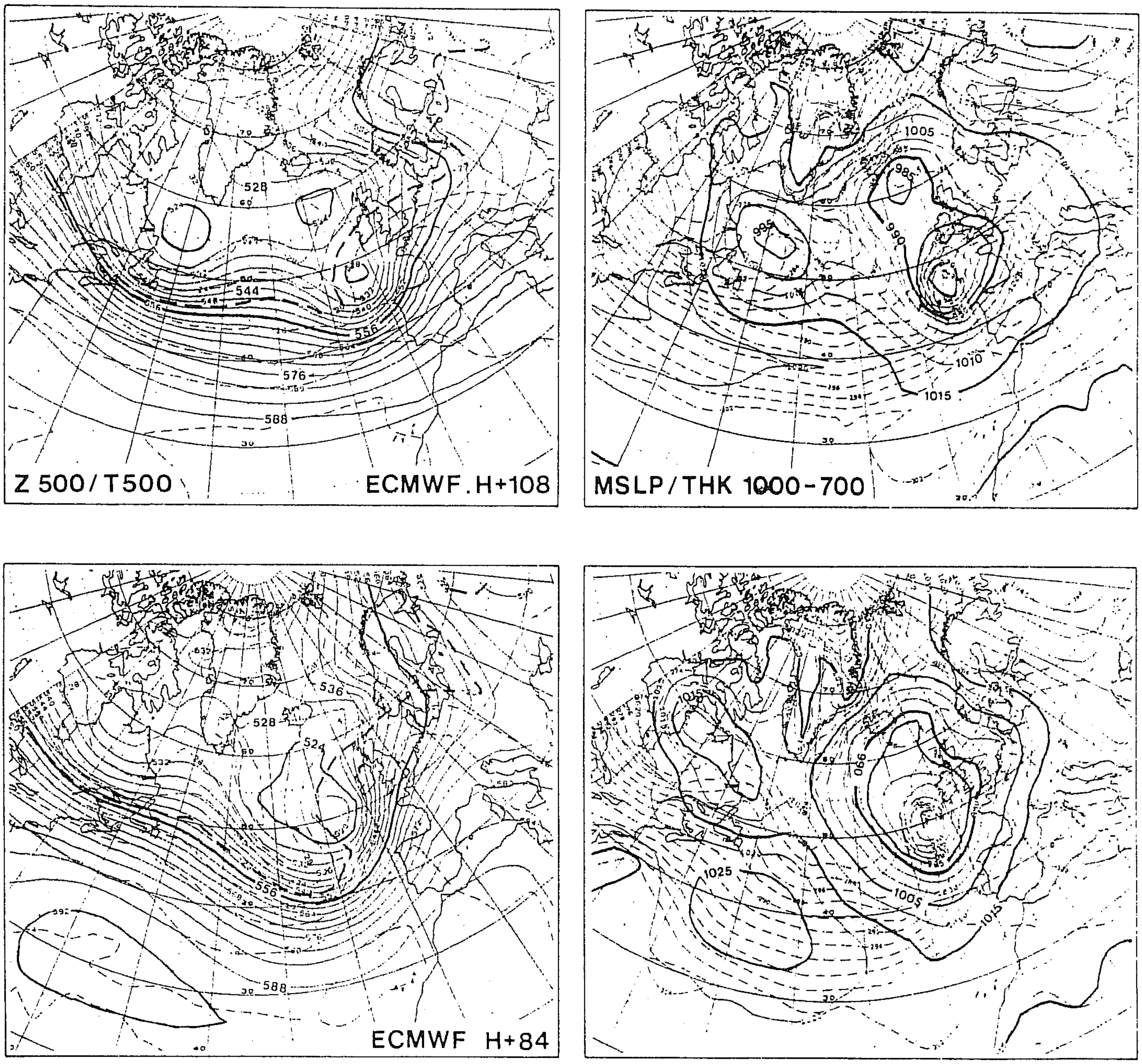


Fig. 2 Left: Geopotential (full lines) and temperature (dashed) at 500 hPa for 108 h ECMWF forecast from 10 UTC 11 October (top) and 84 h ECMWF forecast from 12 UTC 12 October (bottom).
Right: same for the menu sea level pressure (full lines) and 1000-700 hPa thicknesses (dashed).

