False mesoscale cyclogenesis in the ALADIN model - Sensitivity study on initial conditions, physical parameterisations and horizontal diffusion

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Introduction

During the last three years, forecasts of spurious mesoscale cyclones appeared several times in the outputs of the ARPEGE/ALADIN models. This phenomenon was carefully examined within the COMPAS and GMAP teams of Météo-France (Tardy, 2003) and in the LACE centre in Prague (Vakula, 2002). However, the mechanism of creation of such small-scale storms in the model is still not entirely known and despite of some successes, e.g. with the parameterisation of shear-linked convection (Bouyssel and Geleyn, 2002), the problem of false cyclogeneses remains even in the recent operational versions of the ARPEGE/ALADIN models.

The original purpose of the study described in this paper was :

a) to evaluate the sensitivity of a false cyclogenesis to initial conditions using the adjoint of the ALADIN model
b) if possible, to perturb the initial conditions and to create a reference run without the storm prediction. The reference run will be further compared with the one producing a storm, with respect to physical fluxes and some diagnostic parameters such as the potential vorticity (PV) field.
c) according to the improved knowledge of the storm mechanism, to find ways to eliminate the storm by adjustments of physical parameterisations in the ARPEGE/ALADIN model

Short description of the selected case

The false cyclogenesis that appeared in the "20.07.2001 00 UTC" run of the ALADIN-LACE model, in the Adriatic sea, belongs to the most resistant cases. Several tests were done on physical parameterisations, that are described in the report of Vakula (2001). More recently, tests of the parameterisation of the so-called shear-linked convection (see the article of Bouyssel and Geleyn, 2002) were performed also on this situation, without significant achievements.

Looking at the forecasts of mean-sea-level pressure with a 6-hour frequency, one can follow the development of the mesocyclone, that originates from a synoptic-scale cyclone, having the centre above Northern Italy in the initial state, at 00 UTC (Fig. 1). Vertical cross-sections through this area indicate a well developed baroclinic environment according to the couple of upper and low-level potential-vorticity anomalies, where the latter shows for the troposphere unusually big values up to 4 PVU (Fig. 2b). However, the analysis of further runs shows a fast decline of the cyclone, together with the mesoscale, low-level maximum of potential vorticity. In the model run, the cyclogenesis seems to continue, reaching its peak departures from model analysis after 24 hours of integration. At that time, convection was estimated in the area of Adriatic sea (Vakula, 2001), probably connected to a shallow surface-low. However, the structure of the forecasted cyclone according to the vertical profile of potential temperature and potential vorticity seems to be unrealistic (Fig. 2c).

Adjoint sensitivity tests in the case of the so-called Adriatic storm of 20.07.2001

For the run of the adjoint of the ALADIN model, a domain with an horizontal resolution of 18 km and 37 vertical levels was chosen (the one used for the computation of boundary conditions for the operational ALADIN-LACE model). The model version used both for the reference run and for the experiments with the adjoint of ALADIN model was *Al25T1-op2*. The adjoint run started at 21.07.2001 00 UTC and finished at 20.07.2001 00 UTC after 24 hour integration, using the simple physical parameterisation of Buizza (1993) and the so-called dry total energy as a norm (for more details about using the adjoint of the ALADIN model see the article of Soci et al., 2003). The selected target area of the storm environment is marked by a green rectangle in Fig. 1e. The reference at the beginning of the adjoint run was the model analysis valid at 21.07.2001 00 UTC.

