ORGANISATION OF 3D VARIATIONAL ANALYSIS WITHIN THE "IFS/ARPEGE" PROJECT

FUTURE PLANS AT METEO FRANCE

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Abstract

The "IFS/ARPEGE" system is a numerical weather prediction system which has been developed in cooperation between ECMWF and METEO FRANCE since 1987. IFS (Integrated Forecasting System) is the ECMWF name of the project; ARPEGE (Action de Recherche Petite Echelle Grande Echelle) is its French name. Among other scientific applications, this system is able to carry out 4D and 3D variational assimilation runs using all the current operational observations. The variational assimilation aspects of the project are described in this paper with particular emphasis on 3D variational analysis (3DVAR).

1. INTRODUCTION

A review of the developments in the variational assimilation configuration is carried out in this text, stressing the key scientific motivations which were followed during the development work. The current status (November 1992) of the variational work at ECMWF and METEO FRANCE is then analysed, with special emphasis on the modularity and the "multi-option" character of the system. Finally the special aspects of the plans at METEO-FRANCE regarding variational assimilation are described.

This paper does not provide any result; it should be seen as an introduction paper on 3D variational analysis, inside the ECMWF workshop proceedings. Experimentation results can be found inside these proceedings, see for example papers by *Heckley, Vasiljević et al., Andersson.*

2. HISTORICAL BACKGROUND ON THE "IFS/ARPEGE" SYSTEM

Two key scientific ideas were at the origin of the design of the IFS/ARPEGE system:

a) The need to perform 4D variational assimilation (4DVAR) experiments with a model which is not too far from operational models;

b) The demonstration that it was possible to develop a global spectral model, with a stretched horizontal coordinate in order to have a variable resolution.

These two scientific ideas have been at the core of the development of the IFS/ARPEGE system since 1987, together with the preoccupation that this system should provide the operational model for both ECMWF and METEO FRANCE, in addition to its use in research mode on many aspects of data assimilation and Numerical Weather Prediction (NWP).

2.1 The variational assimilation aspects of the "IFS/ARPEGE" system

Previous work on data assimilation, such as the one performed by *Le Dimet and Talagrand* (1986) or *Lewis and Derber* (1985) have demonstrated the feasibility of a 4D variational assimilation scheme which would compute a model trajectory, entirely consistent with the observations on a time period (t1, t2). This previous work was carried out with very simple barotropic models. It was demonstrating that the appropriate tool needed for 4D variational assimilation is the adjoint model.

The main advantage of 4D variational assimilation is that it integrates in one single consistent process the analysis step, the Normal Mode Initialization (NMI) step and the forecast step, which are independent processes of most of the operational data assimilation systems. It then solves most of the "spin-up" problems produced by analysis schemes which are not consistent with the model dynamics. However, when the IFS/ARPEGE system was designed, the benefits of 4DVAR had still to be evaluated in the context of a primitive equation model which is as close as possible to an operational one. The ratio "benefits/costs" of 4DVAR was required special attention because of its high computer cost.

To perform a 4D assimilation on a time period (t1, t2), one needs to find the model trajectory which minimizes the fit to all the observations on the time period, as well as the fit to a guess at time t1. This guess $\boldsymbol{Xg}$ represents the best estimate of the model state $\boldsymbol{X}$ at time t1, prior to any collection of observations at and after time t1. As in all the operational assimilation schemes, the guess $\boldsymbol{Xg}$ represents a summary of all the information on $\boldsymbol{X}$ accumulated before t1. It is generally provided by the most recent numerical forecast available for time t1. As documented in *Pailleux* (1988, 1990), the cost function to minimize can be written:

$$J(X) = Jo + Jg + Jc \qquad (1)$$

where:

- $\boldsymbol{Jo}$ is the distance to the observations; the natural distance is the quadratic form built on the inverse of matrix O (covariance matrix of observation errors) and on the vector of observations departures: $\boldsymbol{HX} - \boldsymbol{d}$ ($\boldsymbol{d}$: vector containing all the observed data; $\boldsymbol{H}$ is the OBSERVATION OPERATOR which produces the equivalent of vector $\boldsymbol{d}$ from model state $\boldsymbol{X}$);

- $\boldsymbol{Jg}$ is the distance to the guess $\boldsymbol{Xg}$; the natural distance is the quadratic form built on the inverse of matrix $\boldsymbol{P}$ (covariance matrix of forecast errors) and on the vector $\boldsymbol{X} - \boldsymbol{Xg}$ (departures of model state to the first guess);

- *Jc* is an optional penalty term which contains physical constraints to apply on the model state ***X***; the constraint which has been developed in the IFS/ARPEGE code is proportional to the square of the norm of gravity mode tendencies.

