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Research topic: Coupling a variational assimilation of gridpoint surface fields with a 4d variational assimilation of upperair spectral fields
Title of doctoral thesis: Analysis of soil moisture in a mesoscale weather prediction model

The analysis of soil moisture in a mesoscale numerical weather prediction (NWP) model is considered. A linearised variational technique for the analysis of total soil water content via the assimilation of screen-level observations has been implemented and evaluated in the ALADIN-NWP model. The main hypotheses on which is based the variational approach are investigated by mean of several simulation experiments. The results of soil moisture analyses are validated by comparison to a hydrologic off-line system (SIM - Safran-Isba-Modcou) over France and by an improvement of the weather forecast issued from the new soil moisture initialisation.

Introduction

The soil moisture over land is a key component of the surface water and energy budgets. The soil water content regulates the partition of latent and sensible heat fluxes at the surface affecting a large number of boundary-layer and low-troposphere processes. An accurate estimate of this quantity over extensive areas might provide opportunities for many applications and for this reason agricultural, hydrological, meteorological and climatological studies have considered it for quite some time. No extensive observation network exists because of the difficulty and the expense associated with measuring soil moisture on a routine basis. For this reason, the assimilation of indirect observations from ground-base (raingauges, radars, screen-level) and satellite instruments (infrared and microwave radiometers), has been studied for the analysis of soil moisture. In particular, the assimilation of 2m temperature and relative humidity observations with the optimum interpolation (OI) technique (Mahfouf 1991, Bouttier et al. 1993 I,II) has proven to be reliable in obtaining the soil water content under specific meteorological conditions, and is currently used in operations in different NWP centres (Giard and Bazile 2000, Douville et al. 2000). In recent years, several studies have shown the reliability of the variational technique for the analysis of soil moisture via the assimilation of screen-level observations, by Callies et al. (1998), Rhodin et al. (1999), Bouyssel et al. (2000), Hess (2001).

A simplified variational analysis for soil moisture

The present work focuses on the analysis of the total soil water content in a two-layer force-restore land surface scheme, via a bi-dimensional (z and t) variational approach (2D-VAR). The analysis is performed on each grid point separately. As given by the variational analysis theory, the optimal weighting of the observation and the background components is achieved by the minimisation of a cost function J, which is of the form

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + \frac{1}{2}(\mathbf{y} - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x}))$$

where $\mathbf{x}$ is the vector containing the variables to be analysed, $\mathbf{x}^b$ the background state (a short range weather forecast) and $\mathbf{y}$ the observations vector. $\mathbf{B}$ and $\mathbf{R}$ are, respectively, the background and the observation error covariance matrices, and H is the observation operator, that transports the model state vector $\mathbf{x}$ into the observation space, including the interpolation in space and integration in time. Under the Tangent Linear (TL) hypothesis, the H operator can be expressed by its first order Taylor expansion

$$H(\mathbf{x} + \delta\mathbf{x}) = H(\mathbf{x}) + \mathbf{H}\delta\mathbf{x}$$

where $\mathbf{H}$ is the TL observation operator matrix; the cost function is then quadratic. The $\mathbf{H}$ matrix is evaluated using a finite difference approach. The minimization of $J(\mathbf{x})$ is often an iterative process that uses the tangent linear and adjoint models to evaluate the cost function and its gradient but, for low dimension problems, the minimum of the cost function, imposed by $\nabla J(\mathbf{x}) = 0$, can be directly obtained. The estimate of the observation operator is obtained from extra integrations of the numerical model from perturbed initial states, and allows a direct computation of the analysis increments given the small dimension involved. The analysis increment for the total soil moisture W_p is given by multiplying the gain matrix $\mathbf{K}$ (defined as $\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$), and the innovation vector $(\mathbf{y} - H(\mathbf{x}^b))$, in this case containing the observation departure of 2m temperature and relative humidity. The final expression for the analysis is given by

$$W_p^a = W_p^b + \begin{pmatrix} k_1 & k_2 \end{pmatrix} \begin{pmatrix} \Delta T_{2m}^{(1)} \\ \Delta RH_{2m}^{(1)} \end{pmatrix}$$

In a first phase of the work, a better understanding of the relationship between soil and near-surface variables is pursued by the study of the linearised observation operator and the gain matrix obtained on selected real situations using soil moisture perturbations on initial conditions.

The validity of the theoretical assumptions

The estimate of the observation operator is studied in detail to optimise its evaluation, and to verify two fundamental assumptions of the method: linearity between the analyzed and the assimilated variables and horizontal decoupling between grid points, that allow the 2D formalism.