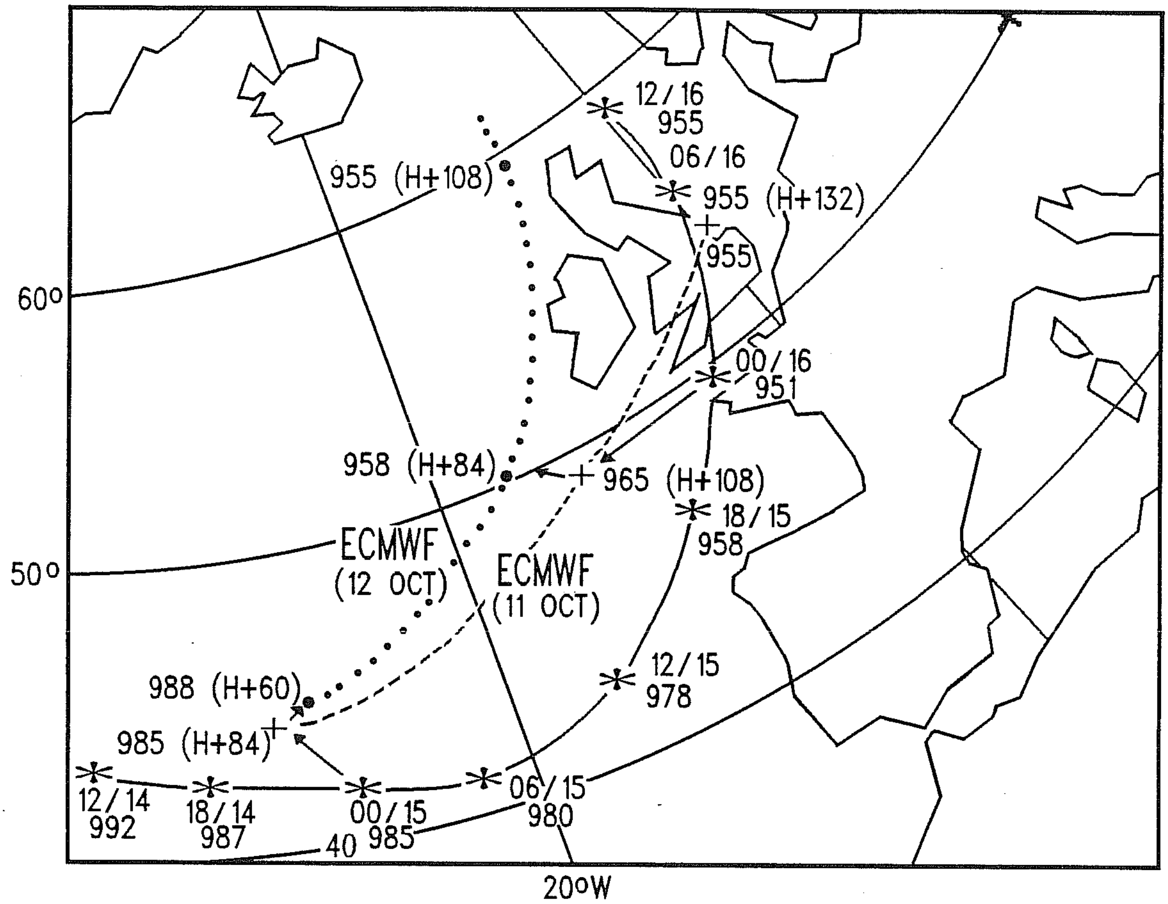


Fig. 3 Trajectory and depth (in hPa) of the depression. Full line: analysed position and depth at various times are indicated (e.g. 00/16 951 indicates the centre's position at 00 UTC on 16 October with a central pressure of 951 hPa).
Dashed: ECMWF Forecast from 11 October 12 UTC valid at 00 UTC 15 to 17 October (forecast ranges are indicated within brackets).
Dotted: ECMWF forecast from 12 October 12 UTC.

which merges the knowledge of the meteorological (wind) and oceanic (waves, currents) conditions and of the ship characteristics (especially its speed with respect to the wind, the so-called Velocity Performance Programs) to produce, using a decision process algorithm, the best route between the current ship position and the arrival point (Ohl et al., 1989). Generally, the routeing is part of an assistance contract between the ship members and a team in a control centre. At any time, the final advice to the crew must take into account not only the results of the routeing program but also the current shape and mood of the crew, plus other elements like the race rules, strategy, security, fine topography (small islands,...) unknown by the programme, etc...

