(4D) VAR DEVELOPMENTS AT METEO-FRANCE

Jean-Noël Thépaut

Météo-France, Centre National de Recherches Météorologiques, Toulouse, France

contributors :

P. Caille, V. Cassé, J.-F. Geleyn, P. Haution,
M. Janisková, P. Moll, J. Pailleux, F. Taillefer, F. Veersé

Résumé

This paper describes the state of the art of the work undertaken at Météo-France concerning the development of a four-dimensional variational assimilation system (4D-Var) for short-range numerical weather forecasts. The developments concern mainly:

- studies aiming at cutting the cost of 4D-Var along the lines developed in the framework of the incremental approach (Courtier et al. 1994),

- the improvement of the assimilating model by defining an adhoc physical package compatible with robustness, realism and smoothness,

- mini OSSEs to evaluate the performance of new sources of information when assimilated with a dynamical data assimilation system.

1 Introduction

Optimal interpolation based data assimilation systems are progressively giving place to three-dimensional variational (3D-Var) systems which allow a global use of observations (no data selection is needed anymore) and a better handling of data nonlinearly related to the analysis variables.

A future step forward in data assimilation for Numerical Weather Prediction (NWP) centres will certainly consist in 4D-Var type assimilation methods (Rabier *et al.*, 1997, Zupanski, 1997) which is known to implicitely use flow dependent structure functions (Thépaut *et al.*, 1996) and to use consistently asynoptic data such as TOVS radiances or scatterometer winds. With the new high resolution data coming shortly (interferometer, Doppler Wind Lidar (DWL),...), it is important to evaluate the performance of these new data assimilation systems to treat these observations correctly.

In parallel, a susbtantial activity is devoted to the improvement of the assimilating model in the 4D-Var framework, in particular in the inclusion of physical processes in the assimilating model (Zou *et al.* 1995, Mahfouf et al., 1997).

Last but not least, a key point for operational implementation of 4D-Var remains the cost of the assimilation procedure, specially when one has to cope with short cut-off.

Météo-France is about to move its operational data assimilation system from an OI based system to a 3D-Var system jointly developed with ECMWF.

Some reflexion about a limited area version of the 3D-Var system is currently being carried out while in parallel, the scientific aspects of 4D-Var related above are evaluated in some academic context.

2 Multi-incremental four-dimensional variational assimilation

The incremental approach (Courtier *et al.*, 1994) aims at reducing the dimension of the minimization space and simplifying the model with which the assimilation is performed.

Along those lines an alternative approach is proposed, called multiple-truncation incremental technique, inspired by the previous study and remotely based on multigrid theory grounds, which tries to combine the different benefits obtained in the two methods.

2.1 Methodology

Let us recall the general formalism of the incremental 4D-Var.
From the original 4D-Var cost function :

$$\begin{aligned} \min \mathcal{J}(\mathbf{x}(t_0)) &= \min \left\{ \mathcal{J}^b(\mathbf{x}(t_0)) + \mathcal{J}^o(\mathbf{x}(t_0)) \right\} \\ &= \min \left\{ \tfrac{1}{2} [\mathbf{x}(t_0) - \mathbf{x}^b(t_0)]^T \mathbf{B}^{-1} [\mathbf{x}(t_0) - \mathbf{x}^b(t_0)] \right. \\ &\quad \left. + \tfrac{1}{2} \textstyle\sum_{i=0}^{n} [H_i\mathbf{x}(t_i) - \mathbf{y}_i^o]^T \mathbf{R}_i^{-1} [H_i\mathbf{x}(t_i) - \mathbf{y}_i^o] \right\} \end{aligned} \quad (1)$$

where

$\mathbf{x}(t_0)$ is the initial state of the model;

$\mathcal{J}^b(\mathbf{x}(t_0))$ is the distance of the model at initial time t_0 to the background state $\mathbf{x}^b(t_0)$, which summarizes essentially the past information of the atmosphere. It usually results from a forecast valid at the initial time of the assimilation period;

$\mathbf{B}$ is the covariance matrix of background error;

$\mathcal{J}^o(\mathbf{x}(t_0))$ is the distance of the model to the observations:

$\mathbf{y}_i^o$ is the observation vector at time t_i;

H_i is the observation operator at time t_i. It computes the model-equivalent quantities and interpolates them to the observation locations;

$\mathbf{x}(t_i) = M(t_i, t_0)\mathbf{x}(t_0)$ is the model state at time t_i;

$\mathbf{R}_i$ is the covariance matrix of observation error, which accounts for measurement and representativeness errors.

One can define the increment $\mathbf{x}'(t_0) = \mathbf{x}(t_0) - \mathbf{x}^b(t_0)$;

4D-Var can be approximated to first order as finding the analysis increment $\mathbf{x}'^a(t_0)$ which minimizes the cost function :

$$\mathcal{J}(\mathbf{x}'(t_0)) = \frac{1}{2}\mathbf{x}'(t_0)^T\mathbf{B}^{-1}\mathbf{x}'(t_0) + \frac{1}{2}\sum_{i=0}^{n}[\mathbf{H}'_i\mathbf{x}'(t_i) - \mathbf{d}_i]^T\mathbf{R}_i^{-1}[\mathbf{H}'_i\mathbf{x}'(t_i) - \mathbf{d}_i], \quad (2)$$

where $\mathbf{x}'(t_i) = \mathbf{M}'(t_i, t_0)\mathbf{x}'(t_0)$ and $\mathbf{d}_i = \mathbf{y}_i^o - H_i\mathbf{x}^b(t_i) = \mathbf{y}_i^o - H_iM(t_i, t_0)\mathbf{x}^b(t_0)$, $\mathbf{M}'(t_i, t_0)$ being the resolvent of the tangent linear model between the instants t_0 and t_i. The analysis is obtained by adding the analysis increment $\mathbf{x}'^a(t_0)$ to the background,

$$\mathbf{x}^a(t_0) = \mathbf{x}^b(t_0) + \mathbf{x}'^a(t_0). \quad (3)$$

A simplification operator S is introduced, along with its linearized operator $\mathbf{S}'$ and generalized inverse operator $(\mathbf{S}')^{-I}$. The simplified state vectors are $\mathbf{w}(t) = S\mathbf{x}(t)$, while the simplified increments are $\mathbf{w}'(t) = \mathbf{S}'\mathbf{x}'(t)$. We introduce a simplified dynamics $\mathbf{L}$ approximating $\mathbf{S}'\mathbf{M}'(\mathbf{S}')^{-I}$, and a simplified observation operator $\mathbf{G}$ approximating $\mathbf{H}'(\mathbf{S}')^{-I}$. 4D-Var can then be further approximated as finding the simplified analysis increment $\mathbf{w}'^a(t_0)$ which minimizes the cost function

$$\mathcal{J}(\mathbf{w}'(t_0)) = \frac{1}{2}\mathbf{w}'(t_0)^T\mathbf{B}_{(w)}^{-1}\mathbf{w}'(t_0) + \frac{1}{2}\sum_{i=0}^{n}[\mathbf{G}_i\mathbf{w}'(t_i) - \mathbf{d}_i]^T\mathbf{R}_i^{-1}[\mathbf{G}_i\mathbf{w}'(t_i) - \mathbf{d}_i], \quad (4)$$

with $\mathbf{w}'(t_i) = \mathbf{L}(t_i, t_0)\mathbf{w}'(t_0)$ and $\mathbf{B}_{(w)}^{-1}$ approximating $[(\mathbf{S}')^{-I}]^T\mathbf{B}^{-1}(\mathbf{S}')^{-I}$. The analysis is obtained as

$$\mathbf{x}^a(t_0) = \mathbf{x}^b(t_0) + (\mathbf{S}')^{-I}\mathbf{w}'^a(t_0). \quad (5)$$

This approximate solution to 4D-Var can be improved by iterating the process in order to take the nonlinearities into account.

In the multiple-truncation incremental strategy, the simplication operator S is the same as in the incremental technique but is no longer restricted to be the same for all the minimizations. In fact, we vary it by increasing the truncation at which the minimization is performed with the number of updates of the trajectory.

