SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Validation and improvement of high-impact weather process understanding in Europe with the aid of high-resolution WRF simulations and sophisticated data assimilation (VALPUDA)
Computer Project Account:	spderap
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	Dr. Hans-Stefan Bauer Prof. Dr. Volker Wulfmeyer Dr. Thomas Schwitalla
Affiliation/Address:	Institute of Physics and Meteorology University of Hohenheim Garbenstr. 30 70599 Stuttgart Germany
Other Researchers (Name/Affiliation):	none

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project had two major aims. The first was to simulate high impact weather events on different spatial and temporal scales ranging from severe local convection to synoptic-scale systems. Recently, also very high resolution simulations with grid sizes of 100 m for boundary layer and process studies were performed. The forecast performance were increased by combining high-resolution modelling with advanced data assimilation of state-of-the-art observations.

The second task was the improvement of quantitative precipitation estimation (QPE) by combining observational methods with high-resolution modelling and data assimilation. For this purpose, the assimilation system of WRF was extended by an observation operator for polarization radar. Its development started during the special project and is continued afterwards.

Summary of problems encountered

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

No problems encountered.

Experience with the Special Project framework

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

No problems encountered during the application procedure, adequate workload for progress reports.

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 WRF-RUC system with a 1-hourly cycling of the 3DVAR was applied for model-based quantitative precipitation estimation (QPE) for an interesting case study of a frontal passage and subsequent development of convection. A huge data set of surface stations, radio soundings, GPS zenith total delay water vapour estimates, satellite derived wind fields and reflectivity and radial velocities from German and French radar systems was assimilated. The experiment demonstrated the potential of numerical models for the estimation of precipitation. The development of the forward operator was continued and its results were compared with the operator of the ARPS model. Finally, WRF was set-up in a configuration with four domains down to a horizontal resolution of 111 m to simulate in more detail the representation of atmospheric processes for different case studies.

A more detailed report is attached to the same Email

List of publications/reports from the project with complete references

Reviewed papers:

Bauer, H.-S., Schwitalla, T., Wulfmeyer, V., Bakhshaii, A., Ehret, U., Neuper, M. and Caumont, O., 2015: QPE based on high-resolution numerical weather prediction and data assimilation with WRF – a performance test. **Tellus A**, 67*,* http://dx.doi.org/10.3402/tellusa.v67.25047

Schwitalla, T. and V. Wulfmeyer, 2014: Radar data assimilation experiments using the IPM WRF Rapid Update Cycle. **Meteorol. Zeitschrift**, 23, 79-102.

Selected conference contributions:

Bakhshaii, A., Y. Jung, T. Schwitalla, H.-S. Bauer, and V. Wulfmeyer, 2014: WRF dual polarized radar forward operator evaluation on a supercell event in Central Europe. The World Weather Open Science Conference, 16-21 August, 2014, Montreal, Canada.

Bauer, H.-S. , T. Schwitalla, V. Wulfmeyer, A. Bahkshaii-Shahrbabaki, U. Ehret and M. Neuper, 2014: Comparing and combining of observation-based QPE methods with high-resolution numerical weather prediction and data assimilation. The World Weather Open Science Conference, Montreal, Canada, 16-21 August, 2014 .

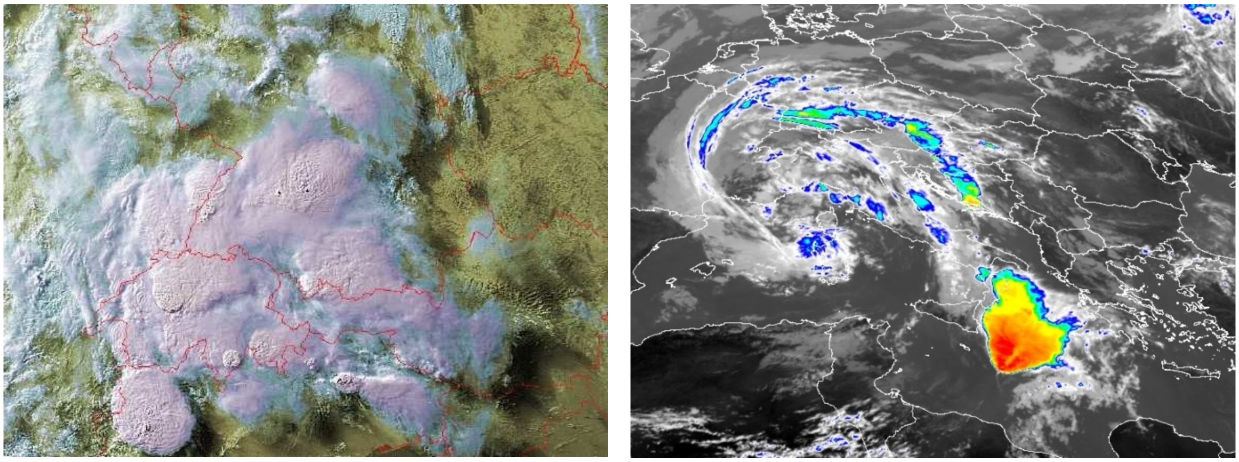
Schwitalla, T., H.-S. Bauer, J. Milovac, V. Wulfmeyer, A. Bahkshaii-Shahrbabaki, U. Ehret and M. Neuper, 2014: Quantitative precipitation estimation by combining observations and a high-resolution numerical weather prediction model with 3DVAR. World Weather Open Science Conference, 16-21 August 2014, Montreal, Canada.

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 science in Quantitative Precipitation Estimation (QPE), process understanding of high-impact weather systems and boundary layer research is continued in the second phase of the CAOS research group funded by the German research foundation. At the moment no application for a new special project is submitted.

Validation and improvement of high-impact weather process understanding in Europe with the aid of high-resolution WRF simulations and sophisticated data assimilation (VALPUDA)



Examples of high-impact weather developing over Germany and the Mediterranean (Source: Internet)

Dr. Hans-Stefan Bauer, Prof. Dr. Volker Wulfmeyer and Dr. Thomas Schwitalla

Institute of Physics and Meteorology, University of Hohenheim, Garbenstr. 30, 70599 Stuttgart

1. Motivation

A continuous improvement of the predictive skill of models with respect to the simulation of high-impact weather events is extremely beneficial for society and economy. Recent results of related projects of WWRP, particularly the Research and Development Project COPS[1] (Wulfmeyer et al., 2011), demonstrated the importance of high-resolution mesoscale modeling for providing reliable information down to the relevant scales for end users such as catchments for flash flood forecasting. Errors due to the convection parameterization can apparently be reduced by applying a convection-permitting resolution of ~3 km. It has been clearly demonstrated that these models provide a significant advance with respect to predictive skill and reduction of systematic errors particularly in complex terrain (e.g. Schwitalla et al., 2008; Weusthoff et al., 2010; Bauer et al., 2011, Schwitalla et al., 2011).

According to the Strategic Plan of the WWRP Working Group on Mesoscale Weather Forecasting (MWF), future advances in short-range NWP require a combination of high-resolution modeling on the convection-permitting (CP) scale (of the order of 1 km) with advanced data assimilation of high-resolution observations (WMO, 2010; Weusthoff et al., 2010; Bauer et al., 2011).

