SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Implementation and validation of radar data-assimilation in the HARMONIE mesoscale weather prediction model
Computer Project Account:	spnlverk
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	Dr. W.T.M. Verkley
Affiliation/Address:	Royal Netherlands Meteorological Institute (KNMI) PO Box 201 3730 AE De Bilt The Netherlands
Other Researchers (Name/Affiliation):	

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The original objectives were (a) to study the impact of radial velocity and reflectivity data from the Dutch radar stations in De Bilt and Den Helder on analyses and forecasts made by a test-version of the HARMONIE mesoscale weather prediction model and (b) to investigate the influence of the quality control of the data used, in particular of the BALTRAD quality control software. In the course of the project, data from the Belgian radars in Jabbeke, Wideumont and Zaventem were added, made available every five minutes (as are the Dutch data) for research purposes by the Royal Meteorological Institute of Belgium (KMI). Many more data from other European countries became available still later (on an hourly basis) through an OPERA ftp-site. As it became clear in the course of the project that the latter data were to be quality controlled centrally by the BALTRAD software, objective (b) has effectively been replaced by the aim to process more radar data and to use a larger horizontal domain of the model.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

In the beginning of the project there had been some technical problems with the BALTRAD quality control software that was used locally, but these were solved in the course of time. Later the quality control was left to the OPERA data centre where it was performed on all disseminated radar data in a uniform way. There have also been some computer memory problems in handling the radar data, but these could be solved by sufficiently thinning the data in a pre-processing stage. In the course of the project pre-processing of radar data became regular practice anyway as it has been the wish of the radar data-assimilation community to do all the thinning and averaging in a separate pre-processing script instead of letting it be handled by the data ingesting software (BATOR) of HARMONIE. Some additional stress during the project was provided by two changes in the ECMWF computer platform: a change from AIX based ecgate to Linux based ecgb in the winter of 2013 and a change from IBM to Cray HPC service in the summer of 2014.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

In my experience all procedures ran quite smoothly. The format is clear and concise and did not cause more administrative stress than is to be expected when deadlines are to be met.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

The original idea of this special project was to assimilate the Doppler winds (radial velocities) and reflectivities from the two Dutch radars, in De Bilt and Den Helder, in a test version of the HARMONIE mesoscale weather prediction model. The model version that was used initially is 36h1_radar and was run on a 300 × 300 horizontal grid (2.5 km grid distance) and with 60 η-levels in the vertical in a small domain around The Netherlands. The domain is displayed in Fig. 1. For the assimilation of the radar data three-dimensional variational data-assimilation (3D-Var) was used. A general introduction to the model is given in Seity *et al*. (2011), whereas more detailed technical information is provided by the website: http://www.hirlam.org/index.php/documentation/harmonie.

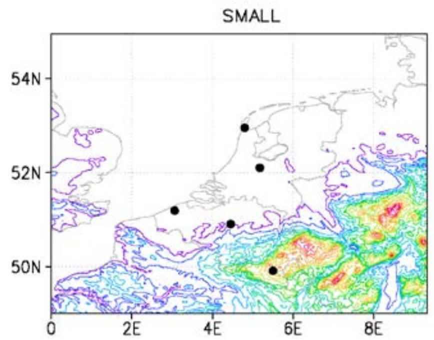

Figure 1 The small domain on which the HARMONIE model was run during a large part of this study. The horizontal resolution is 300 × 300 grid points, 2.5 km apart. The model has 60 η-levels in the vertical. The coloured contours are the orography and the dots are the positions of the two Dutch and three Belgian radar stations that were used in this study.

In 2012 we started with a configuration in which the Dutch radar data, available every five minutes in the form of a local (KNMI) hdf5 data format, were read in by a program called CONRAD and then transformed into Meteo France (MF) bufr. The latter format could then be handled by the program BATOR which, after some screening and cleaning, stored these data into the observation data base (ODB) of HARMONIE. The CONRAD program was developed by Martin Grønsleth of the Norwegian Meteorological Institute (met.no). A schematic of the procedure is given in Fig. 2.

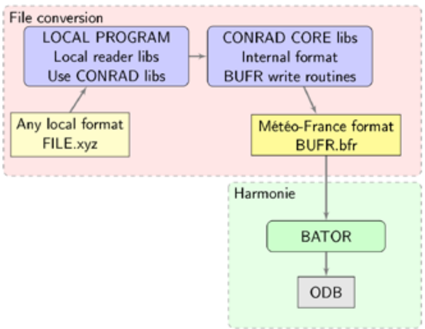

Figure 2 Schematic of the way in which the radar data were originally read by the test version of the HARMONIE weather prediction model. The local format is KNMI hdf5, for which a local program has been written to read the data. These data are then converted by CONRAD (developed by Martin Grønsleth of met.no) into MF bufr, which is then read by BATOR into the observation data base (ODB) of HARMONIE.