There is some analogy with the multigrid method for solving partial differential equations, since the change of truncation involves a change of grid in physical space; but this use of several grids is the only common point. The multigrid method relies on the fact that the scale associated with the grid size is easily captured. The idea then is to use several grids in order to capture the corresponding scales. Moreover this method involves some computations to be performed repeatedly on all the grids, in ascending and descending order successively, leading to the so-called V or W-cycles (Hackbusch, 1987). In the current implementation of the multiple-truncation incremental technique, the computations are done only in ascending order since the minimization truncation is always increasing. Moreover the key idea here is to exploit the fast convergence on the large scales during the first iterations of the minimization (Thépaut and Courtier, 1991; Tanguay *et al.*, 1995): the large scales are resolved at low truncation, and the minimization truncation is increased to include more and more scales in the solution.

2.2 The model, the meteorological situation and the observations

We use a 2D barotropic vorticity equation model defined as:

$$\begin{cases} \frac{\partial}{\partial t}\Delta\psi + J(\psi, \Delta\psi + f) = 0, \\ \psi(0) = \psi_0, \end{cases} \tag{6}$$

where ψ is the stream function, f is the Coriolis parameter and J is the Jacobian operator. These equations model the barotropic evolution of the atmospheric flow at 500hPa, where the horizontal wind is nearly non-divergent. Since they express the conservation of the absolute vorticity field, there exists a unique solution which depends continuously on the initial data. The model is discretized using a spectral global method with a decomposition on spherical harmonics and a triangular truncation. A regular Gaussian grid is used.

The meteorological situation which has been used as a test case for variational assimilation is a temporal window from 10 September 1993 00UTC to 11 September 1993 00UTC. Rabier *et al.* (1996) showed the sensitivity of this situation to the initial conditions for the short-range forecast of an extreme event hitting the French Britanny and the Britain coasts severely on the 13 September 1993 00UTC (this situation is known as the Floyd case).

Comparison of forecasts from background and standard 4D-Var analysis showed the ability of 4D-Var to capture the depression, although it was incorrectly located. The Floyd situation may thus contain a barotropic component that makes it useful for assessing assimilation schemes with barotropic models.

We use geopotential height TEMP observations from 10 September 1993 00UTC to 11 September 1993 00UTC. The observations are quality-controlled using the Météo-France operational OI based quality control, and grouped in 1-hour packs centered at the observation times. The covariance matrix of observation error is a multiple of the identity matrix

$$\mathbf{R} = \sigma_o \, \mathbf{I}, \tag{7}$$

where the standard deviation σ_o is set to 12.8 m.

As for the observation operator, the linear balance equation is solved:

$$\Delta\phi = div(f\ \mathbf{grad}\ \psi), \tag{8}$$

where ϕ is the geopotential and ψ is the streamfunction. Such a coupling between the mass field and the wind field is unrealistic in the tropics (see e.g. Daley, 1991 pp 228-230). As a consequence all observations poleward of 20 degrees of latitude have been discarded for the present study.

To generate the background field, operational fields from the data base of Météo-France, valid for 09 September 1993 00UTC, are processed in order to get the corresponding spectral fields at truncation T95 on the 500hPa pressure level and for a regular Gaussian grid. The streamfunction field is extracted and integrated during 24 hours with the barotropic vorticity equation model to make it consistent with the dynamics. This 24-hour forecast constitutes our background field, valid for 10 September 1993 00UTC.

The covariance matrix of background error, which corresponds to horizontal homogeneous correlations in grid-point space, is diagonal in spectral space

$$\mathbf{B} = \sigma_b\ \mathbf{D}, \tag{9}$$

where the diagonal matrix $\mathbf{D}$ contains the parametric power spectrum of Courtier *et al.* (1993) and the standard deviation σ_b for the streamfunction corresponds to a standard deviation of 21 m for the geopotential height at 45 degree N.

Three types of experiments have been performed and compared. For each of these, we give a short name and a description:

Std T95 This is a classical 4D-Var 24-hour assimilation. The control variable has a T95 triangular truncation. 80 iterations of minimization are performed, leading to a three-order decrease of the gradient norm.

Inc. T95/T63 This is an incremental 4D-Var experiment. The background field is at truncation T95, and 4 minimizations of 20 iterations are performed at truncation T63.

Inc. T95/T79 This is the same as Inc. T95/T63 except that the 4 minimizations are performed at truncation T79.

Multi-trunc. Inc. This is a multiple-truncation incremental 4D-Var experiment. The background field is still at truncation T95. 4 minimizations of 20 iterations are successively performed at truncations T21, T42, T63 and T79. After each minimization, the T95 first guess is corrected by adding the computed departure $\mathbf{x}'$ on the corresponding scales.

In all the experiments, the minimization problems have been preconditionned by a change of variable using the square root of the covariance matrix of background error.

The minimizations were performed using the limited-memory quasi-Newton minimizer N1QN3 (Gilbert and Lemaréchal, 1989). This algorithm refines an approximation of the inverse hessian at each iteration by adding a rank-two correction to the previous approximation. A 'warm-start' option is included to allow a start of the minimization with an already available approximation of the inverse hessian. In all the incremental experiments this facility is used.

2.3 Numerical Results

The geopotential height corresponding to the 24-hour prediction from the background field and from Std T95 4D-Var solution at the end of the assimilation period are shown on top and bottom panels of Fig. 1 respectively, for latitudes greater than 20 degree N. The contour interval is 50m and the geopotential has been deduced from the streamfunction via the linear balance Eq. (8). One can see significant changes between the background and the analysis; these are due to the poor quality of our background field. Such a poor background was required to test the effectiveness of the assimilation process with such a simple model: 80 iterations lead to a three-order decrease of the gradient norm, to be compared with the required 100 iterations for a two-order gradient-norm reduction when using a primitive-equation model and a good quality background field (Courtier *et al.*,1994).

Fig. 2 show the geopotential height differences between the incremental analyses and Std T95 4D-Var analysis, at the end of the assimilation period. One can see that the differences are small, pointing out to the fact that the Multi-trunc. Inc. method has converged satisfactorily.

Two forecasts have been performed for 13 September 1993 00UTC from the background and the Std T95 4D-Var analysis respectively. Although we did not intend to predict the full baroclinic development of Floyd with a simple 2D barotropic model, the prediction from the 4D-Var analysis exhibited a low in the near Atlantic whereas the one issued from the background had only a loose trough (not shown).

One possibility to assess the performance of the various methods is to compare the final values of the different terms appearing in the nonlinear cost function. Those values are reported in Table 1. Among the incremental experiments, Multi-trunc. Inc. has the lowest total cost function $\mathcal{J}$ and distance to the observations $\mathcal{J}^o$, as well as the highest distance to the background field $\mathcal{J}^b$. These are the closest values of the cost functions to Std T95 ones. However all the cost functions $\mathcal{J}$ have similar magnitudes, from which a similar quality of the analyses can be expected.

Table 1 presents the final values of the cost function for the different types of experiments.

But what is really important is not how well the observations are fitted over

TAB. 1 - *Final values of the cost functions $\mathcal{J}$, $\mathcal{J}^o$ and $\mathcal{J}^b$.*

Experiment	$\mathcal{J}$	$\mathcal{J}^o$	$\mathcal{J}^b$
Std T95	.15496632E+04	.88591132E+03	.66375183E+03
Inc. T95/T63	.16164509E+04	.96774432E+03	.64870660E+03
Inc. T95/T79	.16216021E+04	.97771350E+03	.64388855E+03
Multi-trunc. Inc.	.16000685E+04	.94695776E+03	.65311072E+03

TAB. 2 -

Experiment	Rough-time ratio (%)
Std T95	100
Inc. T95/T63	28.40
Inc. T95/T79	57.95
Multi-trunc. Inc.	23.19

the assimilation period, but rather how the forecast from the analysis fits the real behaviour of the atmosphere past the end of this period. Consequently 48-hour forecasts have been performed from the various analyses and the global geopotential height RMS to TEMP observations have been computed every 12 hours and are plotted at the top of Fig. 3. The period between -24h and 0h is the assimilation period. The best fit to the observations occurs in the middle of the assimilation period, in agreement with the results of Pires *et al.* (1996). One can see that the various forecasts have a similar quality.