Additionally, CP models in combination with sophisticated data assimilation are a unique tool for improving process understanding (e.g. Wulfmeyer et al., 2006; Kawabata et al.,2007; Grzeschik et al., 2008; Zus et al., 2008; Kawabata et al., 2011; Schwitalla et al., 2011). Therefore, we are convinced that the new

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[1] COPS: Convective and Orographically-induced Precipitation Study (http://www.cops2007.de)

generation of mesoscale models in combination with assimilation of new observations can be applied for process studies over a wide range of spatial scales.

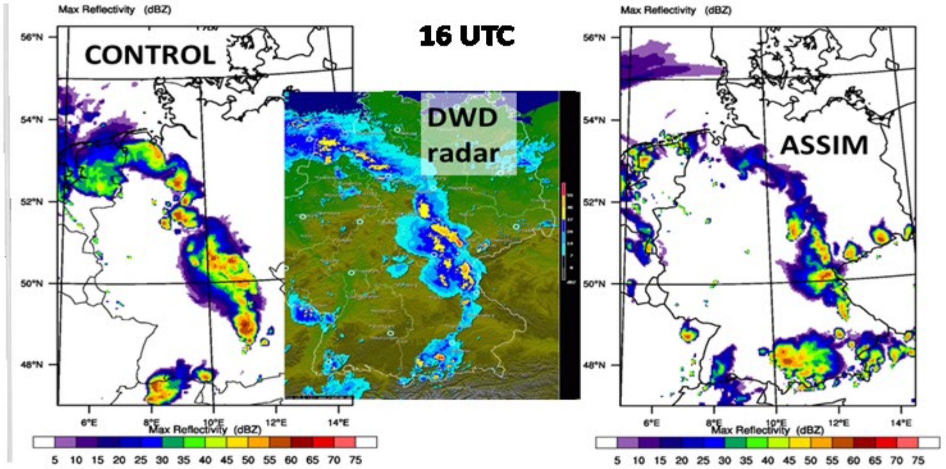


Figure 2: Comparison of one time step during the evolution of a convective event during COPS (IOP 9c, 20 July 2007). CONTROL: WRF simulation without assimilation (only initialized with the ECMWF analysis). DWD radar: DWD radar composite. ASSIM: WRF simulation with the assimilation of radar reflectivity from German radar systems (Schwitalla et al., 2011).

Of particular importance is an as accurate as possible estimation of precipitation since it is required as an input field for flood forecasting. Historically, rainfall was only measured at point locations. To get information about the spatial distribution of rainfall, interpolation methods of different complexity (e.g. inverse distance weighting or Kriging) were applied. However, the spatial representativeness of point observations remains poor, especially for convective precipitation with a large spatial variability. To overcome the problem of spatial non-representativeness of rain gauges, weather radar with its high spatio-temporal resolution as complementary data source has been investigated for several decades. However, there are strong limitations on any straightforward combination of radar and rain gauge observations. This is mainly due to the indirect nature of the radar measurement, non-agreement of radar and rain gauge sampling location and volumes as well as radar error sources like attenuation or clutter and unknown radar Z-R relationships.

Atmospheric modeling has the potential to strengthen exactly the weak point of observation-based approaches: It produces consistent states with respect to the 3D thermodynamic atmospheric fields, cloud water, cloud ice, and diagnostic variables such as precipitation. An optimal combination of observational and modeling techniques is therefore a promising approach for improving quantitative precipitation estimation (QPE).

2. Model and Methodology

In this project, the combination of the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) and its assimilation system WRFDA was applied to understand key processes during high impact weather situations and for QPE research. WRFDA includes 3DVAR (Barker et al., 2012), 4DVAR (Huang et al., 2009) as well as hybrid ensemble-variational (Wang et al., 2008a, b) capabilities. The 3DVAR system was applied during the project.

WRFDA will be applied with as many as possible high-resolution observations. Basis for the assimilation are the GTS observations available in the ECMWF MARS archive. They are complemented by additional data sets. Important for the initialization of the water vapor field are GPS data provided by the GFZ Potsdam (ZTD) and radar reflectivity from German and French radar systems. For the accurate initialization of the dynamics, radar radial velocities and Meteosat atmospheric motion vectors (AMV) from EUMETSAT were assimilated. In addition satellite radiances further densify the observational network especially over the oceans. The assimilation is performed in a so-called Rapid Update Cycle (RUC), performing several analyses with 1 to 3 hour time intervals. The continuous inclusion of observations over several hours ensures a better adjustment of the model to the observed situation. Figure 2 illustrates our RUC system.

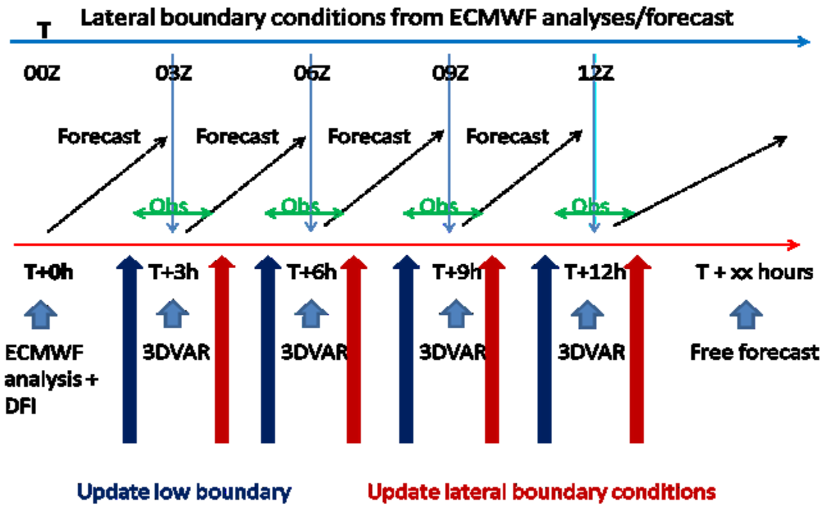


Figure 2: Setup of the Rapid Update Cycle (RUC) for case studies.

To improve the capability of the model to simulate the development of precipitation, the existing forward operator for radar radial velocity and radar reflectivity in the WRFDA system is extended to also be able to assimilate observations of polarization radar. This allows a better adjustment of the cloud microphysics to the observed state, especially when 2-moment microphysics schemes, supported by the WRF system, are applied.

The WRF model system was applied to investigate the representation of selected high-impact weather events in Europe occurring on several temporal and spatial scales ranging from the evolution of severe convection in orographically structured terrain of Germany or severe European winter storms. Aims were the improvement of the process understanding and the physical representation of such systems in the WRF model system.

Furthermore, with the assimilation of polarization data, the modeled quantitative precipitation estimation (QPE) is expected to be improved, since the adjustment of the cloud microphysics to observations will be beneficial for the whole process chain in the model and the development of precipitation at its end. Within the DFG research group “Catchments As Organized Systems (CAOS), this will be tested for several synoptic situations in a target area in Luxemburg. An additional improvement of QPE is expected when the model results are combined with data from instrumentation deployed in the field starting in summer 2012.