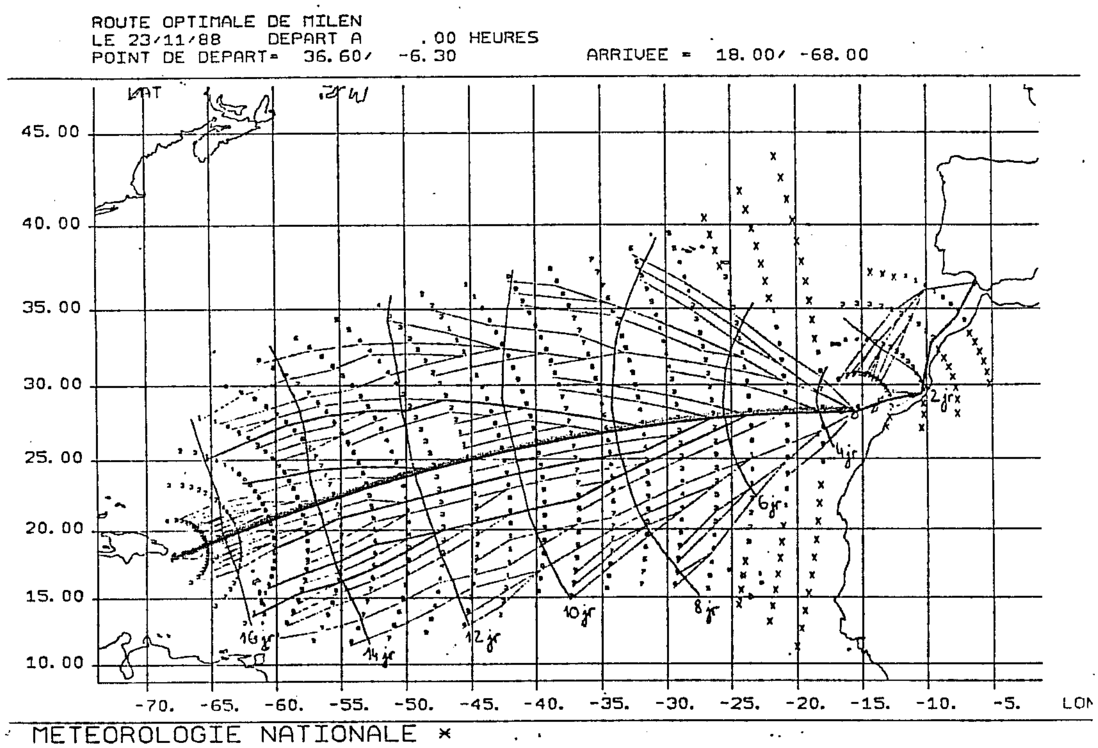
For races lasting less than 3 days, outputs from the French forecasting models is used. But for longer races, ECMWF products are used systematically. For very long races, ECMWF products are complemented using the climatology to "reach" the destination point in the routing program. Of course, other ways of using the routeing model exist for these cases and are agreed upon in advance with the crew. For instance, in the case the crew has to decide on the day of the start of the race (for instance to break a time record) climatological wind fields can be used as input for the routeing program. Thus a decision can be made either on the most probable time of the year to have the race or on the best type of ship, the latter being just a possibility of the programme. Fig.4 shows optimum routes for an Atlantic crossing for two different ships using December climatology.

For instance, the ship routeing program has been run during the Lorient-Saint Barthelimy race for three different ships. ECMWF products have been very useful especially for selecting a "south" option for Tabarly's route in the second half of the westward crossing (fig.5), moving the ship in first position 500 miles from Saint-Barthelimy (Unfortunately, Tabarly's ship capsized during the return crossing while being again in first position!).

4.2 Trajectory-Pollution studies

The "Etudes Spéciales" Bureau of DMN has had, since 1983, a trajectory model (Martin et al., 1984) similar to most of the lagrangian type model, the principle of which is the computation of an atmospheric parcel trajectory using numerically produced wind fields. Turbulent diffusion around the trajectory is simulated using simplified gaussian type distributions of turbulent parameters. Though this type of model has demonstrated its usefulness, especially to study both meteorological or pollution large scale problems, it has inherent difficulties to incorporate physical processes parametrization, which are of primary interest to simulate pollution episodes with some realism and accuracy.

The Chernobyl accident was one of the factors which contributed to motivate DMN to develop an Eulerian type model, the MEDIA model (Piedelièvre, 1989). This model is used