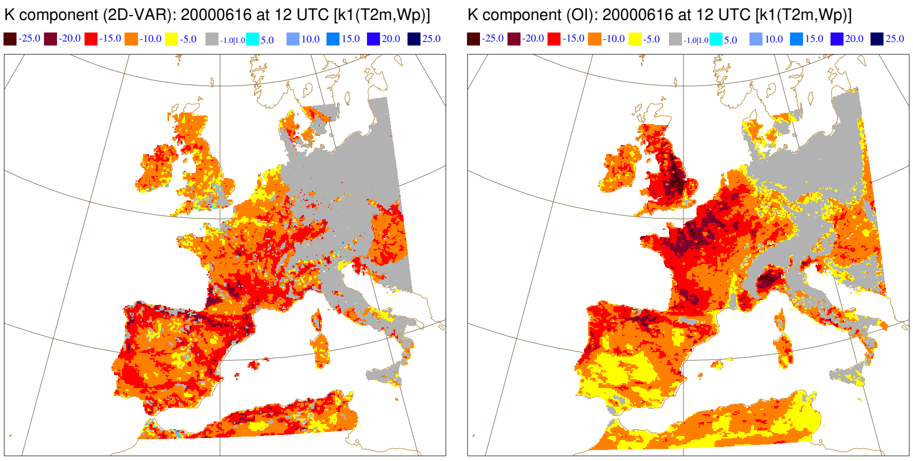

Figure 1 : The $\mathbf{K}$ matrix compared with the optimum interpolation coefficient for (T_{2m}, W_p)

The validation of the method is shown with simulated observation experiments, that confirm the generally good approximation of both the linear and the horizontal decoupling hypotheses.

The influence of model resolution as well as the sensitivity of the model parameterizations to perturbation of the control variable are highlighted as important factors to be taken into account for the optimisation. The gain matrix presents several features that show the capability of 2D-VAR to take into account the synoptic situation and the soil state. The comparison with the OI coefficients (figure 1) shows a clearer relationship with the radiative forcing together with the physiographic characteristics. Limits in linearity appear locally in perturbed meteorological conditions due to the higher variability of model screen-level response. Two solutions for the problem have been proposed: the use of a masking technique (as implemented in the OI) and an ensemble approach for the linear estimate of the observation operator. The mask of non-sensitive zones is realized in the 2D-VAR via a simple set of thresholds that remove cyclonic and frontal areas. The comparison of 2D-VAR with OI shows the similarities of the two techniques and the potential improvements brought by the variational approach. This test also permits the evaluation of the magnitude of total soil moisture analysis increments applied by the OI sequential assimilation. The 6-h analysis increments amount to about 15% of the soil wetness index (SWI) active range, resulting in a relative low information content ascribed to the model background. This aspect is of contribution to a too high spatial and temporal variability of soil moisture (figure 3). The capability of the 2D-VAR analysis to correct a prescribed soil moisture error is tested, with special regard to the horizontal decoupling hypothesis, on a 6-h assimilation test with simulated observations (figure 2).