To solve completely the above 4D assimilation problem, one needs the following features which have been developed in the IFS/ARPEGE system:

a) a forecast model and its adjoint;

b) a minimization scheme;

c) an algorithm to compute cost function (1) and its gradient.

Regarding the minimization scheme, the software has not been developed in the IFS/ARPEGE; minimization packages have been borrowed from research groups where experts are working on this kind of mathematical problem. Most of the experimentation carried out at ECMWF and METEO FRANCE has been made with minimization packages borrowed from INRIA (Institut National de la Recherche en Informatique et Automatique); see *Gilbert and Le Maréchal* (1989).

Regarding point a), the adjoint has been developed only for the adiabatic part of the model; this is also a way to avoid possible difficulties coming from non-differentiable processes which are in physical packages.

In this modular approach, the pure analysis part of the 4D assimilation algorithm is part c). Parts a) and b) can be used for applications which are different from assimilation, such as sensitivity studies.

2.2 3DVAR as a particular case of 4DVAR

The cost function (1) can be minimized in the particular case when t1 = t2, i.e. when all the observations are close to time t1 and can be compared to model state ***X*** at time t1. In this case the 4DVAR algorithm degenerates in a 3D variational analysis (3DVAR).

It can be shown that under the following assumptions a 3DVAR scheme is equivalent to a global multivariate Optimum Interpolation (OI), see *Lorenc* (1988):

- geostrophic assumption on the increments used;
- the same observations ***d*** and the same guess ***Xg*** are used in both systems; this implies that the OI uses all the observations globally without any data selection;
- the same assumptions are made in both systems to model the observation error and guess error statistics (matrices O and P).

Such a 3DVAR analysis does not require the forecast model and its adjoint, consequently it is much cheaper than the general 4DVAR algorithm described above. It can be used like the multivariate OI as an independent analysis step performed, for example, every 6 hours in a data assimilation suite. The American "SSI" scheme, implemented operationally in NMC (Washington) in June 1991 is a 3DVAR scheme (see *Derber and Parrish*, 1992). However, the variational scheme, as it had been developed in the IFS/ARPEGE system, does not contain any quality control procedure. Consequently the variational analysis has to rely on current quality control techniques such as the ones which are implemented operationally in the ECMWF multivariate OI (traditional guess check and analysis check). This is why the operational data assimilation systems (at ECMWF and METEO FRANCE) may work in the near future with an analysis step (performed every 6 hours) containing both an OI analysis and a variational analysis: the OI analysis might be reduced to its quality control part, ... or might be as complete as nowadays in order to provide a good initial point to the minimization algorithm required by the variational analysis. Operations are likely to remain in this state until a 4DVAR scheme which is cheap enough has been worked out (see *Courtier and Thépaut*, 1991) in this volume.

Studies on the use of TOVS data in the analysis have been performed at ECMWF during the last few years in parallel to the IFS development (see, for example, *Andersson et al.*, 1991 and *Kelly et al.*, 1991). These studies have stressed the potential interest of using TOVS radiances directly in a variational analysis. The main ideas are the following:

- In equation (1) above, the observation operation H does not need to be linear; it can include a radiative transfer model computing TOVS radiances from a temperature/humidity profile; this is an advantage compared to OI where the link between observed quantities and model variables has to be linear.
- The adjoint of H is needed to perform the gradient computations, consequently the adjoint of the radiative transfer model is needed in this approach.
- Using TOVS radiances directly has the advantage of avoiding using retrieved profiles (such as SATEM profiles) which do not represent properly the real information content of TOVS instruments.
- This technique is equivalent to integrating a retrieval algorithm in the 3D analysis; it would solve many difficulties encountered in stand-alone retrieval algorithms (difficulties due to lack of auxiliary information).