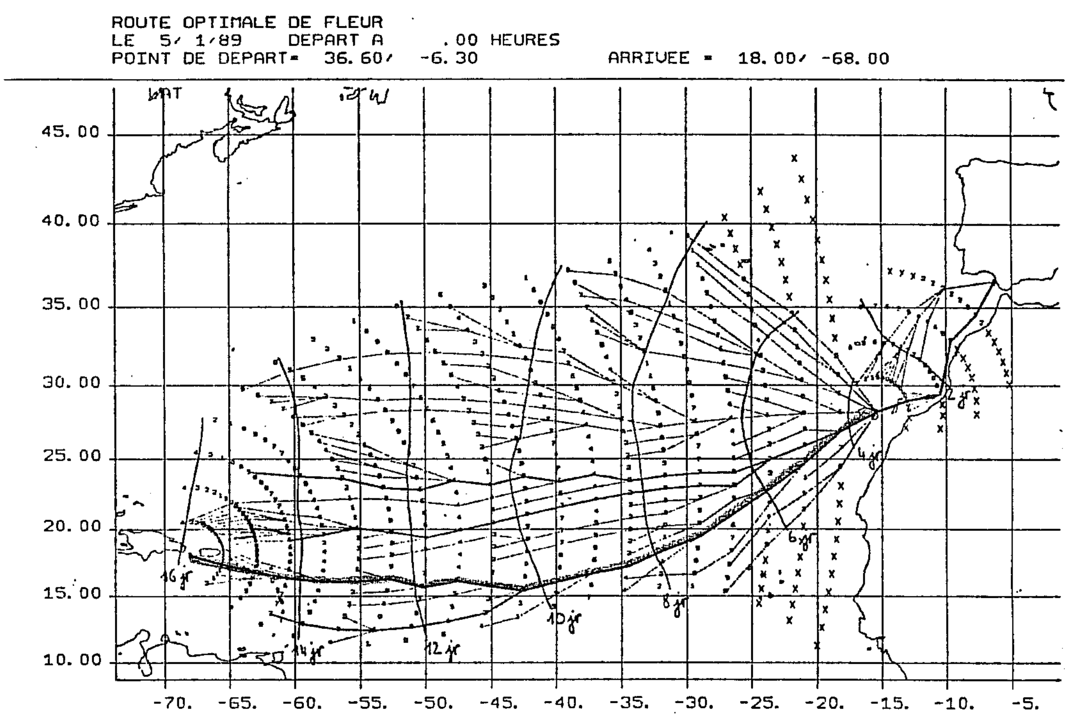
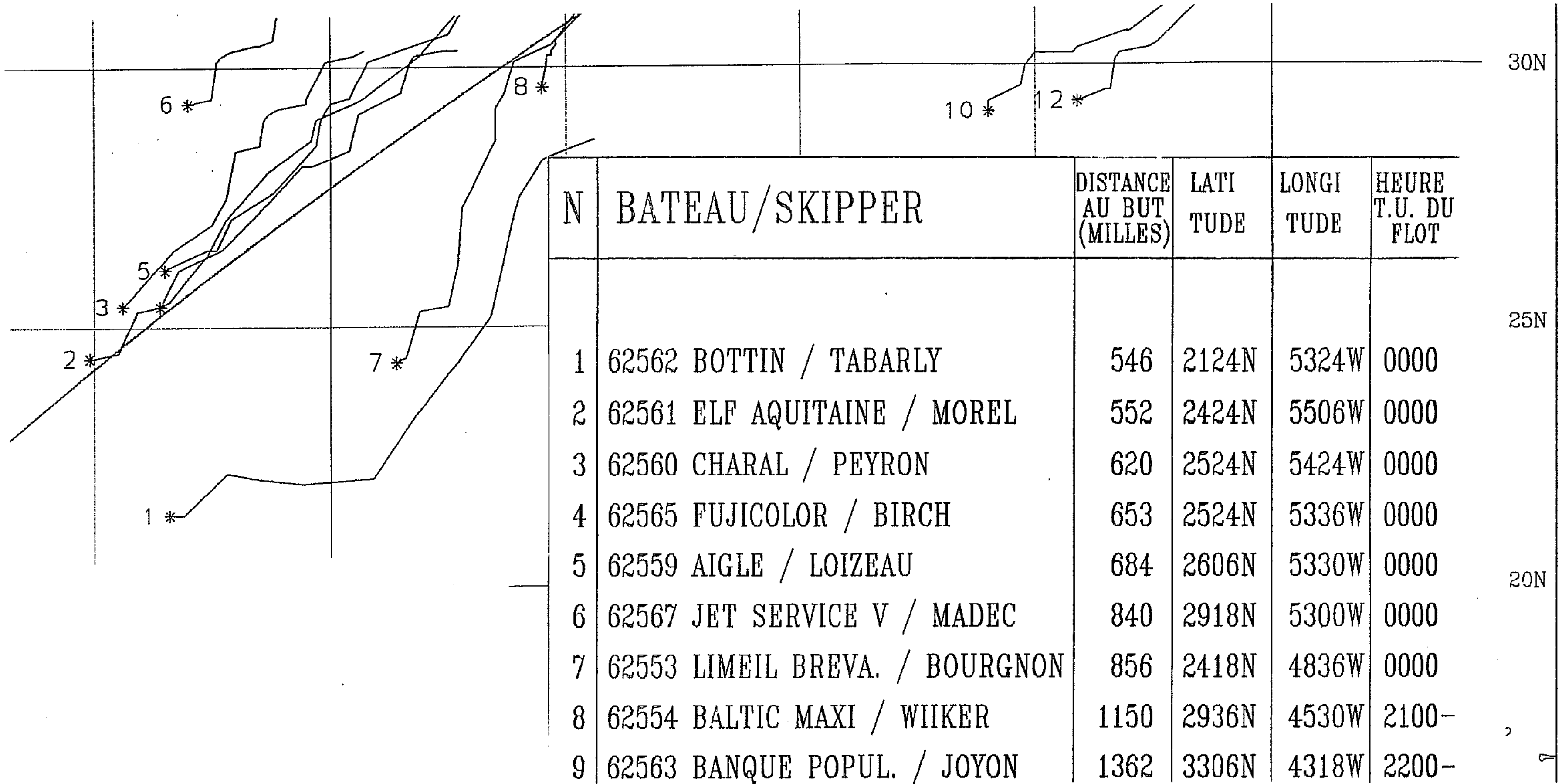


Fig. 4 Climatological routes valid for December computed for two ships having different velocity performances.