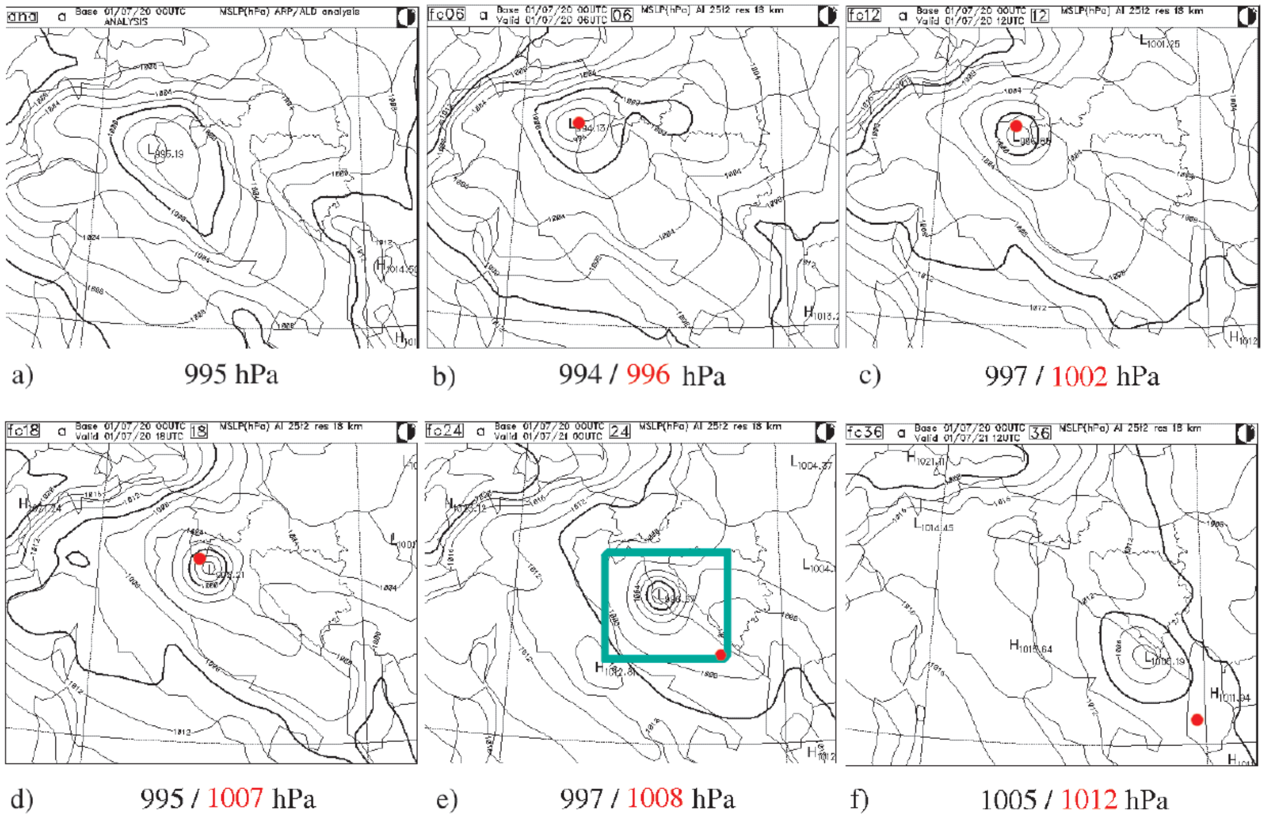
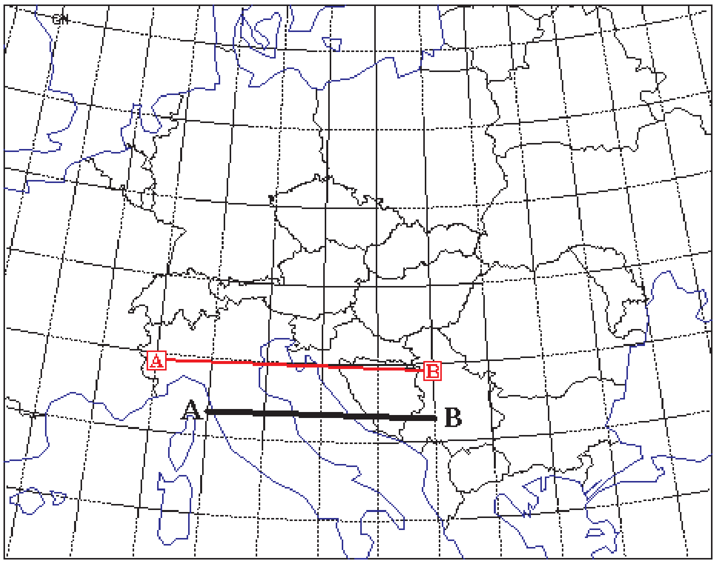
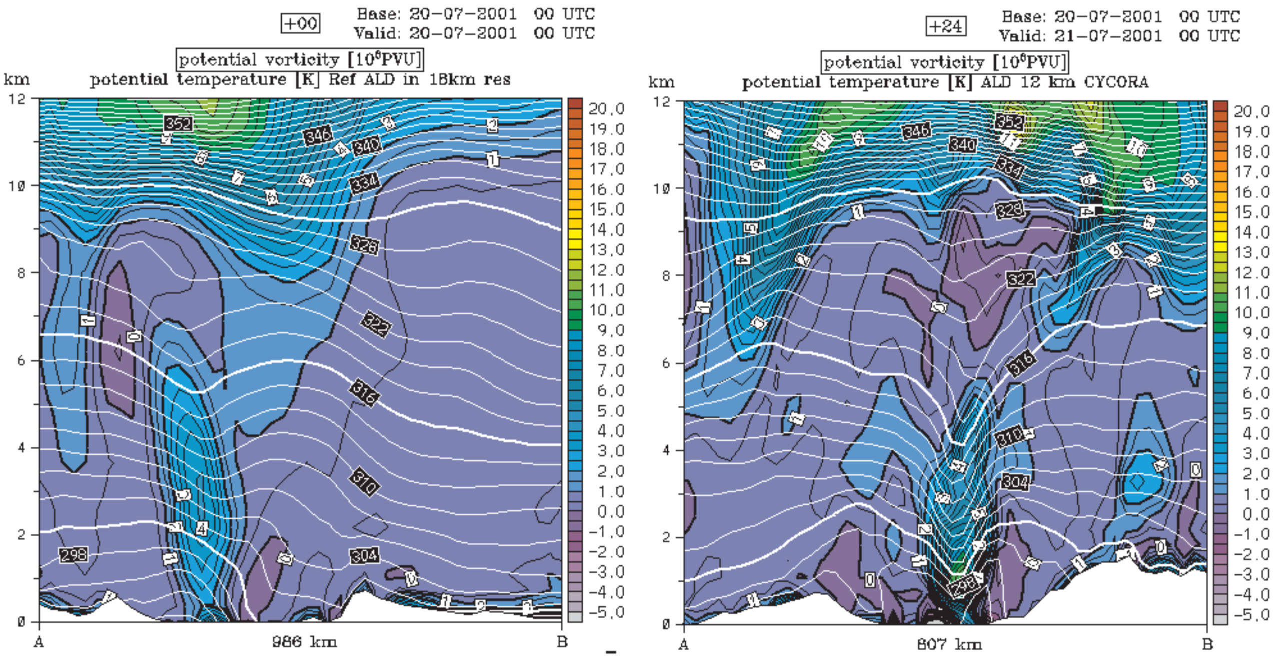


