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Abstract

Water vapour (WV) radiance mesasurements from satellites can give valuable information on the state of the atmosphere. To a first approximation, they indicate the topography of the tropopause. The potential vorticity (PV) on certain isentropic levels is also indicative of the tropopause topography. By comparing WV from satellites with PV of a numerical weather analysis, it is possible to identify errors in the numerical weather analysis. The fundamental idea in this project is that when such an error is detected, one should be able to modify the PV of a model field based on WV observations and subsequently let the numerical model calculate a new (better) forecast.

A method has been developed to modify the PV of a numerical weather analysis and to assimilate this modified potential vorticity in HIRLAM, KNMI's operational weather forecasting model. From the modified analysis, a new forecast can be produced. In a previous project (Vosbeek *et al.*, 2001) the foundations were laid; in the current project the method was implemented in the operational version of the model and further refined. Now it runs fast enough to be used operationally. The previously developed graphical interface to compare and modify PV and WV was used to determine modifications. But a new graphical interface was developed for future use.

Two cases where investigated in which the modification method was used as a research tool. The development of a small upper-level low and a larger upper-level cyclone were studied. There was no reason to modify the original analysis since the forecast was accurate. But by eliminating or reinforcing some PV structures the effect of these structures on the development of the upper-level low and the cyclone could be investigated. The results gave indeed more insight in the source area of the PV structures that were essential for the development and in the effect of other PV structures on the final position and shape. The high resolution and the possibility to study realistic meteorological cases made the method a valuable research tool.

A third case was studied which was indeed motivated by a mismatch between the WV images and the PV of the analysis. In the ensuing forecast the development of a depression was underestimated. A displacement of PV improved the forecast in terms of mean sea level pressure of the depression. But the mechanism of development was not identical to the actual development. To test the sensitivity to the precise modification, similar but slightly different modifications were applied. These simulations gave a stronger depression than the original run, but not all were strong enough or predicted the right position. The correspondence between PV and WV is too qualitative to constrain the modification well.

Results were compared with the ECMWF ensemble in terms of mean sea level pressure and position of the depression, showing that the original forecast corresponds to an extreme ensemble member whereas the modified run was closer to the average. The modifications have created a 'poor man's ensemble'. But the important difference with classical ensemble methods is that the ensemble is not based on maximum growth of structures but on observations and conceptual models

applied by a meteorologist. In the near future, the developed PV modification method has most potential for the operational forecasting practice when it is used to generate short-term ensembles.

Executive summary

In this project a method was explored to use water vapour (WV) satellite images for improving a weather forecast. Hazardous weather conditions like heavy rain and wind have a large impact on society. Therefore, accurate and timely forecasts are of great value. Despite the large development in numerical models and increase in available observations, sometimes the early stages of development are not picked up by an automatic numerical weather analysis. WV satellite images are a valuable source of information about the position of the jet stream and the presence of depressions. They can be compared with the potential vorticity (PV) of a weather analysis. Due to their properties, patterns of PV and WV should match qualitatively. When a feature is not represented properly by the analysis, one would like to correct the analysis. Since the relation between PV and WV requires interpretation, this cannot be done automatically. The input of a human forecaster is essential.

A method has been developed to manually adjust a numerical weather analysis. During the project USP-2 11/AP-10 (1998-2000), the foundation of the present project was laid. In that project, PV and WV images were combined in images that can be consulted on the KNMI intranet site, a graphical interaction method was designed to determine an appropriate modification, and the assimilation of a modified PV field in the HIRLAM numerical weather prediction model was implemented. The main results was that human intervention could be applied. The assimilation of modified PV field in HIRLAM indeed leads to a new analysis with the required modification, and an alternative forecast can be made in this way. However, it was an experimental system and it was too slow to be used in an operational environment. Furthermore, the effect of the modification on the forecast was only tested for one case.

The present project started in November 2004 and was completed in October 2006. The objectives were to implement the method for PV assimilation in the present version of HIRLAM, to test the method in a number of cases and to enable the regular use of the system. First, the software that was used to produce PV-WV images for the intranet was installed on a new workstation and programs were adapted to the actual HIRLAM grid, which was refined. Then the software for the assimilation of PV in HIRLAM was adapted to the operational HIRLAM system (version 6.3.5, operational at November 2004). This involved parallelisation of the previously developed code. HIRLAM runs were now done on the same system as the operational runs. This made our system fast enough to do a PV modification and run an alternative forecast in between two operational HIRLAM runs. Some practical changes were made with respect to the old implementation. The relation between PV and WV, the modification method and the subsequent assimilation method are described in Chapter 2. Also the graphical interaction program was translated to a Metview environment instead of GrADS to make the system more flexible and user-friendly. The interface is shown in Chapter 3. Thus the implementation workpackages (WP) 1000 and 2000 were completed.

The method was applied in a few case studies (WP 3000). First, the method was used to

investigate the mechanism of a case in more detail. This is an easier task than aiming at an improved forecast. The relation between PV and WV is not used and hindsight can be used. By modifying selected features, their impact on and relevance for the dynamical development of a weather system can be studied. This is done in Chapter 4 for the development of an upper-level low and a case of tropopause cyclogenesis.

The method has also been tested on a case where a mismatch between PV and WV indeed appeared and the developing storm was underestimated . This case is described in Chapter 5. The alternative forecast indeed predicted the deepening of the depression better. Also similar but slightly different modifications were applied, which gave a deeper depression than the original run but not all were strong enough or predicted the right position. The results were compared with the ECMWF ensemble, showing that the original forecast corresponded to an extreme ensemble member and that the modified run was closer to the average.

The investigation of the case described above has shown that the relation betweem PV and WV is too qualitative to correct a weather analysis. Therefore the method was not yet tested by meteorologists in an operational environment (WP 4000). But new ideas were developed to use the method in a sensible way. Modification can in the future be used to test the sensitivity of the forecast to perturbations. Using the experience of a human forecaster to select relevant areas and modifications may be a valuable addition to classical (automatic) ensemble methods. The method presented and tested here can contribute to the generation of such short-range ensembles in which the insight of a meteorologist is optimally included.

Chapter 1

Introduction and objectives

Accurate predictions of storms, snow and heavy precipitation are important for society. Although numerical weather prediction models become increasingly accurate, there are still cases in which extreme weather conditions are predicted at a very late stage, leaving little time to give warnings and take protecting measures. In most cases the quality of the forecast is limited by the accuracy of the initial weather analysis. The accuracy of an analysis may suffer from a lack of observations or from an erroneous rejection of extreme values in the automatic quality control of the data-assimilation system. An experienced meteorologist can detect errors in the numerical weather analysis by comparing it with observations. When such an error is detected, the next step is to modify the analysis and produce an alternative forecast. In this project a method to modify a numerical weather analysis is explored.

Satellite Water Vapour (WV) radiance observations are an important source of information in areas where conventional observations are relatively scarce, as is the case over the oceans. Their horizontal and time resolution are very good. Dark and light patterns on a WV radiation image can be related to the structures of potential vorticity (PV) on an isentropic surface around the tropopause. PV is a quantity which effectively summarizes the dynamical state of the atmosphere. Details about WV, PV and their relation are given in Chapter 2.

When a mismatch is detected, one would like to modify the weather analysis accordingly. PV is invertible, so that a modification in PV leads to the modification of the dynamical variables temperature, pressure and wind in a consistent way. However, the correspondence between PV and WV is not one-to-one. The skill and experience of a meteorologist are needed. WV images may for example show traces of clouds deeper in the atmosphere, where no correspondence with PV can be expected. An extensive treatment of this correspondence with many examples can be found in Santurette and Georgiev (2005).

The idea to modify a numerical weather analysis using PV-WV comparison was applied successfully by Demirtas & Thorpe (1999) in a few case studies. But in the follow-up study by Swarbrick (2001) it appeared that it is extremely difficult to find a quantitatively correct PV modification since every case is different. A way to get more hold on the PV-modifications is to use singular vectors (SVs). Røsting *et al.* (2003) tested this for the 1997 Christmas storms. They used SVs to identify modifications which had significant impact on the forecast. In selecting the right modifications, hindsight was used and the near-surface modifications could not be motivated by a mismatch between WV and PV. Also Vosbeek *et al.* (2001) and Verkley *et al.* (2005) presented a method to modify the PV of a weather analysis. The method was illustrated with a case where a local weakening of the jet stream led to a less strong depression than the run from the operational analysis. However, hindsight was used instead of a clear mismatch between PV and WV, which illustrates the difficulty in relating PV and WV quantitatively. A slightly different approach was taken by Guerin *et al.* (2006), who do not assimilate a PV field but the height (pressure) of the 2PVU plane, which is directly related to the tropopause topography. They only present one case of cyclogenesis, in which the forecast was improved using PV pseudo-observations, but the strength of the developing depression was still underestimated.

Due to these mixed results, direct modification of a forecast has gained attention. Carroll & Hewson (2005) reported a successful application of a forecast modification tool, where perturbations were directly applied on the output grid and were allowed to evolve according to a prescribed function. This method led to an improvement of the short-term (up to 24 h) forecast in a number of cases, without large chances of deteriorating the forecast. Good results were obtained by moving precipitation areas based on radar data. The relation between observations and modifications is then more direct than in our conceptual PV-WV comparison. However, advantage of modifying an analysis is that the full nonlinear model dynamics and physics are used to calculate a forecast, which becomes important from about +12 h.

In the present study we continue the work of Vosbeek *et al.* (2001) and Verkley *et al.* (2005). First the relation between PV and WV is discussed. Then the method of PV modification and the assimilation of the modified PV field in HIRLAM (HIgh Resolution Limited Area Model) is treated. Chapter 3 presents the graphical interface for PV modification based on Metview. In Chapter 4, case studies are shown in which the method of PV modification is used to study the effect of synoptic-scale features on the development of certain systems (an upper-level low and a case of tropopause cyclogenesis). This can be regarded as an intermediate step, since the relation between PV and WV is not used and hindsight is used. Nevertheless, these cases are interesting in their own right and contribute to the understanding of dynamical developments. Then a case is presented in which the original HIRLAM analysis clearly showed a mismatch with the WV image. The subsequent deepening of a low was too weak. The sensitivity of the forecast to the precise modification is tested and a comparison with the ECMWF (European Centre for Medium-Range Weather Forecasts) ensemble will be made. Finally the conclusions and an outlook on the future use of the method are formulated. Technical details about the implementation and use of our software can be found in the appendices.

Chapter 2

Theoretical background and method

2.1 Water vapour images and potential vorticity

Water vapour satellite images are a useful tool when studying the large-scale flow in the atmosphere. They have a large resolution, cover a considerable area and have a relatively high sampling rate (every 15 minutes for the current METEOSAT 8 satellite). The observations in the 6.3 μm water vapour (WV) channel can be interpreted in terms of the tropopause height. The stratosphere is extremely dry, so the radiation temperatures observed by a satellite represent the temperatures around the tropopause. Since the temperature decreases with height, high radiation temperatures (by convention black in images) correspond to a low tropopause. This is illustrated in figure 2.1. A depression can be recognised by its high radiation temperatures, a tropopause fold by its sharp transition from high to low radiation temperature. However, this model is oversimplified. Dry regions in the troposphere and high clouds give also high and low radiation temperatures. respectively, without being directly related to the height of the tropopause. The picture needs interpretation. A wealth of cases with their dynamical interpretation is discussed in Santurette & Georgiev (2005).

The dynamical tropopause is also characterised by a rapid increase of the potential vorticity (PV). Here we have used the the hydrostatic approximation to Ertel's PV. PV can then conveniently be expressed in isentropic coordinates as

$$P = -g(f + \mathbf{k} \cdot \nabla_\theta \times \mathbf{v})\frac{\partial \theta}{\partial p} \tag{2.1}$$

with g the gravitational acceleration, $f = 2\Omega \sin \phi$ the vorticity due to the Earth's rotation (Ω being the angular frequency of rotation, ϕ the latitude), $\mathbf{v}$ the velocity, θ the potential temperature, p the pressure. The vector $\mathbf{k}$ is the local unit vertical vector and the gradient operator ∇_θ had θ as vertical coordinate. PV is high at high latitude (large f), in eddies (large vorticity) and in the stratosphere (strong temperature stratification). PV is generally expressed in PV units, 1 PVU=10^{-6} m^2 s^{-1} K kg^{-1}. The tropopause corresponds to the transition from 1 to 2 PVU, most often the 2 PVU surface is taken as the tropopause. The use and significance of PV are discussed thouroughly in Hoskins *et al.* (1985).

The quantity PV is determined by all the dynamical fields (velocity, temperature and pressure). Therefore it is a convenient means of summarizing the dynamical state of the atmosphere. Under the assumption of balance and a reference state, it is also invertible. Furthermore, in the absence of diabatic processes and friction it is materially conserved. For the synoptic timescale in meteorology (a few days) this is a reasonable assumption in many cases.

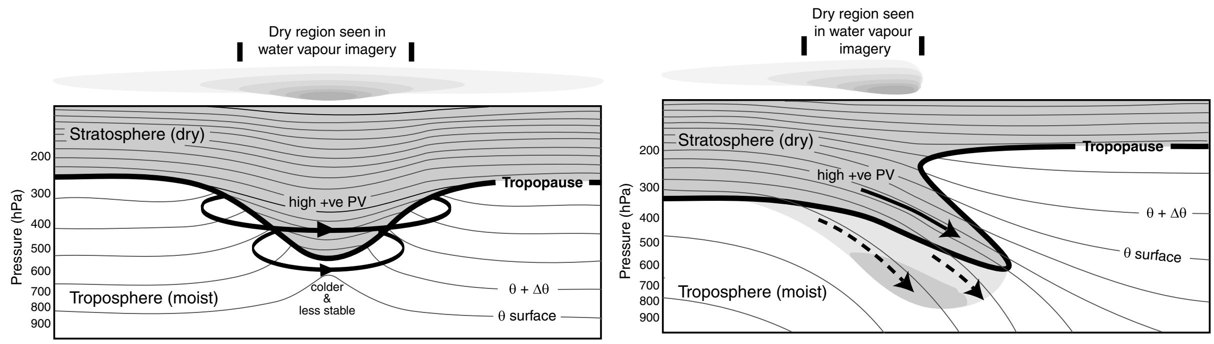


Figure 2.1: Cross-section of the atmosphere with potential temperature contours and the corresponding grey-values observed in a WV image. Left: depression, right: tropopause fold. Pictures courtesy of N. Roberts (Roberts (2000).

For these reasons, when the PV on an isentropic surface and a water vapour image are compared, they should show corresponding features at midlatitudes. Which isentropic surface is most suitable depends on the season. In winter the 315 K isentrope is a good indicator, in summer the 330 K isentrope is more appropriate. If the PV structure from a numerical weather analysis does not match the WV observations, the analysis may be wrong. One could think of correcting the weather analysis by correcting the PV and translate this back to the dynamical field. This idea forms the basis of the present work.

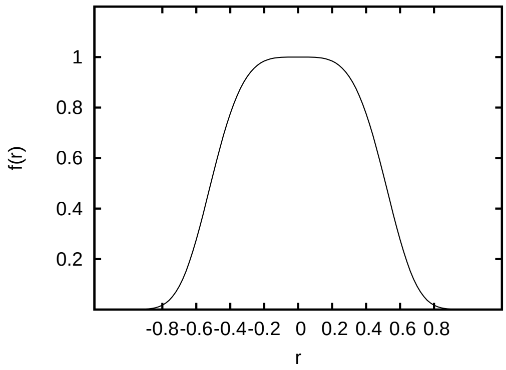
2.2 Modification

The idea of modification is applied to KNMI's operational HIRLAM model. The essential features of HIRLAM are described in Undén *et al.* (2002), but HIRLAM is updated continuously. Main changes are an increase of resolution and parameterizations of physical processes, which do not affect the PV modification procedure developed in Vosbeek *et al.* (2001) and in the current project. Details about the PV calculation on HIRLAM's hybrid vertical η coordinates can be found in Vosbeek *et al.* (2001). At present, the model has 40 vertical layers with layer 1 at the top of the atmosphere (10 hPa) and level 40 at the Earth's surface. In the next sections the modification method is described. Modifications are determined using a graphical interface (see Chapter 3) and communicated to HIRLAM via a parameter file. Then the modification is calculated directly on the HIRLAM grid to avoid interpolation errors which negatively affect the assimilation procedure of the PV modifications. Furthermore, the use of a few parameters to characterize a modification makes the modification highly reproducible and well quantified as compared to contour manipulation procedures often used (e.g. Demirtas & Thorpe (1999), Røsting *et al.* (2003)).

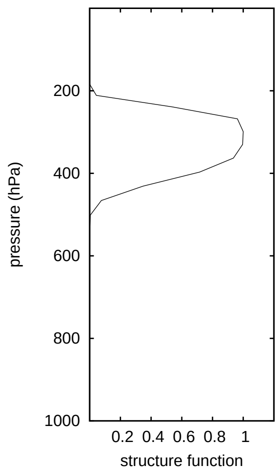
Horizontal structure

A modification is applied in a horizontal circular region with radius b. This region is called the *influence area*. The modification is strongest in the centre of this region and decreases towards the boundaries to reduce discontinuities. The modification function f is given by

$$f(r; b, \alpha) := \exp[(\ln \epsilon)(r/b)^{2\alpha}], \qquad 0 < r < a, \tag{2.2}$$



a



b

Figure 2.2: Structure functions for modification. (a) Horizontal structure function for $\alpha = 2.0$. (b) Vertical structure function with maximum at 300 hPa level and an asymmetric decrease towards higher and lower levels.

with $r = ((\lambda - \lambda_0)^2 + (\phi - \phi_0)^2)^{1/2}$ the distance to the centre (λ_0, ϕ_0) of the modification area. The coordinates λ, ϕ are lon-lat coordinates. The dimensionless factor α is the steepness factor. For $\alpha = 1$ the function is Gaussian, for $\alpha > 1$ the structure is broader with a flat 'peak'. The value of ϵ is chosen small (ϵ=0.00005) to ensure that the values of $f(b; b, \alpha) = \epsilon$ are close to 0 at the boundaries of the influence area. There is a certain trade-off between the choice of the radius of influence and the steepness parameter. Fig. 2.2a shows the $f(r)$ for $\alpha = 2.0$.