N	BATEAU/SKIPPER	DISTANCE AU BUT (MILLES)	LATI TUDE	LONGI TUDE	HEURE T.U. DU FLOT
1	62562 BOTTIN / TABARLY	546	2124N	5324W	0000
2	62561 ELF AQUITAINE / MOREL	552	2424N	5506W	0000
3	62560 CHARAL / PEYRON	620	2524N	5424W	0000
4	62565 FUJICOLOR / BIRCH	653	2524N	5336W	0000
5	62559 AIGLE / LOIZEAU	684	2606N	5330W	0000
6	62567 JET SERVICE V / MADEC	840	2918N	5300W	0000
7	62553 LIMEIL BREVA. / BOURGNON	856	2418N	4836W	0000
8	62554 BALTIC MAXI / WIIKER	1150	2936N	4530W	2100-
9	62563 BANQUE POPUL. / JOYON	1362	3306N	4318W	2200-

Fig. 5 Positions on 4 May 1989 of competing ships during the first part of the Lorient - Saint Barthélimy race. Full line indicates the orthodromy (shortest route). Note the very southern route followed by Tabarly selected by the DMN routeing program.

to solve the transport diffusion equation of an atmospheric pollutant (inert, radio active or chemically active) knowing the spatial and temporal distribution of anthropogenic sources. It accounts for atmospheric transport and turbulent dispersion, wet (providing precipitation data be available) and dry deposition, physico-chemical transformations (currently, only very simple chemistry can be introduced), radio-activity decay and natural sources. It is not within the scope of this paper to document the MEDIA model, but it is worth stressing that a major care has been taken to handle the numerical problems (mass conservation, spurious diffusion, negative concentrations). The MEDIA model can be coupled to both the French EMERAUDE and PERIDOT models, and to the ECMWF model (analysis or forecast). This model has undergone many validations and sensitivity tests, using Chernobyl related data especially. Fig.6 illustrates one of the numerical runs reproducing Cesium boundary layer averaged concentration 6 days after the beginning of the accident.

The Chernobyl accident revealed the precarity at the time, of the tools a priori designed to help decision makers in such circumstances. Amongst other modern countries, France has enhanced its effort to be able to manage such accidents. As far as the atmospheric aspect of it is concerned, DMN will be represented at all decision levels and the MEDIA model will be one of the tools available to the people in charge of managing the emergency. For many cases, ECMWF products will be of primary interest to feed the MEDIA model (it is only hoped it will not have to be used for such problems!).

The main use of the MEDIA model concerned past situations for which ECMWF analyses were used. Stricto sensu, this may not be considered as an application of the medium-range weather forecast done at ECMWF. But, at least in the author's mind, it is difficult (and not justified) to decouple the forecast itself from the remaining part of the ECMWF effort and competence to produce the forecasts, especially the data assimilation.

5. EXAMPLES OF THE USE OF MEDIUM-RANGE FORECASTING IN DECISION PROCESS

The previous sub-section contains two examples of the use of ECMWF products leading to decision making eventually. However, the accent was put more on the (numerical) way the products were exploited than on the decision process itself. In the following sub-sections, we give two examples in which the ECMWF forecast is (or will be) used as a piece of information in a decision process. This aims at illustrating the potential of medium-range weather products in two very different domains, but also their current limitation related to the lack of confidence margins which can be attributed to each individual forecast.