Figure 1 : Analysis (a) and forecasts (b : 6 h, c : 12 h, d : 18 h, e : 24h, f : 30 h) of mean-sea-level pressure from the reference storm-creating run based on 20.07.2001 00 UTC. The experimental run was using the model version *AL25T1*, on a domain an horizontal resolution of 18 km. The values indicated below the figures compare the predicted pressure in the centre of the cyclone (black) with the value from model analysis (red). The red dots mark the position of the centre of the cyclone in model analyses. The green rectangle (e) represents the target area used for sensitivity studies.

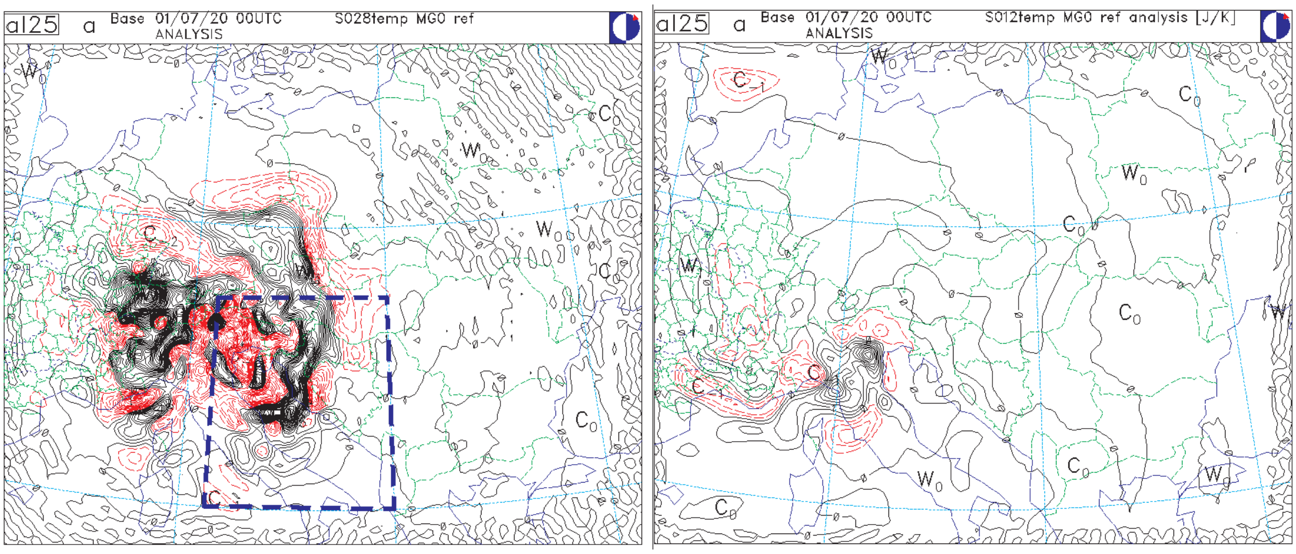


a



b c

Figure 2 : a) Vertical cross-section used to analyse fields in Fisg. 2b (red) and 2c (black).
b) Vertical cross-section of potential-vorticity (coloured isolines) and potential-temperature fields (white ones) in the reference analysis, valid at 20.07.2001 00 UTC. Note the well-developed low-level anomaly of potential vorticity near the centre of the cyclone and regions with dry symmetric instability (negative values of PV).
c) Vertical cross-section for the 24-hour forecast valid at 21.07.2001 00 UTC, which is using the CYCORA (CY21) package of physical parameterisations (operational in the 12-km ALADIN-LACE model in the years 2000-2001). Note the areas of exaggerated PV values in the lower troposphere, and the "warming" effect on the isolines of potential temperature in the environment of the storm.



a b

Figure 3 : a) Gradients of the 24-hour forecast-error cost function, for the model run based on 20.07.2001 00 UTC, with respect to the temperature and with the dry total energy as the norm, at model levels 28 (a) and 12 (b). The result shows the sensitivity of the forecast error to the ALADIN initial conditions (according to the verifying analysis valid at 21.07.2001 and the target area marked in green in Fig.1e). The dashed blue rectangle marks the area used for the budget calculations mentioned hereafter (domain ADRI).