The main interest of the multiple-truncation incremental assimilation is the numerical cost of the method.

A 'rough-time ratio' of the different assimilation experiments has been computed and is displayed in Table 2.

To these figures correspond the execution time of the experiment divided by the execution time of Std T95 experiment, excluding the time spent in post-processing activities. The Multi-trunc. Inc. experiment has clearly the smallest execution time. In Multi-trunc. Inc. experiment about 10 % of the execution time is spent in the first two minimizations, 30 % and 60 % are spent in the third and fourth minimizations respectively.

In conclusion, and despite the simplicity of the experimental framework (in particular the assimilating model), Multi-trunc. Inc. seems to give results of comparable quality to the standard incremental assimilations, and at a much smaller cost. This approach exploits the fact that the minimization converges on the large scales first.

This result, if confirmed in the context of a multi-level primitive equation model, shows a further potential for cutting the cost of 4D-Var while keeping the main benefit of 4D-Var: the use of dynamical structure functions.

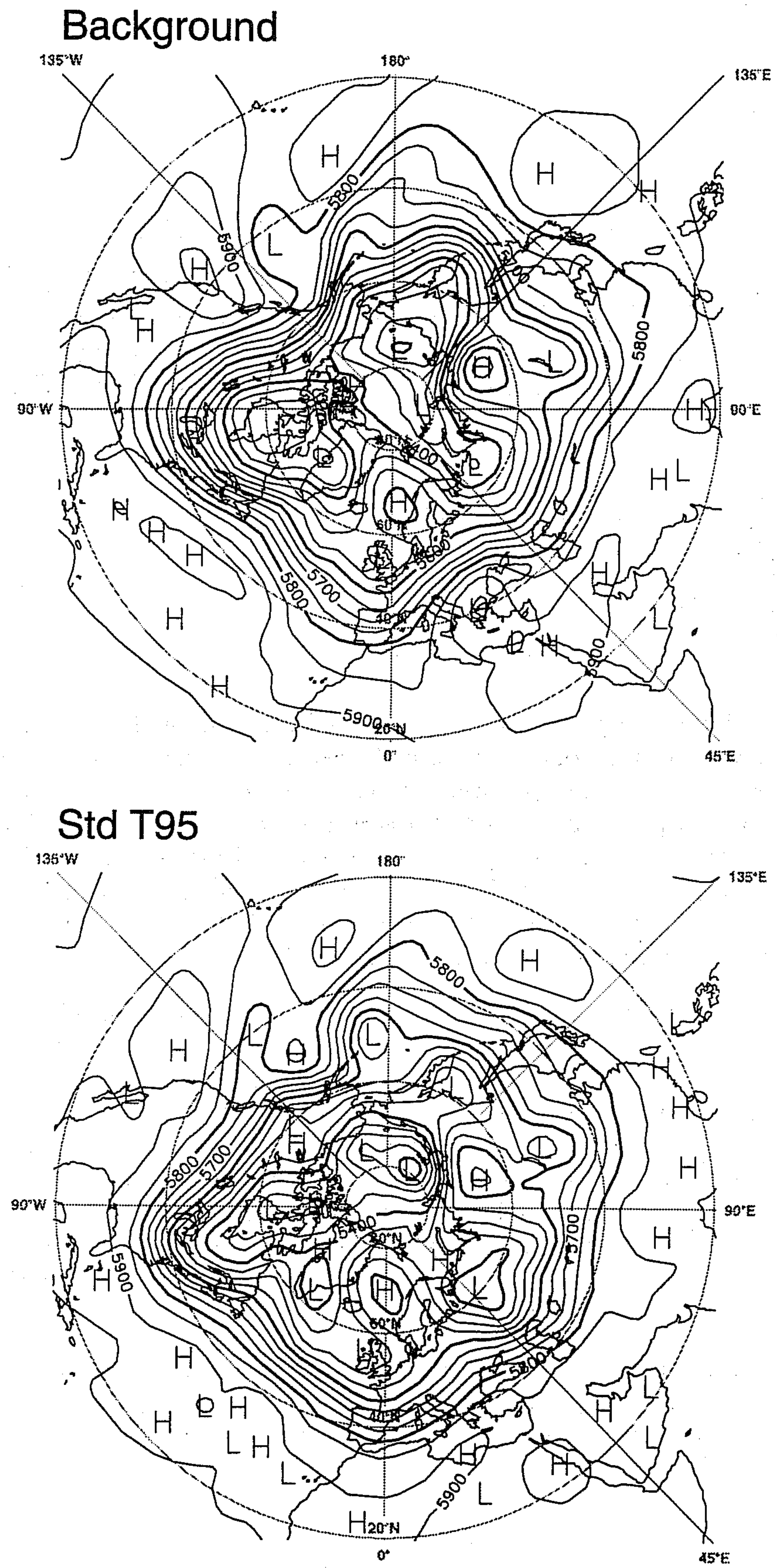


FIG. 1 - *Geopotential height fields: (top) 24-hour prediction from the background field, (bottom) Std T95 4D-Var analysis at the end of the assimilation period. Contour interval: 50m.*

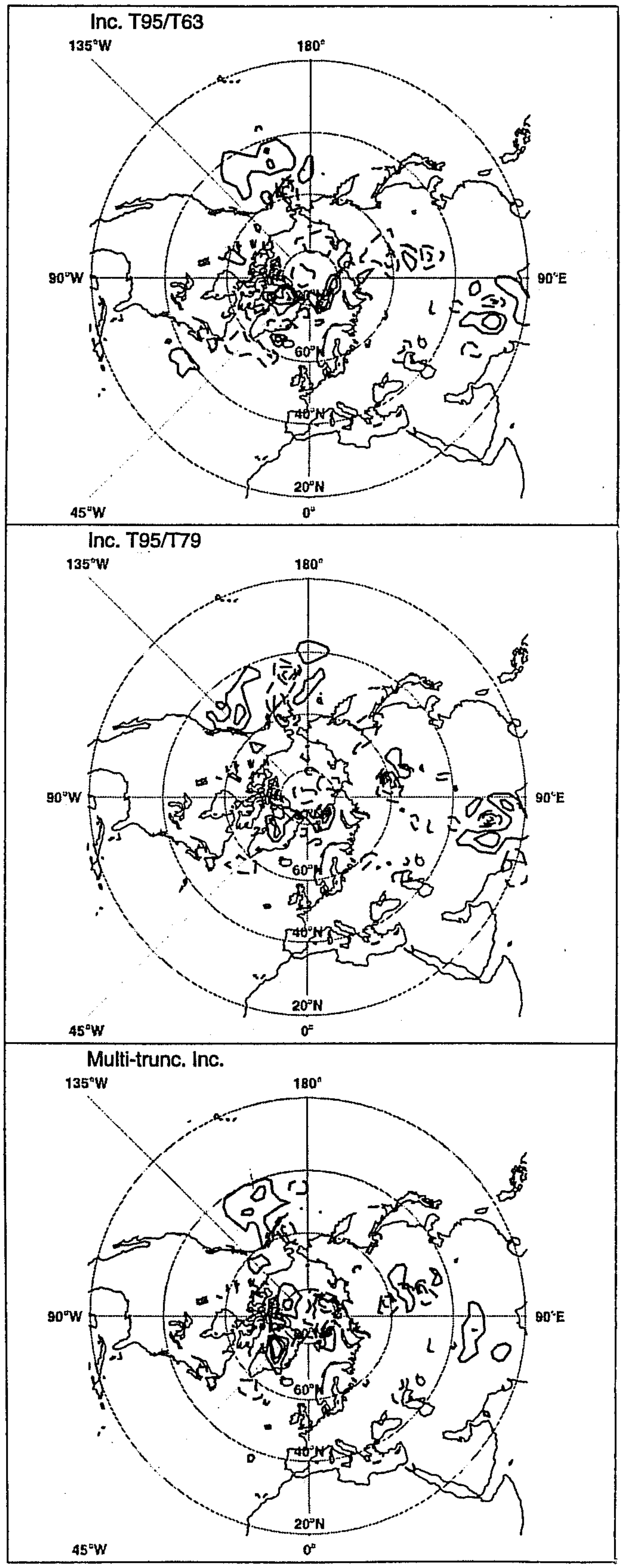


FIG. 2 - *Geopotential height differences between the incremental analyses and Std T95 4D-Var analysis, at the end of the assimilation period. Contour interval is 5m, positive/negative differences are indicated by solid/dashed contour lines.*

