Sensitivity studies using a limited-area model and its adjoint for the mesoscale range

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This work gives the first experimental frame for the evolution and the performance of an adjoint model for the mesoscale range. The goal was to assess the behaviour of a *diabatic* adjoint model at *full* non-linear model resolution. As a tool the high resolution limited-area model ALADIN was utilized. Also, the sensitivity of a forecast aspect with respect to perturbations of initial conditions was the subject of this study on real data cases.

The difference between the non-linear model solution, $\mathbf{x}(t)$, and the analysis valid at the forecast time, $\mathbf{x}^a(t)$, is defined as the forecast error. This misfit can be quantified by a diagnostic function, J, usually called forecast error cost function which typically is a weighted squared function which can be written as

$$J = \frac{1}{2} < \mathbf{x}(t) - \mathbf{x}^a(t), \mathbf{x}(t) - \mathbf{x}^a(t) > \quad (1)$$

In our study the square norm $<,>$ is the so-called total energy which reads

$$< \chi, \chi > = \frac{1}{2} \int_0^1 \int_\Sigma (u^2 + v^2 + \frac{c_p}{T_r} T^2 + w_q \frac{{L_c}^2}{c_p T_r} q^2) d\Sigma \frac{\partial p}{\partial \eta} d\eta + \frac{1}{2} \int_\Sigma R_d T_r (ln p_s)^2 d\Sigma \quad (2)$$

In the definition of the norm, χ is the vector representing a *perturbation* of the atmospheric flow. The weights given to its components are a function of the reference temperature, T_r, the specific heat of dry air at constant pressure, c_p, and the gas constant for dry air, R_d. L_c is the latent heat of condensation and w_q is a constant. $p(\eta)$ is the pressure at η levels, η being the vertical coordinate, 0=surface and 1=top of the atmosphere. Σ represents the horizontal integration domain, an error concentrated area, on which the diagnostic function is computed. Hereafter, this is referred as a target area. When using a target area, the input to the forecast error norm is set to zero outside and only inner values are kept for further computations. This is important for the estimation of the initial forecast errors because in such a way the obtained gradients are relevant to that target area. In our experiments, the adjoint backward integration was performed along a diabatic basic state computed with the operational physical package of the non-linear model.

The adjoint integration provides an estimate of the gradient (∇J) of the forecast error cost function with respect to the initial conditions. By subtracting a fraction α of this gradient from the original initial data fields, one may derive an alternative initial model state which may lead to an improved forecast. Generally, the perturbed model state fields were the temperature, the horizontal wind components and surface pressure. However, in one case study (3 May 2001), when the gradients were computed using the moist forecast error cost function, also the specific humidity field was "corrected" with a perturbation of the form

$$\delta \mathbf{q}_0 = -\alpha \cdot \frac{\sigma_q}{\overline{\sigma}_q} \cdot \nabla_q J_0$$

where σ_q is the background standard deviation of specific humidity as tuned for being used in the 3D-VAR assimilation system for the same limited-area model. $\overline{\sigma}_q$ represents the average background standard deviation over the whole model atmosphere and acts as a weighting factor.

In the adjoint model, two physical parameterization schemes were employed by turn. Primarily, the simple physics describing the surface drag and vertical diffusion (Buizza 1994 [1]) was used. This scheme developed for a global model was utilized for validating the ALADIN adjoint model at low resolution ($\Delta x = 30\ km$, 19 vertical levels). In this respect, the sensitivity of a 36-hour forecast error objective function was computed. The application case was a severe storm which proved to be a short range forecast failure for several global models. Our results revealed a substantial improvement in the forecast skill by correcting the initial conditions in a wide area over the Atlantic Ocean with knowledge of the forecast errors. This result is in agreement with the findings obtained with the ARPEGE model by Hello et al.(2000 [2]) for the same case.

The simple physics, as developed for a coarser grid model, were found to trigger numerical instability into the high resolution model ($\Delta x \sim 10\ km$, 31 vertical levels) used for the computation of the gradients of a 18-hour forecast error cost function with respect to the initial conditions. As a case study a rapidly evolving cyclone was chosen, the so-called Second French Christmas storm. As illustrated in Figure 1a, noisy and spurious wavy gradient patterns develop especially over the Alps but also in the vicinity of the northwestern coast of Spain. These structures are not only confined to the lowest model levels, but spread throughout the vertical levels. Investigations with the purpose of adapting the simple physics scheme to a high resolution model were performed. It was found that the onset of the numerical instability can be controlled by modifying the values for the wind velocity scaling factor and the reference height which contribute in the computation of the vertical diffusion. The result plotted in Figure 1b for comparison with that in Figure 1a reveals two sensitive areas over the Alps and the Atlantic Ocean. In panel (b) the gradient values over the mountainous regions are about 17 times smaller than in panel (a).

The examination of the results of the adjoint computations suggests that the trajectory around which the gradients are calculated plays a very important role, especially when the adjoint model is diabatic. The high resolution adjoint solutions depend on localized changes in the trajectory computation.