When the model is able to simulate severe weather events with high performance, a deep insight can be achieved into the processes evolving during the development of such high impact weather systems e.g. the simulation of mesoscale vortices and thermally induced slope flows which are important for the development of convection.

3. Work done between 2012 and 2014

In the first year of the project, the RUC was optimized with respect to the different remote sensing systems as GPS, radar and satellite radiances. The work plan for the high-impact weather part of the project is illustrated in Figure 3.

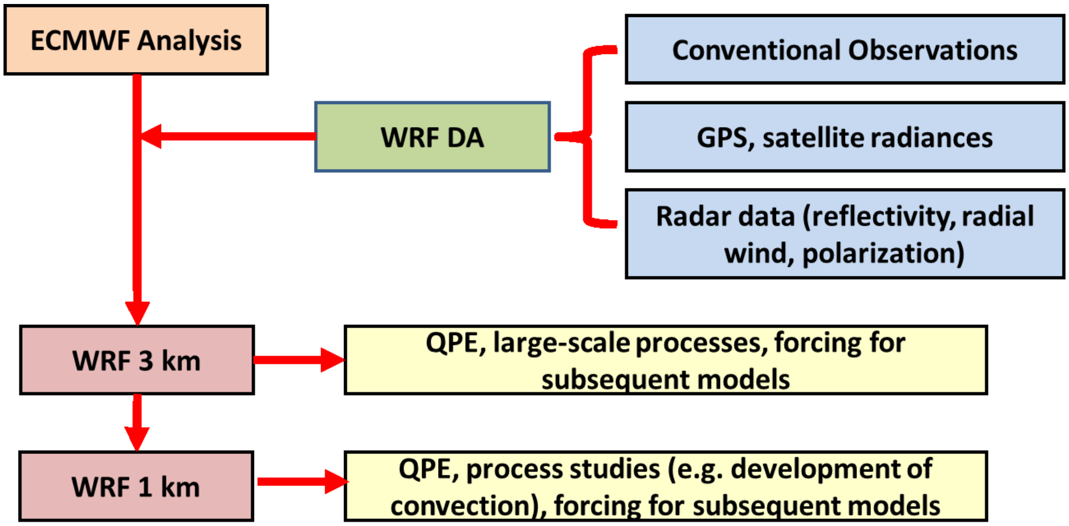
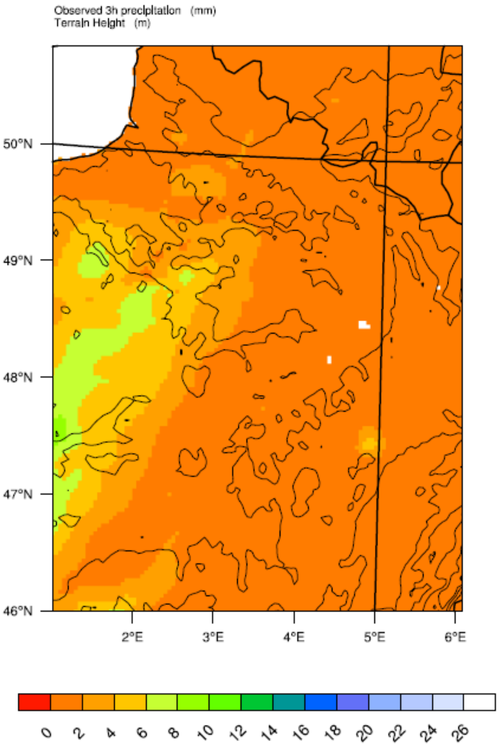
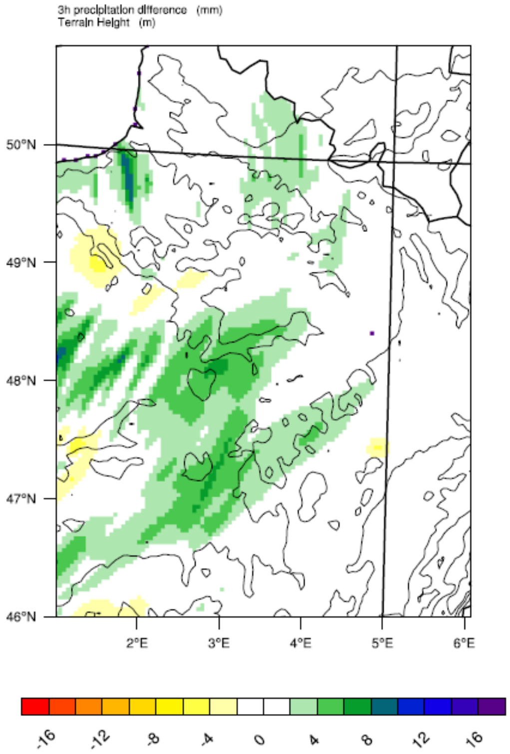


Figure3: Illustration of the different steps followed for the investigation of the representation of high-impact weather events and for QPE research.

This system was applied for the simulation of high-impact weather situation on different spatial and temporal scales. Figure 4 shows an example. Schwitalla and Wulfmeyer (2014) investigated the influence of combining German and French radar observations (reflectivity as well as radial velocity) on the forecast performance. As case, July 23rd 2007 (COPS intensive observation period 10) was selected. This was a typical weather situation for the COPS period with a low pressure system located west of Brittany and a high pressure ridge located over Central Europe. The constellation collected colder air masses in the upper troposphere and advected warm and moist air masses from the Mediterranean causing a destabilization of the atmosphere. In addition, the strong pressure gradient caused strong surface winds over France.

The system moved to the east and initiated severe convection in the western half of Germany and Eastern France in the morning hours of 23 July. The maximum observed 3-hourly precipitation reach 35mm in the Bordeaux area.





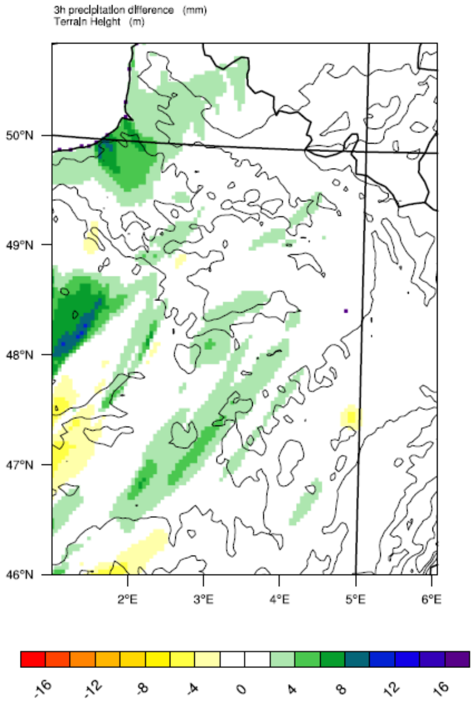


Figure 4: Upper left: 3-hourly precipitation distribution (mm) derived from the JDC precipitation data set. Upper right: Difference model-observation (mm) for the simulation without assimilating radar data. Lower left: Difference model-observation (mm) for the simulation with radar data assimilation.

It is seen that, especially in regions with good radar coverage, the short-range precipitation forecast is improved.