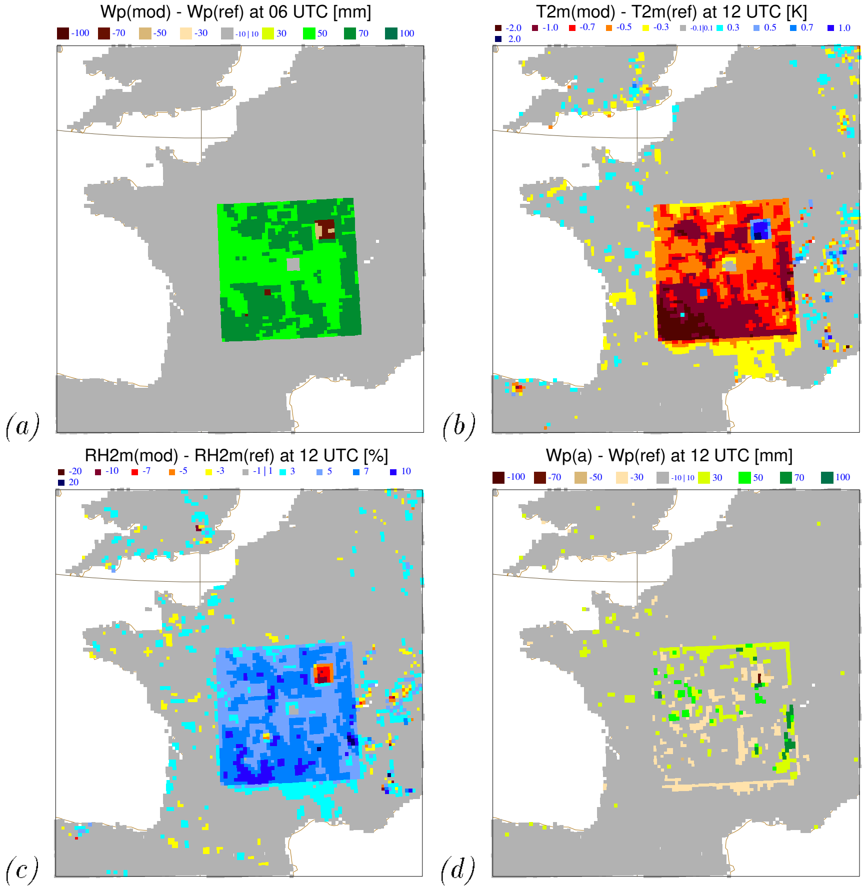

Figure 2 : Test on the 2D-VAR analysis convergence and the validity of the horizontal decoupling hypothesis. A perturbation of W_p is set on the 20000616 at 06UTC *(a)*. The plots *(b)* and *(c)* report the perturbation obtained after 6h integration on 2m temperature and relative humidity (innovation vector for the soil moisture analysis). The analysis of W_p at 12UTC is given in the plot *(d)*.

The optimisation in a mesoscale NWP model

The second part of the work has been devoted to the optimisation of the method. A careful choice of the perturbation added to the control variable is able to improve the accuracy of the linear estimation of the observation operator. The use of multiple perturbations enables to avoid the masking of non-sensitive zones (implicitly taken into account) extending the analysis to the whole domain. The 2D-VAR technique takes into account the full physics of the model, so that the corrections applied to the control variable are implicitly adapted to the current meteorological conditions and the grid point characteristics (texture and vegetation), as well as to the previous soil state without empirical adjustments.