In the beginning we have used this configuration to study the form and time evolution of analysis increments. These are defined as the differences between an analysis with and without the use of certain observation sets, in our case radar data. These studies were carried out on the basis of several periods of ten days in which analyses and forecasts were produced with and without the use of radar data. An example taken from one of these periods, 10 – 19 December 2012, is given in Fig. 3. The left panel of this figure shows the total precipitation in mm/h at 12 December 2012, 12:00 UTC. The precipitation field covers the north-east of the Netherlands and is embedded in a moderate westerly to south-westerly wind field at the surface. The middle panel shows the difference between the analysed temperature field at 12 December 2012, 12:00 UTC, on model level 50 (about 900 hPa), in which radar data were included in the assimilation, and the analysed temperature field in which these data were not assimilated. The assimilation was performed by the 3D-Var-system of the HARMONIE weather prediction model, using radial velocities from the radar in Den Helder. In the right panel we show the same difference field, but now after one hour forecast time, i.e., at 12 December 2012, 13:00 UTC. We see that, although the grander dipole shaped temperature increment at analysis time can still be recognized, a substantial amount of small-scale structure is added after one hour of forecast time. This small scale structure is present from the beginning of the forecast, can also be seen in other fields than temperature, diminishes somewhat with height, but persists during the whole forecast period of 24 hours.

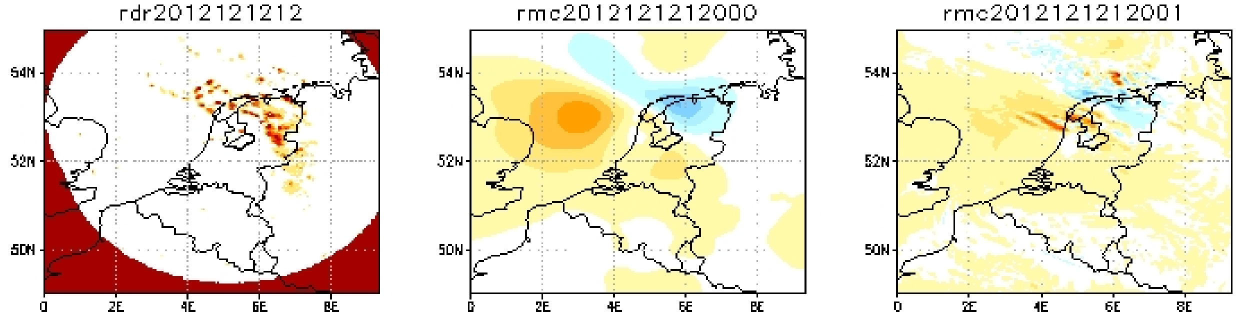

Figure 3 Left: Total precipitation (mm/h) at 12 December 2012, 12:00 UTC. Middle: difference in temperature (K) at model level 50 (around 900 hPa) between the analysis with and without inclusion of radial velocity data from the radar in Den Helder at 12 December 2012, 12:00 UTC. Right: difference in temperature (K) after one hour forecast time. The contour ranges in the different panels are 0.1 mm/h-3.2 mm/h, -0.32 K - 0.24 K and -0.64 K - 0.96 K with contour intervals of 0.1 mm/h, 0.08 K and 0.32 K, respectively.

We have noticed that, if no more radar data are assimilated after the start of the forecast, the impact of these data is maximal after about six hours after the start of the forecast. This can be seen from Fig. 4. This figure shows the root-mean square of the difference between the temperature field at model level 50 with and without assimilation of radar data at the start of the forecast as a function of forecast time. The graphs of all ten forecasts in the period 10 – 19 December 2012 are shown. The highlighted (red) graph corresponds to a case in which there was a rather strong wind-field that quickly advected the increment out of the flow domain.

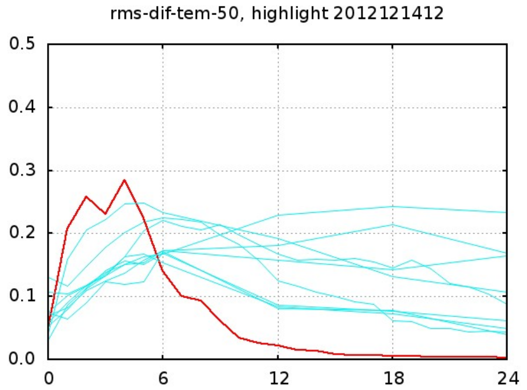

Figure 4 Root-mean square of the difference between a forecast with and without assimilation of radar data at model level 50 as a function of forecast time. The highlighted (red) graph corresponds to a case in which the analysis increment was advected out of the flow domain by a rather strong basic wind field.