For the improvement of QPE, the existing radar forward operator in the WRFDA system is extended by the capability to assimilate polarization radar data. The development for this task started in September 2012. An important step at the beginning was the choice of the cloud microphysics scheme that provides the microphysical variables for the derivation of the polarization radar moments. Based on our experience from earlier case studies (e.g. Schwitalla et al., 2011), we selected the sophisticated Morrison 2-moment scheme (Morrison et al., 2009).

As case study for the development of the operator, a severe convection case in southwest Germany was selected. In the afternoon of June 30th 2012, supercells developed upstream of a cold front and moved on a west-east track to the north of Stuttgart. They lead to material damage due to torrential rain and large hail along their tracks. Such a case is important for the operator development since all types of hydrometeors are present during the evolution of this phenomenon.

Figure 5 shows one time step during the development of the supercell as seen by radar (DWD RADOLAN RX data and the same time step for a first WRF simulation with 1 km horizontal resolution and 57 vertical levels.

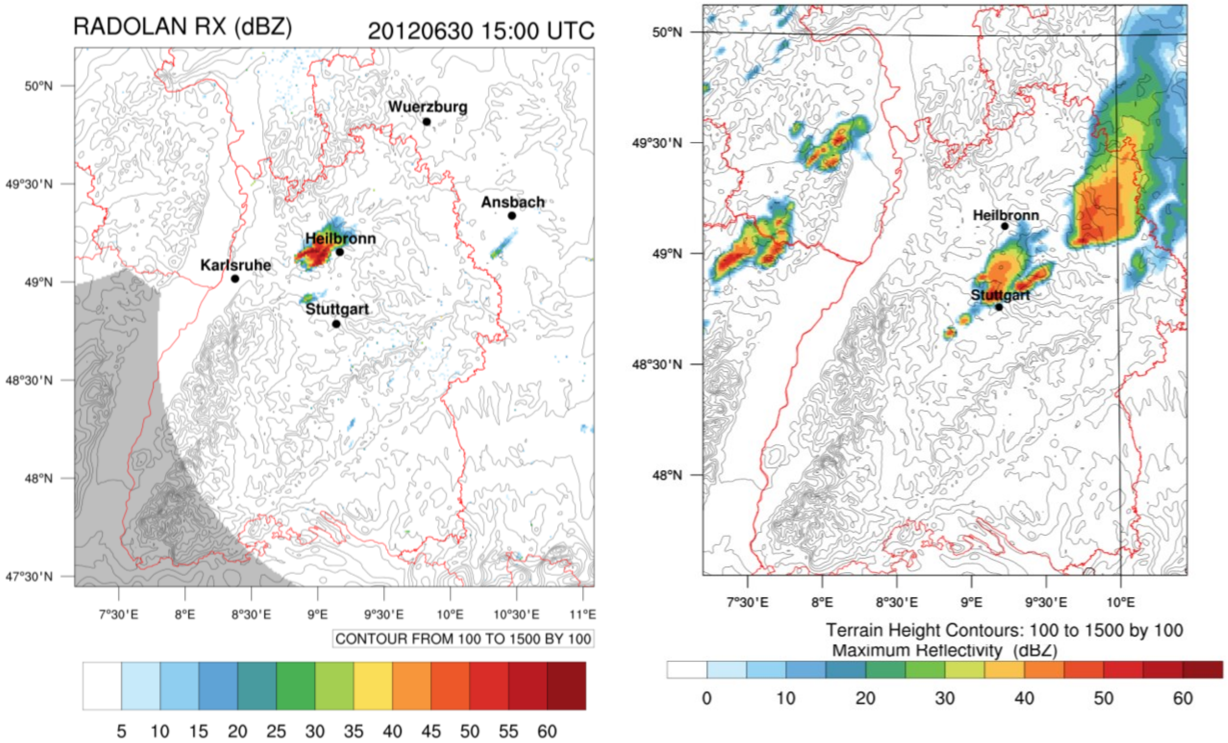


Figure 5: One time step (15 UTC) during the development of the supercell in the afternoon of June 30th, 2012 as seen by radar (DWD RADOLAN RX) (left) and in a WRF simulation initialized by ECMWF analysis data (right).

It is seen that the synoptic situation is captured. However, more thunderstorms develop in the model simulation and the cells are simulated too far to the south. We expect to improve the representation with the aid of data assimilation in future simulations. In the meantime we are more interested in the process representation of the supercell evolution and the performance of the variable converter in the forward operator for polarization radar than in its correct location.

The results of the WRF operator (Bakhshaii et al., 2014) were compared with the polarization operator developed by Jung et al. (2008) for the Advanced Regional Prediction System (ARPS, Xue et al., 2003). To do the comparison, the WRF results from this simulation were fed into the ARPS operator to derive the same variables. Figure 6 compares the horizontal reflectivity derived from both operators from the same model output.

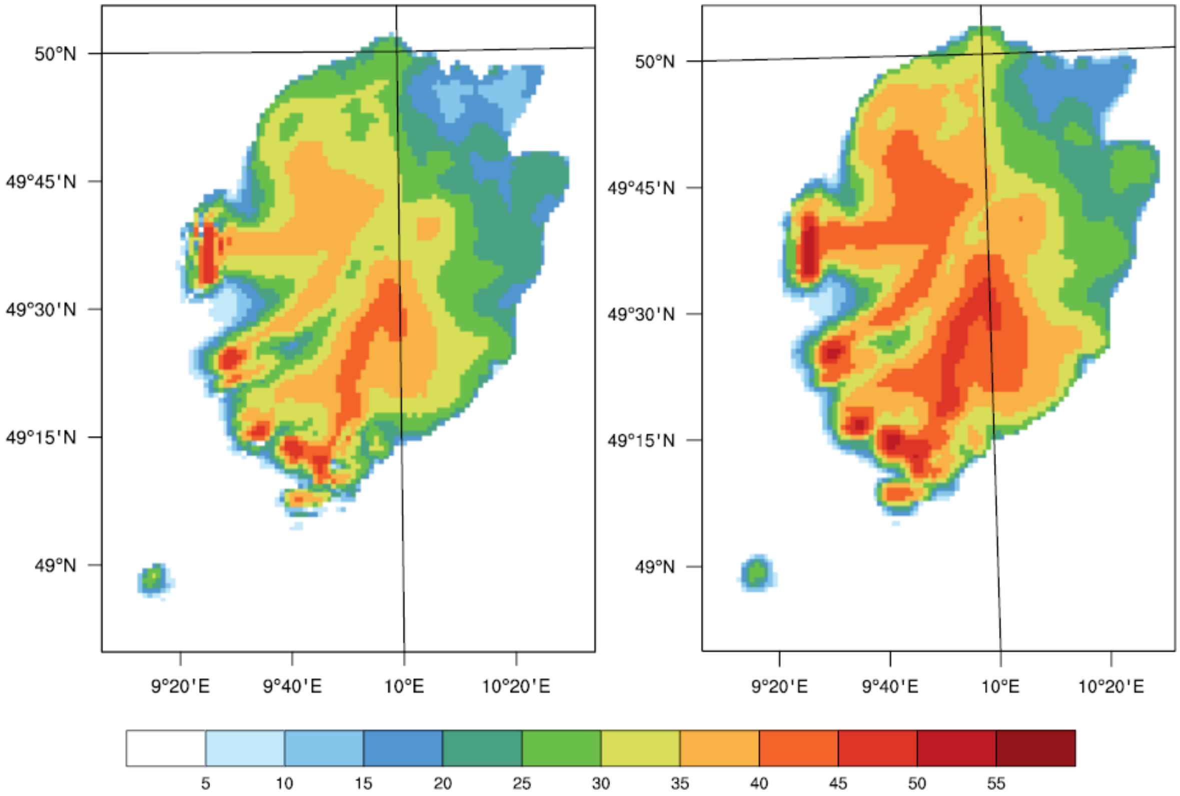


Figure 6: Comparison of the horizontal reflectivity (dBZ) derived from WRF output with the polarization operators of WRF (left - Bakhshaii et al., 2014) and ARPS (right - Jung et al., 2008)