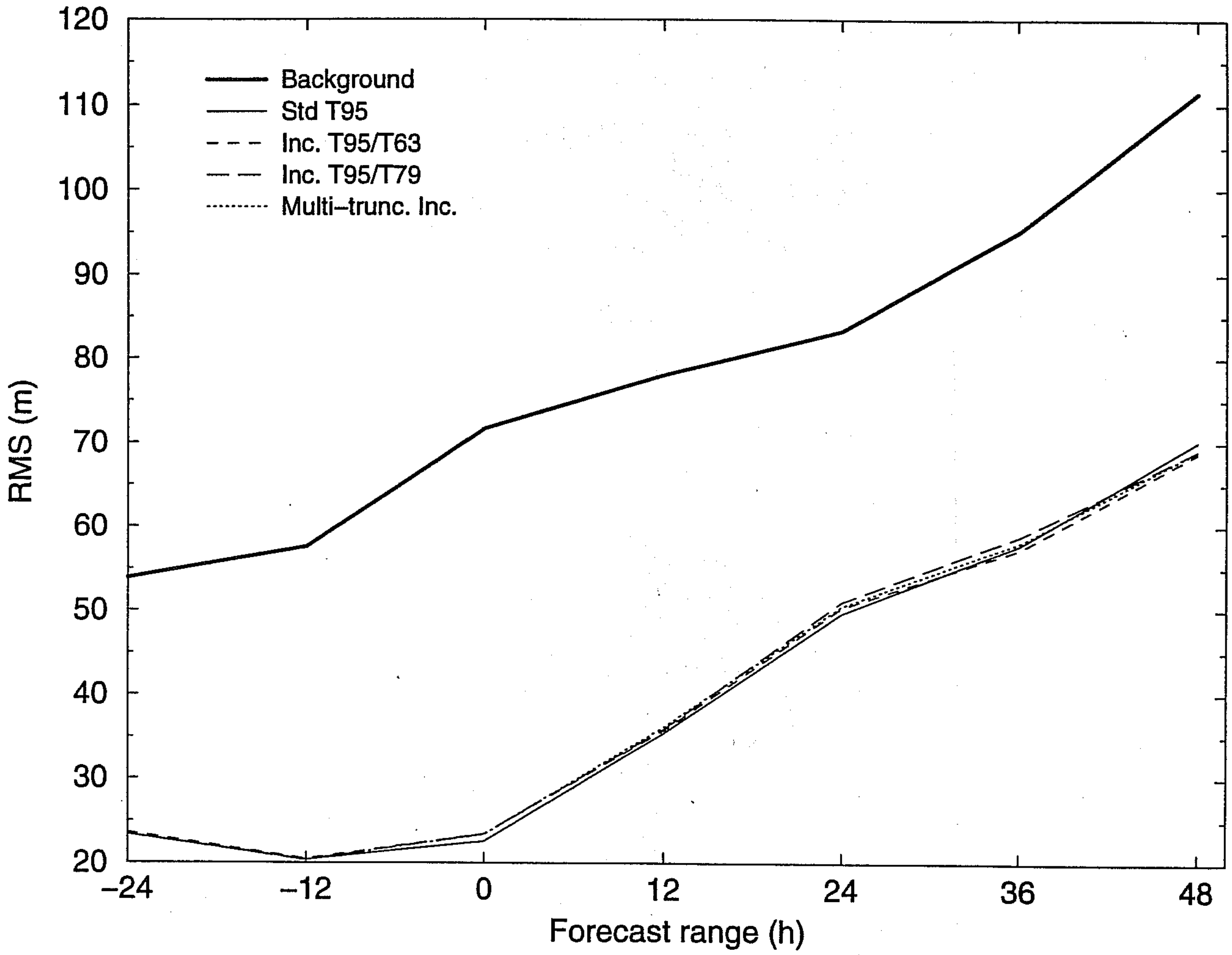


FIG. 3 - *Geopotential height RMS of differences between predictions and TEMP observations poleward of 20 degrees of latitude.*

3 Simplified physical package for incremental 4D-Var

The second topic related to 4D-Var on which Météo-France is active concerns the general problem of improving the assimilating model. Rabier et al. (1996) have shown that a T63 adiabatic model used in sensitivity experiments was able to represent to a reasonable accuracy phenomena linked to baroclinic instability. However, for high resolution models tuned for short-range weather prediction, the moist processes start playing a crucial role. Therefore it is of utmost importance that these processes are taken into account in the assimilating model. Moreover, the inclusion of such processes is a necessary step towards the use of the observations related to the model's physics, such as precipitation, clouds, etc.

The incremental approach allows an improvement of the linearized model by introducing physical parametrization.

However, the physical processes (such as condensation, convection, vertical diffusion, etc.) are highly nonlinear and often discontinuous, which may cause serious convergence problems in the minimization. To avoid this problem the physical parametrization used for 4D-Var should be simple and regular, while respecting the order of magnitude and general feed-backs of physical phenomena present in the atmosphere. This leads to a modification of the "perturbation" forecast model to make it more continuous (by eliminating some of the most serious discontinuities), but at the same time to preserve the quality of the forecast of the "errors".

3.1 Main features of the different physical packages

The proposed set of simplified physical parametrizations contains a simplified computation of radiative fluxes, vertical turbulent diffusion, orographic gravity waves, deep convection and stratiform precipitation fluxes. For the simplified physics we suppose that the soil variables (surface temperature T_s, surface humidity q_s, roughness length z_0, snow cover) are considered as constant in time and taken from a model trajectory run with a full physical package. Despite this separation of atmospheric and surface problems, the treatment of physical processes in 4D variational assimilation is still rather complex.

Stratiform precipitation.

For stratiform precipitation we suppose that all supersaturation is immediately removed from the system on one hand, and everything is evaporated when the given sub-cloud layer is unsaturated on the other hand. Melting of falling precipitations happens when the temperature is equal to or greater than 0^o C.

Gravity wave drag.

The scheme which is used in ARPEGE is a modified version of the scheme of Boer et al. (1984), where during the computation of the linear deposition rate the flux is assumed to be only saturated (the so-called Lindzen criterium) at the surface and is also determined by the same condition during the upward propagation of the wave. An important feature of the scheme is blocking of the low level flow, when the effective height of the sub-grid scale orography is high enough.

The simplified version for parametrization of gravity wave drag contains only the linear part of computation of orographic gravity-waves breaking effects on momentum. Non-linearities of the atmosphere behaviour, such as resonant damping or enhancement of the surface stress, are omitted. Similarly, trapping of the waves below an unstable layer is not taken into account.

Vertical turbulent diffusion.

The parametrization of vertical diffusion is a very important part of the parametrization of atmospheric processes.

The exchange coefficients for heat and momentum are computed according to Louis et al. (1981) while the shallow convection is parametrized with a slightly modified version of Geleyn (1987). The assumption of constant fields for surface temperature and surface humidity allows the simplification of the original vertical diffusion scheme and the use of two independent matrices for the computation of turbulent fluxes for specific humidity and dry static energy, as it is usually done for the computation of turbulent fluxes for momentum.

Radiative processes.

In order to facilitate the derivation of the adjoint of the radiative parametrization scheme we propose a method for the computation of long wave and short wave radiative fluxes built up under the assumption that the properties of gases are constant (this is probably acceptable up to 24 hours).

The coefficients, which represent the properties of transmission, absorption, scattering and reflection of gases (resp. liquid water) for short-wave radiation, are computed during one time step integration of the full radiation scheme for a mean solar angle. The dependency of the coefficients on actual cloudiness is recomputed during the integration of the simplified model and the solar fluxes are obtained by using the basic flux equations.