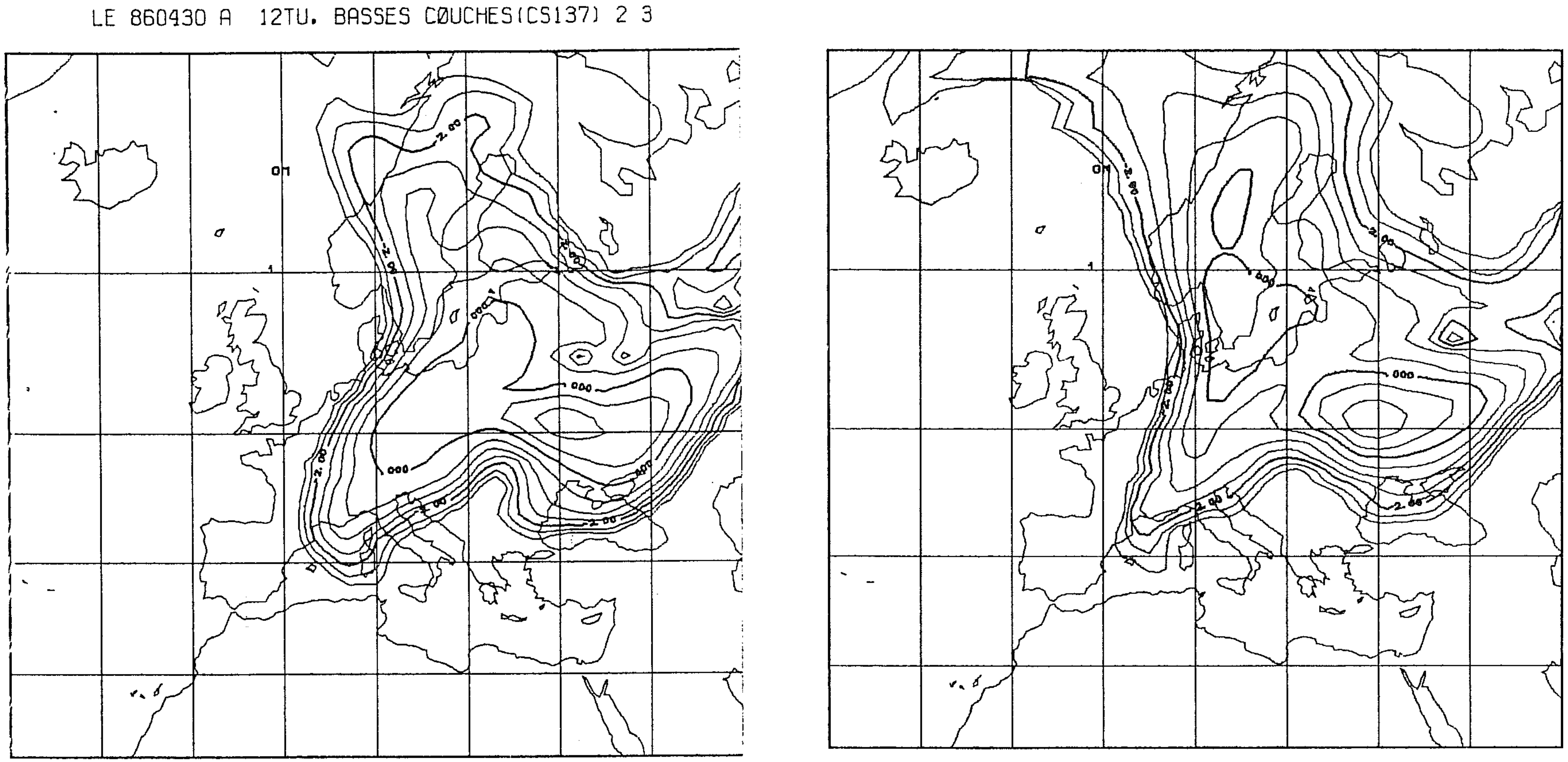


Fig. 6 Boundary layer averaged distribution the 30 April 1986 of an inert pollutant emitted from Chernobyl between the 24 and the 26 April 1989.
Left: Concentration computed using ECMWF analysis between 12 UTC 24 April and 12 UTC 30 April.
Right: Concentration computed using ECMWF analysis between 12 UTC 24 April and 12 UTC 27 April and ECMWF forecast from 12 UTC 27 April up to 12 UTC 30 April.
Isoline units are in log10 of 6 hour average concentration.

5.1 GALIVE (Groupe central d'ALerte hIVErnal)

In 1987, an alert group has been created to study and propose necessary measures in case severe winter conditions occur. The meteorological situations of interest are: i) massive snow falls in regions not specifically equipped to deal with such events (non mountainous areas), ii) very cold wave (temperatures around or lower than -10°C), iii) black ice expected to last several hours and concerning a vast zone (a French administrative region for instance). Apart D.M.N, administrative services involved are mainly those in charge of transports (air, train and road) and nature protection.

This group gathers following an order of its president and at the DMN initiative if meteorological forecasts justify it. In fact before the official meeting, if the ECMWF and/or the EMERAUDE forecast indicate a major risk, specific instructions have to be followed inside the forecasting service within a pre-alert procedure. After a complete and thorough assessment of the situation, the GALIVE president is warned and a decision is made to put the other members of the GALIVE group on pre-alert. From this stage on, the meteorological situation is carefully assessed and if necessary, the group meets in the DMN buildings in Paris to listen to a detailed explanation of the meteorological situation and its possible developments, so that the various necessary actions be clarified and well coordinated.