The emergence of small-scale structures in the evolution of the analysis increments, as seen in Fig. 3, remains somewhat puzzling although it could be related to the spectrum of mesoscale atmospheric motions. This view is supported by a little experiment of which the results are shown in Figs. 5, 6 and 7.

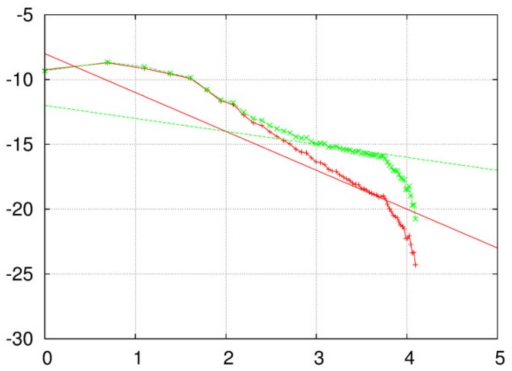

Figure 5 Energy spectra (on a log-log scale) of the end result of a simulation with a simple two-dimensional doubly periodic flow system, described by the vorticity equation. The two spectra, with different degrees of steepness, are caused by different types of dissipation.

In Fig. 5 we show two energy spectra resulting from a run with a simple flow system, the two-dimensional vorticity equation on a doubly periodic domain. The red graph results from a run with linear damping and viscosity, the green graph from a run with linear damping only. Due to the presence of viscosity the spectrum of the first run is steeper (for the larger wavenumbers) than the spectrum of the second run. In Fig. 6 we show in the upper left panel the vorticity field at some instant of time and in the upper right panel an idealized Gaussian analysis increment. The lower left panel shows the vorticity field four units of time later and the lower right panel shows the evolved increment at that time.

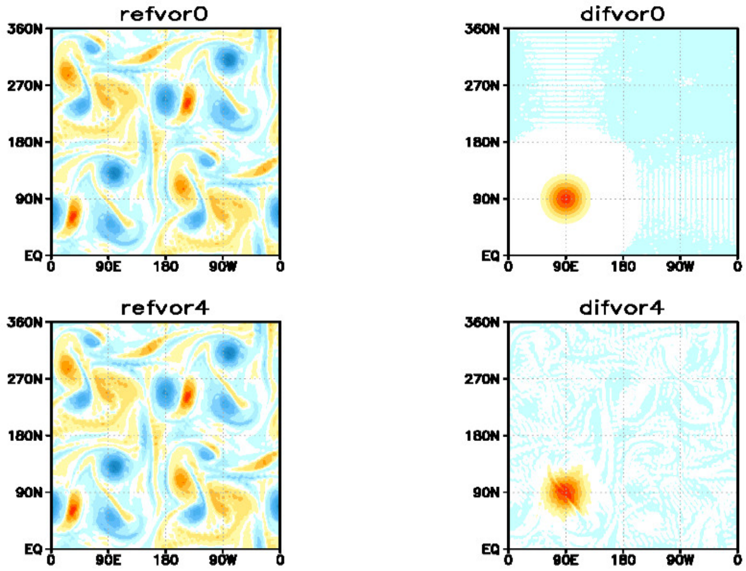

Figure 6 Evolution of a regular Gaussian-shaped increment after four time-units in the case of the model run with the steep spectrum.

Fig. 7 is organised in the same way as Fig. 6, but now refers to the run that results in the shallow spectrum. The shallowness of the spectrum is evident from the vorticity field that contains a large amount of small-scale structure. Interesting about this figure is the fact that the evolved increment, although having the same smooth initial structure as in Fig. 6, now develops more small-scale structure.