The gradients of the 24-hour forecast-error cost function with respect to temperature show a huge sensitivity to initial conditions. High sensitivity can be observed above all in the PBL (Fig. 3a) and is present in a relatively wide area, concerning also places distant from the original target. In upper tropospheric levels, areas of sensitivity occur in even more distant places (on West and Northwest of the domain). However, the centre of the impact remains near the position of the low at initial time (Fig. 3b).

Model runs with adjusted initial conditions

The results of the first tests encouraged us to continue with step b), i.e. the fields of gradients of the forecast-error cost function (∇J_{t0}) were used to perturb the original model analysis, valid at 20.07.2001 00 UTC. The resulting analysis was later used for model runs with the same physical package as for the reference one, to check the impact of the perturbed initial conditions (sensitivity forecast run). The vector of the perturbation, δX_0, was computed as : $\delta X_0 = - a \nabla J_{t0}$, where α is a scaling factor, that should not exceed 1. (refer to the article of Soci et al., 2003). For our experiments, three values of *a* were used : 0.1, 0.5, 0.75 . Finally, a new initial file was creating by adding this vector (in spectral space) to the reference ALADIN analysis.

The experiment with *a*=0.1 shows a very small influence, with respect to the forecast of the storm. Sensitivity appears in the case of *a*=0.5, and by choosing *a*=0.75 one can see finally an almost entire liquidation of the storm after 24 hours of model integration (Fig. 4a).

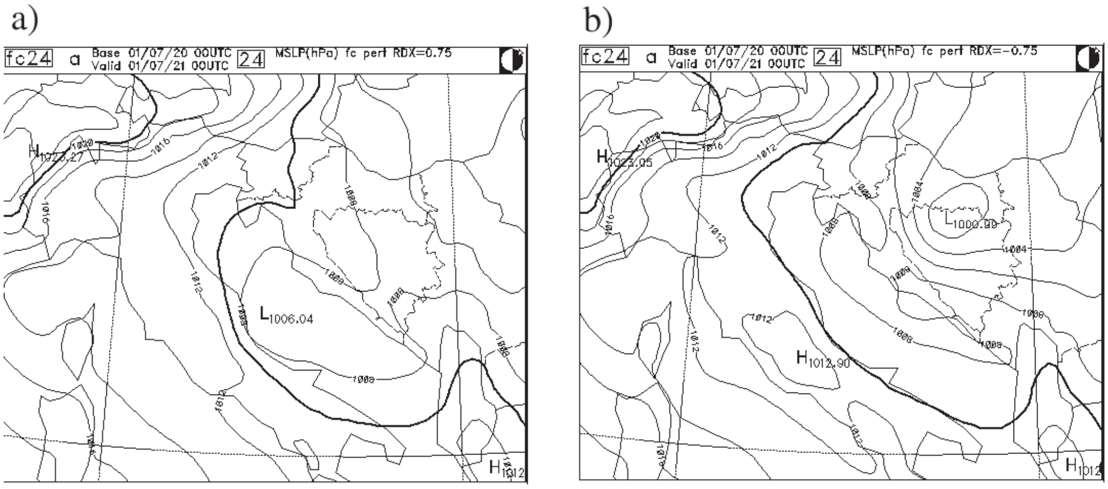


Figure 4. a) Experimental 24-hour sensitivity forecast run, valid at 21.07.2001 00 UTC and based on the original analysis perturbed by the gradient fields with the scaling factor *a*=0.75.
b) Experiment with adding the gradient fields to the initial field using the scaling factor *a*=-0.75 (opposite procedure as in the experiment corresponding to Fig.4a). Note the worse result when compared to Fig. 4a, but the relatively improved forecast of the storm when compared to the reference run (Fig. 1e) !

This result tell us some important things. First, it is possible to eliminate completely the targeted storm only by changing the initial conditions, without touching the physical parameterisation. On the other hand, the magnitude of the scaling factor used for the corresponding test is quite big : generally acceptable values are of magnitude 0.1 or even smaller.

The vertical cross-section through the centre of the cyclone at 20.07.2001 00 UTC applied to the perturbed analysis shows new structures in the potential vorticity field, mainly West from the centre of the low and below the tropopause (Fig. 5).

We get an interesting comparison between the 12-hour basic run, the 12-hour run with perturbed analysis, and the analysis valid at 20.07.2001 12 UTC. Looking at the same vertical cross-sections of potential vorticity and wind fields, one can realize that the sensitivity forecast run is not closer to the verifying analysis than the reference one (Figs. 6a-c). Nevertheless the structure of the low-level

PV anomaly in the environment of the cyclone is reorganized and, thanks to that, conditions are created for strong upslope motions, that are accompanied with the presence of vertical wind-shear. Note, that vertical wind-shear in the storm and its nearest environment is very small in the original, storm-creating run, while compensated with a strong horizontal wind-shear (Fig. 6a).