It is clear that this process can only start when a sufficient confidence in the risk probability is reached. Currently, the GALIVE procedure can only be activated with a two or three day notice. It is worth noting in passing that this is only a crude guess, since winter conditions had been very mild for the last two years!

5.2 SPOT control

SPOT (Sous Programme d'Observation de la Terre) is a french program dedicated to the survey of the earth surface at a very fine resolution (10 metres). Its domain of application is quite wide and spans from vegetation and orography survey, equipment (road, airport, harbour) implementation studies, or assessment of major natural catastrophies (fires, floods, volcano eruptions, etc...). The satellite used is under the control of the SPOT commercial agency, but its activity program is governed by the outside demand. Though the possibility of observing a specific place under favourable conditions occurred quite frequently, it could be important to know in advance if the desired scene will not be hidden to the satellite by a cloud deck (unless the user is specifically interested in clouds, which could be the case for volcanic plume studies, or simply cloudiness studies). The programming of a scene acquisition has to be done at least two days in advance, therefore reliable cloudiness forecasts at the two or three day range will be required to ensure a satisfying monitoring of the satellite. Clearly, this would apply only to those long term requests which need a lot of images. Other users have to take the risk to pay for images even if the ground is not visible from the satellite, essentially because the provided information has to be used in a short term, or because the image acquisition aims at capturing a short lasting feature.

The current quality of cloudiness forecast is such that no meteorological information is taken into account in the satellite programming, neither from the SPOT side or the user's side. However, the SPOT agency is very much interested in a financial a posteriori evaluation of the use of cloudiness information in a programming scenario. For this purpose, a pilot study is trying to be set up between SPOT and DMN, in which ECMWF archives will be used.

Whatever the result of this study, it is simply fascinating to see that such studies are beginning, whilst ten years ago, medium-range weather forecasting was still a formidable scientific challenge!

6. RESEARCH ACTIVITIES.

For any user, the use of meteorological forecasts always involves an explicit or implicit weighing of the information by a "confidence" coefficient. The quality of the current ECMWF forecasts makes them potentially usable in the range 3-6 days. The previous sub-sections illustrate possible direct use of the forecast products. However there is an increasing need for having an a priori estimate of the forecast quality. Several centres have started research activities in this domain, including DMN pursuing an original method.

Forecast errors have two causes:

i) the trajectory in phase space followed by the model is not the trajectory the real atmosphere would have followed starting from the same point: the model is imperfect.

ii) The origin of the trajectory is not correct: the initial conditions are not appropriate.

There is also an amplification factor, since trajectories starting from close origins will diverge as the forecast time elapses.

From a practical point of view, several methods have been proposed to obtain estimates of the forecast errors, or more specifically their variance-covariance matrix. Statistical methods like Monte-Carlo forecasting or the lagged averaged forecasting have already been tried and showed their limitations. For instance, the spread of the forecasts is not an intrinsic indication of the forecast quality. Other statistical methods have been implemented at ECMWF (see Palmer's contribution in these Proceedings) but their evaluation have demonstrated that they were, at the time, far from giving exploitable results (ECMWF, 1988).

Another method consists in postulating that a perturbation of the atmosphere around its basic state evolves linearly, at least up to a certain range. In this case the Kalman filtering theory can provide a direct estimate of the variance-covariance matrix. The Kalman filter is a sequential algorithm which solves a 4-D optimum interpolation problem. At each time step, the model state is known in a consistent way by its two first statistical moments, and this thanks to the temporal advection of the error statistics. This last solution is currently explored at D.M.N.

Some results have already be obtained. The validity of the linearity assumption has been studied and quantified for a barotropic model, or in a bi-periodic model (Lacarra et Talagrand, 1987). This method has also been used to highlight the limitations of the current method used to approximate the error statistics in a forecasting model, namely the separability (horizontal/vertical) of the structure functions and their temporal extrapolation (Moll et Durand, 1987).

To go further along this approach, two main research axes have to be explored. Firstly the linearity assumption has to be further assessed using a fully baroclinic model. Secondly, numerical experiments using the adjoint of the linear tangent model have to be set up. This will be done using the ARPEGE code.

To develop an automatic method to predict the skill of the forecast is very useful, however it will nor help to understand the causes of the quality (either bad or good) of the forecast neither provide guidance for correcting a wrong forecast. Therefore it is necessary to study the forecast errors, their origin (analysis, spin-up, diabatic processes parametrization) and the way they propagate during the assimilation and the forecast.

At ECMWF, specific diagnostics have been carried out (Klinker et al., 1988) to relate the model systematic errors to the unbalance between expected diabatic forcing as required by the model state to satisfy the model equations, providing dynamical tendencies are correct, and the computed diabatic forcing as given by the physical parametrization. This method has already been applied with success to diagnose weaknesses of the formulation of the gravity wave drag and the vertical diffusion parametrization schemes (Miller, 1988).