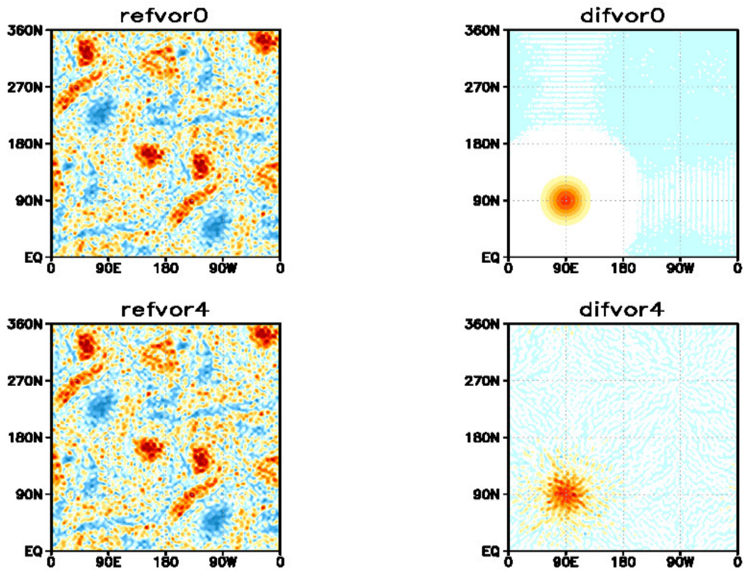

Figure 7 Evolution of a regular Gaussian-shaped increment after four time-units in the case of the model run with the shallow spectrum.

We conclude from this experiment that the generation of small-scale structure of analysis increments might be typical for mesoscale models.

As mentioned above, the impact of the assimilation of radar data is maximal after about six hours if the data are assimilated only at the beginning. To investigate the effect of assimilating the data more frequently we did the following experiment. From a particular day in one of the periods of study, i.e., 16 September 2013 12:00 UTC, we initiated five 24 hours forecasts, all using the same first guess at the initial time and the same (hourly) boundary fields from ECMWF. In the first forecast (ref) no observations were assimilated except for the conventional observations at the initial time. The ensuing forecast can thus be considered as free running, except for the hourly boundary fields. In the second forecast (dat) conventional data were assimilated every hour. In the third forecast (daa) only radial velocities from the radar in De Bilt were added. In the fourth forecast (dab) only reflectivities were added, these data being processed using the French method of translating these reflectivities into humidity profiles (Caumont *et al*. 2010). In the fifth forecast (dac) both radial velocities and reflectivities were added.

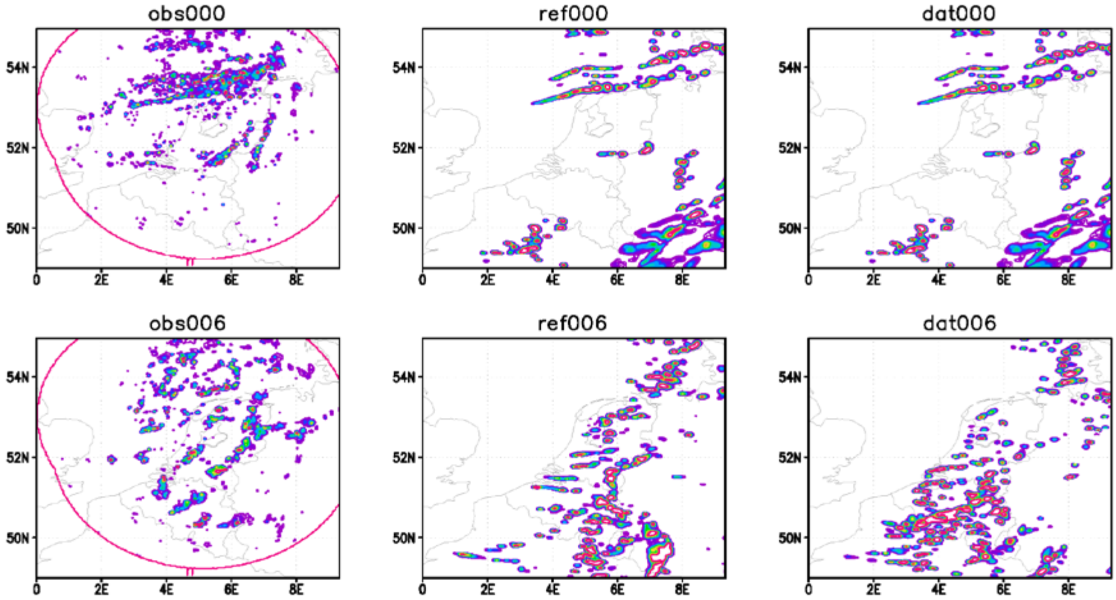

Figure 8. Left column: rainfall rate (in mm/h) as derived in a semi-empirical way from reflectivity data obtained from the Dutch radar stations in De Bilt and Den Helder. Middle and right columns: rainfall rate (in mm/h) produced by the two forecasts ref and dat, respectively. The contour interval is 0.1 mm/h, with blue colours denoting small and red colours denoting high values. The upper and lower column refer to analysis time (16 September 2013, 12:00 UTC) and 6 hours later, respectively. The way in which the different forecasts differ is explained in the text.