For thermal radiation, the simplification consists in calling the complete ARPEGE radiation routine only for recovering the coefficients of the so called Curtis matrix. Then the coefficients of this matrix are recomputed as a function of cloudiness in the simplified physical parametrization. The thermal radiation flux is obtained by using the Stefan-Boltzmann law multiplied by this matrix.

Moist convection.

The moist convection parametrization is undoubtebly the most difficult part of the parametrization problem because of its strong interaction with all the other parametrizations.

The proposed scheme is a mass-flux type scheme (Geleyn et al. 1982, Motte and Ruiz, 1987). The effect of convection on environmental properties is computed according to the vertical distribution of the cloud mass flux. This leads to a realistic forecast of the convection effects on the balance of temperature and humidity, while allowing at the same time a simple parametrization of the effects on the momentum. The closure assumption is of Kuo-type. When there is a positive convergence of moisture in a model layer and conditional instability aloft, all the moisture increase (dq/dt) is either rained out or detrained at the top of an ascent. The mentioned closure assumption provides a satisfactory way of partitioning moisture convergence between rainfall and moistening. The necessary parametrization of the liquid water provides an extra degree of freedom to build a self-regulating mechanism in this partitioning.

3.2 Validation of the simplified direct physical package.

The first validation of the simplified physical parametrization has been done by comparing the forecasts performed (up to 24 hours) using the model with the complete physics and the model where particular physical parametrizations of the full model where gradually exchanged by simplified physical parametrizations. Such comparisons allowed us to evaluate the behaviour of each simplified physical parametrization itself. Although the experiments have been performed on only few cases, the simplified scheme seems to behave quite reasonably. There is some problem in vertical diffusion scheme producing noise in the mountains area which has not been solved yet. Of course, once the package of simplified physical parametrizations is complete, it will be necessary to concentrate on more systematic validation and on tuning the most important parameters.

3.3 validation of TL and Adjoint models

The tangent-linear and adjoint of above mentioned physical parametrizations has been developed. After the standard validation of the tangent-linear and adjoint codes (Taylor formula and adjoint identity), comparisons have been done between on one hand the evolution over 6 hours of a perturbation (of the order of magnitude of analysis increments) with the simplified tangent linear model and on the other hand the finite difference between two nonlinear forecasts using full physical parametrizations, one from a basic state and the other from a perturbated state (Fig. 4). For this type of validation, the global ARPEGE model (using 19 levels and a spectral resolution) was used and the tangent-linear parametrizations (vertical diffusion, large scale condensation, gravity wave drag) developed at that stage were tested (Fig. 7). The results were compared also with an adiabatic tangent linear model (Fig. 5). We concentrated on the comparisons of the zonal mean of temperature, water vapour and zonal wind. In Fig. 4 - 7 the diagnostic for temperature is presented.

The physics is far more nonlinear than the dynamics. This is why the aim is to develop a physical parametrization for the tangent-linear model which is simple and regular. The problem of regularization is to find a trade-off between a linear physical parametrization with no full description of physical processes,

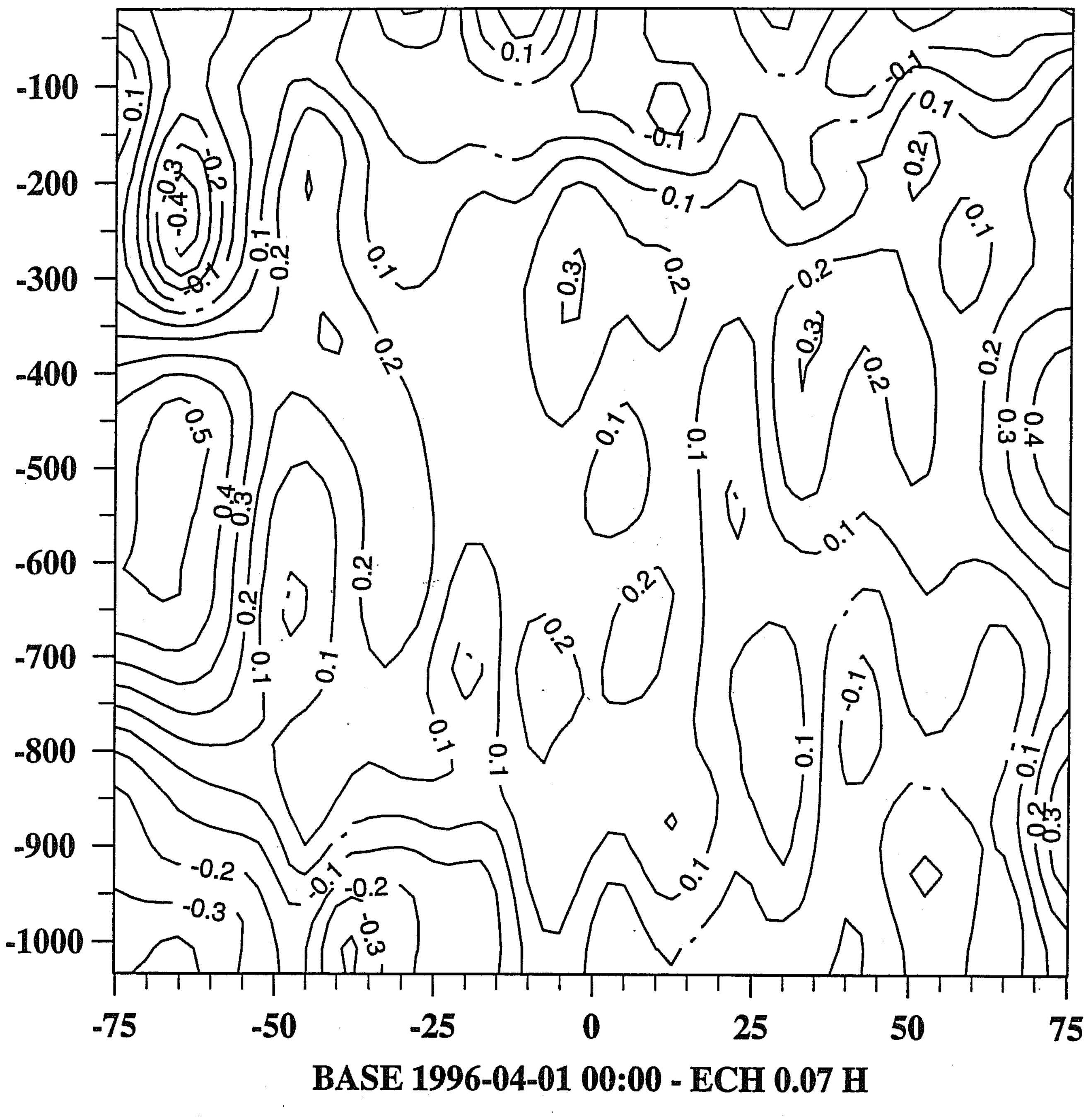


FIG. 4 - *Zonal mean of the finite difference of temperature between two nonlinear forecasts, one from a basic state and the other from a perturbated state, for 6 hours integration.*