An additional experiment was performed, with the parameter *a* set to –0.75. This was meant as a contradictory experiment. If the fields of gradients are correctly computed, the sensitivity forecast run should not improve the forecast in this case. The resulting forecast from this experiment was producing the cyclone (though its position was moved), nevertheless it can be still considered as better than the forecast of the basic unperturbed run (Fig. 4b).

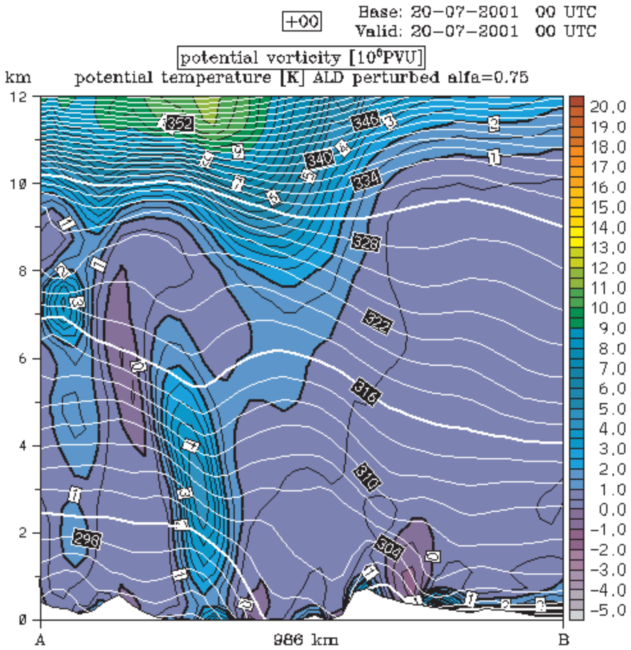


Figure 5. Vertical cross-section through the fields of potential vorticity and potential temperature, valid for the 20.07.2001 00 UTC perturbed analysis. The scaling factor for the gradient field was set to 0.75. The cross-section is the same as for the reference analysis (see Fig. 2a). Note the creation of additional PV anomaly in the far western side of the cross-section, for vertical levels between 6 and 8 km.

Diagnostics of the physical fluxes

Originally, it was supposed that a run improving the forecast (as the run with perturbed analysis using *a*=0.75) can be used as a reference for comparing physical fluxes and tendencies in the storm environment. Hence it would perhaps be possible to find ways to cancel false cyclogenesis entirely by changes in the physical parameterisations. With respect to the sensitivity gradient fields and the development of the storm, several areas were chosen to follow the differences between the sensitivity forecast run and the original, not perturbed run (domain ADRI is marked in Fig. 3a). The fluxes were computed with the help of the DDH tool (Piriou, 2001). Budgets for water vapour, temperature and energy were compared in the 24-hour period from 20.07.2001 00 UTC until 21.07.2001 00 UTC. For water vapour and temperature, the budgets for the domain ADRI show tendencies to decrease moisture and increase the temperature in the storm-producing run (Fig. 7a). The precipitation fluxes seem to have the biggest importance among the physical fluxes. However, in limited-area domains, the advection part (dynamical terms) is not negligible and can even dominate over the tendencies obtained from physical fluxes, which makes the interpretation difficult. The turbulent fluxes are important for the budget of kinetic energy, where the storm-producing run leads to bigger dissipation of energy in the PBL, due to turbulent transport. Nevertheless, this addition is compensated by strong forcing of the so-called baroclinic term (containing the conversion of potential and internal energy to kinetic energy), that slightly increases the overall tendency of the kinetic energy in the storm-producing run (Fig. 7b).