It is seen that the result of the two operators is almost identical suggesting that the derivation of the polarization variables works properly in the WRF operator. During the course of 2014, different approaches to do the variable conversion between the microphysics and the polarization moments were tested to find the optimal configuration for the operator development. Furthermore, the spatial interpolator from the model variables to the observation location was coded, so that the integration into the WRF software structure remains as task for future work.

To support the model- and observation-based QPE, 2 micro rain radars and 6 disdrometers were installed in the Attert catchment in Luxembourg. They provide continuous data since September 2012 that is directly applied in observation-based QPE and served as validation data for model-based QPE experiments. The strategy for the improvement of QPE in CAOS is illustrated in Figure 7.

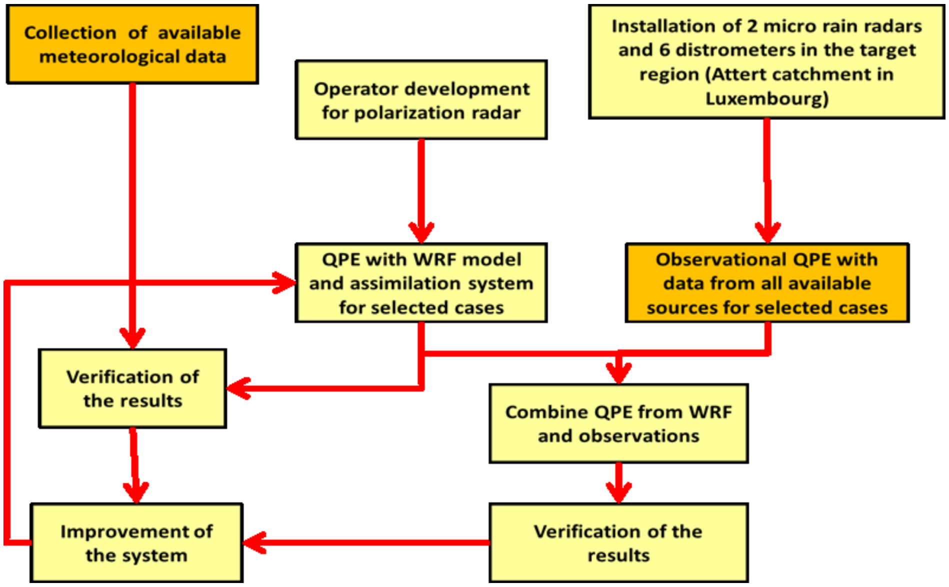


Figure 7: Illustration of the different steps followed for the investigation of the representation of high-impact weather events.

Furthermore, the model configuration for the QPE experiments was refined. Figure 8 shows the model domain setup for the model-based QPE experiments ranging from 3 km in the outer domain to 1 km. For the simulation of a CAOS two-day case-study from 26th to 27th of September 2012 (Bauer et al., 2015), the RUC increment was set to 1 hour. Figure 9 shows the observations selected for the assimilation.

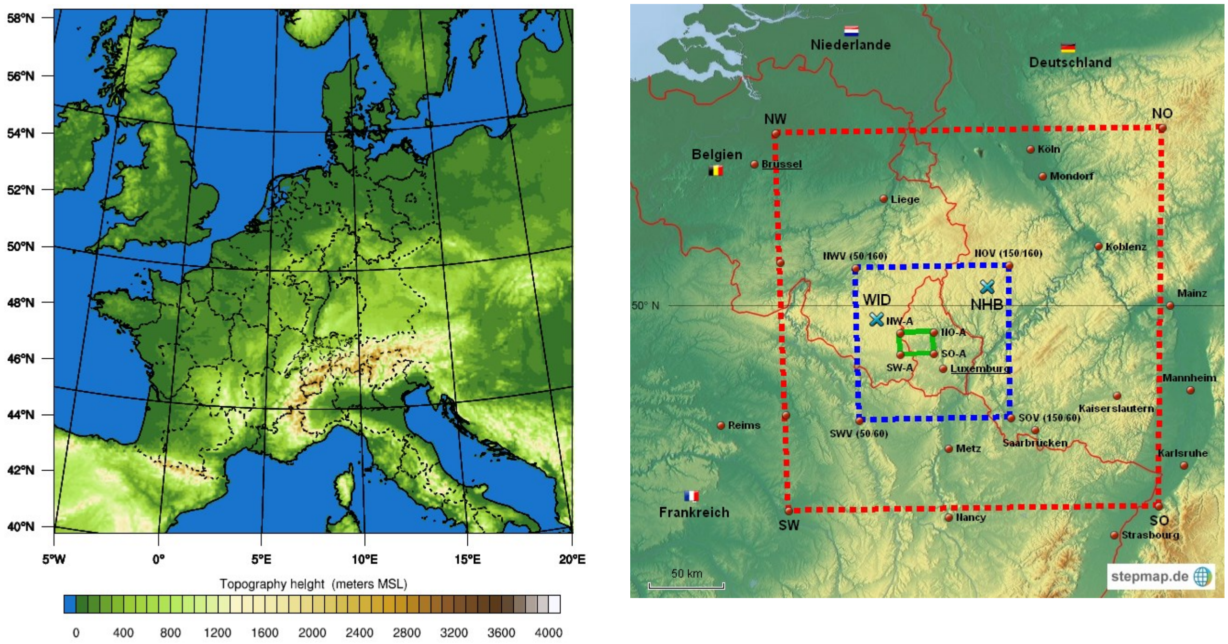


Figure 8: Domain configuration for the WRF-QPE experiments. Left: 3 km model domain with 681x692 grid cells. Right: 1 km domain with 250 x 250 grid cells (red frame) in which the model-based and observation-based QPE methods were compared. The blue frame shows a smaller verification domain focusing on Luxembourg. The blue crosses mark the locations of the radar systems Wideumont (WD) in Belgium and Neuheilenbach (NHB) in Germany. The green frame marks the Attert catchment.