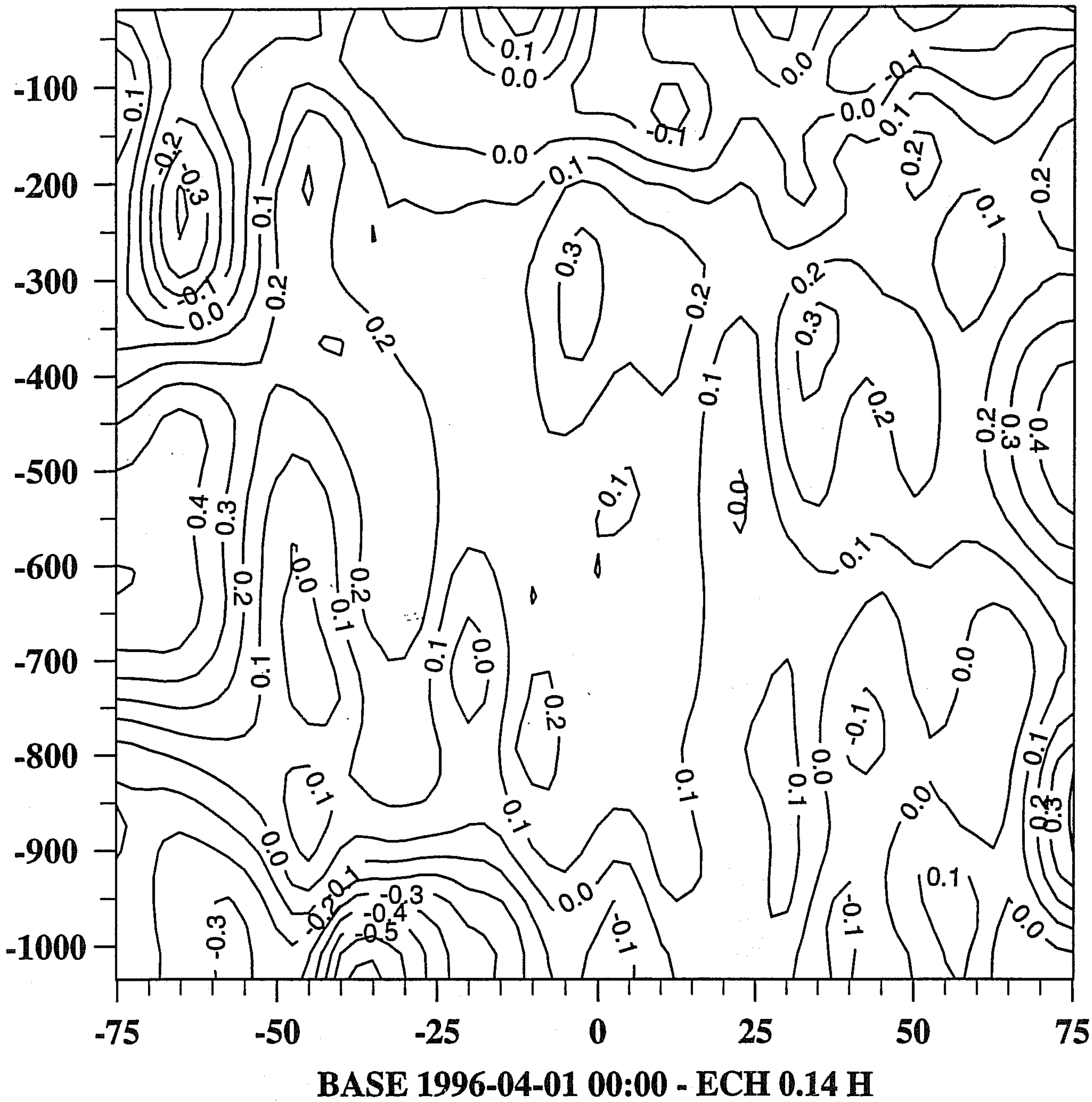


FIG. 5 - *Zonal mean of the perturbation evolution of temperature (with the order of magnitude of analysis increments) after 6 hours integration with the adiabatic tangent linear model.*

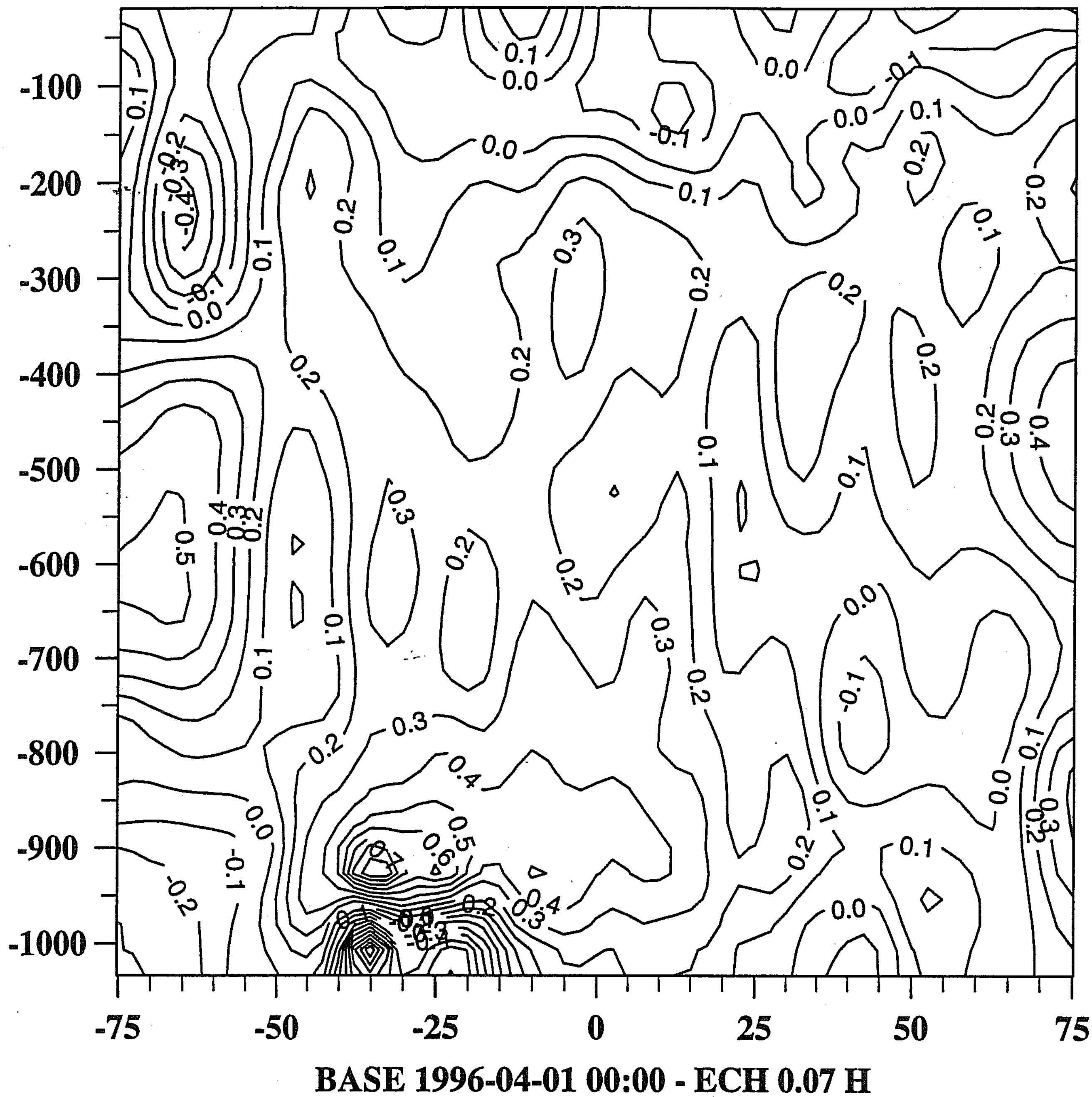
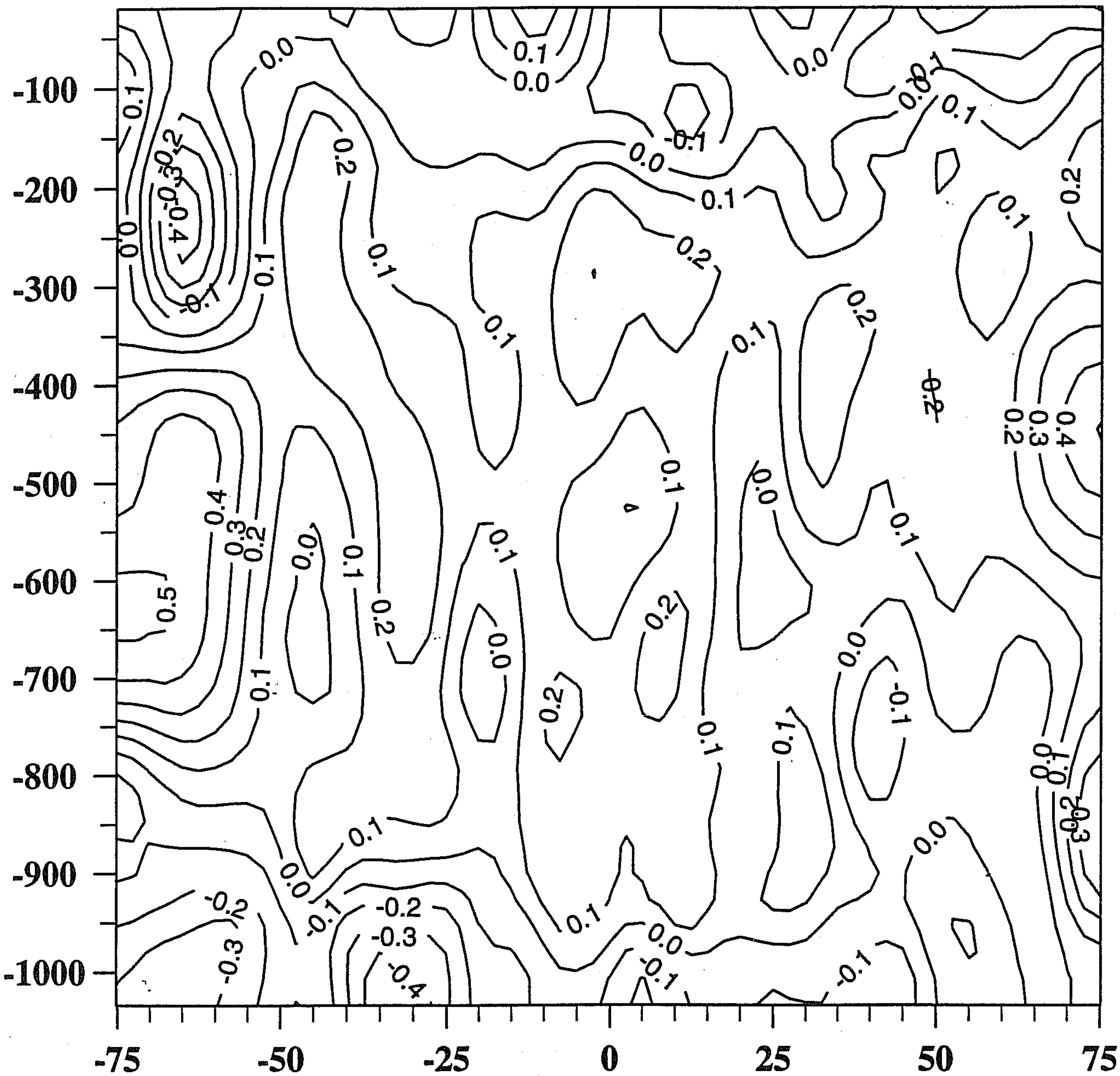


