2. Gianpaolo BALSAMO : "Mesoscale variational assimilation for land surface variables"

The PhD manuscript is now ready and the thesis has to be defended in April, 2003, in Genoa, Italy. Here is the synthesis of the overall work.

The analysis of soil moisture in the ALADIN 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 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 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-based (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 a,b) 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).

The present work focuses on the analysis of the total soil water content in ISBA, a two-layer force-restore land surface scheme (Noilhan and Planton, 1989), 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

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

where $\mathbf{x}$ is the vector containing the variables to analyse, $\mathbf{x}^b$ 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 :

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

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 estimate of the observation operator is studied in detail to optimize its evaluation, and to verify two fundamental assumptions of the method: linearity between the analysed and the assimilated variables and horizontal decoupling between grid points, that allow the 2d formalism. 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 consider for the optimization. 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.

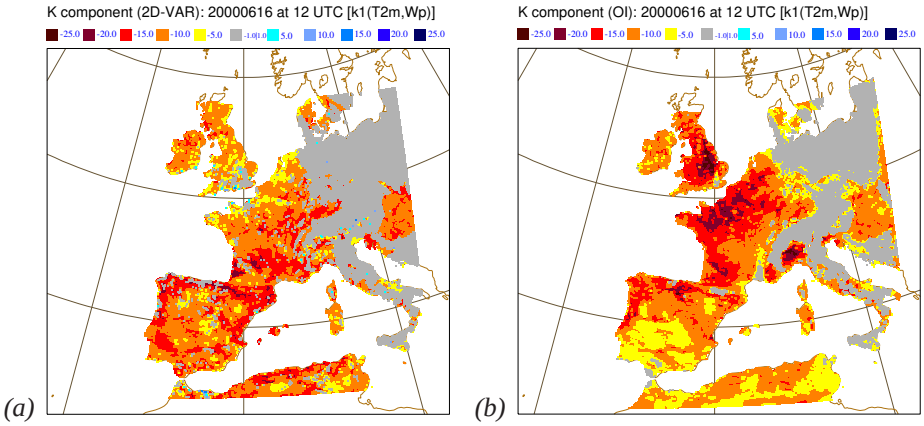

Figure 1 : The **K** matrix *(a)* compared with the optimum interpolation coefficient *(b)* for (T_{2m} , W_p).

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 6h 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 6h assimilation test with simulated observations (figure 2).

The second part of the work has been devoted to the optimization 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 avoids the masking of non-sensitive zones (implicitly taken into account) extending the analysis to the whole domain. The 2d-