The sensitivity forecasts performed for the Second French Christmas storm did not show any substantial improvement. The relative failure of the 18 hour sensitivity forecasts can be explained by the fact that even if dry dynamics and instability dominated at

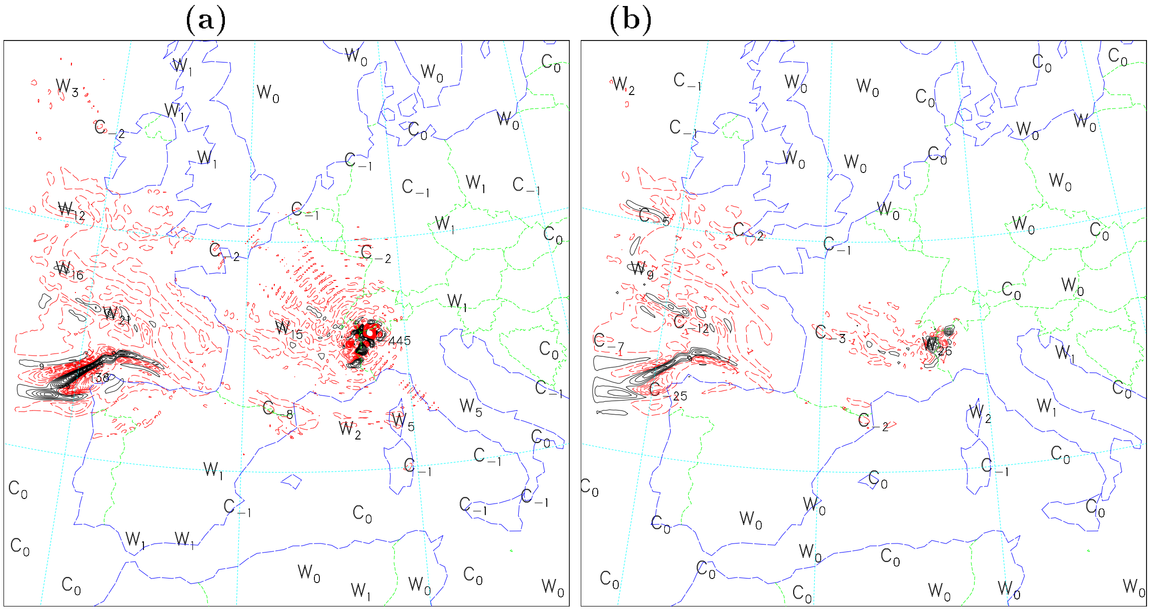

Figure 1: 18-h $\nabla_T J$ fields at model level 31 computed with an ADM with simple physics (a) as tuned for a coarse horizontal grid and (b) as tuned for a high resolution model.

least on the synoptic scales, the gradients could not provide information within the whole model atmosphere due to the boundedness of the domain.

Another set of experiments was designed to determine whether the mesoscale sensitivity can be utilized for improving the high precipitation forecast. An important goal of this work was to assess the potential benefit of using the simplified physical parameterization (Janisková 1998 [3], Janisková et al 1999 [4]) in the gradient computations. As a case study, a misforecasted rainfall event which occurred in France on the 3rd May 2001 was chosen. Here we focus on the sensitivity of a mesoscale convective precipitation system, embedded in a larger subsynoptic frontal band. Several experiments have been initiated in order to improve the precipitation forecast within the range 6-12 UTC by using sensitivities of the 6-h forecast error to the initial conditions. We stress that the verification time was 06 UTC 3 May 2001. As depicted in Figure 2, the 6-h forecast was performed

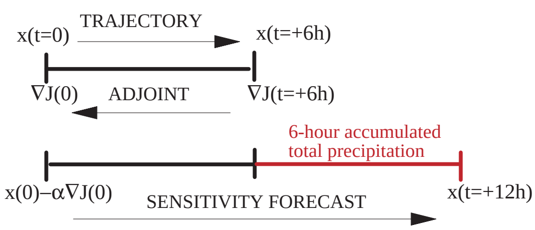

Figure 2: Schematic representation of the sensitivity experiments carried out for improving the precipitation forecast. Case 3 May 2001.

for creating the trajectory and then followed by an adjoint backward integration. The 12-hour sensitivity integrations were carried with the goal of improving the last 6-hour of accumulated total precipitation forecast. Thus, both the utility of the simplified physics and the impact of the adjoint model solutions on the forecast of precipitation are tackled in this last situation.

At the beginning of this new type of sensitivity analysis, the simplified physical parameterization schemes were validated for a high resolution model. It was found that the linearized large scale precipitation scheme produces numerical instability in the ALADIN adjoint model. After investigations, this problem was overcome but with a rather high cost, namely a substantial reduction of the non-linear precipitation flux. Yet, we cannot firmly state that by using this scheme for a higher model resolution or for some particular local forcing, the numerical instability will not outbreak again. This study has shown the necessity to further improve the linearized physical parameterizations, for example the regularization function in the stratiform precipitation scheme.

The study of the 3rd May 2001 convective system, embedded in a larger scale frontal evolution, shows perhaps both the potential and the limitations of the linear adjoint tools. On the one hand, the adjoint model apparently is able to capture the dynamical instabilities where the vertical stability is crucial, but on the other hand the subsequent perturbed forecast is more sensitive to the sign and to the amplitude of the initial state "correction", rather than to the structure of the gradient. Obviously, the importance of the sign and amplitude of the 'α' coefficient point to the non-linear aspects of convection. The results obtained for this meteorological situation have revealed that all forecasts basically could be classified in a two member ensemble. In other words, this convective system might have been also sampled and understood in the light of an ensemble approach.

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