There are three types of modifications: the addition of a source or sink, the local strengthening or weakening of an existing structure and the displacement of an existing structure. It is also possible to apply a combination of these modifications.

When a source with absolute strength γ (in PVU units) is added, the new P becomes

$$P(r) = \begin{cases} P(r) + \gamma f(r; b, \alpha), & 0 \le r \le b \\ P(r), & r > b. \end{cases}$$

For the local strengthening or weakening of an existing structure with relative factor β the new PV becomes

$$P(r) = \begin{cases} P(r)(1 + \beta f(r; b, \alpha)), & 0 \le r \le b \\ P(r), & r > b. \end{cases}$$

For a negative value of β the structure is weakened. It should however fulfill $\beta > -1$ to avoid the introduction of negative PV values.

A displacement is calculated according to the elementary advection scheme

$$P_m(\lambda, \phi) = P(\lambda, \phi) - \left[\Delta\lambda \frac{\partial P(\lambda, \phi)}{\partial \lambda} + \Delta\phi \frac{\partial P(\lambda, \phi)}{\partial \phi} \right] f(r, b, \alpha)$$

The displacement is in general done iteratively, with the displacement subdivided into smaller intervals. In the code, a central difference is used to compute the derivatives. The displacement can be regarded as an advection of the PV structure by a local wind field. Since this advection scheme is not very stable, the step size in the iteration must be very small.

Vertical structure

The modifications are not applied to the full vertical column, except for the displacement where the total column is displaced.

For a source, the PV modification is constrained in the vertical, using the same structure function as used in the horizontal (Eq. 2.2). The maximum is fixed, at HIRLAM model level 13 (300 hPa), the modification extends from level 9 (180 hPa) to 20 (530 hPa) in the present configuration with 40 vertical levels (Fig 2.2b). This gives an asymmetric curve with respect to level 13. The steepness α is set to 2 for both the upper and the lower part of the curve. Adding a constant value throughout the atmosphere would give relatively large constibution in the lower atmosphere, where only small PV values are found, which is undesirable.

Also for a strengthening, the PV modification is constrained in the vertical, using the same structure function as in the horizontal (Eq. 2.2). The maximum is fixed, at Hirlam model level 13 (300 hPa), the modification extends from level 9 (180 hPa) to 20 (530 hPa), again with $\alpha = 2$. Multiplying high PV values in the upper atmosphere with the same factor as near the tropopause would lead to unrealistically high values there, these values are now damped. The particular choices for the vertical strucutre were based on the idea that tropopause depressions mainly affect the PV in the region mentioned above. Furthermore, the modification procedure is based on the idea that the WV image only gives information about the tropopause region. The PV-WV method can therefore not justify modification at lower levels.

When it is intended to add a tropical storm, a feature which is not always picked up well due to its relatively small scale and extreme values of pressure and wind speed, the vertical structure should be adapted. In such case, the PV anomaly must extend further down to the Earth's surface. The vertical structures are hardcoded but can be easily adapted in the HIRLAM code (see appendix). They are not part of the input file to reduce the number of decisions that has to be made when used in operational forecasting. For completeness it must be mentioned that PV modifications of equal magnitude have more impact on the forecast when they are applied well below the tropopause where the ambient PV values are small than when they are applied around the tropopause level. This is particularly relevant when a source is added.

2.3 Assimilation of PV using 3D-var

At present, the PV method is implemented in the three-dimensional variational (3D-var) assimilation method used by the operational HIRLAM. Conventionally, the analysis is determined from a previous forecast, valid for that time (first guess, background) and observations. In our experiments, the HIRLAM analysis is used as first guess (background) and conventional observations were not assimilated again. The modified PV field is treated as new observations. A new analysis is obtained by minimizing a cost function consisting of a background term J_b and a PV term J_p.

$$J = J_b + J_p \tag{2.3}$$

The background term consists of the difference between the model state and the first guess. The PV term consists of the difference between the (PV of the) model state and the modified PV-field. It is defined as

$$J_p = \frac{1}{2}\mu \sum_{k=1}^{nlev} \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} w_p(k)(P(i,j,k) - P_m(i,j,k))^2 \tag{2.4}$$

The weights $w_p(k)$ are introduced to give all levels a comparable contribution to the cost function. Otherwise, the high PV values in the stratosphere dominate over the small values in the troposphere. It is defined according to

$$w_p(k) = \begin{cases} 0, & \text{for } k\text{=1,2,3,4, nlev-1,nlev} \\ 1, & \text{for k} \neq \text{1,2,3,4, nlev-1, nlev, and } \bar{P}_b(k) < 1 \\ \frac{1}{P_b^2(k)}, & \text{else} \end{cases} \tag{2.5}$$

with

$$\bar{P}_b(k) = \frac{1}{n_x n_y} \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} P_b(i,j,k)$$

the average vorticity field of the background. The PV term is given an additional weight factor μ which can be used to express the uncertainty. In practice its value is set to 10 to force the solution towards the modified PV field. Strictly speaking it is not an inversion method, but in practice the difference will be small. Details about the choices for the data assimilation can be found in Verkley *et al.* (2005). The advantage of using the variational method instead of an inversion is that it automatically respects the balance conditions of the model. Furthermore, the method can be easily implemented in a 4D-var environment, making it possible to modify a forecast based on the most recent observations.

The minimization method makes use of so-called adjoint equations. The adoint equations for the PV calculations can be found in Vosbeek *et al.* (2001). The mimimization itself is in general not carried out at the full model resolution but on a more coarse resolution. This reduces the computation time considerably, which is important for operational use. The minimization, even on a reduced grid, takes nearly as much time as a 48 h forecast. We have done the mimimization on the reduced grid in our case studies. The minimum of the cost function is determined in an iterative procedure (M1QN3, Gilbert & Lemaréchal (1989)). As a convergence criterium the norm of the gradient of the cost function $||g||$ must satisfy

$$\frac{||g_k||}{||g_1||} < \epsilon_g. \tag{2.6}$$

For the convergence parameter the operational value $\epsilon_g = 0.05$ is chosen. A maximum number of iterations and simulations must be set to restrict the computation time. These are set to 100 and 110 respectively. In our test cases, convergence was not always reached within 100 iterations, but the PV of the resulting analysis did not differ significantly from the modified PV field. When convergence is reached, at often around 70 iterations were needed. The convergence is very sensitive to the precise modification and it is difficult to predict when convergence is difficult to reach and when not. Possibly the localised structure of the modification leads to different behaviour from the minimization of the observation function, with observations spread over a large part of the domain instead of a substantial modification over a very limited part of the domain. A 48 h run with assimilation of the modified PV field on a 22 km HIRLAM grid is nearly as fast as the operational model, which opens up the possibility to use it operationally.

Chapter 3

Graphical interface for modification

The interface which is used to determine a modification is a Metview application. In this chapter, a description is given of how to use the graphical user interface for PV modification. For technical details about Metview and the macro described here we refer to Appendix B.

Metview can be started from a shell using the command `metview-new &`. In the older (default) Metview version some utilities for file handling do not work properly at the moment of writing. The folders which were on display the last time Metview was closed, are opened in Metview windows. The relevant files are directly below the metview folder in the user directory on the nobackup or scratch disk. The macro and help files are available in `.../metview/modifyPV`.

The macro `ModifyPV.mc` contains the actual macro. It opens the files, plots the files and calculates the modifications. The filenames of the grib files with WV data and the PV on isentropic levels can be changed in this macro by editing it. The modification parameters are in the interface `Modification parameters`. To start the procedure, click on `Modification parameters` using the right mouse button and select `edit`. A window pops up (see Fig. 3.1). Click on `Stay open` in this new window.

To visualise the original PV and WV fields, select `Original Fields` from the `Fields` section. Select an isentropic level (`level`) and click on `Apply`. Then go back to the metview folder window. Click on `Modification parameters` with the right mouse button and select `execute`. The fields are now visualised.

To modify the PV field, select `Modify PV` from `Fields`. Choose a function. The coordinates can be determined from the visualised fields. When one clicks on the right mouse button when the the pointer is over the visualised fields, a menu appears from which the option `Show coordinates` should be chosen. This results in the appearance of a cross-hair with the corresponding lat/lon coordinates. It is also possible to zoom in, after clicking the zoom icon (with blue asterisk) in the upper left of the plot window. The coordinates of the centre of the area that is to be modified must be typed in the parameter window. *Always give* `enter` *after typing in the parameter window*, otherwise the default values are taken. Type the strength of the modification, set the influence-radius ruler and type the steepness. In case of a displacement, the coordinates of the new location must be typed. When finished, click on `apply` and execute `Modification parameters`.

The new PV field is plotted and the modification area is indicated by a polygon. Also the file `pvmod.DAT` is generated, containing the modification parameters. This is the input file that is read by HIRLAM when it is placed in the correct directory. By default it is written to the subdirectory `data` (Fig. 3.1). When the modification is not satisfactory, a new modification can be calculated

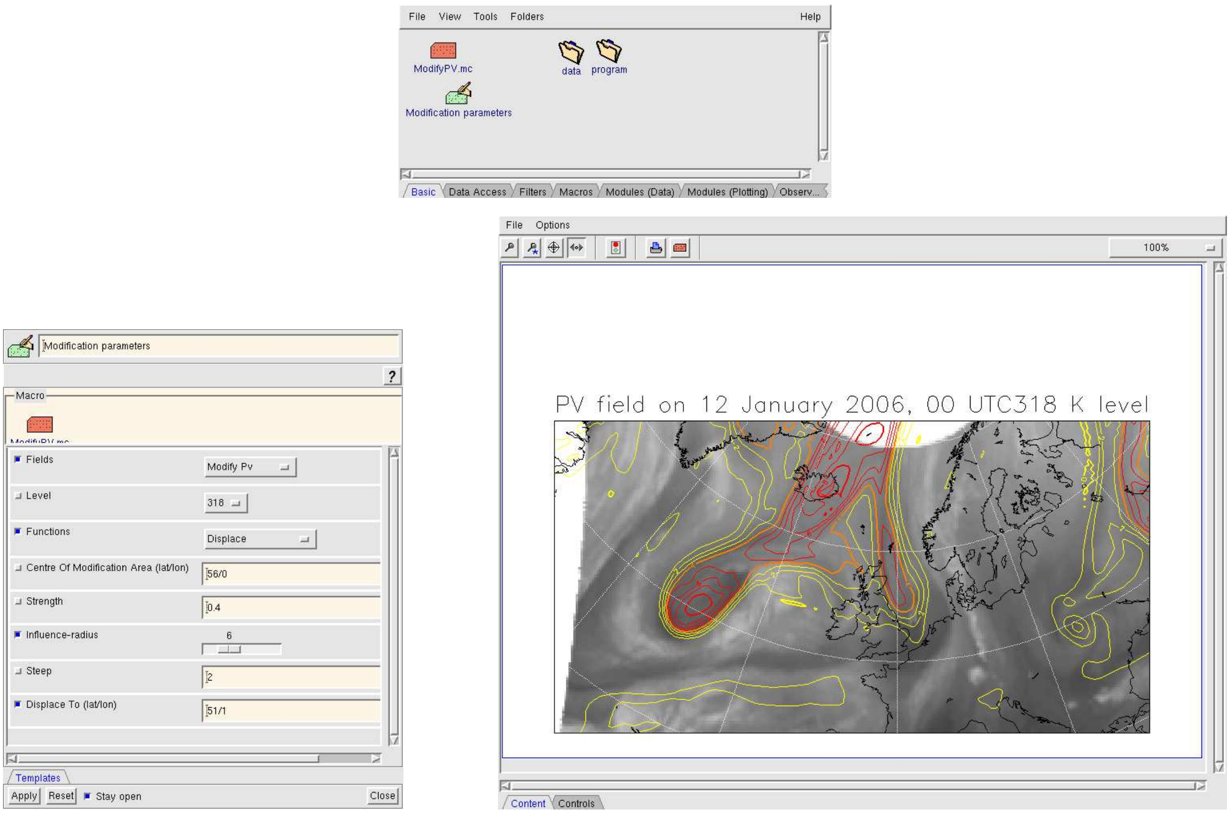


Figure 3.1: Metview interface for PV inspection and modification

and the output file is overwritten. It is not yet possible to combine modifications in the graphical interface, but it is relatively straightforward to implement this.

Chapter 4

Testing conceptual ideas

4.1 The development of an upper-level low

In the night of 14 to 15 May 2005 an upper-level low passed over the Netherlands. This small-scale feature was a classical example of such a phenomenon, with a clear signature in the WV observations, a corresponding small area of high PV values and a typical pattern of precipitation. It was very well predicted by the operational HIRLAM run. The question came up how special this case was. PV modification was used manipulate the weather systems that were present and the effect of every modification on the development and location of this upper-level low was investigated by calculating new forecasts. In this way the contribution of the different weather systems to the develpment of the upper-level low could be studied. This experiment was the first test case for our system.

Modified runs

The modified runs are presented in two sets. The first set is the modification of the analysis of 14 May 2005 06 UTC. The effect on the +21 h forecast is studied. This forecast is valid for 15 May 03 UTC, the moment in time when the upper-level low (ULL) is well developed and right over the Netherlands. The second set consists of modifications of the analysis of 13 May 2005 06 UTC with the same verification time. In this case the modified analysis has more time to evolve. The modification parameters are indicated in Table 4.1. All modifications are weakenings. In these exeperiments, the vertical structure was not as indicated in the previous chapter, but the weakening was multiplied with the vertical structure $h(k) = (2/\pi \arctan(k-2), k = 2, nlev, h(1) = 0$ as in Vosbeek *et al.* (2001) and Verkley *et al.* (2005) to reduce its effect at the upper stratospheric levels. Convergence of the miminization in 3D-var was reached in around 30-50 iterations.

Modifications on 14 May

To verify how well the ULL was predicted by the model a control forecast was produced (Fig. 4.1). Indeed, the 21 h forecast starting on 14 May captured the development very well, with the ULL over The Netherlands on 15 May 03 UTC. The verifying analysis is not shown. Four modifications were done, in which potentially relevant features in the large-scale patterns are perturbed. The results are shown in Fig. 4.2. The first modification consisted of a weakening of the large-scale depression over the Atlantic, resulting in a reduction of PV with 2 PVU in the centre of this depression. The

run	β	lat	lon	radius	α
14-run1	-0.2	-18.0	45.5	9.0	2.0
14-run2	-0.5	0.0	54.0	4.0	2.0
14-run3	-0.3	9.5	57.0	4.5	2.0
14-run4	-0.4	-3.0	52.0	5.0	2.0
13-run1	-0.3	8.0	62.0	4.5	2.0
13-run2	-0.3	-23.5	51.0	9.0	2.0
13-run3	-0.3	3.5	54.0	5.5	2.0
13-run4	-0.3	28.0	55.0	4.5	2.0

Table 4.1: Modification parameters for the upper-level low.

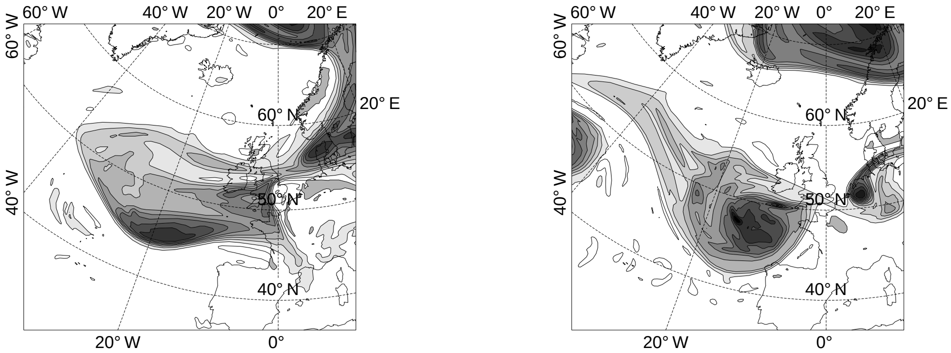


Figure 4.1: PV contours on the 315 K isentropic level, intervals of 1 PVU of the original analysis on14 May 2005 06 UTC (left panel) and of the resulting +21 h forecast valid for 15 May 03 UTC right panel).

modification did hardly affect the strength of the ULL but its position was slightly more to the south. The strength of the large depression remained weaker than in the original forecast. The second modification weakened the narrow filament which connected the systems above Denmark and England (not well visible in the figure). This modification did not alter the strength of the ULL but shifted its position to the East. It is no longer connected to the large depression above the Atlantic, the PV around 50° N 22° W was also affected.

The third modification directly weakened the precursor of the ULL over Denmark. This reduced the strength of the ULL, it is more to the west and connected to other features, becoming less prominent. The fourth modification weakened the feature above south-west England, which resulted in a shift of the ULL to the east. Around 50° N 22° W the PV was also affected.

So only a direct modification of the strength of the developing ULL resulted in a significant change in the development. The other modifications only led to a change in position of the ULL, and had a long-term effect on the system they were applied to.