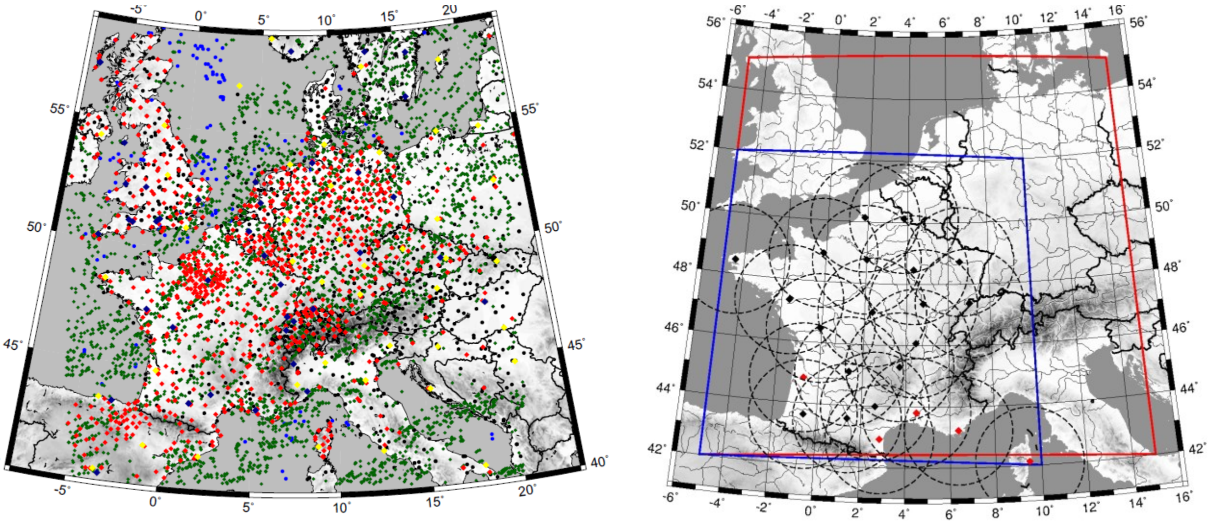


Figure 9: <u>Left</u>: Observation types and their locations for the assimilation at 00 UTC, September 26, 2012. Black = Surface stations (SYNOP + Metar), blue = ship observations (SHIP), green = aircraft observations and atmospheric motion vectors from satellite (AMDAR + SATOB), red = GPS zenith total delay, yellow = radiosondes (TEMP) and brown = wind profiler. <u>Right</u>: Coverage of the different radar systems applied in the WRF experiment.

The synoptic situation was chosen since two different weather regimes important for the estimation of precipitation follow each other. On September 26th, a frontal system passed the region of interest and brought precipitation amounts of more than 30 mm in the CAOS region of interest. Following the cold front, cool maritime air flooded Europe, destabilizing the atmosphere and leading to the development of convection on the 27th of September 2012. Figure 10 shows natural color composites of the EUMETSAT MSG satellite for 12 UTC of both days. In Figure 11, model results for one time step during the development of the situation are presented.

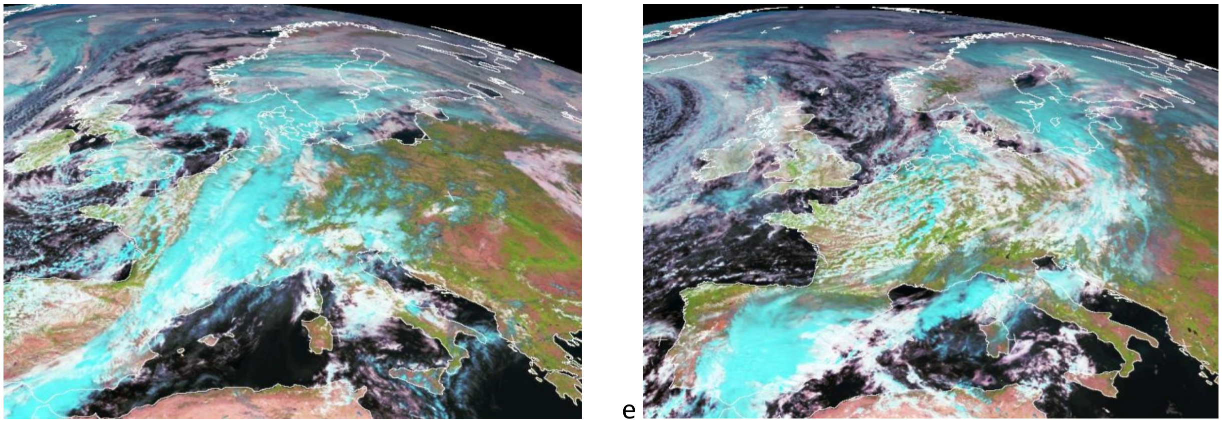


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Figure 10: Composite image of the Meteosat Satellite for 12 UTC, 26th September 2012 (left) and 12 UTC, 27th September 2012 (right). (Source: NERC satellite receiving station, Dundee University, from http://www.sat.dundee.ac.uk)