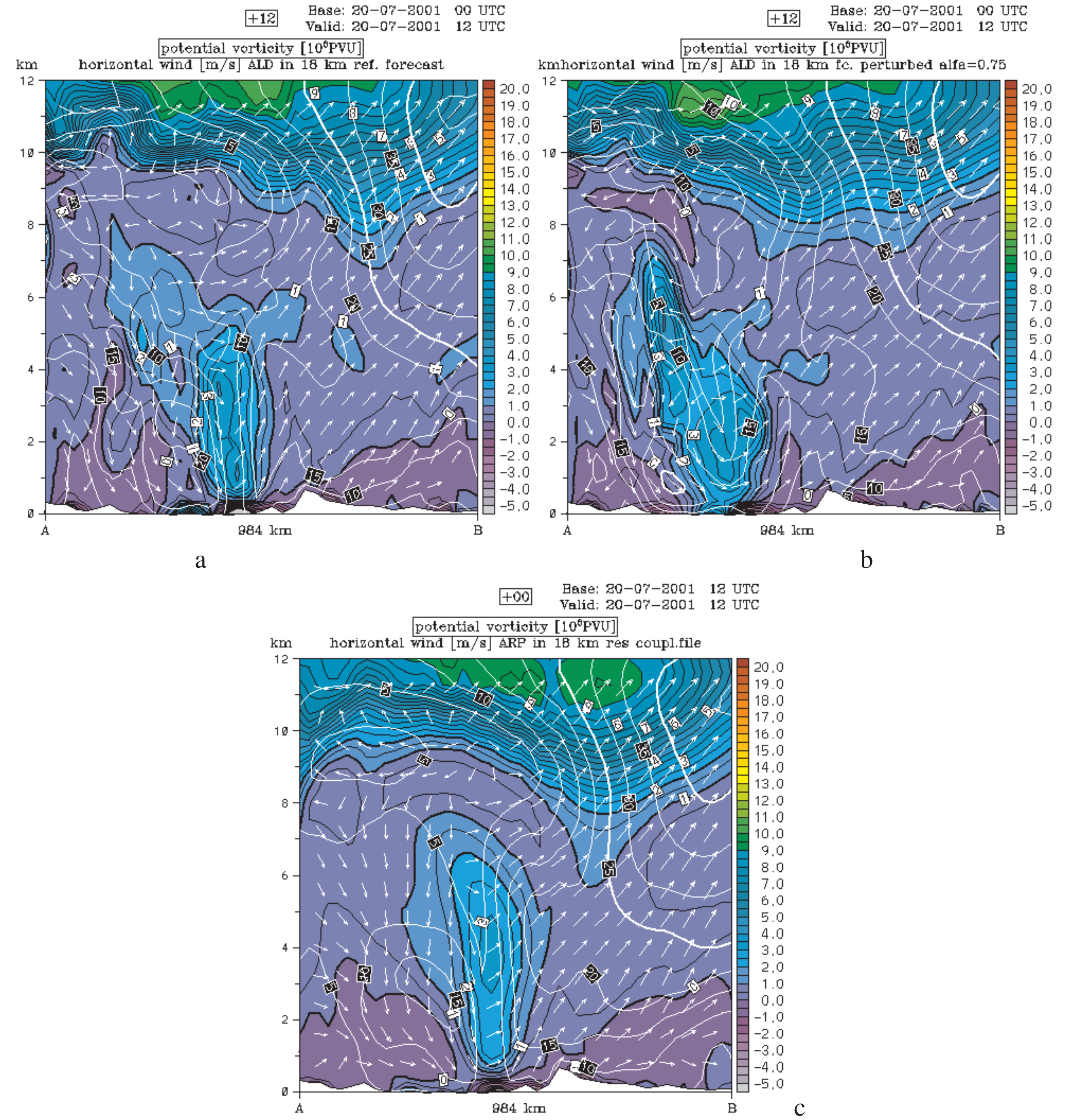


Figure 6.

a) Vertical cross-section through the fields of potential vorticity and horizontal wind in the 12-hour reference forecast, valid at 20.07.2001 12 UTC. Note the almost symmetric structure and small vertical shear of wind in the region of low-level PV anomaly (the sense of the cross-sections in Fig. 6a-c was shifted by 25’ northward against the cross-section used in Fig.2b, to intersect the centre of the forecasted storm).

b) Same as in Fig. 6a but for the run with perturbed analysis (*a*=0.75). Note the redistribution of the PV field westward from the forecasted storm centre, causing rearrangement of the wind field (horizontal wind-shear suppressed, vertical wind-shear established). In contrary to the reference case, this environment is more favourable for slantwise up- and downdrafts, than for purely vertical motions.

c) Same as in Figs. 6a-b, but for the verifying model analysis valid at 20.07.2001 12 UTC. Note the similar structure as in Fig. 6a, but with considerably smaller amount of low-level potential vorticity above the surface-low centre.