The arguments in favour of using TOVS directly in a 3D variational analysis are valid for all the observed data which are linked to model variables through an operator H which is non linear. It stresses the importance of 3DVAR for using current conventional data which are badly used (e.g.: 2 m temperatures and 10 m winds from SYNOP), and also new and future satellite data (ERS1 scatterometer data, future satellite instruments which are under development). Regarding scatterometer data, the appropriate observation operator and its adjoint have recently been developed in the IFS/ARPEGE system and some results are presented in this volume: *Thépaut et al.* (1992).

Another technical aspect which supports the case of a 3DVAR system is the data selection. There is some evidence that the data selection schemes which have to be introduced in operational OI systems are creating some noise in the resulting analysed fields. This is true for the ECMWF data selection scheme where the analysis is performed by boxes: noise is appearing at the box boundaries due to the fact that different data are used to analyse different boxes. This is even more true for the schemes where a data selection is performed grid point by grid point, and each grid point is using a different set of observed data.

Although originally the main motivation for developing a variational assimilation scheme in the IFS was the study of the 4D problem (see point a) at the beginning of section 2, the importance of 3DVAR on its own has been progressively increased because of the previous considerations (and results) on satellite data and data selection.

2.3 CANARI: development of an OI analysis in IFS/ARPEGE

Very early in the development phase of the IFS/ARPEGE project it was decided to code a multivariate OI in the system, in order to meet the operational requirements of METEO FRANCE:

- An operational analysis was needed to initialise the ARPEGE model at METEO FRANCE in a time scale of three to four years.
- Within such a time scale, it was not possible to rely on variational analysis only, as too many scientific problems had to be examined before at this time (in 1988-89).
- This new analysis had to work in stretched mode, as the variable mesh was (and still is) an important ingredient of the French operational plan.
- It was not possible to use the previous French operational analysis codes (EMERAUDE and PERIDOT analysis codes) which were built on too restrictive assumptions: PERIDOT analysis written to work on a limited area of mid-latitudes only, and EMERAUDE written to analyse a given set of standard pressure levels rather than the model levels directly.

CANARI (Code d'Analyse Nécessaire à ARPEGE pour ses Rejets et son Initialisation) is the "French OI analysis" application which has been integrated into the IFS/ARPEGE system. It is a multivariate OI with a geostrophic assumption on the increments (relaxed into the tropics). The OI scheme is performed:

- first on surface pressure Ps;
- then on temperature and wind components (simultaneously) on each model level;
- then for relative humidity on model levels (univariate OI);

- finally for a few surface variables.

The OI is performed grid point by grid point and model level by model level. A small OI system (up to 24 pieces of observation) is built for each grid point and each level.

CANARI, like any OI system, requires the computation of the guess at the observation points in order to evaluate the departures "observation - guess". In other words one needs to compute ***HXg*** (according to notations of equations (1)). The observation operators ***H*** have been built in the IFS code in a modular way, so they can be used both by the variational analysis and the French OI CANARI. Some operators may be used by the variational analysis and not the OI, or vice-versa. For example, the TOVS radiance computation is used by the variational analysis, and not by the OI as no attempt is made to use TOVS radiances directly in CANARI. Also the adjoint observation operators which are in the IFS/ARPEGE code are used in variational analysis and not in the OI. Finally, let us note that some parts of these operators are used in the system for applications which have nothing to do with the analysis (e.g.: postprocessing of the model which requires vertical interpolation to standard levels).

3. CURRENT STATUS OF THE IFS/ARPEGE SYSTEM

The IFS/ARPEGE system became operational at METEO FRANCE on 29 September 1992 in replacement of the EMERAUDE system (previous large scale system). The applications of IFS/ARPEGE which are operational in this context are:

- The direct forecast model run at T79, with 15 levels, no rotation and no stretching being applied to the horizontal geometry.
- The CANARI analysis performed at the corresponding resolution.

Two physical packages are available in the IFS/ARPEGE system: the ECMWF and the French ones. This has an impact on some observation operators, such as the boundary layer ones, which are dependent on the physical parametrizations: two parallel options are then available for these operators.