FIG. 6 - *Same as Fig. 5, but with the original vertical diffusion scheme.*



BASE 1996-04-01 00:00 - ECH 0.14 H

FIG. 7 - *Same as Fig. 5, but with a smoothed function of the Richardson number in vertical diffusion scheme.*

and a full physical parametrization which is very nonlinear.

Although we have tried to develop the set of simplified physical parametrization as much differentiable as possible, several difficulties remain, which can appear from a differentiation point of view in the physical processes like discontinuities of some functions themselves describing the physical processes - some on/off processes (for instance produced by supersaturation), some discontinuities of the derivative of a continuous function or some strong non-linearities. To overcome some of the mentioned difficulties the smoothing modifications of parametrized discontinuities can be developed.

As an illustration of potential problems, the results from the validation of the tangent linear model are also presented for the tangent linear model with a simplified physical parametrization without applying any smoothing. One can see in Fig. 6 spurious noise in the 6 hours evolution of the perturbation of temperature close to the surface. We discovered that the noise problems come from the vertical diffusion scheme and it arises from a function of the Richardson number $f(Ri)$. This function itself as well as its derivative has a significant rate of change around the point of singularity (neutral state of the atmosphere). To solve this problem we have applied a smoothing of the function $f(Ri)$, where the turbulence is increased a little bit in stable regime and decreased in unstable situations, for an interval where the Richardson number is close to neutrality. This removed the pike of the derivative (the jump around zero). The results presented in Fig. 7 correspond now well to the finite difference between two nonlinear forecasts.

After solving the mentioned problem the simplified tangent-linear model behaves well. Comparing the results presented in Fig. 4, 5 and 7, one can see that the tangent linear model describing the evolution of a perturbation with the simplified physical parametrization can fit the finite difference between two nonlinear forecasts much better than the adiabatic tangent linear model. This strongly suggests that the inclusion of the physical parametrization in 4D-Var will improve the simplified linear model.

3.4 Perspectives

For the incremental 4D variational assimilation, a set of simple, regular and realistic physical parametrizations is being developed and the first validation of the simplified physics has been done. For the time being the parametrization schemes for vertical diffusion, large scale condensation, gravity wave drag and the radiative processes have been developed. The development of the TL/AD of the simlified convection scheme is under development. A more systematic validation and tuning of the whole package will then be done.

The next step will be the scientific validation of the tangent-linear radiation scheme and the development of the tangent linear and adjoint codes will be completed by the development of the adjoint of the convection scheme. It might then be necessary to remove most of the thresholds in physical parametrizations which can affect the range of validity of the tangent linear aproximation while keeping the description of atmospheric processes physically sound.

4 4D-Var OSSE experiments

An important issue in the context of data assimilation is the general feeling that to improve the initial state of the atmosphere in NWP, a considerable effort should be put in global space-based remote sensing systems to overcome the deficiencies of the current conventional observational network which suffers from important weaknesses, specially over the oceans. For example, evidence has been shown of the benefit of using cloud-cleared radiances from the NOAA satellites in data assimilation (Andersson et al., 1994) and several operational centres are currently using them (European Centre for Medium Range Weather Forecasts, National Meteorological Centre of USA).

General observation requirements for NWP have been established by WMO (World Meteorological Organisation) in terms of accuracy and horizontal,vertical and time resolution. They distinguish the global needs (resolution desired uniformly over the globe for global models) from the regional needs (other requirements for one particular area of the globe). They state that by the end of the nineties, the 3D-Structure for temperature and wind should be observed in the atmosphere with at least a 100 km resolution in the horizontal and 15 levels in the vertical (10 in the troposphere and 5 in the stratosphere). These requirements are the global ones; the regional ones are èven much more stringent. Although these figures give only rough indications based on the likely evolution of NWP models in the next few years, they illustrate very well the deficiencies of the present observational network, where some data gaps larger than 1000 km exist in the observation of vertical wind and temperature profiles. This deficiency is even more striking for the wind field inside the tropics as it cannot be inferred indirectly from the mass field through the geostrophic balance, as it can be done in mid-latitudes. Indeed 3D observations of the wind inside the tropics are one of the major requirements, not only for meteorological applications inside the tropics, but also for medium range mid-latitude NWP forecasts which are affected by the initial analysis in the tropics.

Up to now, current global space-based systems provide 3D information on temperature (TOVS data) or single-level wind (SATOB winds from Meteosat, surface scatterometer winds from ERS1). A 3D description of the wind field is still missing, and it is of utmost importance to evaluate the potential of this product as a prerequisite to a possible set-up of such a new global space-based system.

A DWL system on a polar orbiting satellite is very promising to that respect, since it seems to have the capacity to measure globally the vertical profiles of the wind above the clouds, at least in the troposphere and in the lower part of the stratosphere. This would constitute an enormous step compared with the current wind observation situation.

Before such an instrument is operational (the ALADIN project from the European Space Agency - ESA- is planned towards 2005, Marini et al. 1995), some quantitative assessment of the impact of DWL data can be done. The object of the work undertaken at Météo-France was to evaluate the potential benefit of using this source of observations in NWP through systematic studies based on Observing System Simulation Experiments (OSSE).