Modifications on 13 May

The original forecast starting on 13 May 2005 06 UTC, valid for 15 May 03 UTC, did predict the ULL but it is slightly too weak and its position is more to the west (Fig 4.3. In the +24 h forecast

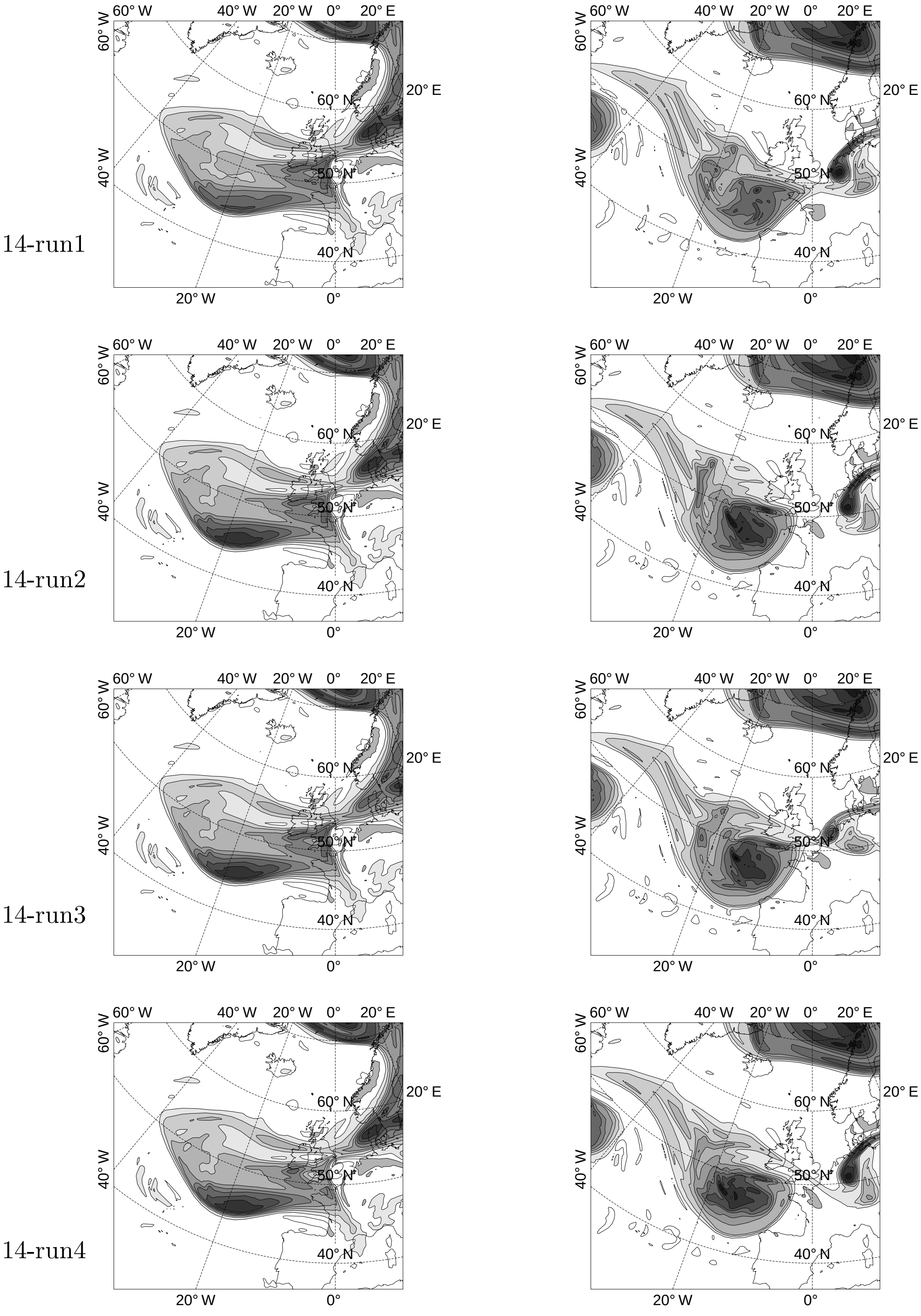


Figure 4.2: PV contours on the 315 K isentropic level, intervals of 1 PVU of the modified analyses for 14 May 2005 06 UTC (left panels) and of the resulting +21 h forecasts (valid for 15 May 03 UTC) (right panels).

(not shown), the PV above Denmark is slightly weaker than in the analysis for that time (figure 4.2). This illustrates the limitations of HIRLAM for longer forecasts and the need for data-assimilation to constrain the model state. Nevertheless, the ULL clearly develops and the impact of several modifications on its strength and location can be studied. The first modification is a weakening of

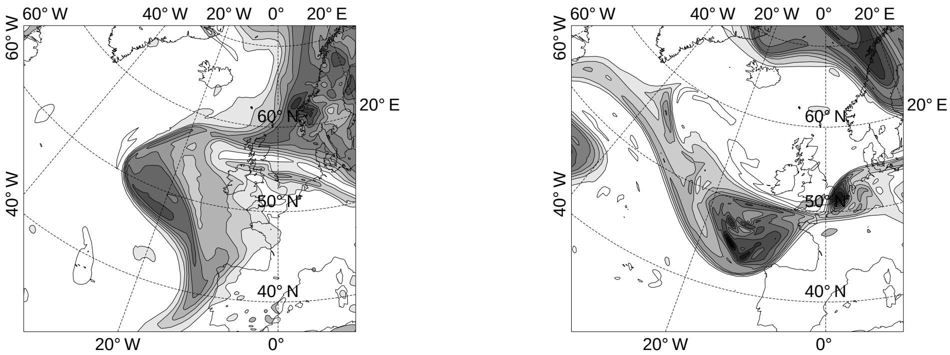


Figure 4.3: PV contours on the 315 K isentropic level, intervals of 1 PVU of the original analysis for 13 May 2005 06 UTC (left panel) and of the resulting 45 h forecast valid for 15 May 03 UTC (right panel).

the small area with large PV values above Norway. This effectively modifies the development of the ULL: after 45 h there is only a weak PV anomaly south of Ireland, which is nearly connected with the large system over the Atlantic. Thus both the strength and the position were seriously affected. The second modification is a weakening of the large system over the Atlantic ocean. This significantly affects the strength and shape of this system in the subsequent development. The ULL still has the same strength but it is displaced and is more elongated. The third modification consists of the weakening of a nortward propagating (weak) PV structure above the North Sea. This results in a more easterly position of the ULL, which is now detached from the large-scale depression. The depression has a slightly different small-scale structure. The fourth modification weakens the depression system above Russia. This again only leads to a change in position of the ULL but it does affect the track and intensity of the northward propagating depression (not shown in the original analyisis and forecast).

Conclusions

The development of the upper-level low is a quite robust feature. Structures develop without much degradation through mixing or diabatic processes; they can be clearly identified and followed in time. PV is indeed a conserved quantity on this timescale in this case for all of the systems in which modification was applied. Only the removal of PV in the direct source area prevents the development of the upper-level low over the Netherlands, the development was mainly a result of advection. However, the strength of other synoptic-scale elements do influence the precise position of the upper-level low. The results support the assumption that PV can in general be considered as a conserved quantity that is advected, like water vapour.

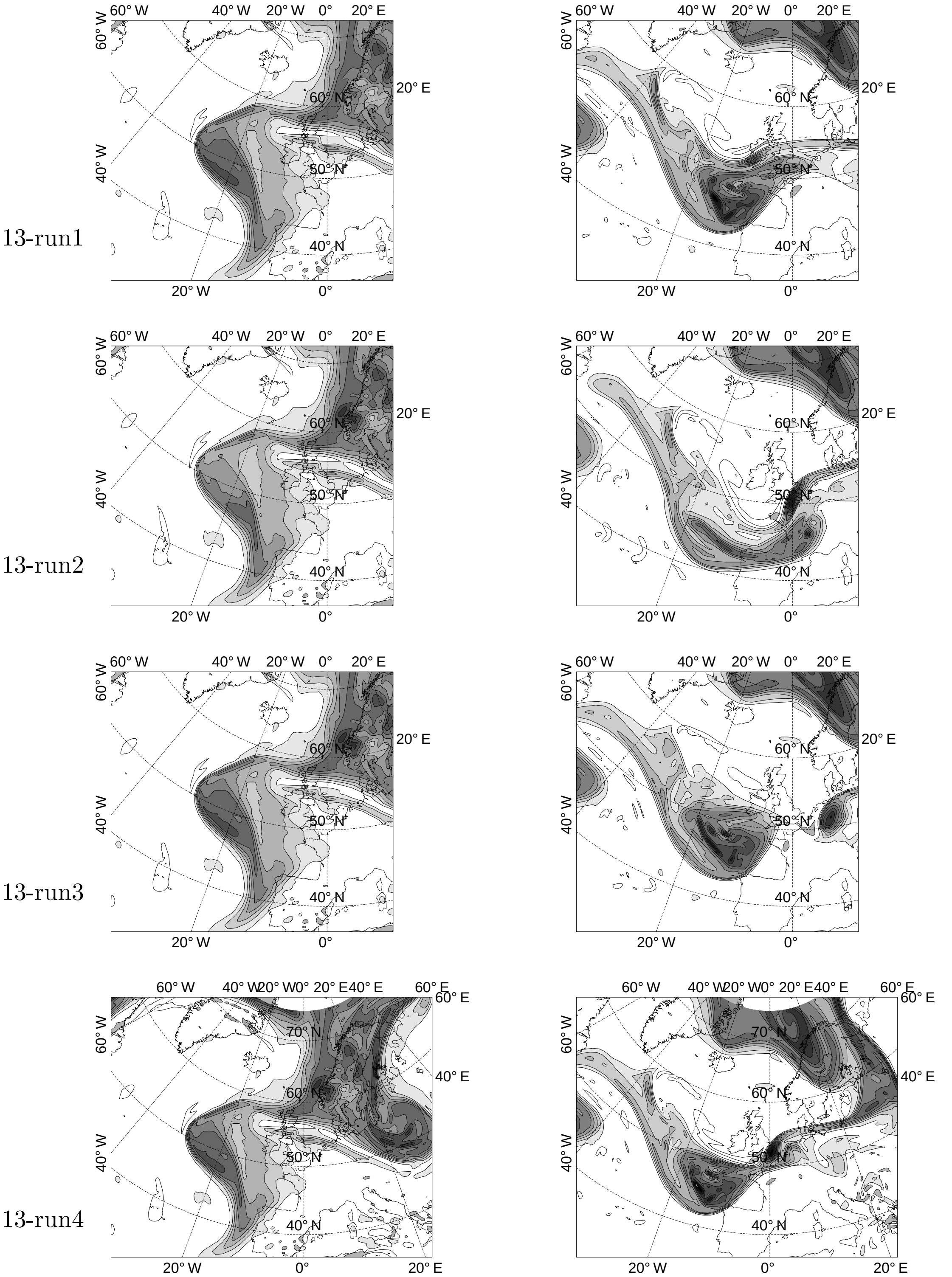


Figure 4.4: PV contours on the 315 K isentropic level, intervals of 1 PVU of the modified analyses for 13 May 2005 06 UTC (left panels) and of resulting 45 h forecasts (valid for 15 May 03 UTC) (right panels).

4.2 A case of tropopause cyclogenesis

With A.J. van Delden and V.C.I. van Leeuwen, IMAU, Utrecht University

A specific case of tropopause cyclogenesis was studied by Van Delden & Neggers (2003). Between May 8 and May 11 1996, an upper-level trough developed into a shear line and a tropopause cyclone (or cut-off low) over the North Sea. The authors propose that the events were triggered by the interaction of two high PV patterns. The PV modification method is now used to eliminate these areas of high PV and verify how the development of the tropopause cyclone is affected. In this section, preliminary results are shown, concentrating on the PV structures only.

The old HIRLAM analysis from 1996 could not be used directly in HIRLAM 6.3.5, so a new analysis had to be prepared. The modification experiments were started from the analysis at 8 May 1996 12 UTC. Figs. 4.5 and 4.8 show the PV at analysis time and the +48 h forecast on respectively the 320 K and the 310 K isentropic level. This run is representative of the situation as investigated by Van Delden & Neggers (2003). In the figures, at analysis time a deep trough is observed over Northern Europe, it is present at both isentropic levels. There is also a banner of high PV extending from Greenland to Great Brittain, which is however only present higher in the atmosphere, it is not visible at the 310 K level. After 48 hours, an upper-level low is formed which is nearly cut-uff from the original trough. The high resolution of the run enables a detailed identification of PV structures within this low. The structures are similar at both isentropic levels, but the structure with high PV values at 320 nearly parallel to the 50°N parallel does not have an equivalent at the 310 K, whereas the high PV values close to Denmark are visible in at both isentropic levels.

Modified runs

Several experiments were carried out in which locally PV was removed or reinforced. The parameters are indicated in Table 4.2. All modifications consisted of strengthenings or weakenings. In the vertical, the influence function as described in Chapter 2 was used, with a maximum impact at the 240 hPa model level and a decreasing impact towards 135 hPa and 600 hPa. Convergence of the minimization procedure in 3D-Var was reached for all modifications within 37-50 iterations. The modified analyses and the resulting forecasts at the 320 K isentropic level are shown in Figs. 4.6 and 4.7, results at the 310 K level are shown in Figs. 4.9 and 4.10.

It was observed that PV was rapidly transported in the PV banner. To remove the high PV values that were taken up in the upper-troposphere low after 48 h, the high PV values above Greenland were removed in modification 1. This indeed removes the high PV values close to 50° N at both isentropic levels, leaving the higher values near Denmark unaffected. The upper-level cyclone is not as clearly cut-off at the 320 K as before, at 310 K the structure is more isolated.

Modification 2 consisted of strengthening of the tip of the trough above the North Sea to verify how this would affect the position of the high and low PV values in the cyclone. However, the modification did not have a significant effect on the forecast of the topopause cyclone. PV stuctures are in essence only shifted a little. Closer inspection revealed that most of the PV in the tip of the trough is advected away to the north and is not taken up in the cyclone.

In modification 3, the area of high PV above Norway is strengthened. The consequences are that the PV values in the cyclone have increased and that the cyclone is shifted to the east. It is more separated from the PV filament around 50° N. The two structures still combine in a large

run	β	lat	lon	radius	α
mod1	-0.9	67.0	-40.0	10.0	2.0
mod2	0.25	57.0	6.0	10.0	2.0
mod3	0.25	66.0	14.0	14.0	2.0
mod4	-0.9	66.0	14.0	18.0	1.0
mod5	mod1 and mod4 combined				

Table 4.2: Modification parameters for the tropopause cyclogenesis.

pattern but it has changed shape.

In modification 4, the PV in the same area is weakened. A slightly larger radius and a smaller steepness parameter than in modification 3 were chosen to obtain a more natural PV structure for this severe reduction in PV. The result shows that the region of high PV above Norway was indeed the essential ingredient for the development of the upper-level cyclone. It has become substantially smaller and weaker and it has changed position. It can still be recognised at the 310 K level, at the higher level it is more difficult to separate it from other features. The modification has also serious impact on the position of other features after 48 hours. The region of high PV stemming from Greenland is not transported as far south-east: it can be identified with the patten of high PV southwest of Iceland. Also the filament of high PV around 40° N 15° W which was not affected in the previous experiments did broaden its extent. Features above Western Europe at 320 K are no longer determined by the upper-level cyclone but by smaller-scale features stemming from the south. They are not visible at the 310 K level.

Finally, modification 5 eliminates both the high PV-values above Greenland and the high values above Norway. The cyclone can still be recognised, especially at the 310 K. Like the result of modification 4, it is very weak and has changed position. The patch of high PV southeast of Iceland has disappeared, but the higher PV values in the tail of the low extend more to the North now. The cyclone itself is more to the east as compared with modification 4. These features must have been caused by the removal of high PV abover Greenland.

Conclusions

The results are a valuable addition of the research carried out in Van Delden & Neggers (2003). In particular, the identification of PV filaments was possible due to the high resolution, which enabled a much more detailed view of the development. PV was clearly a conserved quantity in the systems of interest, making it relatively easy to identify the source regions. The more frequent forecasting output will enable a better study of trajectories of air parcels. They will be investigated further to compare them in more detail with this study, with special attention for wind and vorticity. The structure of these fields will not have so much detail as the PV fields but these quantities are important for the deeper understanding of the dynamical processes.

The results lead to the preliminary conclusion that development the upper-level cyclone itself results from the reservoir of high PV in the trough above Northern Europe. Removal of PV of this reservoir directly affects the size and strength of the tropopause cyclone. The banner of high PV stemming from Greenland affects the position of the tropopause cyclone, and is in turn clearly affected by the presence of high PV in the trough. The method has enabled the verification of the original hypothesis and has led to a better interpretation of the processes.