At D.M.N, efforts are also devoted to diagnose the errors of the forecasting model by studying the properties of the budgets of the time averaged (30 days typically) and vertically integrated model variables. Provided several simplifying assumptions be fulfilled, it is possible to compare estimated (from the initialized analysis) fluxes at the atmospheric boundaries (top and surface) and the computed (by the model) fluxes at various forecast ranges (Chapelet, 1989). This study is at a developing stage (some assumptions and practical ways of obtaining the diagnostics have to be assessed further), but appears to be very promising. It is intended to apply these diagnostics both using monthly averages and to well identified atmospheric regime or flow pattern situations to highlight the specific errors of the diabatic forcing under these particular conditions.

7. CONCLUSIONS

In this paper, various direct or derived applications of medium range forecasting at D.M.N. have been presented. The broad range of the application domain demonstrates that this activity is very useful, this mainly being attributed to the progress made at ECMWF in producing numerical weather forecast operationally.

As already stressed, ECMWF efforts to continuously improve the forecasts have given benefits to other connected domains, especially data monitoring and assimilation. ECMWF archives, inasmuch FGGE data, are a unique dataset which will be used by a wide scientific community to study the atmosphere and numerical prediction.

Many routes leading to significant potential progress are opened and the application domain is widening.

Ten years ago, medium-range weather forecasting was a challenge. Now it has become a necessary component of the weather forecast. D.M.N will continue to develop its activities to make an efficient use of ECMWF products.

References

Chapelet, P., 1989: Diagnostics en moyene verticale dans le modèle EMERAUDE. Rapport de stage d'approfondissement. Ecole Nationale de la Météorologie (DMN/ENM, Toulouse, France).

Coiffier, J., Y. Ernie, J.-F. Geleyn, J. Clochard, J. Hoffmann and F. Dupont, 1987: The operational hemispheric model at the French Meteorological Service. Journ. of Met. Soc. of Japan. Special volume on "Short and Medium Range NWP", 337-345 (Edited by T. Matsuno, Tokyo, Japan).

ECMWF, 1988: Evaluation of experimental forecast skill prediction, winter 1987-88. ECMWF Expert meeting 22-26 February 1988. Final report (available at ECMWF).

Geleyn, J.-F. and M. Jarraud, 1988: Current plans for NWP at DMN: the ARPEGE project. In Proc. 8th conference on NWP. Baltimore (USA), February 1988.

Guillaume, A., 1987: Validation of VAG against directional data. In proc: 5th meeting of WAM group. Reading (UK), 1987.

Imbard, M., R. Juvanon du Vachat, A. Joly, Y. Durand, A. Craplet, J.-F. Geleyn, J.-M. Audoin, N. Marie and J.-M. Pairin, 1987: The PERIDOT fine mesh NWP system - Description, evaluation and experiments. Journ. of Met. Soc. of Japan. Special volume on "Short and Medium Range NWP", 455-465 (Edited by T. Matsuno, Tokyo, Japan).

Klinker, E. and P. Sardeshmukh, 1988: The diagnostics of systematic errors in numerical weather prediction models. In Proc: "Workshop on systematic errors in models of the atmosphere". Toronto, Canada, 19-23 September 1988, 94-9.

Jarraud, M., J. Goas and C. Deyts, 1989: Prediction of an exceptional storm over France and Southern England (15-16 October 1987). Accepted in Weather and Forecasting.

Laccara, J.-F. and O. Talagrand, 1987: Short range evolution of small perturbations in a barotropic model. Tellus, 40A, 81-95.

Martin, D., J.-P. Granier, M. Imbard and B. Strauss, 1984: Application of a long range transport model to a mount ETNA plume. Bull. Volcano., 47-4 (2).

Miller, M.J., 1988: The sensitivity of systematic errors of the ECMWF global forecast model to parametrized processes. In Proc: "Workshop on systematic errors in models of the atmosphere". Toronto, Canada, 19-23 September, 1988, 289-298.

Moll, P. and Y. Durand, 1987: Application du filtre de Kalman à un modèle plan vertical en équations primitives pour l'étude de l'évolution temporelle des statistiques d'erreurs. Note de travail de l'Establissement d'Etudes et de Recherche Météorologiques (DMN/EERM, Boulogne-Billancourt, France).

Ohl, P. and M. Hontarrède, 1989: Course au large et routage météorologique. Note de travail du Service Central d'Exploitation de la Météorologie (DMN/SCEM, Paris, France).

Piedelièvre, J.-P., 1989: Première validation d'un modèle eulérien de dispersion atmosphérique (MEDIA) sur le cas de Tchernobyl. Note de travail du Service Central d'Exploitation de la Météorologie (DMN/SCEM, Paris, France).