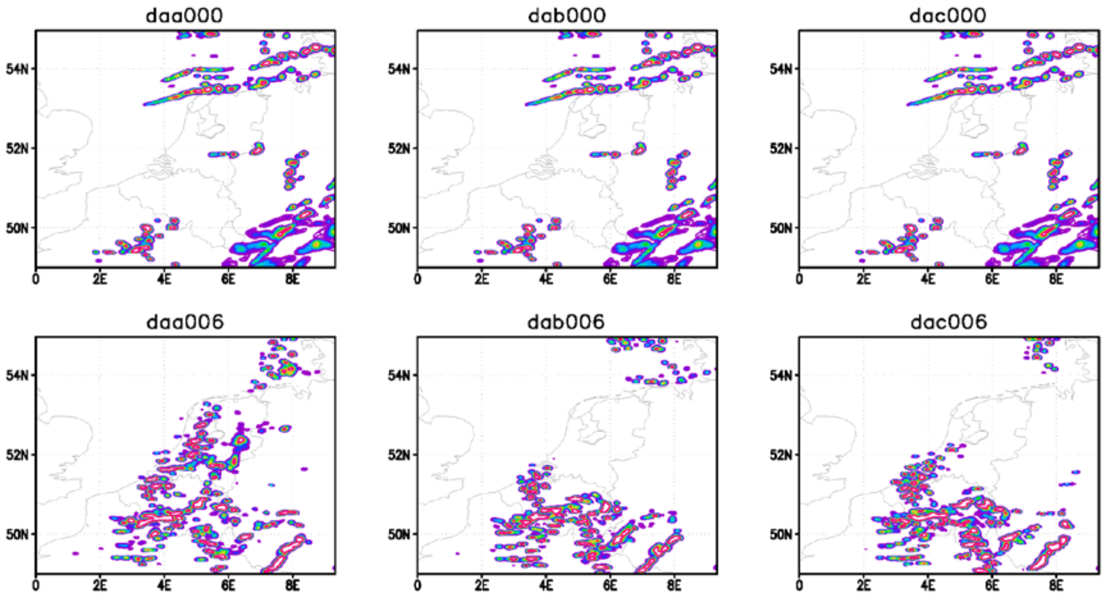

Figure 9 Left, middle and right columns: the rainfall rate in mm/h produced by the forecasts daa, dab and dac, respectively, displayed with the same conventions as the previous figure. More details on the forecasts are given in the text.

In Fig. 8 we display the observed rainfall rates and the rainfall rates as given by the first and second forecast. In Fig. 9 we display the rainfall rates as given by the forecasts three, four and five. The results are shown at analysis time and after six hours into the forecast. The figures show that the accumulation of radar data can cause large differences in the forecasted rainfall rate. The differences are, however, not necessarily improvements as can be seen by comparing the different forecasted rainfall rates with the observed rainfall rates in the first column of Fig. 8. Somewhat more details, including the forecasts at twelve, eighteen and twenty-four hours, are given in a poster made on the occasion of the 24-th ALADIN Workshop & HIRLAM All Staff Meeting, 7 – 11 April 2014 in Budapest Rumania (see list of publications/reports).

In the course of 2013 data from the Belgian radar stations Jabbeke, Wideumont and Zaventem have become available at KNMI for research purposes. The frequency with which the data are supplied is the same as the Dutch data, i.e., once every five minutes. Using a program made available by Hidde Leijnse from KNMI these data could be transformed from OPERA hdf5 format into KNMI hdf5 format and thus be processed in the same way as the Dutch data. Both the Dutch and Belgian data were assimilated using 3D-Var in a semi-operational rapid update cycle with one hour cycling time, maintained by Jan Barkmeijer from KNMI. The HARMONIE model, version 37h1.2, was run on KNMI's Bull computer and was configured for the domain shown in Fig. 1. The system functioned reasonably well although the radar data load occasionally became too heavy. First this was solved by using only radial velocities from less radars (only the Dutch ones). Later a better solution became available by thinning the data using another program made available by Hidde Leijnse. Unfortunately, the use of radar data did not improve the scores in terms of bias and standard deviation of the resulting forecasts.

Another development that took place during the project is that software became available, in the form of subroutines called by BATOR, that makes it possible to read hdf5 radar data directly into the ODB, i.e., without using CONRAD to transform these data into MF bufr. Martin Ridal from the Swedish Meteorological and Hydrological Institute (SMHI) and Mats Dahlbom from the Danish Meteorological Institute (DMI) have played a leading role in this development. Also, from autumn 2013 onwards, volume radar data from a substantial number of European countries became available from an OPERA ftp-site. These data are quality controlled and available in OPERA hdf5 format every hour. In combination with the first development, this makes it possible to use more radar data and process these data in a uniform way.