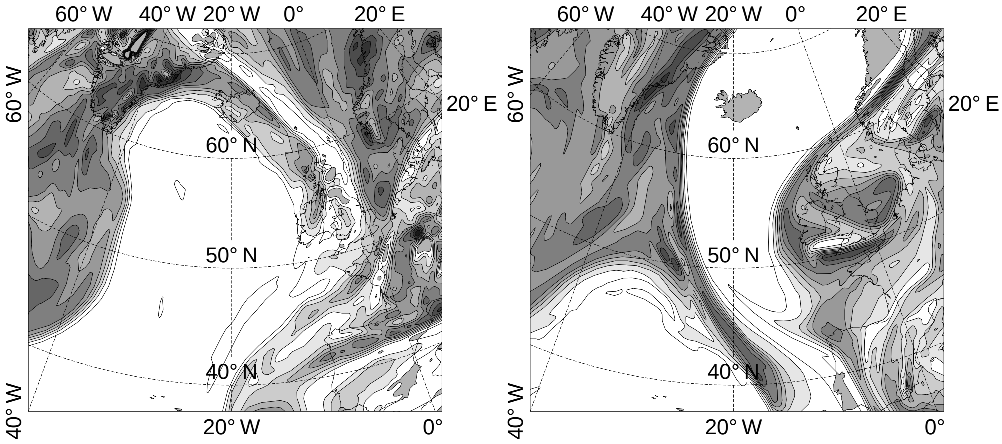


Figure 4.5: PV at the 320 K isentropic level for the analysis at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

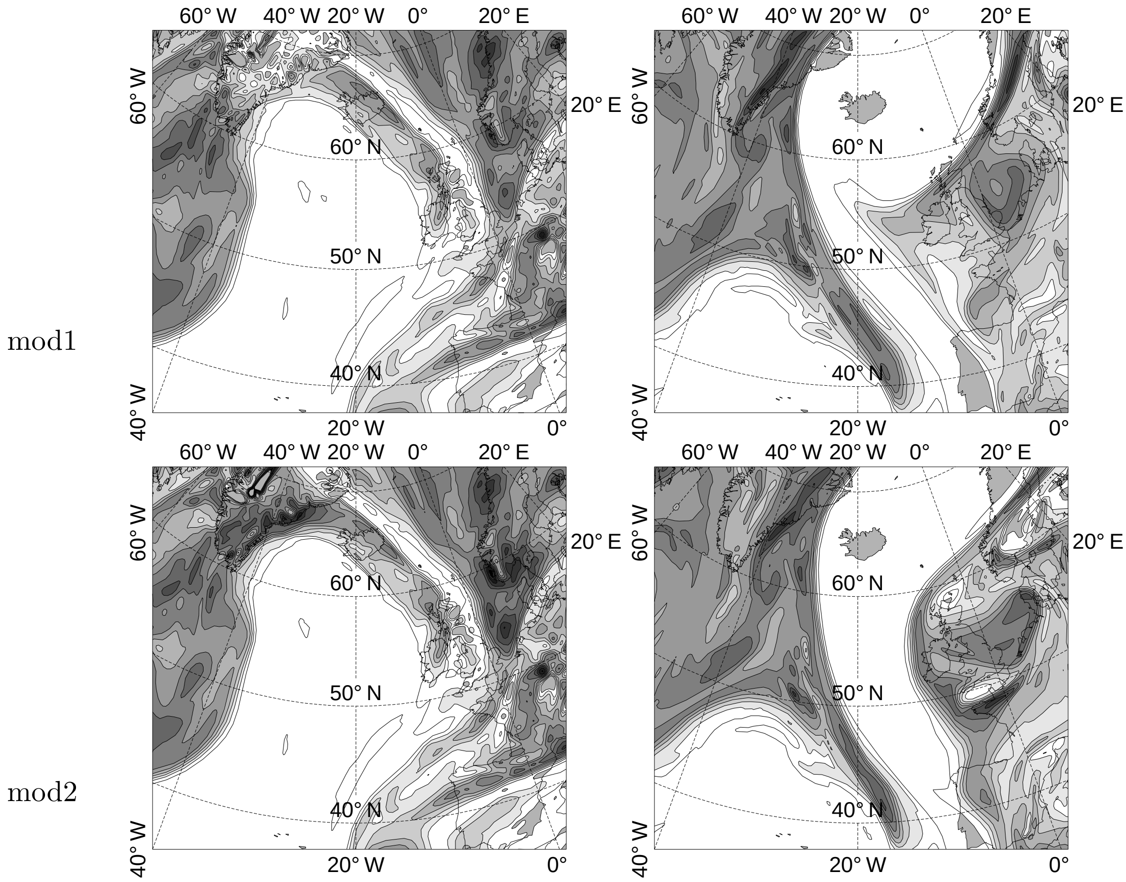


Figure 4.6: PV at the 320 K isentropic level for the modified analyses at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

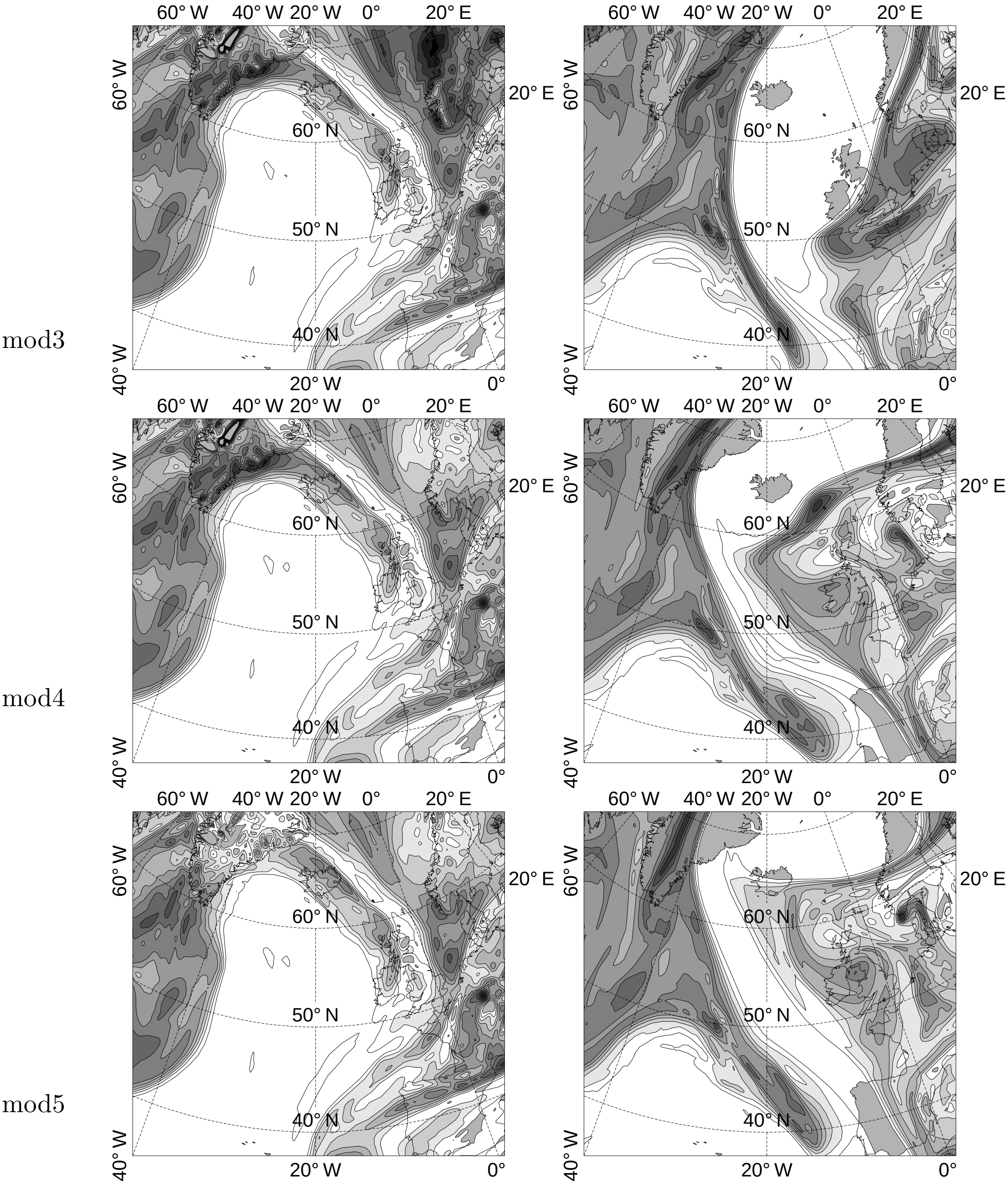


Figure 4.7: PV at the 320 K isentropic level for the modified analyses at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

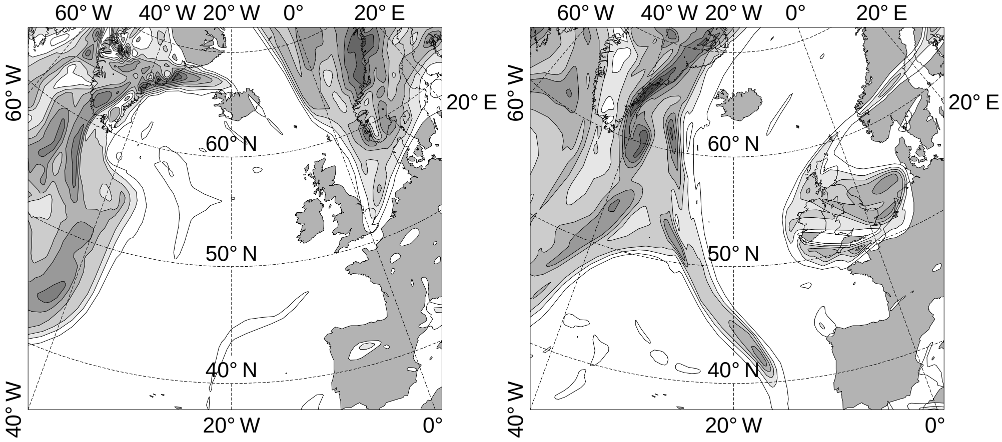


Figure 4.8: PV at the 310 K isentropic level for the analysis at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

mod1

mod2

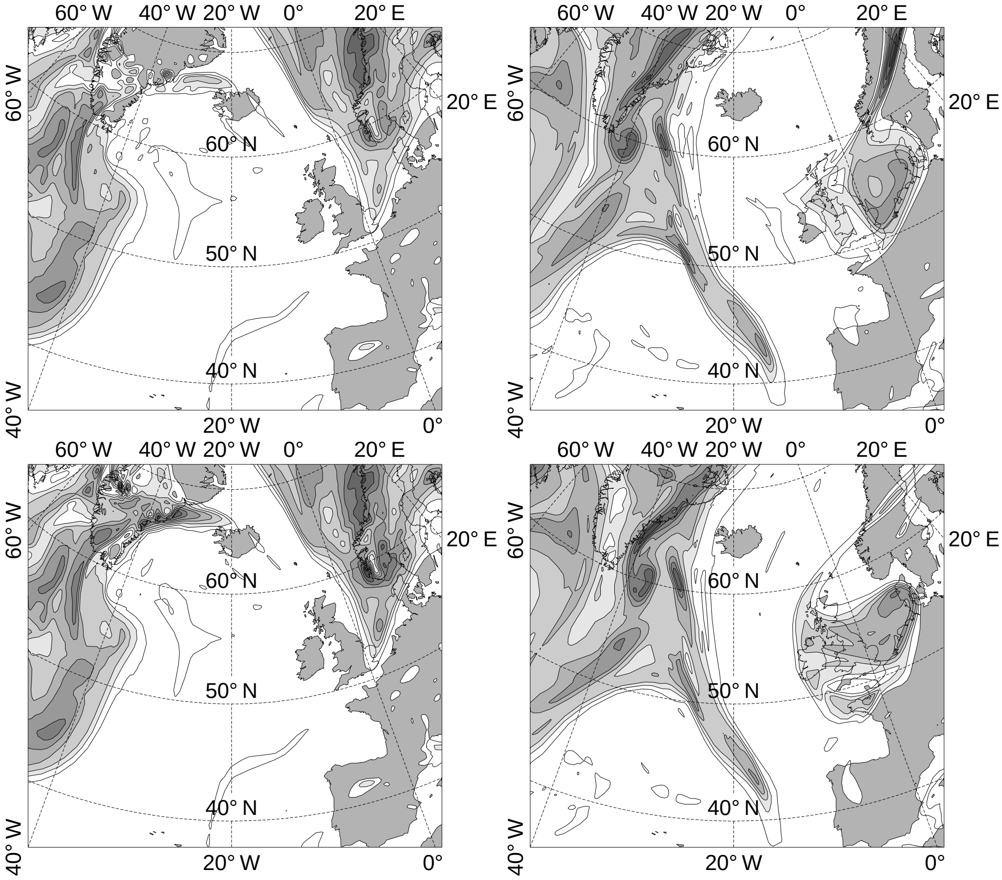


Figure 4.9: PV at isentropic levels for the modified analyses at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

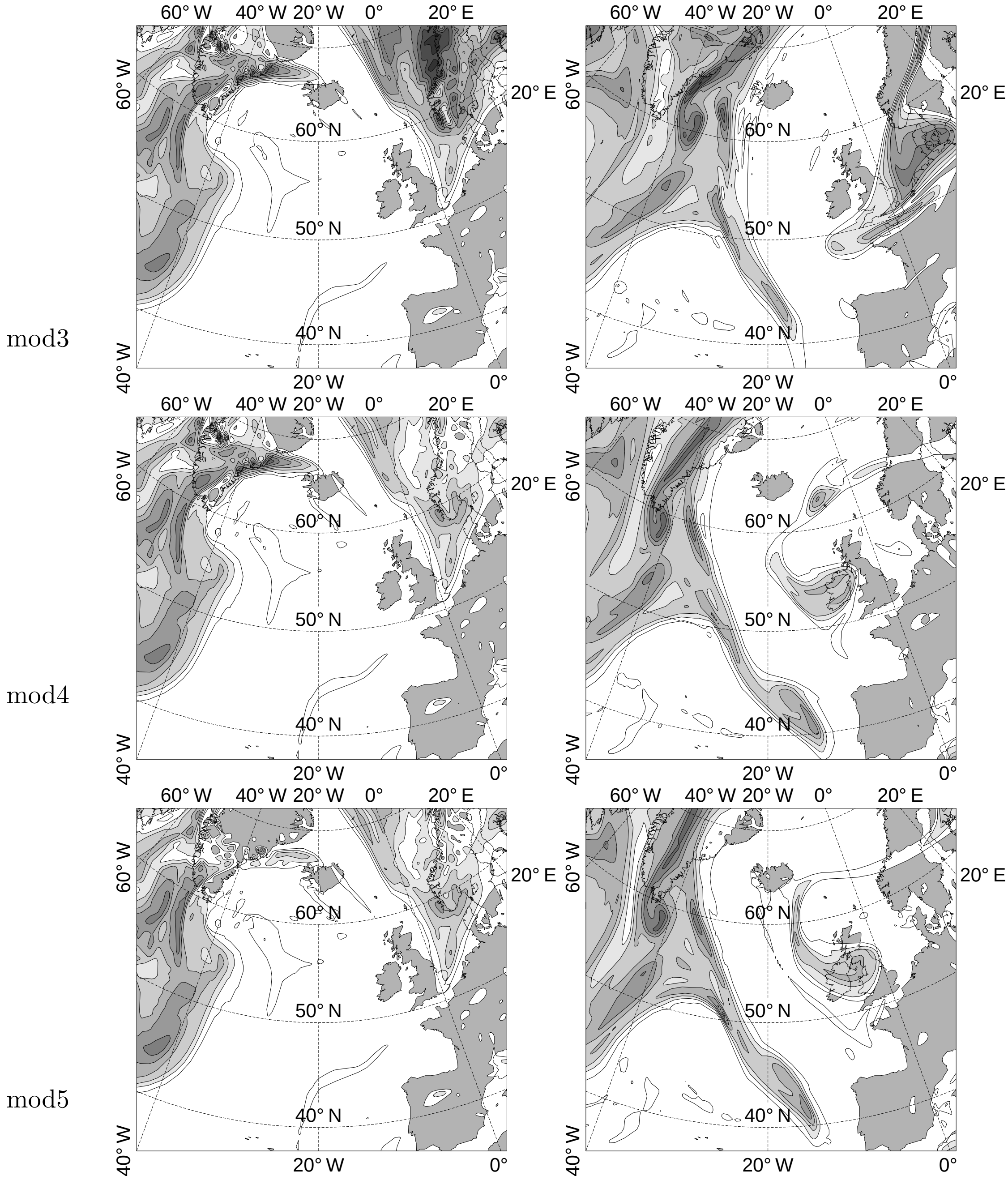


Figure 4.10: PV at the 310 K isentropic level for the modified analyses at May 8 1996 12 UTC (left) and the resulting +48 h forecast (right). Contours of 1 PVU, grey > 2 PVU.

4.3 Discussion

The method to modify a numerical weather analysis was applied with success. It has made it possible to eliminate or enhance PV in limited areas and to study the subsequent development. This has led to better insight in where PV features originate from, how they evolve in time and how systems interact with each other. As compared to idealised models, the method offers a fast and high-resolution alternative with the big advantage that realistic cases can be manipulated and be investigated in detail.

The possibilities to manipulate a case in this meteorological playground seem infinite. Therefore it is important to tightly restrict oneself to a few experiments tailored for testing the hypothesis. In these cases, we have restricted ourselves to weaken, nearly eliminate or reinforce patterns. In these cases, the assimilation of the modified PV fields was successful; convergence of the minimization was reached within a reasonable amount of iterations Even for modification in two large areas the procedure was not much slower than for a single area. The advantage of a strengthening or weakening is that the basic patterns of a the field were unaffected. For displacements or the addition of a source of PV the convergence appeared more problematic.

More important than a rapid convergence is that the atmosphere appears quite robust to the modifications. Only the modified area is seriously influenced with a corresponding effect on the forecast, other systems are only affected through the way they interact with the modified area during the forecast. In other experiments it has also become clear that modifications in small areas do not affect the forecast significantly, they tend to disappear in the first hours of the forecast. This can be understood from the fact that the size of the PV modification is very important for the pressure and wind fields which have a much larger scale and a less detailed structure (Hoskins *et al.*, 1985). Small-sized perturbations are then rapidly smoothed out.

Experiments like these case studies are highly interesting on their own. But they also help to develop a feeling for the development of PV structures. This feeling is important when one aims at modification of a PV structure for weather forecasting. Apart from the detection of a mismatch itself, successful modification requires an understanding of the development of PV structures present in the analysis and a rough idea of what would be the consequence of a certain modification. Therefore case studies can be used for training in PV-thinking for operational forecasters before PV modification can be used in the forecasting practice.

Chapter 5

Improving a forecast

In this chapter a cases is described where operational forecasters detected a serious mismatch between PV and the corresponding WV image. This case, in which the strength of the cyclogenesis was underestimated, was taken as a test case and the analysis was modified. The dynamical development was investigated to find out what was actually improved by the modification. Furthermore, slightly different modifications were applied to check the sensitivity with respect to small variations in the exact location of t the modification. The modification method is compared with the ensemble prediction results from ECMWF. This case study is also described in Manders *et al.* (2006).