Currently (November 1992), no other application of the system is used into operations. The variational assimilation application should go into operation in 1993 in its 3D form, after the necessary tunings, optimisations and experimentations have been carried out. All the parts of the system which are necessary for an operational 3DVAR have been developed in a modular way:

- ***Jo***, with all the observation operators needed to use the observations currently introduced into the OI, plus the cloud-cleared TOVS radiances, plus the scatterometer data; options are available to use only some observation types, some observed variables ... which gives a lot of flexibility for research experiments in order to investigate thoroughly say one observation type, or to develop the observation operator (and its adjoint) for a new observing system which has to be studied.

- *Jg* which also contains several options for the representation of the matrix ***P*** of forecast error covariances (options depending on the space used for some computations, on the mass-wind balances which are assumed). Let us note, however, that all the current formulations of *Jg* are based on a "diagonality assumption" of the horizontal correlation matrix in the spectral space (see *Heckley*, 1992) in this volume.
- *Jc*, based on the norm of the tendencies of the gravity modes, can be used optionally. It may not be used in the first operational implementation of 3DVAR at ECMWF, as a "multivariate *Jg*" may be good enough to ensure a proper mass - wind balance in the variational analysis: see papers by *Heckley, Derber and Parrish* in this volume.

As mentioned before, the observation handling of the IFS/ARPEGE systems allows the use of any combination of real observations. In addition, it provides the possibility of using simulated observations rather than real ones: these simulated observations can be spectral fields ... or fields interpolated at real observation points. The "simulated observation" options have been used extensively in research experiments carried out recently (see, for example, *Thépaut and Courtier*, 1991 and *Rabier et al.*, 1992). The observation handling is also set up in such a way that it is easy to switch from a 3DVAR experiment to a 4DVAR experiment or vice versa, by plugging the forecast model and its adjoint. In 4DVAR the observations are normally inserted in the assimilation with 1 hour time windows; in 3DVAR this time window is by default the usual operational one: 6 hours around the analysis time.

In spite of all this flexibility, let us note that the variational assimilation has been designed essentially to analyse upper-air fields, i.e. all the model variables which are normally handled in spectral coefficients. The main reason is the *Jg* computation which is dependent on the diagonality assumption of ***P*** matrix in spectral space. More work and developments are needed in order to integrate surface fields such as surface temperature and snow in the control variable vector of the variational analysis. Also the behaviour of the variational analysis in stretched coordinate has not been studied yet.

4. PLANS RELATED TO VARIATIONAL ANALYSIS AT METEO FRANCE

During the last few years, most of the analysis efforts at METEO FRANCE have been devoted to the CANARI application of the IFS rather than the variational assimilation (taking into account that the direct observation operators are common between the OI and the variational analysis applications). These efforts led to the first operational implementation of the system in September 1992 at METEO FRANCE. The next important step for French operations is to move from a T79/15L non-stretched version of the system to a T127/21L stretched version: the pole of the transformation will be chosen over France and the stretching factor will be 3.5, producing the equivalent of a T440 resolution over France, and a resolution about

12 times coarser on the opposite side of the earth. The short term work concerning the CANARI analysis consists of adapting it to the stretched geometry and do the necessary tunings (mainly structure functions).

Regarding variational analysis, the specific tasks which are or will be carried out at METEO FRANCE are the following:

- A study of the error statistics of TOVS radiances: determination of the part of the 0 matrix (equation (1)) related to cloud cleared radiances.
- Research on the stretched coordinate aspects of the variational analysis and on the variational surface analysis.

4.1 Error statistics of TOVS cloud-cleared radiances

For most observation types the computation of the ***Jo*** cost function (equation (1)) is based on the assumption that observation errors are not correlated in space. This assumption is reasonable for conventional observations but not for cloud-cleared TOVS radiances, for which horizontal and inter-channel correlations on the observation errors are present because of the cloud-clearing process and because all the observed quantities are coming from the same instrument.