4.1 The observations

The contribution of DWL data to NWP strongly depends on their amount, quality and distribution. In this respect, a project called : "Theoretical Studies of the Impact of Doppler Wind Lidar Data - Preparation of a Data Base" has been completed for ESA, end of 1994, at ECMWF (Stoffelen et al., 1994). The goal was to prepare a 30 day data base of DWL and conventional observations for use in OSSEs. Several orbit and instrument scenarios have accounted for, which allows a more complete evaluation of the impact of such data in function of their quality/coverage. Another advantage of this simulated data base is that the "truth" or "true atmosphere" is known, since it is the atmospheric model itself. We have used this data base to perform our experimentations.

4.2 The assimilation experiments

We have used the 4D variational assimilation facility which has been developed at ECMWF in collaboration with Meteo-France (Rabier et al., 1996). The advantage of the method is firstly that that it allows a consistent use of observations and the dynamics (and potentially the physics). Secondly, 4D-Var is capable of using asynoptic observations at appropriate time, which is of interest for those simulated DWL data. Lastly, by 2005, 4D-Var assimilation techniques are good candidates to be the operational systems when (and if) DWL instruments are flying.

A series of small OSSEs with these DWL simulated data have then been carried out using a 4D-Var system on a 12 h period range of 5 february 1993 (Haution, 1993) and with the simulated observations from the above mentioned data base. The assimilating model was at much lower resolution (T42L31) than operational models and basically adiabatic.

4.3 Numerical Results

Despite the limitations due to the model resolution, the main outcome of these experiments was that the direct assimilation of the Line Of Sight (LOS) wind components provided in the data base is possible and works as expected in advanced assimilation systems such as 4D-Var. As an example, Fig. 8 represents the fit to observations at the end of the assimilation period (the assimilation having used both conventional and LOS wind data) from the background trajectory (thick line) and the analysis (thin line) for conventional radiosonde wind observations and for different geographical areas. We have verified that the fit to conventional observations was virtually the same whether the LOS wind observations were used or not (not shown).

The fit of the 4D-Var trajectory at the end of the assimilation period to the DWL observations is presented in Fig. 9, showing a reasonable fit in the Northern Hemisphere, Tropics and Southern Hemisphere.

Moreover, one could identify some areas over the pacific ocean which were clearly improved by the use of LOS wind observations (not shown).

4.4 OSSE plans

The investigation of the performance of 4D-Var to use DWL data will continue to be carried out in a more realistic context, in particular using a higher resolution model and the new scenarios which are currently evolving.

Lastly, let us mention that we have some plans to evaluate the impact on the wind field of passive tracers in a 4D-Var assimilation (this project belongs to the Météo-France proposal to the CNES/EUMETSAT IASI project) and more generally to tackle the problem of assimilation of ozone observations (SODA project).

5 Conclusion

Although it is difficult to give any firm dates for an operational implementation of 4D-Var in the operational system in Météo-France (a new computer is for example a prerequisite), a number of issues related to 4D-Var are being tackled in Météo-France, the long-term goal being twofold :

- to develop a **fast** 4D-Var system at **high resolution** with a **good** assimilating model. To achieve this, work is being done on the multiple truncation incremental approach and on the development of a dedicated physical package. Work has also started in the definition of a 3D-Var system for a limited-area high resolution model (this work is done in collaboration with HIRLAM and LACE). The 4D-Var step will come afterwards. This will include a generalization of the variational method for the surface analysis, area where some work is also starting at Météo-France currently.

- to evaluate the potential of new sources of observations. The work which has been undertaken in evaluating 4D-Var using simulated DWL observations is an example of the interest that Météo-France is showing in this area. Some effort should also be put in the use of GPS data. This work is of course related to the development of an adjoint physics.

6 References

Andersson, E., Pailleux, J., Thépaut, J.-N., Eyre, J., McNally, A., Kelly, G. and Courtier, P. 1994: Use of cloud-cleared radiances in three/four-dimensional variational data assimilation. Q.J.R.Meteorol.Soc, 120, 627-653.

Boer G.J., McFarlane, N. A., Laprise, R., Henderson, J.D., Blanchet, J.P., 1984: The Canadian Climate Centre spectral atmospheric general circulation model. Atmos. Ocean, 22, 1984, 397-429.

Courtier, P., Andersson, E., Heckley, W., Kelly, G., Pailleux, J., Rabier, F., Thépaut, J.-N., Undén, P., Vasiljevic, D., Cardinali, C., Eyre, J., Hamrud, M., Haseler, J., Hollingsworth, A., McNally, A. and Stoffelen, A. 1993: Variational assimilation at ECMWF. ECMWF Tech. Memo., 194, 84 pp.

Courtier, P., Thépaut, J.-N., Hollingsworth, A. 1994: A strategy for implementation of 4D-Var, using an incremental approach. Quart. J. Roy. Meteor. Soc., 120, 1367-1387.

Daley, R. 1991: Atmopsheric Data Analysis, Cambridge atmospheric and space sciences series, Cambridge University Press.

Geleyn, J.F., 1987: Use of a Richardson number for parametrizing the effect of shallow convection. J.Meteor. Soc. Japan, Special NWP symposium issue, 141-149.

Geleyn, J.F., Girard, C., Louis, J.-F., 1982: A simple parametrization of moist convection for large-scale atmospheric models. Beitr. Phys. Atmosph. Vol.55 No.4, 325-334.

Gilbert, J.-C. and Lemaréchal, C. 1989: Some numerical experiments with variable storage quasi-Newton algorithms. Mathematical Programming, B25, 407-435

Hackbusch, W. 1987: Multigrid Methods and Applications, Academic Press.

Haution, P. 1995: Impact potentiel des mesures de vent par Lidar Doppler sur la prévision numérique en météorologie. Rapport de stage d'option de l'école des Mines de Paris, France.

Louis, J.F., Tiedke, M., Geleyn, J.F., 1981: A short history of the PBL parametrization at ECMWF. Proceedings of the ECMWF workshop on planetary boundary parametrization. Reading, 59-80.

Mahfouf, J.-F., Buizza, R. and Errico, R.M. 1997: Strategy for including physical processes in the ECMWF variational data assimilation system. this volume

Marini, A. and A. Culoma, 1995: ESA activities for spaceborne Doppler Wind Lidar. Proceedings of the ESA Doppler Wind Lidar Workshop, ESTEC, Noordwijk, 20-22 September 1995. Available from ESA/ESTEC.

Motte, P., Ruiz, F., 1987: Elaboration d'un ensemble simplifie de "parametrisations physiques". Note de travail de l'ENM. May 1987, 133 p.

Pires, C., Vautard, R. and Talagrand, O. 1996: On extending the limits of variational assimilation in nonlinear chaotic systems. Tellus, 48A, 96-121.

Rabier, F., Thépaut, J.-N. and Courtier, P. 1997: Four dimensional variational assimilation at ECMWF. ECMWF seminar on data assimilation, 2-6 september

1996.

Rabier, F., Klinker, E., Courtier, P. and Hollingsworth, A., 1996: Sensitivity of forecast errors to initial conditions. Q. J. R. Meteorol. Soc., 122, 121–150.

Stoffelen,A., B. Becker, J. Eyre and H. Roquet, 1994: Theoretical Studies of the impact of Doppler Wind LIDAR data. Preparation of a Data Base. ESA contract report no AO/1-2345/90/HGE-1

Tanguay, M., Bartello, P. and Gauthier, P. 1995: Four-dimensional data assimilation with a wide range of scales. Tellus, 47A, 974-997.

Thépaut, J.-N. and Courtier, P. 1991: Four-dimensional variational data assimilation using the adjoint of a multilevel primitive-equation model. Q.J.R.Meteorol.Soc, 117, 1225-1254.

Thépaut, J.-N., Courtier, P., Belaud, G. and Lemaître, G. 1996: Dynamical structure functions in a four-dimensional variational assimilation: a case study. Q.J.R.Meteorol.Soc, 122, 535-561.

Zou, X., Kuo, Y.H. and Guo, Y.R. 1995: Assimilation of atmospheric radio refractivity using a non-hydrostatic adjoint model. Mon. Wea. Rev., 124, 2229-2249.

Zupanski, D. 1997: A general weak constraint applicable to operational 4DVAR data assimilation systems. Submitted to Mon. Wea. Rev.