5.1 Description of the case

On 7 November 2005, 00 UTC, a wave developed in the left exit region of the jet stream over the North Atlantic, around 46° N 30° W. This wave was not captured well by the HIRLAM analysis. The PV field on the 315 K isentrope showed a clear mismatch with the METEOSAT 7 01 UTC WV image (Fig. 5.1). This image was not available at 00 UTC but at 01 UTC the system will not have developed significantly. In the image a cloudhead and a dry intrusion were observed without corresponding structures in the PV field. The mismatch in the PV field consisted of the following features

1. the large gradient of the PV (associated with the jet stream) is situated too far to the north
2. a maximum in PV in the dry intrusion area is lacking
3. a minimum in PV in the cloud head region is lacking

At 00 UTC, close to the position of the mismatch the minimum mean sea level pressure (mslp) was 1003.8 hPa (HIRLAM analysis, 1003.3 hPa from ECMWF). The operational run predicted a developing low (Fig. 5.2), with a surface pressure of 981.2 hPa after 24 hours (8 November 00UTC) over North-West Scotland. However, the actual development was more dramatic, with a mslp of 973.1 hPa after 24 hours. At 18 UTC the cyclogenesis is more or less completed; this will be used as our verification time. The ECMWF forecast from the ECMWF analysis of 7 November 00 UTC did represent the rapid deepening much better and the +18 forecast was consistent with the 18 UTC analysis. Therefore the ECMWF run is used as benchmark to compare our run with. The ECMWF analysis is not directly used to construct a modification. Fig. 5.2 shows that at initial time, the developing depression in the ECMWF analysis is slightly more to the South. After 18 h

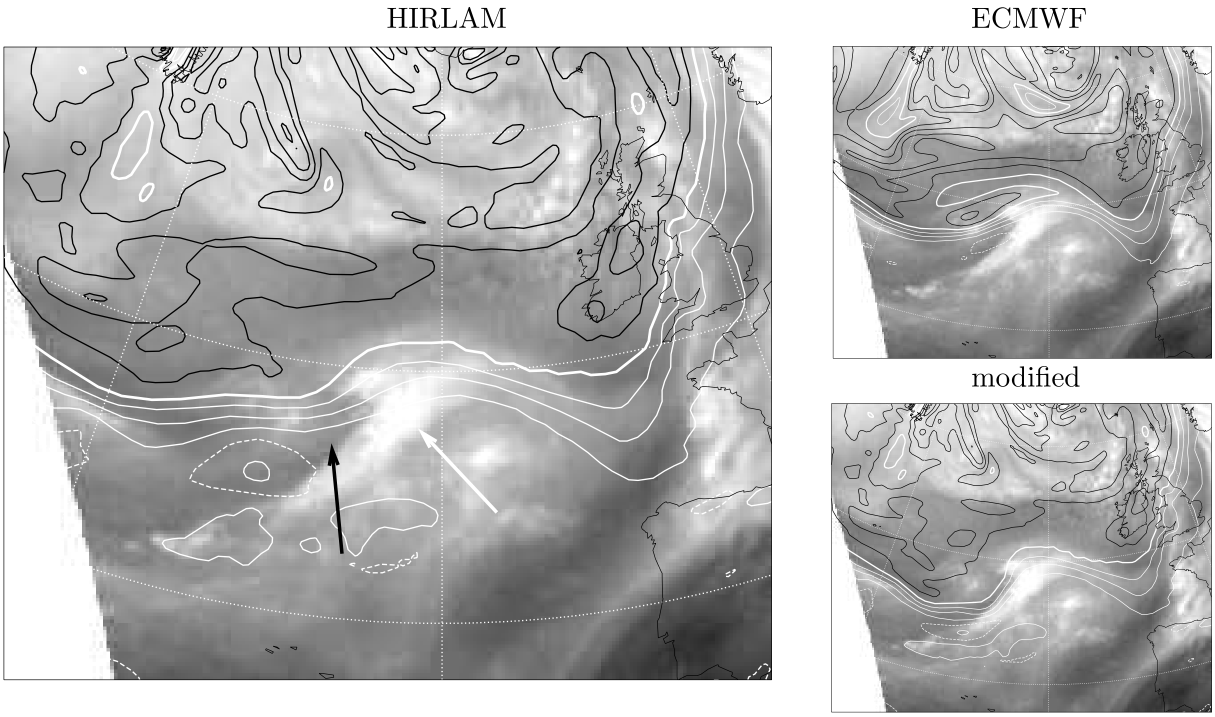


Figure 5.1: Contours of the PV at 315 K of the analysis at November 7 00 UTC and water vapour image at November 7 01 UTC. PV contours are every 1 PVU; thick white=4 PVU, thin white < 4 PVU, black ≥ 5 PVU). Arrows in the HIRLAM analysis point toward the cloud head (white) and dry intrusion (black).

the depression has developed substantially and has been advected to the North-West of Ireland in both the HIRLAM and ECMWF forecast. So the track of the depression is comparable, but the cyclogenesis was less strong for HIRLAM.

The modification consisted of the displacement of an area of radius $b = 8°$, $\alpha = 2$, from 48.8° N 32.0° W to 46.0° N 30.3° W. The resulting analysis is shown in Fig. 5.1. This modification moves the jet locally to the south with a trough corresponding better with the feature in the water vapour image. Essentially, point 1 of the mismatch is solved, with a slight additional reduction of the PV gradient in the cloud head region (point 3). Higher PV values in the dry intrusion have not been obtained.

The resulting pressure development is shown in figures 5.2 and 5.3. The initial mslp in the mismatch area is slightly lower than for the ECMWF and HIRLAM analysis. During the development the pressure in the centre of the depression is slightly lower than the ECMWF forecast, after 12 hours it becomes slightly higher and the curve is close to the ECMWF analysis. This is a substantial improvement with respect to the original forecast. Also the evolution of the mslp patterns closely resembles that of the ECMWF, with a small but deep cyclone to the nortwest of Ireland at 18 UTC. So the modification has not altered the path of the cyclone, but it has enhanced its development. The deepening of the depression for the modified analysis levels off after 24 h.

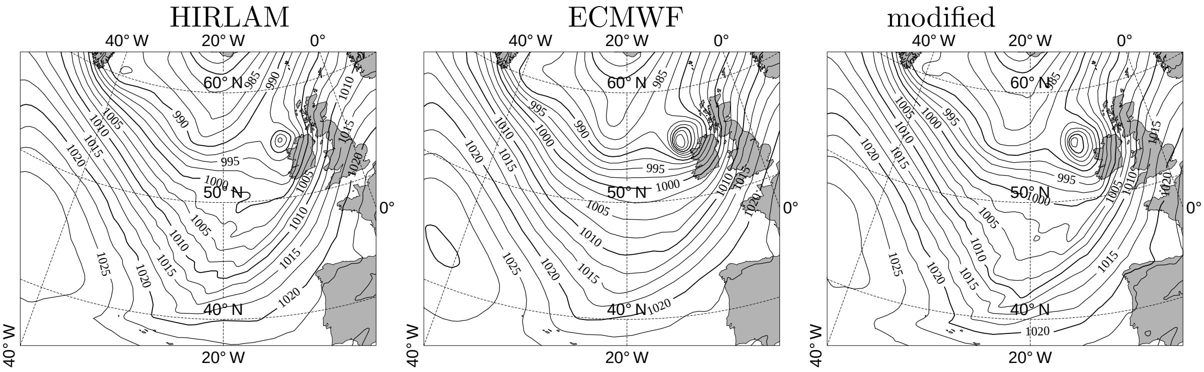


Figure 5.2: Mean sea level pressure of 18 h forecasts for HIRLAM analysis, ECMWF analysis and modified HIRLAM analysis.

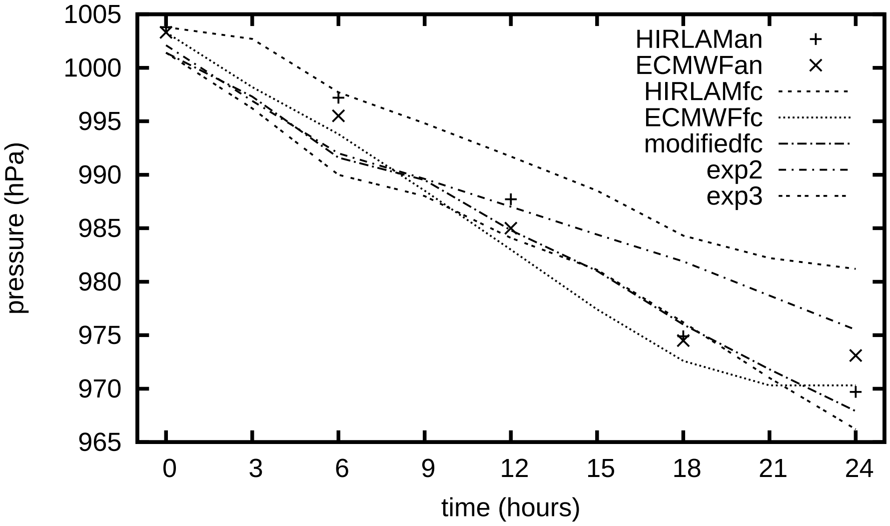


Figure 5.3: Pressure in the centre of the developing cyclone. Exp 2 and exp 3 will be described in section 5a.

5.2 Dynamical development

The pressure development of the forecast starting from the modified analysis and from the ECMWF analysis is comparable. However, the patterns of PV at 315 K at analysis time are still quite different for the modified and ECMWF analysis. Therefore it is important to know what the dynamical developments were and what the effect of the modification actually was. This will now be studied in more detail. First, the PV development of the depression is presented to get a better impression of the dynamics of the runs. Then the effect of the modification on the initial temperature and wind conditions are investigated in more detail.

Time development

Figs. 5.4 and 5.5 show the horizontal structure of the PV anomaly at high level (315 K isentropic level) and at low level (925 hPa). At analysis time, a small but strong low-level PV anomaly is present in the unmodified and the ECMWF analysis. This anomaly is very weak in the modified run at analysis time, but for the +6 h it is already stronger than in the original HIRLAM run. The position of the low-level anomaly is marked by the black crosses in Figs. 5.4 and 5.5. Zonal and meridional vertical cross-sections were made, following this anomaly (through the centre of the cross). The meridional cross-section is shown in Fig. 5.6. The growth of the low-level PV anomaly in case of the original HIRLAM run is clearly weaker than for the modified and ECMWF run. In the modified run, the anomaly is stronger and more confined than for the ECMWF run. In the ECMWF run, at +18 h a coupling between the low-level anomaly and a PV-anomaly at the tropopause can be observed, which is absent in the original and modified HIRLAM runs.

The horizontal development at the 315 K level (Fig. 5.4) is clearly different for the three runs. For the ECMWF run, the ridge evolves more cyclonically than in the other cases, leading to a tongue of high PV over Ireland, which is absent in the HIRLAM runs. This tongue is nearly on top of the low-level anomaly at +18 h (see also the vertical sections Fig. 5.6). The modified run is closer to the ECMWF run than the unmodified run regarding the position of the ridge and trough, but the tongue has not developed in both cases. In both the ECMWF and HIRLAM analyses at 18 UTC this tongue is present, therefore it should have been predicted from a truly accurate analysis.

A mechanism for the growth of a low-level anomaly is latent heat release. To verify the effect of latent heat the cumulative precipitation in intervals of three hours is plotted in figure 5.7. Again, the position of the low-level anomaly at 00 UTC, +6 h and +18 h is plotted. Since the precipitation is a time integrated quantity, one cannot expect an exact match. Still, apart from the first time interval, the position of maximum rainfall and position of the low-level PV anomaly correspond very well. Despite the displacement of PV in the modified analysis, the rainfall has not changed position, since a dry PV is used, only affecting moisture processes in an indirect way through temperature. This may not be completely realistic.

For the original HIRLAM analysis and forecast, the maximum precipitation in the cyclogenesis area was 12 mm (0-3), 10 mm (3-6) and 12 mm (15-18), for the modified run this was respectively 20 mm, 14 mm and 12 mm. The much larger rainfall for the modified analysis and forecast in the first few hours, with the corresponding release of latent heat, can explain the rapid growth of the low-level anomaly in the first 6 hours. In this period the precipitation is stronger than for the ECMWF run (resp. 10, 12 and 18 mm), but at 18 UTC the precipitation is weaker. The location of precipitation roughly follows the low-level PV anomaly, and the growth of the anomaly can be related to latent heat release. However, in the ECMWF run there is an indication of coupling

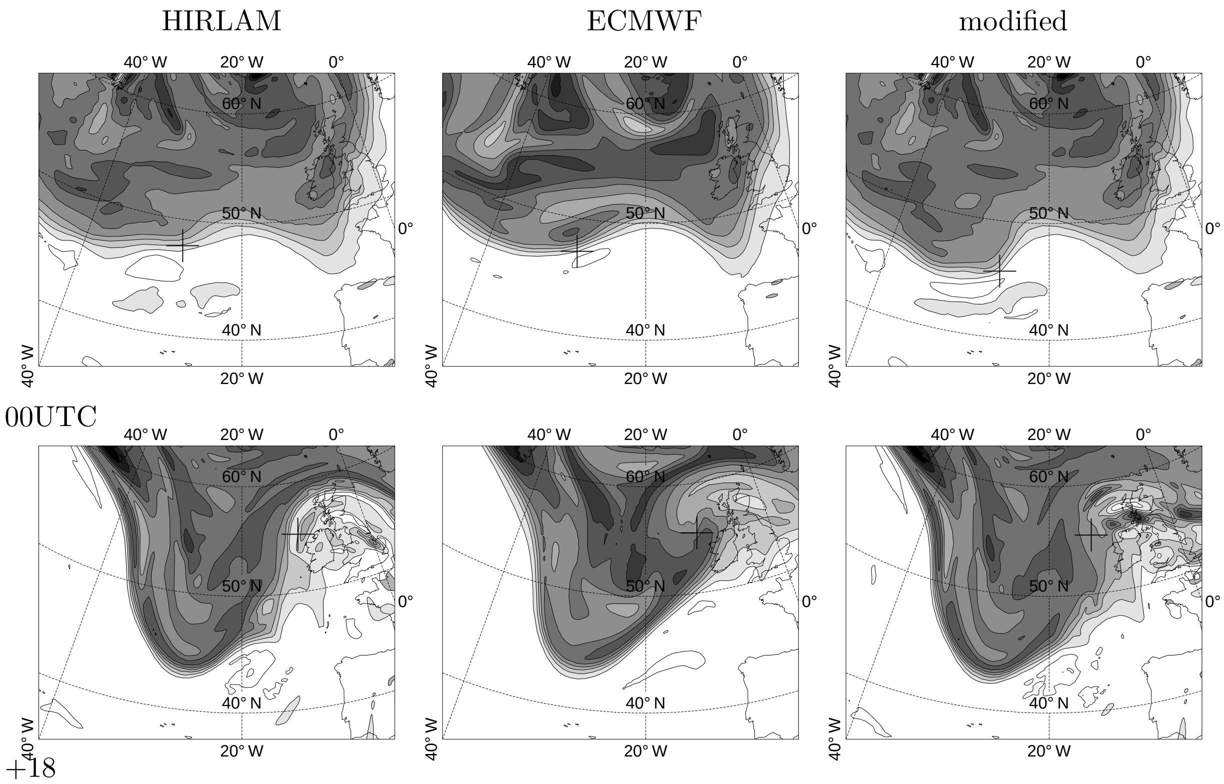


Figure 5.4: PV at 315 K isentropic level for the analysis (upper panels) and the +18 h forecast (lower panels) Contours every 1 PVU, shading from 1 PVU. Crosses indicate the position of the low-level PV anomaly.

between the low-level and high-level anomaly which can contribute to the cyclogenesis. In the HIRLAM runs, the cyclogenesis seems to be mainly determined by the latent heat release.

Effect of modification on temperature and wind

The PV field represents all dynamical variables and can be compared with WV. Here, the effect of the modification on temperature and wind field at analysis time are shown in more detail. They can shed more light on the differences in dynamical development. Temperature and horizontal winds are plotted in Figs. 5.8 and 5.9 at the 300 hPa and 925 hPa level.

The temperature at 300 hPa is lower for the original HIRLAM analysis than for the ECMWF analysis around 46° N 31° W. The cold region also extends more to the west. For the modified analysis, the temperature is still somewhat lower, but over a smaller area and the temperature pattern resembles more that of the ECMWF analysis. At lower level, the HIRLAM analysis and the ECMWF analysis are comparable, after modification the temperature is slightly lower than in the original analysis in the area of interest. This can explain the heavy precipitation: the total moisture content has not been changed but the colder air cannot contain as much moisture. The sharp frontal zone around 46° N 30° W is absent in the ECMWF analysis.

The winds are dominantly westerly at all levels for mid-latitudes. At 300 hPa the jet stream is clearly visible. The strength of the jet stream is comparable in all cases. But the shape of the jet stream in HIRLAM differs substantially from the ECMWF analysis. The modification has partly reduced this difference in curvature and has brought the jet stream to the south around 30° W.