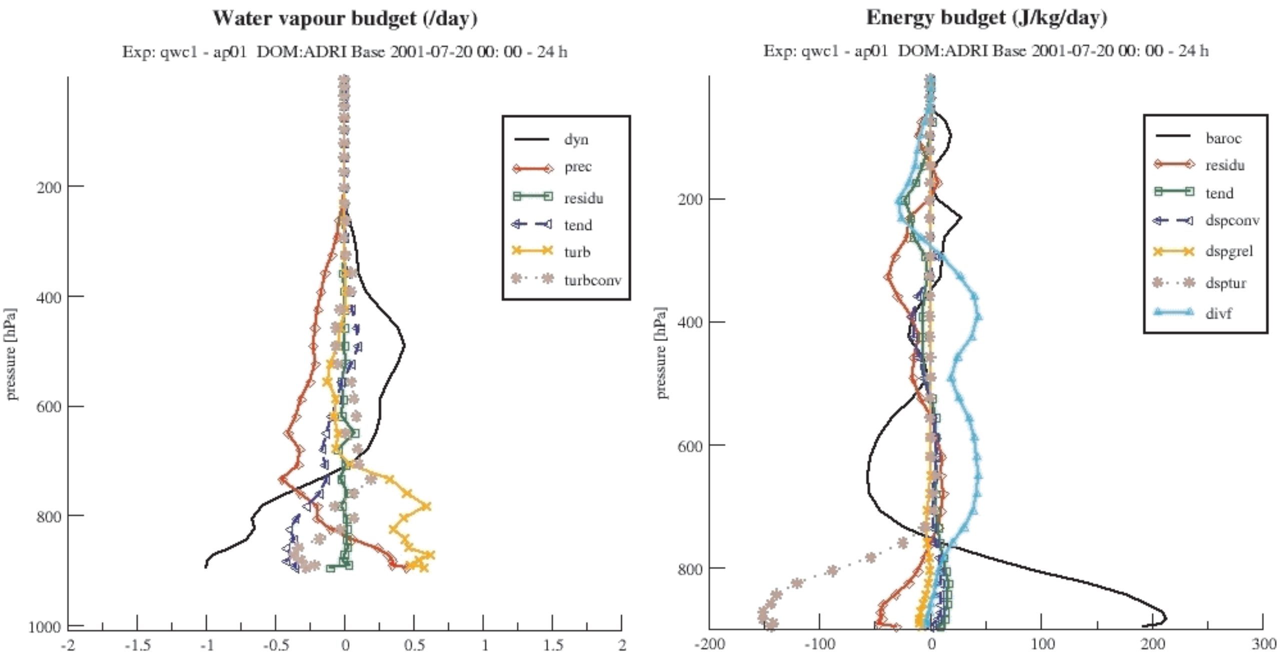


Figure 7.
a) Output of water vapour budget calculations for the differences between the basic forecast and the sensitivity forecast with perturbed initial conditions. The contribution of the terms not including physical fluxes is in black (dyn). Remarkable is the contribution of the precipitation fluxes (prec) and turbulence (turb) to the overall tendency (tend).
b) Difference of the kinetic energy budgets between the basic forecast and the sensitivity forecast run with perturbed initial conditions. The black line represents the so called baroclinic term (baroc). The residual term can contain, besides others, the contributions of the horizontal diffusion or the advection of kinetic energy. Among the physical fluxes is noteworthy the term of turbulent dissipation (dsptur).

Trials with parameterisation of dry and moist symmetric instability

Experiments with the sensitivity forecast runs cannot be taken as a true development of the atmosphere in the case of 20.07.2001. Nevertheless they show the importance of compensation processes in a symmetrically unstable atmosphere. Presence of dry or conditional instability forces slantwise (upslope or downslope) motions, and as a consequence, potential vorticity should vanish in this environment (Emanuel, 1983 and Nordeng, 1987). Actually, this is our goal in the case of the false mesoscale cyclogenesis, where the tropospheric values of PV reach abnormal values.

After the implementation of the shear-linked convection into the ARPEGE/ALADIN code, it was decided to make the vertical diffusion scheme dependent on symmetric instability as well. The adjustment of the scheme followed the work of Bennets and Hoskins (1979). A modified Richardson number was introduced to detect dry/conditional symmetric instability and to enhance the turbulent diffusion in stable PBL layers in the areas of instability. The equation for the modified Richardson number Ri_p , that replaces the original Ri, yields :

$$Ri_p = (N_w^2 / N^2)(\zeta / f)Ri - 1 \quad ,$$

where N^2 / N_w^2 is the dry / moist Brunt-Väisälä frequency, ζ is the absolute vorticity and f is the Coriolis parameter. A more detailed description of the scheme can be found in the work of Simon (2003a).

For the "Adriatic storm" case from 20.07.2001, experiments with parameterisation of dry symmetric instability ($N_w^2 / N^2 = 1$), conditional symmetric instability and conditional symmetric instability coupled with shear-linked convection were performed. The most successful scheme was the first one, since improving the forecast of mean-sea-level pressure in the centre of the storm at least by

2 hPa. However, these properties are lost by application of the full scheme of conditional symmetric instability inside the vertical diffusion scheme. The application of the modified shear-linked convection scheme (Simon, 2003b) has no significant influence on the storm forecast.

Semi-Lagrangian horizontal diffusion - a possible solution ?

Recently, it was shown by Vana (2003), that an application of semi-Lagrangian horizontal diffusion, which is a kind of flow-dependent horizontal diffusion scheme, can bring a considerable progress in the case of the 20.07.2001 false cyclogenesis and also in further similar cases. The positive side of the scheme is not only the reduction of the cyclone to the depth almost corresponding to verifying model analysis. One can see on the vertical cross-sections of potential vorticity, how the originally spurious structure of the low-level PV anomaly was improved due to application of the new horizontal diffusion scheme (Fig. 8). Remarkable is that the semi-Lagrangian horizontal diffusion has in this case a huge impact also in the upper tropospheric and in the stratospheric levels, what was not expected before.