Using version 37h1.1.bugfix of the HARMONIE model, run at KNMI's Bull computer, Jan Barkmeijer from KNMI in collaboration with Magnus Lindskog from SMHI have succeeded in using four-dimensional variational data-assimilation (4D-Var) for the horizontal domain displayed in Fig. 1. The data-assimilation was based on time slots of two hours and ran every three hours, i.e., on 00:00, 03:00, 06:00 UTC, etc. As part of this special project we implemented the new hdf5 reading software in this model to use radial velocity data from De Bilt and Den Helder. In the time slot of, e.g., 12:00 UTC the radar data of 11:05, 11:20, 11:40, 12:00, 12:20, 12:40 and 12:55 UTC were used. The data were thinned by a factor 4 in both radial and azimuthal directions, using Hidde Leijnse's software mentioned above. Furthermore, due to a limitation in the hdf5 reading software (removed later), only the lowest four elevations (0.4, 0.8, 1.1 and 2.0 degrees) were used. The suite with radar data has run for an appreciable amount of time but, in cases of large quantities of precipitation, the assimilation of radar data led to unreasonably large analysis increments to the point of causing numerical instability.

This instability has been the motive to have another look at the analysis increment due to the assimilation of radar data. The idea was now to compare this increment with the increment due to the assimilation of MODE S data, the assimilation of which does not lead to instability. To this end we studied the weather situation of 14 January 2015, 12:00 UTC, of which a few details are given in Fig. 10. The model version used in this study is 37h1.1.bugfix but with 3D-Var instead of 4D-Var for the data-assimilation. For the reference analysis we chose in the file include.ass the following options: SYNOPS_OBS=1, BUOY_OBS=1, TEMP_OBS=1, PILOT_OBS=1 and all further options equal to 0. In a first experiment (A) we repeated the 3D-Var analysis with the extra option AIRCRAFT_OBS=1. Because we used an observation file that also contains MODE S data which, actually, made up the majority of the aircraft data, we mostly added MODE S to the observations in this experiment.

Figure 10 Left: weather chart of 14 January 2015, 12:00 UTC. Middle: radar image ten minutes later. Right: Analysis of HARMONIE, version 37h1.1bugfix, for the horizontal domain displayed in Fig. 1. Shown in the latter panel are the temperature and wind field at model level 50.

In a second experiment (B) we repeated the 3D-Var analysis with instead of AIRCRAFT_OBS=1 the extra option RADAR_OBS=1 in which case the radar data of De Bilt were assimilated. As in the 4D-Var suite, mentioned above, the radar data were read in directly from the hdf5 files. Only the lowest four elevations (0.4, 0.8, 1.1 and 2.0 degrees) were used and the data were thinned by a factor of 4 in both directions, leading to 90 × 60 data points for each elevation. After screening by BATOR 432 data points of the radar remained. The extra data that were assimilated in the two experiments are spatially distributed as displayed in Fig. 11.

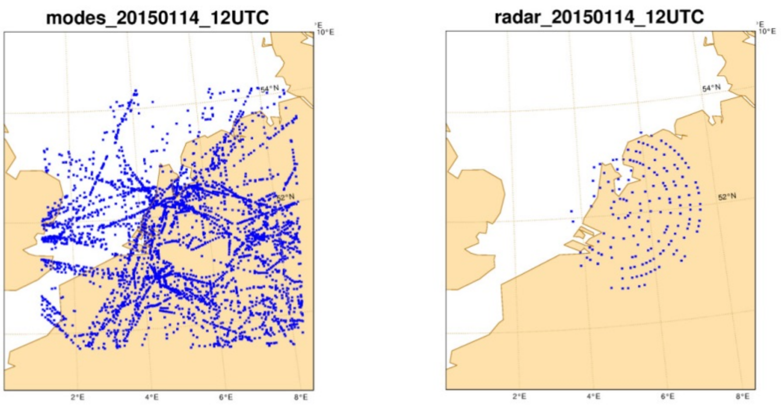

Figure 11 Left: horizontal distribution of the MODE S data that were assimilated. Right: horizontal distribution of the radar data that were assimilated. (courtesy Gert-Jan Marseille of KNMI)

The analysis increments of these experiments, in terms of the temperature and wind field field at model level 50, are displayed in Fig. 12. There are differences in both the temperature and the wind field and it is noted that the analysis increment is smaller in experiment B than in experiment A. In experiment B we then increased the value of the observation error of the radial winds from the standard value around 1 m/s to 2 m/s, 3 m/s and 10 m/s. This led to reductions of the increment, without too much change in structure. As an extreme case we show in the left panel of Fig. 13 the resulting increment of assimilating radar data from De Bilt when the observation error is set to 10 m/s. In the right panel of the same figure the observation error is again the standard 1 m/s but the thinning has been left out. The last panel shows how the amount of thinning influences the amplitude and structure of the analysis increment.