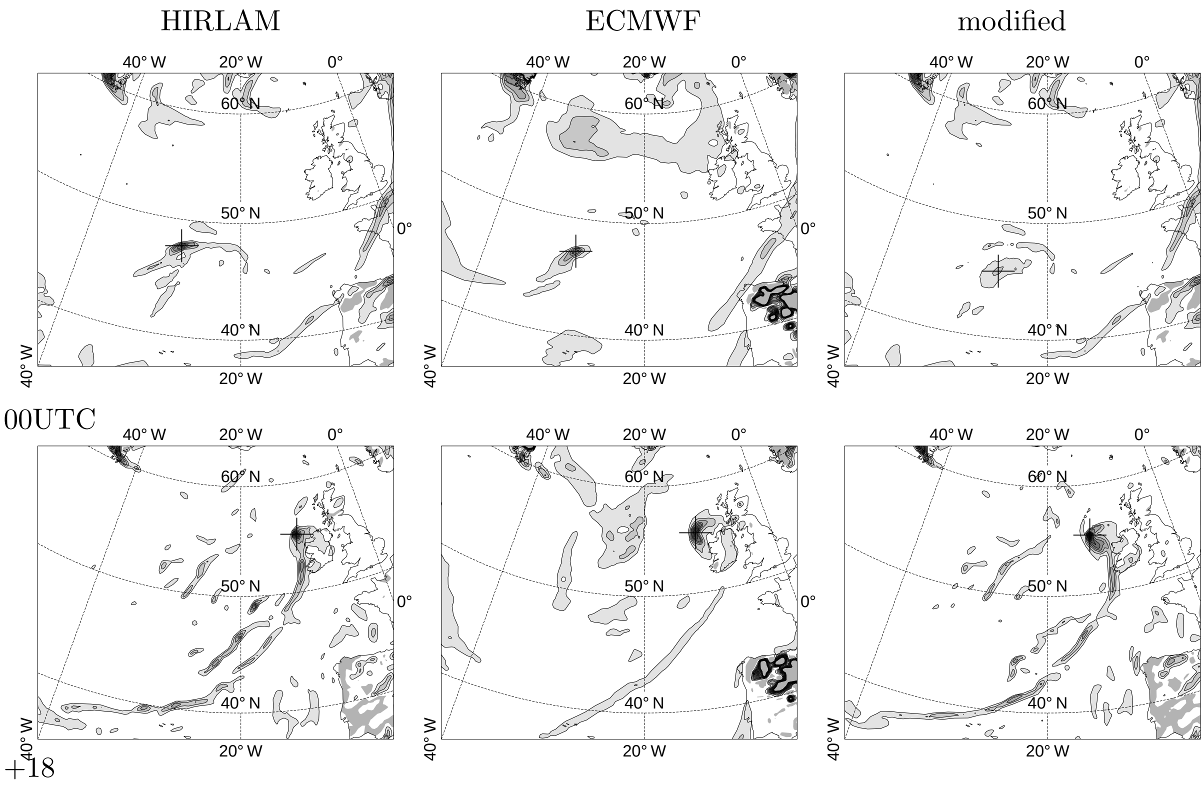


Figure 5.5: PV at 925 hPa level, analysis and +18 h forecast. Contours at 0.5-5 PVU, every 0.5 PVU.

The wind direction itself in the jet stream is now more in accordance with the ECMWF analysis. The modification has also increased the velocity in the region around 43° N 30° W. At low level the original HIRLAM and ECMWF analysis are comparable, whereas the modification has shifted the pattern of high velocity a bit to the south-west and has reduced the velocity around the location of the low-level anomaly.

5.3 Sensitivity

Robustness

To test the robustness of the results with respect to the chosen modification two alternative modifications were applied. These are illustrated in Fig. 5.10 and the mslp development is shown in Fig. 5.3 and 5.10. The differences between the three modifications are expected to be representative of differences that arise when different meteorologists would apply a modification to the same analysis. The subjectiveness will lead to small differences, but the mismatch is clear enough to result in the same kind of modification.

An area with radius 10° was displaced from 50.0° N 34.0° W to 46.0° N 32.0° W (exp2). This modification is similar to the original modification but located more to the west. The jet has been displaced 1° more to the south and the curvature of the jet has changed a little. Now the initial deepening is too strong and after 12 hours the development is too weak. The mslp pattern of the cyclone becomes elongated instead of circular and is too far to the west. The match with the WV is also less elegant than in the original modification. Again, the pressure development as such was

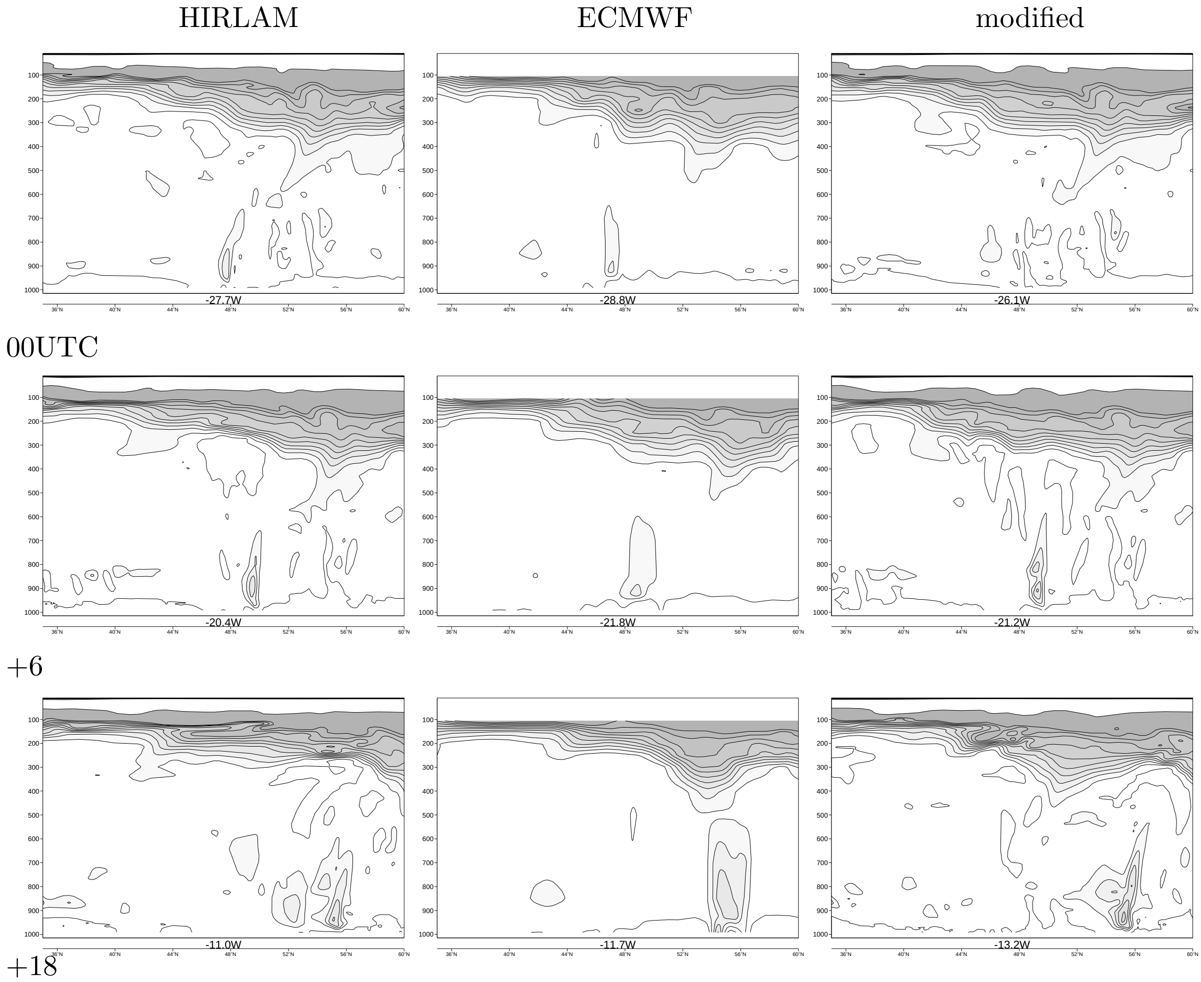


Figure 5.6: PV at model levels, meridional cross-section. Left panels: unmodified forecast, moddle panels: ECMWF , right: forecast with displacement. Contours at 0-10 (every 1PVU), 20 PVU, section from 35 to 60° N.

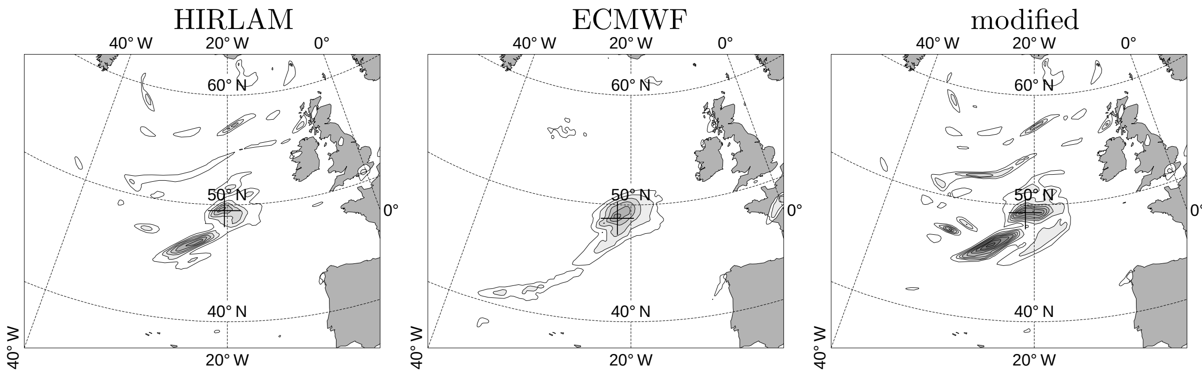


Figure 5.7: Total precipitation in interval 3-6 h forecasts. Contours every 2 mm, the zero contour is omitted.

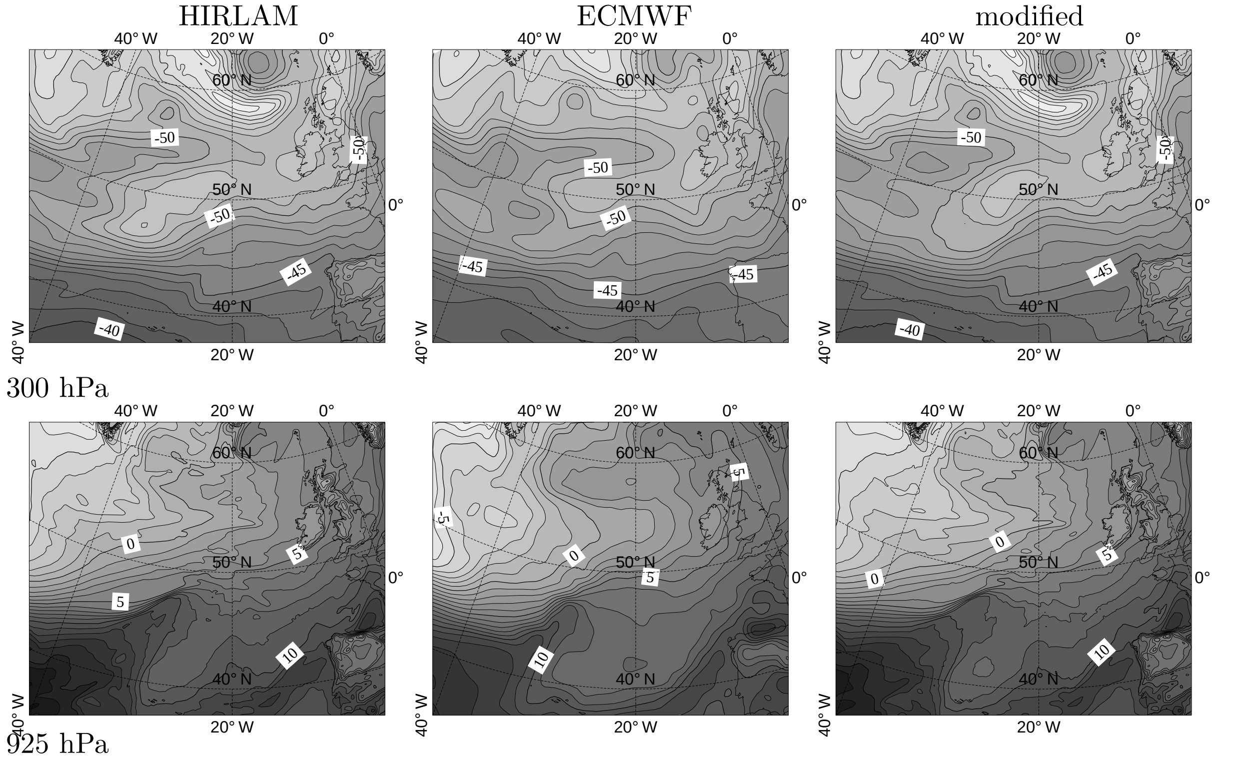


Figure 5.8: T on 300 (upper) en 925 hPa (lower) panels for analysis at 00 UTC. Contours every 1 K.

still better than in the original forecast in the sense that the value of the mslp in the centre was lower, but at the expense of the right location of the depression. One must conclude that this modification did not contribute to a better forecast of the meteorological development.

A second alternative was to displace a region with radius 10° from 49.5° N 32.0° W to 46.5° N 31.0° W (exp3). The development of the pressure was very close to the original modification, with slightly lower pressures. The main differences with the original modification are the radius of the area and the slightly smaller displacement. In essence, the same area was modified and the displacement was in the same direction as the original. The larger influence area may have resulted in slightly larger changes in wind and temperature, which may be partly counteracted by the slightly smaller displacement. The differences in mslp with respect to the original run cannot be called significant. The differences between the analyses of HIRLAM and ECMWF are up to 4 hPa. The modified analysis initially deviated about 2 hPa from the analysis. This becomes nearly 5 hPa in the +6 h forecast, but decreases afterwards and closely follows the trend of a deepening cyclone. The same holds for exp3. The pressure development of exp2 is initially nearly the same, but deviates significantly from the other modifications from + 9 h onwards.

Comparison with ECMWF ensemble

At ECMWF, an ensemble is generated to quantify the effect of uncertainties in the analysis. They are based on Singular Vectors, perturbations which give maximum growth over a certain area after a certain amount of time (Buizza & Palmer, 1995). They can be related to regions of baroclinic instability (Hoskins & Badger, 2000). The SVs are designed for optimal growth in the hemisphere

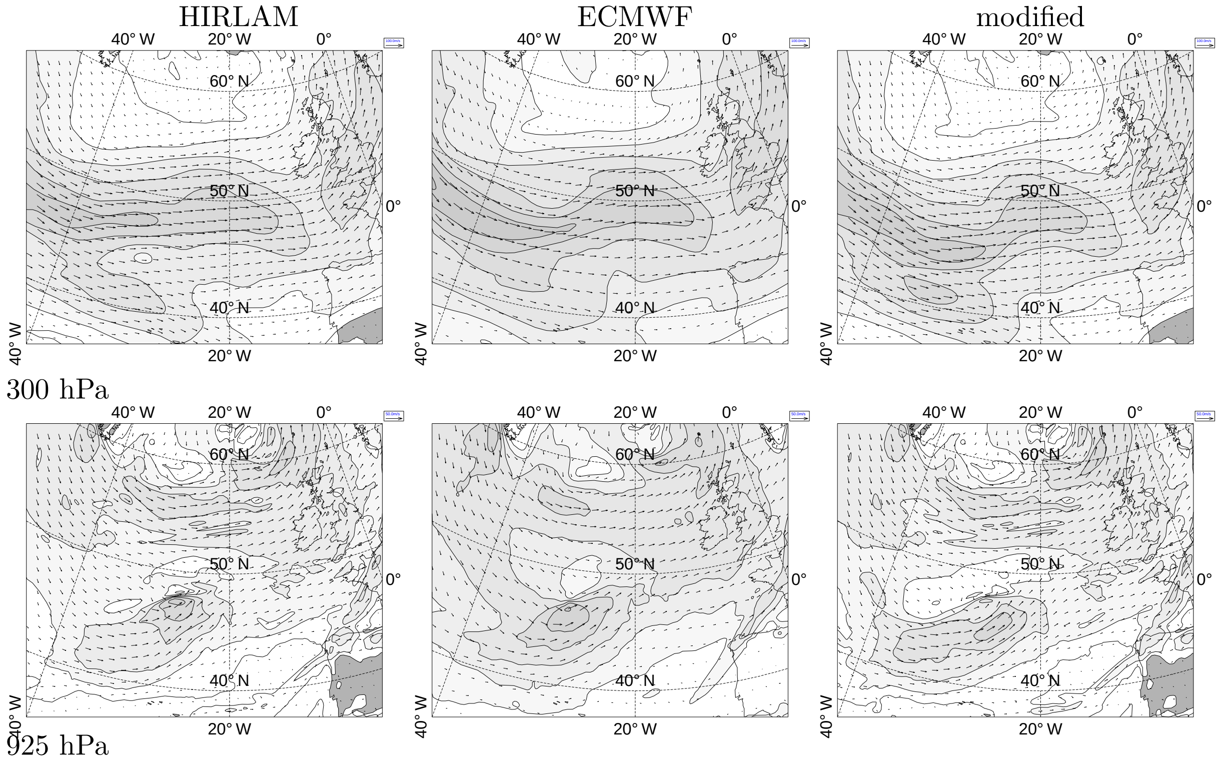


Figure 5.9: Velocity on 300 (upper panel, unit vector in upper right corner is 100 m/s, contour interval 10 m/s) and 925 hPa (lower panel, unit vector 50 m/s, contour interval 5 m/s) at analysis time.

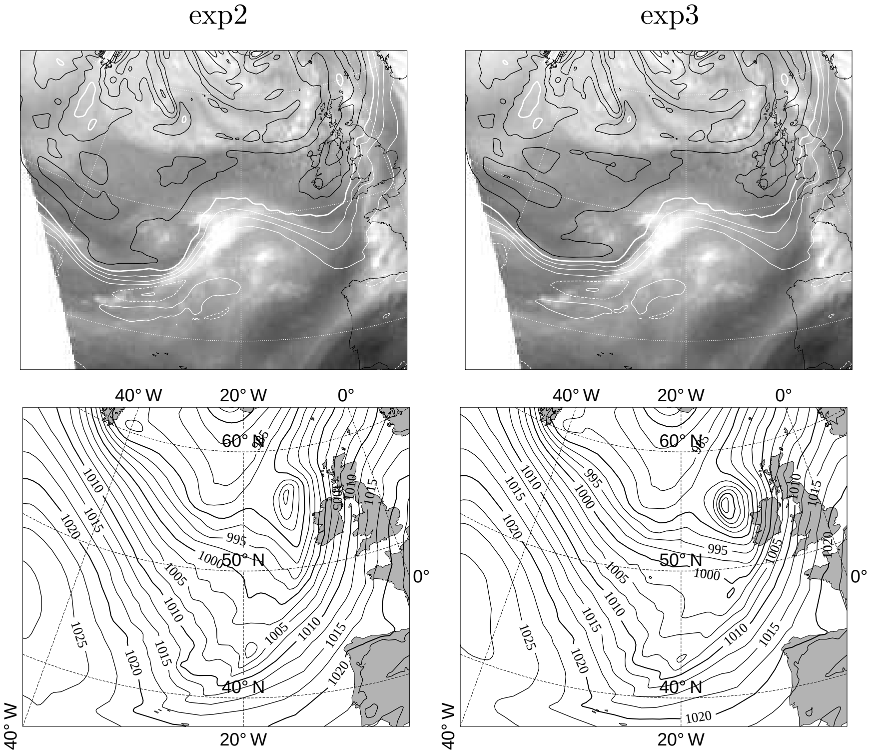


Figure 5.10: Upper panels:PV on 315 K level of analysis for exp2 and exp3. Lower panels: prediction of mslp at 18 UTC for exp2 and exp3. Contouring as in Figs. 5.1 and 5.2.

north of 30° N and are therefore not tailored to our case. Still, they appear relevant for this study. For HIRLAM, ensembles can not yet be generated. In this section the operationally computed ECMWF ensemble members are discussed.