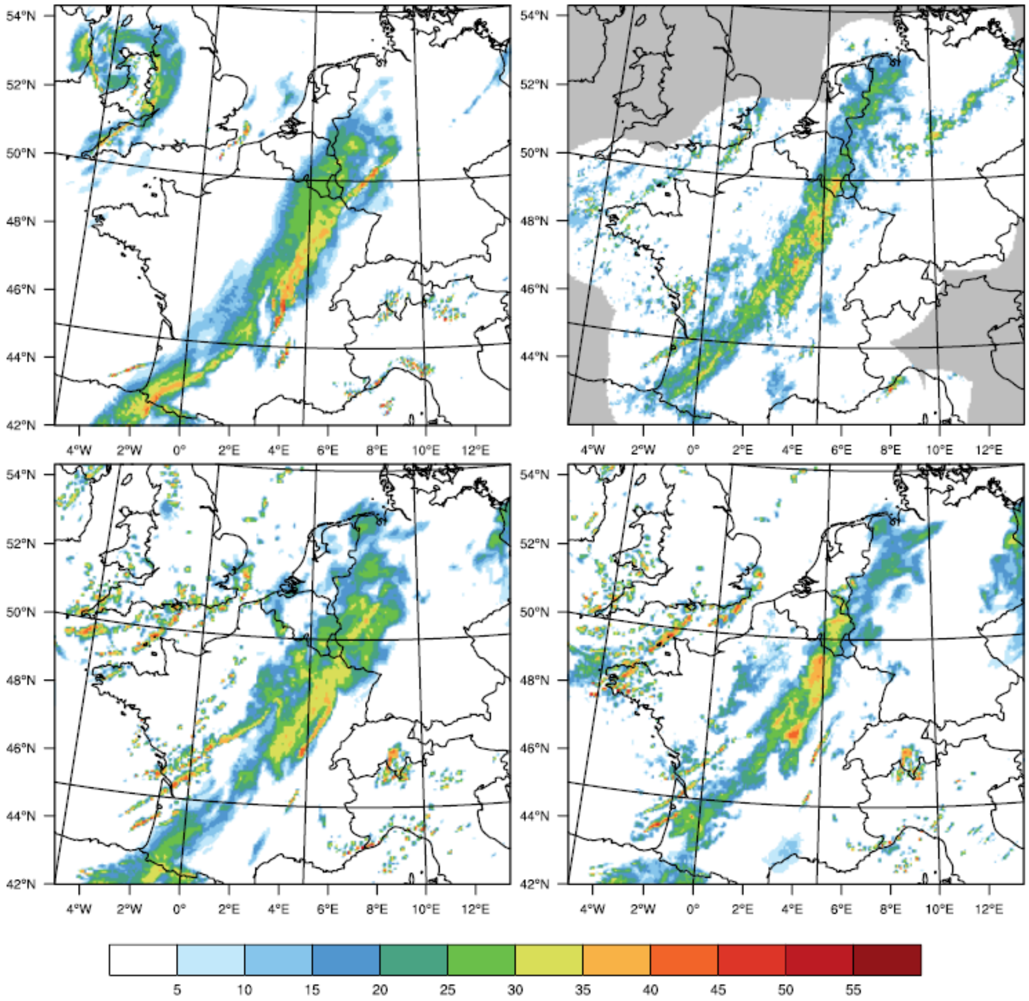

Figure 11: Reflectivity (dBZ) of a WRF simulation only driven by the ECMWF analysis (top left), the merged reflectivity composite of Météo France and DWD (top right) (areas not covered by radar in grey), a simulation assimilating everything apart from radar data (bottom left) and the simulation where all data including radar was assimilated (bottom right) for 02 UTC, 26 September 2012.

The comparison shows that the downscaling from ECMWF reproduces the synoptic situation reasonably represented. However, the cold front is broader than seen by the radar and it moved too fast so that the location of the front is too far to the east. Furthermore, the development of convection to the rear of the cold front is not simulated. Inclusion of data assimilation further broadens the front. However, the convection behind the front is now better simulated. The representation is further improved with the assimilation of radar data (reflectivity as well as radial velocity). The front is sharper and positioned correctly. Even single convective elements are located correctly. A drawback of the current methodology is that convection seems to be overstressed by the assimilation. Several reasons are possible and will be investigated with sensitivity studies in the future to further optimize the QPE system.

At the same time, the model-based approach is compared with current observation-based methods for the same case. Figure 12 shows an example for the same time compared above. The results also indicate the importance of radar data assimilation. However, the model-based QPE cannot yet compete with observation-based approaches. The reason can be manifold. Optimization of the WRF-QPE system will be continued in the future.

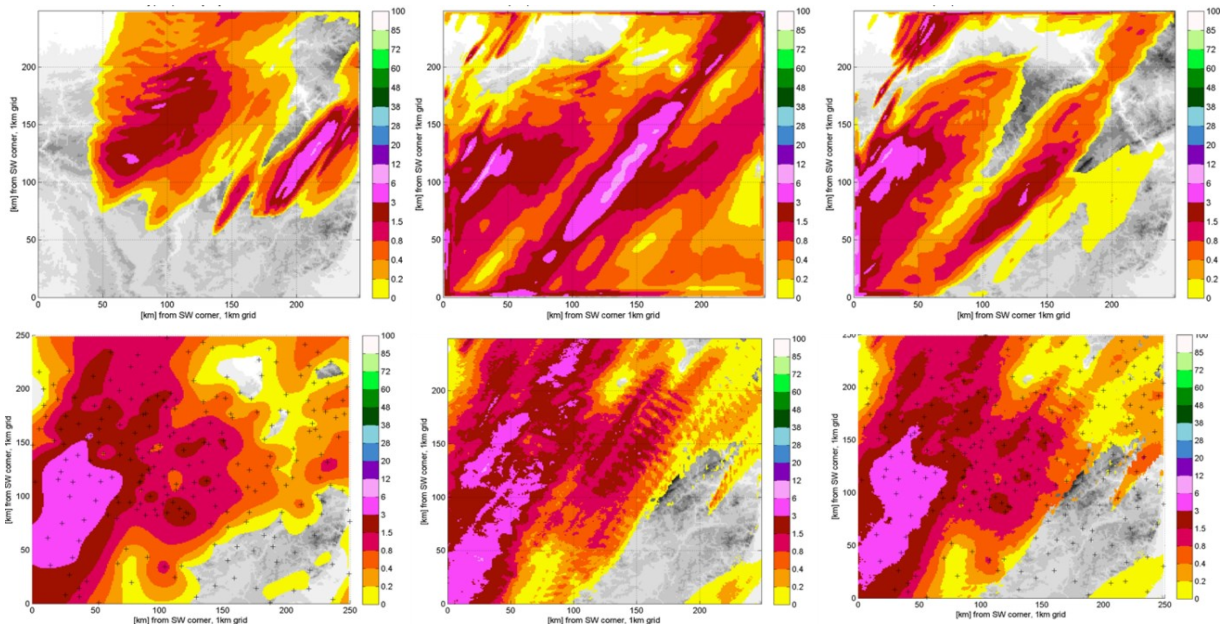

Figure 12: Hourly accumulated precipitation at 02 UTC, 26th September 2012 from different model-based (top row) and observation-based QPE approaches (Bottom row). Top row: Left: Simulation without data assimilation; Middle: Assimilation of all observations available apart from radar; Right: All observations assimilated. Bottom row: Left: Spatial interpolation (Kriging); Middle: Radar; Right: Merging of Kriging and radar.

To further improve the capability for process investigations and optimize the possibility to compare the model data with the various field data collected in the Attert catchment, the model setup was extended to even higher resolutions down to 100 m. This was done with the inclusion of two more nests into the model setup illustrated in Figure 3. To simulate with such fine resolution, WRF can be operated in a "Large-Eddy simulation mode" for simulations below 200 m grid increment. Here, the turbulence parameterization is switched-off and the majority of the energy transporting eddies are explicitly simulated. In addition parameterizations for the non-resolved sub-grid scale eddies are available.

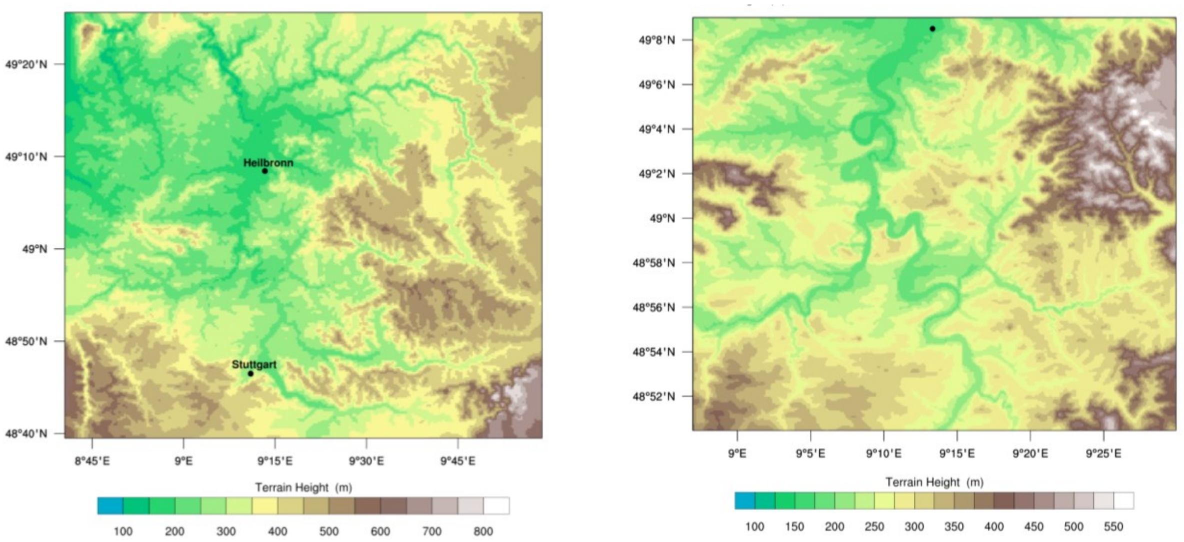

Figure 13: Orography of the two innermost model domains of the WRF-LES supercell simulation with 333 m (left) and 111 m horizontal resolution.