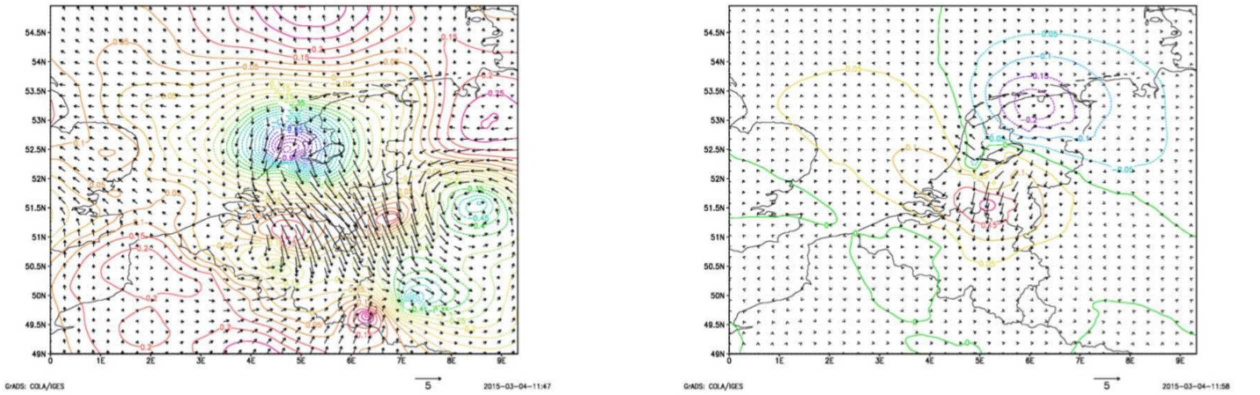

Figure 12 Left: analysis increment in terms of temperature (contours) and wind (arrows) as a result of assimilating MODE S data. Right: analysis increment in terms of temperature (contours) and wind (arrows) as a result of assimilating the radar data from De Bilt. The temperature fields are plotted with a contour interval of 0.05 K.

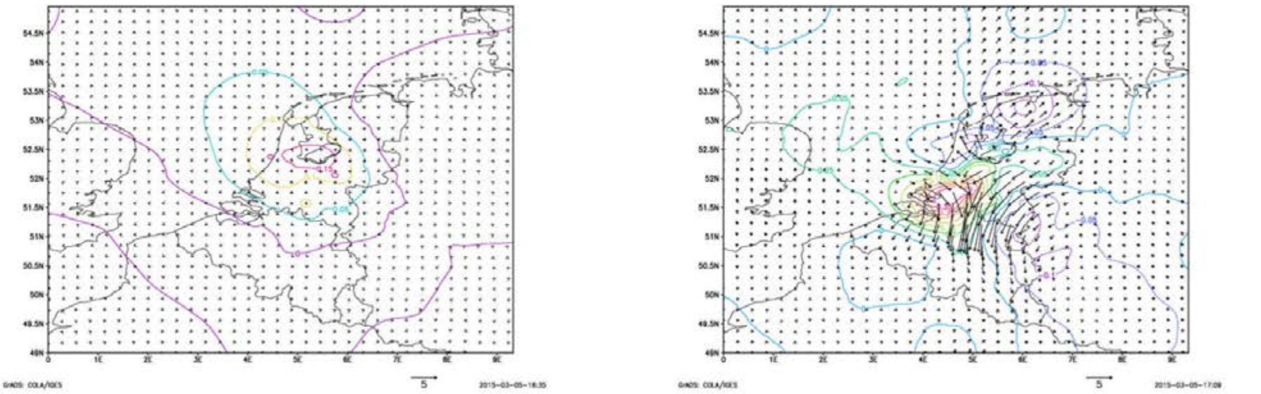

Figure 13 Analysis increment in terms of temperature (contours) and wind (arrows) as a result of assimilating radar data from De Bilt. In the left panel the observation error is 10 m/s and the radar data are thinned, in the right panel the observation error is 1 m/s and the radar data are not thinned. Temperature fields are plotted with the same contour interval as used in Fig. 12, i.e., 0.05 K.