The EMCWF ensemble members were clearly different in the region of interest at 00 UTC. All members had a local maximum in PV near 47° N 31° W at the 315 K level, but with differences in strength, size and exact position. Also the position and curvature of the jet stream showed some variation. None of the members closely resembled the HIRLAM analysis. The resulting forecasts showed a spread in the position of the depression and the mslp in the centre of the depression. At analysis time, the mslp was between 1000.6 and 1006.5 hPa, after 24 hours the mslp was between 959.6 and 982.1 hPa. These outer values were obtained for a pair of perturbations, with positive and negative sign, with a clear change in the jet region (Fig. 5.11), both in the mismatch area and in the trough at 10° W. The maximum difference with the control run was 0.7 PVU. Other ensemble members also exhibited differences of this order of magnitude with respect to the forecast, but in slightly different areas. It is interesting to note that it is not the member with the larger PV anomaly around the dry intrusion which leads to the strongest cyclogenesis. This supports the hypothesis that both the low-level anomaly and the jet location play a significant role during the development.

The original HIRLAM analysis had a development which was clearly at the outer edge of the ensemble range regarding mslp. The position was more in accordance with the ensemble mean. For modification exp2, the mslp was more towards the ensemble mean than the original forecast, but the position was more to the outer edge of the ensemble spread. Both the original analysis

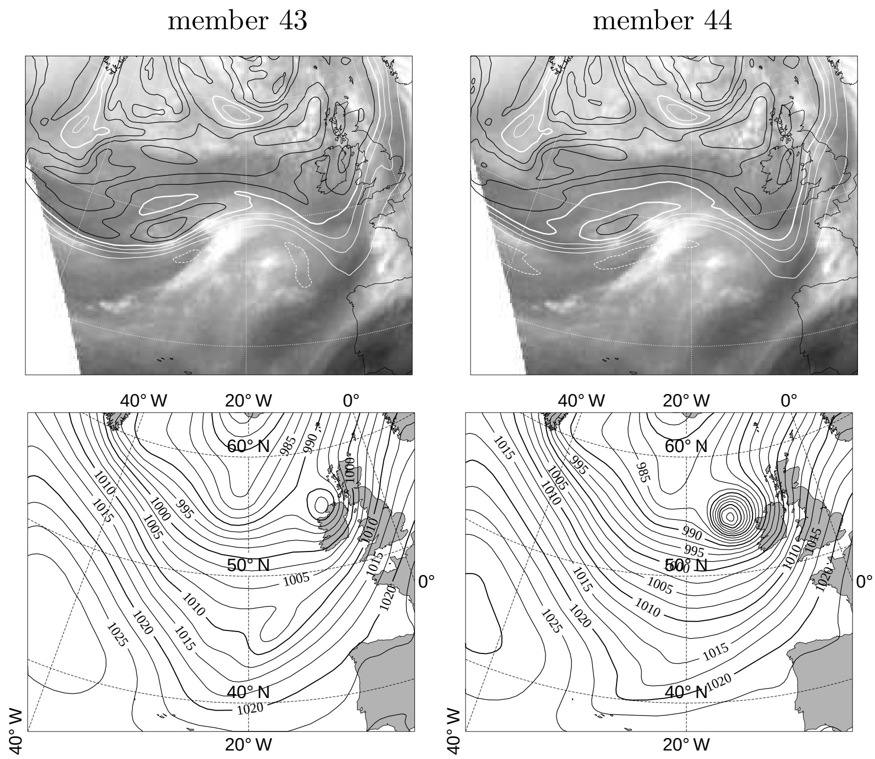


Figure 5.11: Upper panels: PV of ensemble members (contours of 1 PVU, thick white=4 PVU, thin white < 4PVU, black $\geq$ 5 PVU). Lower panels: prediction of mslp at 18 UTC for these members. The left panels are for the weakest, the right panels for the strongest cyclone development.

and the modified analyses are in the ensemble range regarding mslp and position of the depression. Although the ECMWF ensemble members were not constructed for perturbations in the developing cyclone region, they gave a good impression of the uncertainties in the analysis and their effect on the forecast.

Singular Vectors

It is also possible to calculate SVs for a more confined target area. This limits the area where perturbations originate. This approach was pursued by Røsting *et al.* (2003) who based their PV modifications on the structure of the singular vectors on different pressure levels. They combined information about SVs with the areas where a mismatch between PV and WV was present. Apart from modifications in the upper levels of the atmosphere (300-700 hPa), which contributed most to the improvement of the forecast, their SVs additionally indicated regions near the surface where the forecast was sensitive. The modification near the ground indeed led to a small further improvement of the forecast. Such modifications cannot be made based on WV images alone. Furthermore, they based their SVs on the ECMWF model, since SV calculations in HIRLAM are not yet implemented.

In our case, the ECMWF analysis differed considerably from the HIRLAM analysis and correctly predicted the strong deepening of the cyclone. So the SVs indicate where the ECMWF analysis is most sensitive. Nevertheless, they will still be a good indication for the scale of the perturbations and the source area for the HIRLAM run. The SVs were determined for the ECMWF 00 UTC

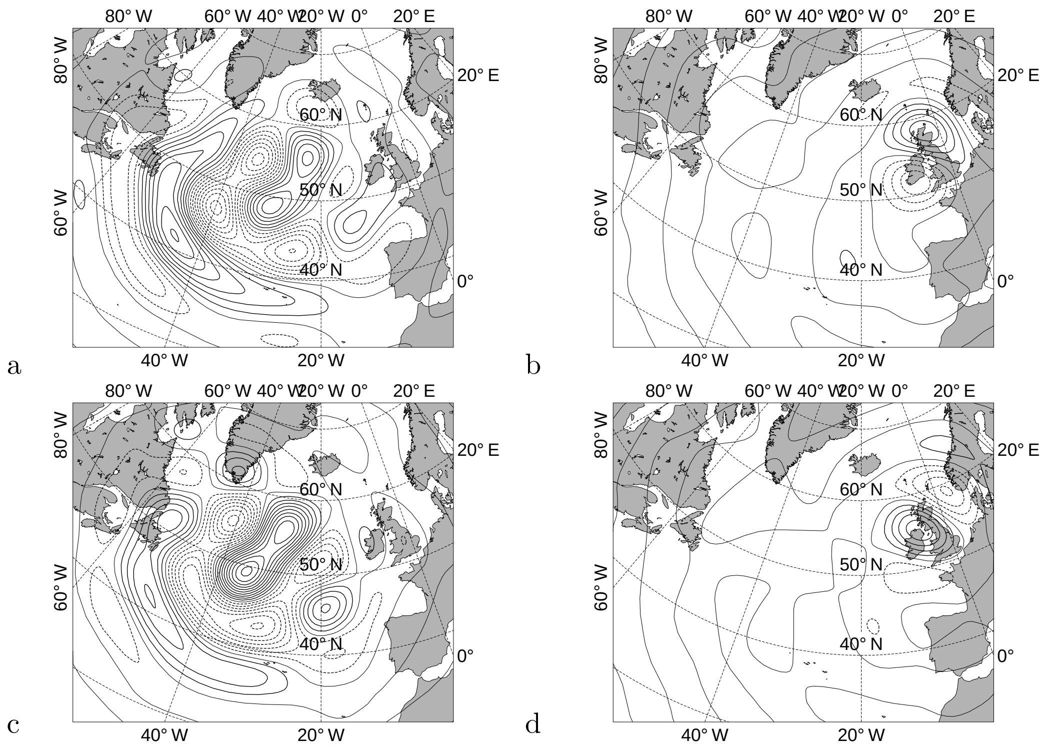


Figure 5.12: Singular vectors of vorticity at 300 hPa for ECMWF analysis. (a) SV1 initial, (b) impact of SV1 on forecast, (c) SV2 initial, (d) impact of SV2 on forecast. The order of magnitude is 10^{-7} with contours of $2 \cdot 10^{-8}$ for the initial perturbations, and 10^{-5} with contours of $2 \cdot 10^{-6}$ for the evolved perturbations. Dashed is negative, solid is positive.

analysis using the ECMWF PrepIfs system[1]. The target area was Great-Britain and Ireland (20° W-5° E, 50-65° N) and the optimization time was 24 h. The first two SVs are shown in Fig. 5.12 in terms of vorticity on the 320 hPa level. This is not the area where the SVs have their largest amplitude; this is around 600 hPa. A larger geographical area is shown to get a full overview of the SVs at initial and optimization time. The growth is a factor 50 to 100 for these vectors. The ECMWF SVs appear to give an indication in which region the HIRLAM analysis should be modified to have an impact on the development of the cyclone. This is a rather large area, around the location of the PV-WV mismatch. The SVs show that the perturbations with most impact on the forecast have a considerable horizontal extent. This corresponds to our findings that modification of an area of 5° or smaller did not yield a significant alteration of the development. SV2 indeed gives a maximum around 50° N 30° W, the location where we successfully modified our HIRLAM analysis.

5.4 Discussion

We have successfully modified a weather analysis based on the comparison between PV and WV. The development in terms of mslp has clearly improved. However, there are some drawbacks and

[1]www.ecmwf.int/services/prepifs

suggestions for improvement, which will be discussed here.

We have investigated the change in initial conditions and the development of the low-level PV anomaly. The modification has changed the position of the jet stream, which was more in accordance with the ECMWF analysis. It has also increased the latent heat release which induced the stronger growth of the low-level PV anomaly. This may not be realistic since the temperature was influenced by the PV modification but the moisture content was possibly not adapted in a consistent way. In this case, it would have been better to use a moist PV (Schubert *et al.*, 2001) instead of a dry PV. This quantity is invertible to the level of the dynamically relevant variables, but additional knowledge is required to find the exact contributions of the water vapour, dry air and condensate. Therefore moist PV requires further research before it can be applied. In the ECMWF run and the verifying analysis at 18 UTC, a coupling between the low-level anomaly and a tropopause-level anomaly was visible. This coupling has probably enhanced the cyclogenesis in the ECMWF run, and the latent heat release is more evenly distributed in time. This can explain the difference in mslp development between the modified HIRLAM run and the ECMWF run. The mechanism of cyclogenesis itself closely resembles the development of the winter storm 'Lothar' as described in Wernli *et al.* (2002). There, latent heat release caused a low-level anomaly which could grow due to the interaction with an unusually strong jet stream and induced a deep tropopause fold.

It is difficult to constrain the modification in the horizontal and vertical. The use of METEOSAT 8 data in the future can help to constrain modifications better, since an additional WV channel is available with maximum response slightly lower in the troposphere. Still, apart from a qualitatively correct modification is may be difficult to also give a quantitatively correct modification. The case discussed in Verkley *et al.* (2005) consisted of a good match between pattens of PV and WV but the PV values appeared to be too high.

The modified runs were compared with the ECMWF ensemble. The results after the modifications were all within the ECMWF ensemble range regarding mslp and position, indicating that the PV modifications were not unrealistic. All the modifications that we have tried (not all described in this report) led to a deepening of the depression, indicating that the original HIRLAM run gave a too weak development. In the present case, it appeared to be difficult to deteriorate the forecast.

Instead of modifying the analysis and calculating a new forecast, one could in principle select ensemble members based on the match of their PV with WV and use them als a preferred alternative forecast. For the ECMWF ensemble, the different members did not show a clearly better or worse correspondance with WV, but they were perturbations on a very accurate analysis. A single pair of ensemble members (positive and negative perturbation) has led to the two extremes in the strength of the cyclogenesis. A HIRLAM ensemble is not yet available but will be developed in the near future.

SVs can be used to support the decision making for modification. They indicate the region where the analysis is sensitive to perturbations, and the scale of the perturbations that will have substantial impact on the development. Thus they can focus the attention of a forecaster. Røsting *et al.* (2003) used SVs to determine PV modifications, also at low level. A problem is that in general SVs have their maximum at lower level (around 600 hPa), whereas the PV-WV method is based on the PV at tropopause level. One could construct perturbations from SVs that match the WV image at tropopause level and use their vertical structure. This would constrain the possible PV perturbations beyond the limit of the WV observations. SVs will become available for HIRLAM in the near future. The ECMWF SVs that were computed for our target area gave an indication of the scale and area of PV perturbations with a large impact on the cyclogenesis. Perturbations with a scale smaller than 10° indeed did not give much impact, they tended to disappear in the next 6 hours as compared with the unmodified forecast. Modifications at lower levels, where the ambient PV is low, had more impact than modifications at tropopause level. The development of Hessian Singular Vectors (Barkmeijer *et al.*, 1998), which take uncertainties in the analysis due to a lack of observations better into account, can also help to bridge the gap. This moves the maximum of the SVs up to around the tropopause level. In our case, the HIRLAM analysis at low level was fairly accurate, but the jet stream was not positioned correctly.

Due to the present uncertainty in the modification, it is not possible to correct the analysis. However, the modification method was successful in investigating alternative developments. The three modifications and their successive forecasts can be used a what is often called a poor man's ensemble. There are some important differences with a regular ensemble. In a regular ensemble, ensemble members are constructed from perturbations which are selected based on maximum growth over a certain time interval and in a certain target area, within a certain norm. These perturbations are related to meteorological mechanisms like baroclinicity and PV unshielding (Hoskins & Badger, 2000), but a priori all ensemble members are equally probable and they give an idea of the accuracy of the forecast. This is in contrast with our method, in which a meteorologist can select realistic modifications based on WV observations and the conceptual models. The subjectivity should not be seen as a shortcoming (*poor man's* ensemble) but as a way to exploit both all observations and the meteorologist's experience.

Chapter 6

Conclusions and outlook

6.1 PV modifications

The project was a continuation of the project described in Vosbeek *et al.* (2001). In that project a method was developed to graphically modify the PV of a numerical weather analysis. This modified PV field is subsequently assimilated in HIRLAM such that a new analysis is obtained from which a numerical forecast is calculated. In the current project the assimilation software was implemented in the operational version of HIRLAM (version 6.3.5, operational in november 2004) which runs in parallel mode. This has made the procedure of assimilation and forecasting fast enough to be used in an operational environment, which is an essential step.

Furthermore, in the previous project, PV modification was calculated externally and the modified PV field was interpolated onto the HIRLAM grid. At present, the externally determined modification parameters are used by HIRLAM to directly compute the modification on the HIRLAM grid which results in better convergence in the 3D-var assimilation. The GrADS interface was translated into a Metview application, which can be more user-friendly and is able to use more directly the products of METEOSAT and HIRLAM. Still, modifications can only be applied on circular regions. This has the advantage that the essential parameters are well-defined and reproducable and they can easily be used as input for modification on the HIRLAM grid. So far, modification in a circular area has turned out to be satisfactory. Modifications can be combined so that it is possible to construct more complex modifications.

The minimization in the 3D-var scheme is still a very costly step. In Verkley *et al.* (2005) the convergence has been slightly improved with respect to Vosbeek *et al.* (2001). In the current project, the vertical structure of a source/sink or strengthening/weakening has been concentrated more around the 300 hPa level which results in better behaviour of the PV near the upper boundary. There are still open questions with regard to a good representation of error covariance matrices for the PV term in the minimization. But since in our present approach the assimilation is used as a kind of inversion instead of an observation term with uncertainties, the choices made so far are considered as natural.

The method of PV modification has been used with success to modify numerical weather analyses. Two cases have been studied in which our method was used to modify initial conditions in situations where the prediction was accurate. Modifications were applied in order to verify the contribution of certain synoptic-scale features to the development of a specific weather system. In this way, HIRLAM is efficiently used as a model for research in dynamic meteorology. This opens perspectives for more detailed case studies. Especially tropical cyclones could be easily introduced and maniputated. Computing facilities at ECMWF should then be used, since there the HIRLAM set-up is more flexible with respect to the chosen domain and computation time is not tigthly restricted to certain slots as on KNMI's operational computing facility.

The original idea was that the method would be used to repair a weather analysis in case of a mismatch between model PV and a satellite WV image. This idea was tested on a case in which a clear mismatch between PV and WV was observed by the operational forecasters and the ensuing HIRLAM forecast led to an underestimation of the strength of a developing storm. The modification, consisting of a displacement of the jet stream, indeed gave an improvement of the prediction. However, the development did not show all features that were present in the verifying analysis and was slightly different from the analysis and development of the ECMWF run which did very well. Also, one variation of the modification did lead to a slightly stronger storm but at the wrong position. Still, the method has potential when modifications are used to generate an alternative forecast. A few of such alternative forecasts can be used as an ensemble. This idea is discussed in more detail in te next section.

The relation between PV and WV is too weak to constrain the modification well. Therefore WV cannot be automatically translated into PV and directly assimilated. In the present set-up METEOSAT 7 data were used. Only a single WV channel was available, which represented the temperature of the tropopause. This limits corrections based on the PV-WV comparison the the region around the tropopause. This satellite was replaced by METEOSAT 8 with higher resolution and two WV channels. The second channel looks deeper into the atmosphere and provides additional information which may facilitate interpretation of the images and give a better idea of the vertical structure. Composite false-colour images of several WV channels are already computed at KNMI, but these are not yet used in the PV modification tool. It may however not be straightforward to relate these additional observations to the PV in the lower troposphere. This is a point of interest that may be addressed in future studies.