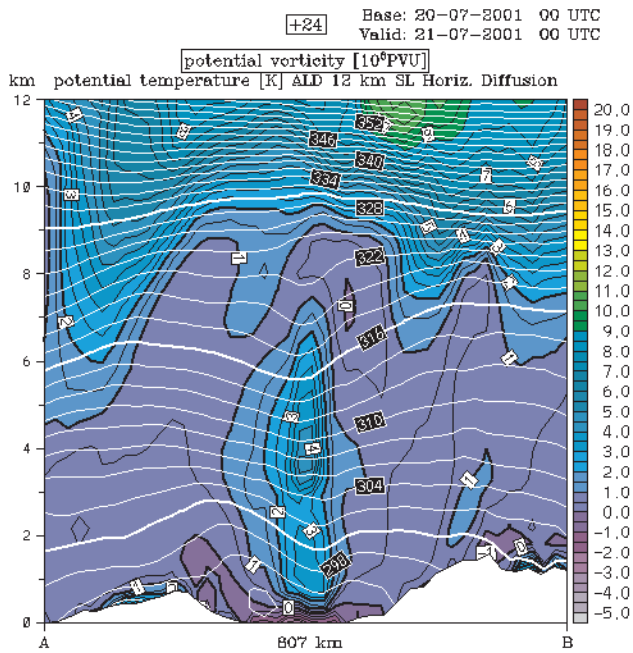


Figure 8. 24-hour forecast of potential vorticity and potential temperature, valid at 21.07.2001 and using the 12-km resolution ALADIN-LACE model, with application of the semi-Lagrangian horizontal diffusion, to be compared to the output of the reference experiment (Fig. 2c, same vertical cross-section).

Conclusion

The experiments with the adjoint of the ALADIN model showed that the process of creating the false mesoscale storm can depend on the initial conditions. Nevertheless, one need to modify considerably the initial files to get satisfying results. The diagnostics via PV field shows that the forecast of the storm is even not corrected by the way, that should fit with the corresponding model analysis.

It seems that the sensitivity gradient fields in the experiments with the adjoint model were created artificially and their computation was possibly influenced by the usage of very simple physical parameterisation for a relatively long period (24 hours).

Hence one can have doubts, whether the forecast of the storm was really a problem of initial conditions. Moreover, most recent experiment with model run based on the ECMWF analysis gave surprisingly small differences in the forecast of the cyclone for both ARPEGE and ALADIN models, comparing to the reference storm-creating forecasts.

However, the contribution of the adjoint sensitivity tests and forecasts mentioned in this article is a larger view on the dynamics-physics interaction, that decides about the creation/cancellation of false mesoscale cyclogenesis. That means - the storm can be cancelled without changing the physical parameterisations, if the dynamics of the storm will be changed (in this case via redistribution of potential vorticity in low and mid-troposphere). This allows us to hope that a reverse process is possible as well (while the low-level PV anomalies are in fact consequences of physical processes as diabatic heating or friction). A determination, how to compensate the effects of dynamics within the physical parameterisations, is not a trivial task as one can see from the results of the DDH diagnostics in this paper. Nevertheless, recent changes in the operational physical parameterisation of the ARPEGE/ALADIN model, namely in the stratiform precipitation and vertical diffusion part (in model versions up from cycle *AL25T1-op3*), are giving already better results in number of problematic cases with false cyclogenesis.

The simulation of dry-moist symmetric instability processes either in convection or in vertical diffusion is most probably not an ultimate solution. False mesocyclones, that show an almost perfect symmetry (as in the case of the Adriatic storm predicted on 20.07.2001) are not sensitive to those schemes. The reason is that the simulated slantwise movements and turbulent exchange can start just in an environment with vertical wind shear (this works well in cases with tilted troughs or cyclones). The partial success of the dry-symmetric instability modification was caused most probably not directly (acting on the dry symmetric instabilities similar to those that appeared in the model analysis, see Fig.2).

Hence the semi-Lagrangian horizontal diffusion looks as an elegant solution to the problem of false cyclogenesis due to its selective properties (and not large effects on scores). A theory, presented in the work of Vana (2003), is telling us, that the semi-Lagrangian horizontal diffusion, although driven only by horizontal components of parameters (such as the tensor of the flow deformation), is in fact applied in three dimensions. Thus, it can simulate the effects of horizontal dissipation (in real atmosphere done by turbulence or molecular exchange) that are not present in the current one-dimensional ARPEGE/ALADIN physical parameterisation of vertical diffusion. According to the achievements of the semi-Lagrangian horizontal diffusion, we can conclude that an improved physical parameterisation of horizontal dissipation is required for correct forecasts of cyclogenesis at smaller scales.

However, further experiments will be required, concerning improved diagnostics on the effects of horizontal diffusion or a new, 3d treatment of the parameterisation of turbulent fluxes. The evaluation of some schemes of turbulent diffusion, taking into account horizontal derivatives of wind field, is currently on the way.

Acknowledgements

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