The results of the latter experiment do not lead to a firm conclusion. The dependence of the analysis increment on the observation error and thinning factor seem quite reasonable. When the right panel of Fig. 13 is compared with the left panel of Fig. 12 we see that, if the radar data are not thinned, the increment due to latter data is of the same order of magnitude as the increment due to MODE S data. It should be noted, though, that their structure, both in terms of temperature and wind field, are quite different. It is still an open question whether the fact that these increments are different points to a problem in the data-assimilation process, given the fact that both observation sets probe the same atmospheric state. It is also quite puzzling that the 4D-Var system sometimes develops an instability even when thinned radar data are used. Indeed, the right panel of Fig. 12 indicates that the increments are probably smaller than the increments due to MODE S data. It cannot be excluded, of course, that errors occasionally appear in the radar data. The applied thinning procedure does not deal with these errors and other procedures, such as averaging, might be more appropriate. Mats Dahlbom (DMI) and Martin Ridal (SMHI) have developed such an averaging (superobbing) procedure as part of the pre-processing of radar data and made this procedure available to us.

A development that is ongoing at the moment of writing this report (June 2015) is that at KNMI impact studies are carried out with different observational datasets: conventional data, MODE S data, scatterometer data, etc. For these studies version 38h1.2 of HARMONIE is run on ECMWF's CRAY computer on a large domain of 800 × 800 points (2.5 km apart) with 65 η-levels in the vertical. A plot of the flow domain is given in Fig. 14. The scores of these studies can be seen on the website: https://hirlam.org/portal/validation/38h1/IMPACT. The results of the experiments with radar data will be posted there as well.

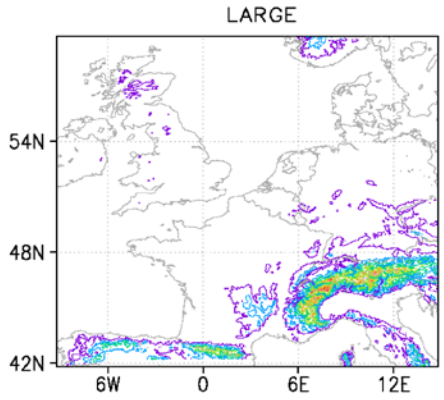

Figure 14 The large domain on which the HARMONIE model was run during the latter part of this study. The horizontal resolution is 800 × 800 grid points, 2.5 km apart. The model has 65 η-levels in the vertical. The coloured contours are the orography.

References

Caumont, O., Ducrocq, V.,Wattrelot, E., Jaubert, G. and S. Pradier-Vabre, 2010: 1D+3DVar assimilation of radar reflectivity data: a proof of concept, *Tellus*, **62**A**,** 173 – 187.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., Lac, C. and V. Masson, 2011: The AROME-France convective-scale operational model, *Mon. Wea. Rev*., **139**, 976 – 991.

List of publications/reports from the project with complete references

During the reporting period 2012 – 2013 Wim Verkley has given a presentation on the status of radar data assimilation at KNMI during the HIRLAM-HARMONIE Working Week on High Resolution Observations in HARMONIE (a follow-up of the extended radar data impact study). This working week was held from 12 – 15 March 2013 at SMHI in Norrköping, Sweden. The presentation can be downloaded from:
https://hirlam.org/trac/wiki/HarmonieWorkingWeek/UseObs201303.

Jan Barkmeijer has given a presentation on HARMONIE at KNMI and future work (including a short report on radar data) at the Joint All Staff Meeting 2013 and 23th ALADIN Workshop of 15 – 18 April 2013 at the Icelandic Met Office in Reykjavik, Iceland. The presentation can be downloaded from:
http://www.cnrm.meteo.fr/aladin/spip.php?article165

During the reporting period 2013 – 2014 two presentations were given on the status of radar data assimilation at KNMI. The first was on 2 December 2013 in Copenhagen during the Harmonie Working Week on Data Assimilation and Observations in HARMONIE, from 2 – 15 December 2013. The presentation can be viewed on:
https://hirlam.org/trac/attachment/wiki/HarmonieWorkingWeek/UseObs201312/status_2013_2.pdf.

The second was on 12 March 2013 in Norrköping during the Harmonie Working Days on Radar Data Assimilation in HARMONIE, from 12 – 14 March 2014. The presentation can be viewed on:
https://hirlam.org/trac/attachment/wiki/HarmonieWorkingWeek/Radar201403/status_2014_wim.pdf.

We also prepared a poster for the 24-th ALADIN Workshop & HIRLAM All Staff Meeting 2014. The meeting was held from 7 – 11 April 2014 in Bucharest, Romania. The poster can be viewed on:
http://www.cnrm.meteo.fr/aladin/IMG/pdf/poster_landscape_asm_03.pdf

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The research carried out during this special project is part of an ongoing effort at KNMI to contribute to the development and use of mesoscale weather prediction models. Assimilation of high-resolution observations such as radar data is an integral part of that effort which will continue in the foreseeable future.