It appears from the case studies that the modification must be substantial to significantly influence the forecast. Scales must be at leat $10°$. Furthermore, around the tropopause modifications must have a significant amplitude (strengthening/weakening more than a factor 0.25, sources and sinks a few PVU). For modifications closer to the Earth's surface, the scale and amplitude may be smaller, since the ambient PV field is weaker. The structure of the modification in the vertical is still a point of discussion. For the moment we have chosen for a modification with maximum amplitude at the 300 hPa level and and a decrease towards 180 and 530 hPa, which matches the vertical extent of observed tropopause anomalies at mid-latitude. Other choices may be made for specific cases.

6.2 Ensemble approach

There are several ways in which the developed method of modifying a weather analysis could be used in practice. Originally, the method was intended to correct a weather analysis in case of a serious mismatch between the PV field of the weather analysis and the water vapour image. Since the relation between PV and WV is rather qualitative, this is too ambitious. Nevertheless, by trying a few modifications a poor man's ensemble can be created which contributes to better insight into the possible developments.

This was shown in the case study in Chapter 5, where all modifications led to a deepening of the depression. The scale of the modification and the area was in accordance with the sensitive areas indicated by SVs. For future use, the method of PV modification based on WV images could be combined with SV methods to appy realistic modifications and produce a few alternative forecasts. The method should, in fact, not merely be interpreted as a 'poor man's ensemble', but as an ensemble method in which optimal use is made of observations and the experience of a meteorologist. The development of Hessian Singular Vectors (Barkmeijer *et al.*, 1998) which take uncertainties in the analysis due to a lack of observations better into account, can also help to bridge the gap.

Also implementation of 4D-Var opens new possibilities. A short-term forecast may be compared with the newest WV observations, which is beneficial since in KNMI's operational practice there is a time gap of about 3 hours between the time at which the analysis becomes available, and the time for which the analysis is valid. This is a result of the fact that all observations must be received before a new analysis can be made. In the present 3D-var setting a new run can be started from a short-term forecast, using the newest WV observations. These ideas remain to be tested further.

Alternatively, it is possible to use this method regardless of a mismatch. A forecaster can select a few modifications based on his/her idea of areas where the forecast will be sensitive to small perturbations. Based on these modifications, an ensemble can be created, leading to statistical information about possible developments. Since these ensemble members are selected on different criteria than singular vectors, they may contribute to the variety of processes that leads to ensemble spread. There is not much known about short-range ensembles, and this research fits with the KNMI PhD project 'De relatieve rol van beginconditiefouten en modelfouten bij het maken van korte termijn weersverwachtingen', that starts at 1 December 2006. In this project HIRLAM ensembles are generated using singular vectors. It will be fruitful to compare and combine these methods. At the NOAA severe storms laboratory/storm prediction centre an experiment in which forecasters could identify sensitive regions did lead to better ensembles with respect to severe weather conditions (Homar *et al.*, 2006).

Recently, a series of experiments has been started in which a modification is applied once a day. The modification is done by a researcher. If no mismatch is present, another interesting feature is modified. This has the aim to gain broad experience in the effective modification of an analysis and its impact on the forecast. Since not only specific cases are studied, these experiments should give insight in the possibilities to positively contribute to the operational forecasting. The alternative forecast can be interpreted as a second ensemble member. The results are yet to be evaluated.

To conclude: at the moment, the relation between PV and WV is too qualitative to improve a forecast in a definite way. But when experiments are done on a regular basis the modifications will probably become more accurate. On the positive side, the use as a research tool of the method developed and the possibility to produce or extend a short-range ensemble using the experience of a meteorologist are valuable intermediate results and a worthwhile goal on their own.

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Appendix A

HIRLAM implementation of the PV modification software

The software was developed for HIRLAM 6.3.5 as operational at KNMI in November 2004. The PV modification routines are implemented in the 3D-Var scheme that is used in the hirvda (hirlam variational data-assimilation) procedures. PV can be also be written to a GRIB file in a different part of the HIRLAM procedure (postprocessing) which is fully independent of hirvda.

A.1 Implementation of PV modification in 3D-var

Logical to switch PV modification on/off

To apply modification, the file which regulates the 3D-var procedure /H22/scripts/VARinput has to be adapted. The parameter lpvmod, part of the namelist, must be set to .t. The HIRLAM software was adapted on the following points:

- in the file `hirnamrun.h` (`~/hirvda_bld/hirvda_src/hirvda/include/varnam/`) the logical lpvmod is added and the parameter lenmrunl was increased from 90 to 91
- in the file `rdnamr.F` (`~/hirvda_bld/hirvda_src/hirvda/hlvar/`) the logical lpvmod was added to the namelist /namrun/
- in the file `hirvda.F` (`~/hirvda_bld/hirvda_src/hirvda/hlvar/`) the logical is used as a switch to call modifypv in high resolution miminization, before the minimization is started
- in the file `miminize_low.F` (`~/hirvda_bld/hirvda_src/hirvda/hlvar/`) the logical is used as a switch to call modifypv in case of low resolution minimization, just after the call to gplowres
- in the file `jgrad_3d.F` (`~/hirvda_bld/hirvda_src/hirvda/hlvar/`) the logical is used as a switch to reach the PV contribution of the 3d-var procedure, just after the spec-obs cost function

Parameters for modification

The modified PV field is directly calculated on the HIRLAM grid, whithin the HIRLAM cycle. This has some advantages as compared to importing a modified PV field. The main advantage is that all interpolation problems are circumvented. The graphical modification environment is completely independent of the actual PV assimilation and grid sizes. This makes the procedure more flexible. When the modification consists of well-described structures the modification parameters are easily summarised and the modification is reproducible.

The modification is calculated on the HIRLAM grid according to the file `pvmod.DAT`. It is placed in the same directory as the observation file (`/scratch/datausr/hl_lvfs/H22/pvmod.DAT`). The file `pvmod.DAT` has the following structure:

`1`	number of modifications
`10.0`	weight factor μ
`1`	type of modification
`-10.0 50.0`	longitude and latitude
`10.0`	radius
`2.0`	strength
`1.0`	steepness
`-8.0 51.0`	longitude and latitude (displacement)

The modification type can be 1 (source), 2 (strengthening/weakening) or 3 (displacement). Coordinates of the centre of the modification area are in lon lat geographical coordinates and are translated into HIRLAM coordinates by the program. The radius of the influence area must be given in (geographical) degrees The strength γ is given in PV-units when a source/sink is added. When used for strengthening/weakening of an existing structure the strength corresponds with the factor β, with negative values implying weakening. Values should be larger than -1 to guarantee a positive PV field. The steepness α is dimensionless. The last set of longitude and latitude coordinates are only used for displacement, they are the destination points of the displacement. This line should always be present, with dummy values if it is not used. Since the file is read in a loop over the number of modifications the number of lines per modification should be constant. To apply more modifications to the same analysis, copies of the lines 3-8 can be appended with the appropriate parameter values. The first line should be changed accordingly. The weight factor μ applies to all modifications defined in pvmod.DAT.

Implementation in 3D-var

The routines mentioned in this subsection are in `~/hirvda_bld/hirvda_src/hirvda/hlvar/` unless stated otherwise. Just before the minimization is started, a modified PV field is created if lpvmod=true. The routine `modifypv.F` calculates the PV using the dynamic fields (u, v, T, p_s) through a call to `calpv.F`. All routines used in the PV implementation in 3D-var expect that the distribution over the processors is only in the meridional direction (zonal strips) with halos for the calculation of horizontal derivatives. Before the modification is applied, the full PV field is collected on a single processor to avoid complications. Also the weight functions are determined. The file pvmod.DAT is opened, the parameters are read and the field is modified using the subroutines `source.F`, `strengthen.F` or `displace.F`. This is done in a loop over the given number of modifications. The horizontal structure of the modification is determined by the parameters in `pvmod.DAT`, the vertical structure is hardcoded. Ideal settings will vary with model resolution and case. In the routines `source.F` and `strengthen.F` the parameter r2 should coincide with a model level close to the tropopause (around 300 hPa). The parameters r3a and r3b indicate how many levels upward and downward of level r2 are affected, with steepness steep2a and steep2b.

After the calculation of the modified PV field on a single processor, the field is distributed over the processors. To reduce the arguments in the subroutine and function calls, a module is used for the arrays pv_mod and wpv (`~/hirvda_bld/hirvda_src/hirvda/modules/pvmodified.F90`). Allocation and deallocation of memory are in `hirvda.F`. For minimization on the full grid, the call to modifypv is in `hirvda.F`, for minimization on a reduced grid (lower resolution, recommended) it is in `minimize_low.F` (minimize_low_sub2) after the proceduce concerning the truncations of the dynamical fields. Alternatively, an externally modified PV field could be read from file (single processor) and distributed over the processors. This was the original set-up but is not recommended because of the need for interpolation which instroduces noise. It is however easy to implement this in `modifypv.F` when desired.

The contribution of the PV cost function is calculated in subroutine `jgrad_3d.F`. The PV cost function and the gradients are added to the total cost function and adjoint variables after a call to `jpvgrad.F`. The latter routine takes care of the actual calculation of the PV of the model (`calpv.F`), the cost function and the adjoints (gradients, `calpv_ad.F`). Since these computations are done in parallel mode, the cost functions on the different processors have to be collected to obtain a total sum. This sum is subsequently distributed over all processors. The adjoint calculation is also done in parallel mode with the exception of the adjoint of the meridional derivatives and the vorticity. This is since values at one latitude affect values at all other latitudes in these operations. In the forward PV calculation the halos are sufficient.

Calculation of PV and its adjoint

The PV and its adjoint are calculated according to the equations and algorithms as given by Vosbeek *et al.* (2001). Minor differences in the code arise since scaling with the Earth radius and pressure are sometimes used to avoid very large or small numbers. Furthermore the treatment of boundaries is sligtly different from the original code by P.W.C. Vosbeek; there boundaries were often forced to zero.

The treatment of boundaries is summarised here:

- halo: a halo of one gridpoint is defined in the mediriondal direction, to calculate derivatives and vorticity. The information on these halos is exchanged when necessary. For the zonal boundaries, the values on the outer halo are set equal to the values on the boundary of the HIRLAM domain.
- pressure: no special needs for boundaries
- potential temperature: theta on level 1 is set equal to thetat on level 2
- Vertical derivatives: surface level (nlev): derivative is set to 0. Top level: derivative in level 1 is set equal to derivative in level 2.
- Horizontal derivatives: derivatives at the boundary of full domain are set equal to the derivative in the interior neighbour point. Halos are determined subsequently.

- vorticity: zeta values on boundaries of the HIRLAM domain are set equal to the values of their interior neighbour point
- rest term: no special needs
- cpv: PV on level 1 is set equal to the PV on level 2.

A.2 Postprocessing, PV output

Independent of the PV modification procedure, PV can be included in the GRIB output files that are generated by HIRLAM. The implementation allows for PV on model levels and PV on isentropic levels. Parameter codes are according to the WMO standards (WMO, 2001).

For the analysis, the file `~/H22/scripts/Postpp` can be extended with PV output parameters. Model levels: `iwmomlp=4` , adapt `nwmomlp`. Isentropic levels: `iwmoslp=4, ltypslp=113, alevslp=315.`, adapt `nslp`. The exact isentropic values are not restricted otherwise than that they should not be too close to the Earths's surface or the top of the atmosphere. For the forecast, the file `~/H22/scripts/FCinput` can be adapted in the same way.

The postprocessing procedure for both the analysis and the forecast is called from `~/H22/gcod/GEMINI.f`. In `~/H22/prpo/POSTPP.f` the PV output is handled according to the scripts Postpp and FCinput. Before the extraction of data is started, the PV is calculated on model levels via `~/H22/gcod/pvfieldpp.f`. The routines for the PV calculation are not equal to those used in 3D-var. This has two reasons. Firstly, the distribution of the model grid over the processors is different in the forecasting procedure than in the 3D-var (analysis) procedure. In particular, the distribution is in our case not strictly zonal, which requires a more complex halo communication for the calculation of vorticity and horizontal derivatives. Therefore, it was decided to collect the fields of the dynamic variables which are distributed over several processors on a single processor for the calculation of PV. Secondly, a staggered grid is used for the horizontal velocities, leading to a slightly different computation of the vorticity and $\partial v/\partial p$ and $\partial u/\partial p$ (see Vosbeek *et al.* (2001)) than in the PV modification and 3D-Var routines.

To write PV output on model levels, the PV array is added as argument to the call to XTRETA in `POSTPP.f`. In `~/H22/prpo/XTRETA.f` itself a PV part is added analogous to the procedure for the extraction of temperature and velocity fields. This is done after the cloud cover part.

For the isentropic levels a procedure analogous to the single level fields is added just before the treatment of the vertically integrated variables. The values of PV on a single isentropic level are determined in `~/H22/prpo/searchlevel.f` to which the full PV and theta arrays are passed. The output of this search/interpolation routine, the PV on a single level, is stored in fstor2. After extraction in `XTR.f` it is written to fstor, the standard array from which the fields are processed further. The isentropic levels must be recognized by the GRIB writing routines. In GRCHK1.f the parameter code 113 was added to table ITAB3. In GRIBEX.f the parameter 113 was added to the selection of level parameters for which the level number must be distributed over 2 octets.

HIRLAM produces so-called Asimof files which contain grib data. These files cannot be used directly for plotting with Metview. The appropriate grib data can be extracted using `wgrib`. To obtain a grib file which can be plotted using Metview, the following steps can be taken:

- `wgrib -v asimoffilename` can be used to identify the record numbers of the fields that should be visualised
- `wgrib -d recordnr asimoffilename -grib -o outputfilename` produces the grib file

Using a script this extraction procedure can be streamlined and individual layers can be combined in a larger grib file.

Appendix B

Metview macros

For the graphical interaction and the visualisation of model output, Metview was used. This is an application developed at ECMWF for the visualisation of meteorological data. Graphics can be manipulated using icons and menus, but it is also possible to write macros. The most recent user manual can be found at `http://www.ecmwf.int/publications/manuals/metview/`.

B.1 Graphical interaction

The programs for graphical interaction to determine modification parameters are in the Metview subdirectory `modifyPV`. The macro `modifyPV.mc` contains the main program. Input files are GRIB files containing PV on isentropic levels and WV satellite data. In the selection of the levels, it may be necessary to adapt the levels to the levels which are available in the isentropic PV data file. The filenames for the PV and WV files are hardcoded in `modifyPV.mc`. They are defined as filename and filename2 respectively and can be changed easily. Other filenames are used for files that are generated and used during the execution of the macro, except for pvmod.DAT which is the file that serves as input for a new HIRLAM run. An external (compiled) Fortran program is used to calculate the displacement. This program, `pvdisplacement`, is in the directory `data`.

The program `pvdisplacement` is written such that it is flexible with respect to the grid of the PV file. However, when the number of gridpoints in one of the horizontal directions is larger than 1000, the array sizes in pvdisplacement.f should be adapted accordingly. The displacement is calculated using a simple iterative advection scheme (see Chapter 2 and Vosbeek *et al.* (2001)). The iteration steps are small (0.1°). This is necessary to avoid instability of the scheme for the displacement of structures with large horizontal gradients. The other modifications, addition of a source/sink or the strengthening/weakening do not require an external program. They are handled in `modifyPV.mc`. Modification is only applied to the PV on an isentropic level, no vertical structure is implemented in this stage.

B.2 Data format

The used Metview applications require GRIB files as input. Metview recognizes the type of field (e.g. wind, temperature, PV) from certain parameters in the GRIB file using the ECMWF GRIB coding standards. However, KNMI works with WMO standards which are not fully identical, for example PV is parameter 4 (WMO) instead of 60 (ECMWF). Therefore the parameter request in the read statements in the macros must be checked before they are used. Metview does automatically rescale EMCWF data to PVU while plotting, but this automatic scaling may get lost when data are processed further. The HIRLAM PV data are already in PVU. Furthermore, ECMWF data are global spectral data. Metview can directly plot these data, but in some cases it is necessary to convert them to gridded data, using `grid:[0.5,0.5]` in the read parameter definitions.

The GrADS datafiles that were generated in the older procedures can be readily converted to GRIB data. The .ctl file and the corresponding .DAT file must be moved to `.../Metview/conversies`. There, conversion macros are available. At the moment, they only work for `metview-new`. The macros which are named something like `grads2grib.mc` read the .ctl file to determine the grid definitions and number of levels. In these macros the filename of the .ctl input file and the grib output file must be set. Also other GRIB coding must be set, like the variable name and the parameter number. Several macros are available, with different parameter settings. For the .ctl file some conventions must be respected. The descriptor items like DSET must be written in capitals, otherwise they are not recognized. Furthermore, the filename of the .DAT file must be preceded by a ^ without further path specifications (e.g. `DSET ^hirlampv.DAT`).

Meteosat 8 data as used at KNMI are available in a hdf5k format. They can be converted to GRIB using the script `hdf5ktogrib.x`. The resulting file is recognized by Metview as a satellite image with pixel values. Metview is able to handle these data in several projections without preceding external conversions.

B.3 Visualisation

Several macros have been developed to visualise the results from the HIRLAM analysis and forecasts. The basic macros for PV plotting that were developed during this project are in the folder Visualisations. Basic macros include plotting horizontal and vertical cross-sections, wind vectors, mean sea level pressure and precipitation. The filenames of the data files, area and projection definitions and contour limits and colours can be easily edited. When ECMWF PV data are plotted using these macros, in most cases the PV values must be multiplied by 10^6 to convert the data to PVU.

Metview has a special tool to handle satellite data with pixel values. The raw pixel values were not converted to physically relevant quantities like brightness temperature. Contouring algorithms do not apply to satellite data, a special image table is available instead. For a good resolution, the image pixel selection frequency should have a large value. At the moment, these meteosat 8 data are not yet used in this format in `modifyPV.mc`, but this can be easily implemented. An example of a macro in which PV and converted Meteosat 8 data are plotted is `plotpvwvm8.mc`.