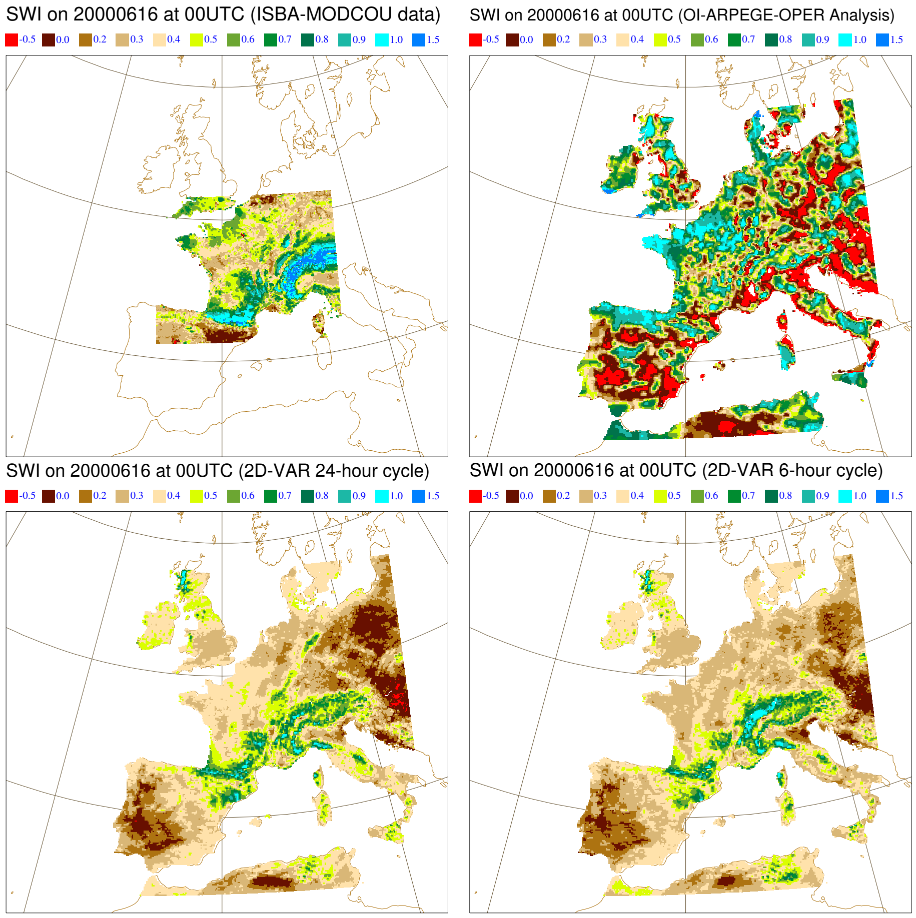

Figure 3 : Initial Soil Wetness Index (SWI): First row, SAFRAN-ISBA-MODCOU (l.h.s.) and ARPEGE analysis (r.h.s.). Second row, assimilation tests using 2D-VAR analysis with a 24-h (l.h.s.) and a 6-h (r.h.s.) assimilation time-window, after 12 days of assimilation.

The validation tests done with real observation experiments show encouraging results for the mesoscale NWP analysis of land surface soil moisture: a net improvement of the 72-h forecast score at 2m (figure 4) is accompanied by a more realistic field of the total soil moisture when comparing it with an off-line hydrological output produced by the SAFRAN-ISBA-MODCOU (SIM) system (figure 3). A sequential assimilation cycle with a 6-hour time window allows the comparison with the optimum interpolation technique, while a 24-hour window is considered to extend the temporal consistency of the assimilated observations in the analysis.

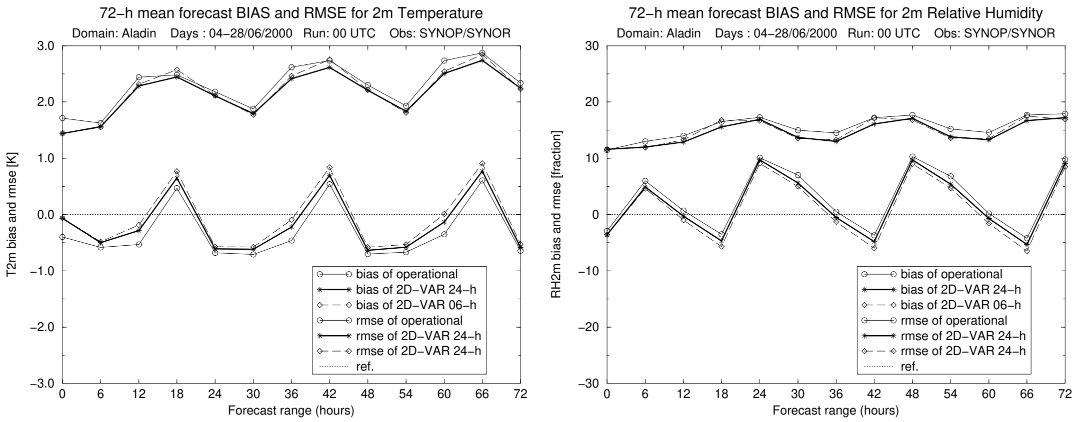

Figure 4 : Scores for 72-hour forecasts of T_{2m} and RH_{2m} using different soil moisture initializations. Mean bia s and rmse of the period 13th-20th June 2000. Solid line: ALADIN oper., solid bold line: 2D-VAR 24-h, dashed line: 2D-VAR 6-h.

Conclusions and perspectives

This work has helped to highlight specific problems of the operational surface analysis (strong analysis increments, spatial heterogeneity), allowing for possible improvements. A major effort has been devoted to develop a simplified 2D-Var for the analysis of soil moisture in the ALADIN-France limited area model and to validate the fundamental hypotheses (TL and 2D) of this method by means of simulated observation experiments. The experimental results have aided to show advantages within comparison to the OI (increased physical and dynamical consistency of the analysis correction). An optimised simplified 2D-VAR which avoids the use of masking is finally tested assimilating real observations. The results combine a more realistic field of soil moisture with an improvement of 2m forecasts. Some limits of the method in presence of a systematic model bias have been shown in a coastal moistening during sea-breeze regime periods. This problem, detected in the preliminary tests, has been partially overcome by accurately tuning the background error statistics. A real solution for persistent model errors should consider a bias filter technique or a relaxation towards an off-line soil moisture field (a variational approach is proposed) to avoid undesired drifts of the analysis. The prospective of applying this method in the frame of the European Land Data Assimilation System (ELDAS) project (van den Hurk, 2002), will consider the use of satellite derived heating rates (from Meteosat and MSG when available) to extend the observation coverage, and the inclusion of analyzed precipitation and solar radiation forcings in order to reduce the main sources of uncertanties in the modelling of soil moisture evolution.

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