At ECMWF, all the cloud-cleared radiances (coming from NESDIS) have been archived together with the corresponding values of the departures to the ECMWF first guess. Statistics have been performed month by month on the departures "observed radiance - guess radiance" (part of the vector "***d*** - ***HX***" corresponding to TOVS radiances). The period which has been examined so far is June to October 1992. All the variational analysis experiments carried out at ECMWF assume a zero inter-channel correlation (vertical part of matrix 0 diagonal for TOVS). There are good grounds to think that this diagonality assumption is often too crude, and the main goal of this study is to get a better estimate of the inter-channel correlation matrix, or perhaps several estimates of these correlations, depending on clouds, satellite, land/sea ... The observation error statistics cannot be derived from the ECMWF archive only, as one needs extra assumptions or an extra source of information to separate the observation error part and the guess error part in the computations performed on "observed radiance - guess radiance".

At the time of writing (November 1992) this study has not yet been completed. The main preliminary results which are worth mentioning are the following:

- There are strong correlations between HIRS1 observation error and the neighbour HIRS channels: this is not due to instrumental error but to representativeness error (especially extrapolation error due to the fact that HIRS1 has a strong contribution of the upper stratosphere which is not represented in the ECMWF forecast model). Unfortunately all the HIRS1 statistics are very unstable from one month to the other; they also vary a lot between land points and sea points, making this correlation very difficult to model in the variational analysis.

- HIRS4 has stronger correlations with neighbour channels in clear sky than in partly cloudy sky; no physical explanation has been found.
- The variances of MSU errors are about 25% bigger for NOAA12 than for NOAA11. This is a result which looks very stable from one month to the other from June to October 1992. It is not clear whether this is due to the satellite instrument or to the ECMWF model which may be better in some areas of the globe (the statistics have been derived on 12Z observations only, consequently NOAA11 always "sees" the same areas which are different from the areas seen by NOAA12).

4.2 Stretched variational analysis and surface variational analysis

So far, the two key scientific ideas which were at the origin of the safe project (4DVAR and stretched geometry, see beginning of section 2) have never been combined in any experiment. METEO FRANCE is more interested in the stretched geometry than ECMWF, because it is a key point of its operational plans. The question which has to be addressed is related to the assumptions which are made to model the $\boldsymbol{P}$ matrix and compute $\boldsymbol{Jg}$: a diagonality assumption in the spectral space is equivalent to an homogeneity assumption of forecast error statistics on the sphere. In stretched mode this homogeneity assumption could be made either on the real sphere or on the transformed one. How good are these two assumptions respectively? Is there any assumption on $\boldsymbol{P}$ (such as an intermediate assumption) which is more realistic and simple enough to be used in practice? These are the questions at the basis of the work to be done on stretched variational analysis.

As it is also related to the $\boldsymbol{Jg}$ formulation, the work needed in variational surface analysis is of a similar nature. As mentioned before, the current set up of the variational assimilation is highly dependent on the spectral formulation of fields. A special formulation has to be worked out for surface fields which are always represented in grid points. Another aspect of the surface analysis is the complexity of the observation operators, which involve the physical parametrizations and may require new improvements in the model surface scheme parametrization. The plan of METEO FRANCE for 1993-94 is to work in parallel on the three following areas which are connected:

- Development of the surface variational scheme in the IFS/ARPEGE.
- Development of more sophisticated surface parametrization schemes.
- Inclusion of more and more surface observations, especially in the area around France where the operational model will have a high resolution and where the local satellite facilities (Lannion) can provide satellite products to complement the global products.

5. CONCLUSION

The IFS/ARPEGE system which has been developed in cooperation with METEO FRANCE and ECMWF is a "multi-option" system which contains a lot of flexible facilities to run 3D and 4D variational assimilation experiments, in addition to more standard applications such as a forecast model and the French OI CANARI. At the end of 1992, no variational application has reached the operational stage, neither at ECMWF nor at METEO FRANCE. It is likely that an operational 3DVAR will be implemented at ECMWF in 1993 and in France 1 or 2 years later.

The main research areas which have to be investigated in the future are:

- The adaptation of 3D variational analysis to the stretched geometry.
- The adaptation of 3D variational analysis to the surface fields.
- Simplifications of 4D variational assimilation in order to reduce its cost to something acceptable for operational implementation.

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