The extended system was applied for the supercell case as well as the CAOS case analyzed for QPE purposes above. Figure 13 shows the domain setup of the two innermost domains for the supercell case. Figure 14 shows exemplary results from the two simulations.

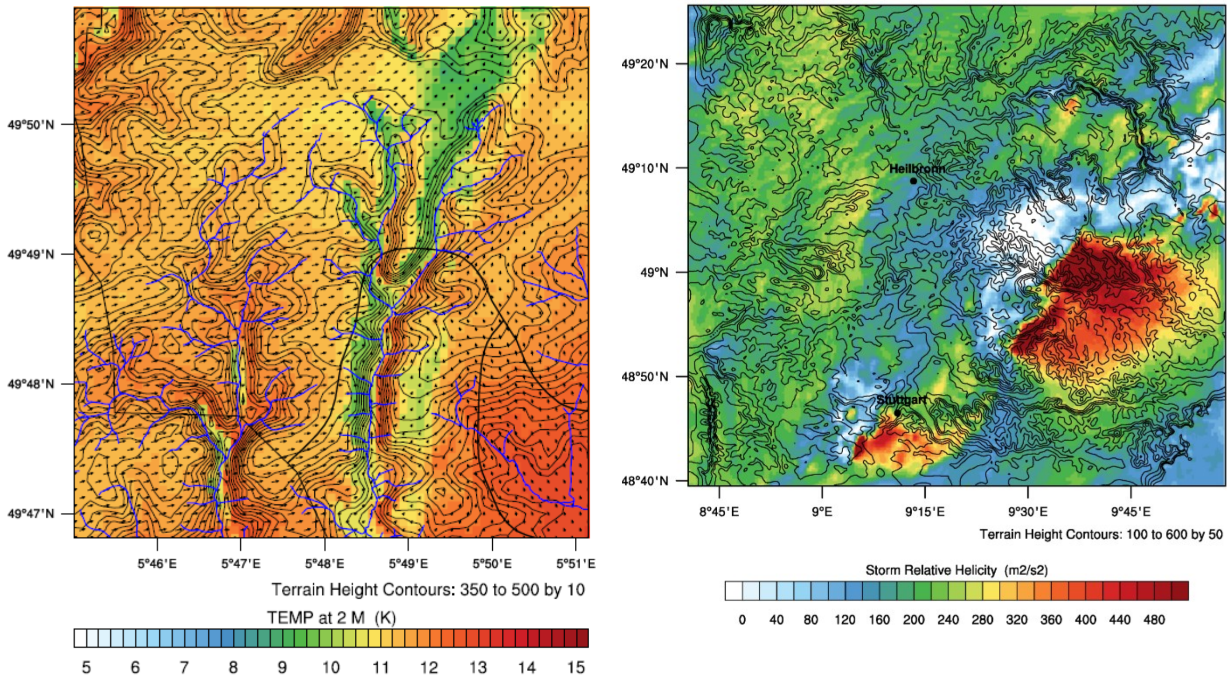

Figure 14: Left: 2 m temperature (°C) at 5 p.m. UTC, 26th September 2012 in a narrow valley of the northern part of the Attert catchment. Right: Storm Relative Helicity (m^2/s^2) in the region of the supercell at 3:30 p.m. (UTC), 30th June 2012.

The simulations clearly demonstrate the benefits of the high resolution for detailed case study investigations. The temperature distribution in the narrow valley in the northern part of the Attert catchment is nicely represented. As expected, the sunny eastern slopes of the valley (sunset in the west) experience the higher temperatures. This is what one expects – but at coarser resolution the narrow valley is not reproduced and therefore these fine-scale details are not simulated. When looking at subsequent time steps even the flow of cold air down the valley can be tracked.

The right panel of Figure 14 shows the storm-relative helicity (SRH) in the 333 m simulation of the supercell case. SRH marks regions where rotation around a horizontal axis is transferred into rotation around a vertical axis. Values larger than 400 m^2/s^2 are typical for the warm air inflow region into a supercell. The white regions with almost no SRH mark the region of the rotating mesocyclone. The simulation therefore nicely reproduce the conceptual model of a supercell.

Finally, a convection-permitting 3 km simulation for the whole year 2012 was performed to provide high-resolution model forcing for subsequent models (e.g. hydrology) of other sub projects in the CAOS research group. Figure 15 shows the domain configuration and Figure 16 an exemplary result of the simulation.

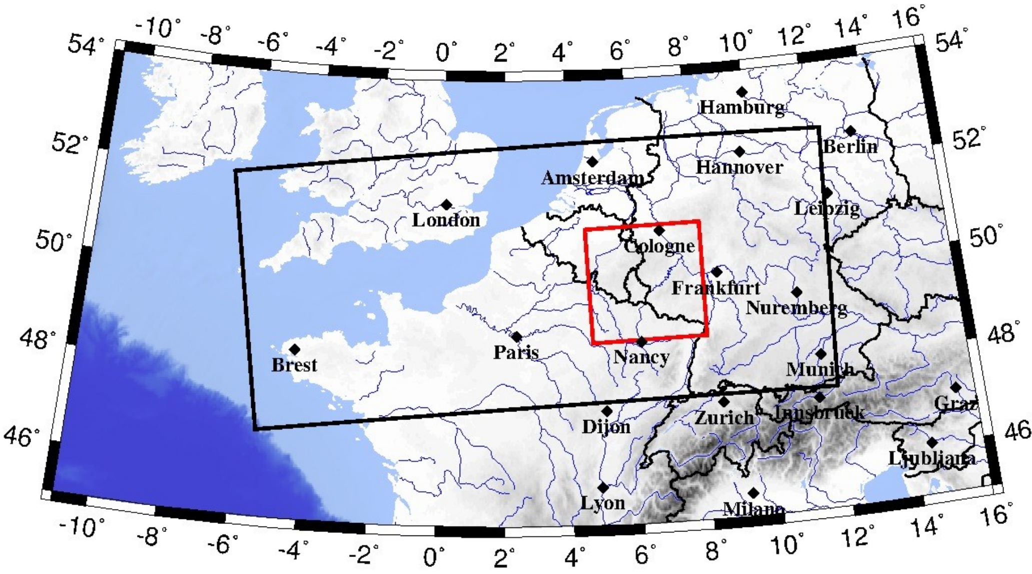

Figure 15: Domain configuration (black frame) for the 3 km annual WRF simulations within the CAOS project. The red frame marks the region in which selected variables are provided to other groups of the CAOS project.

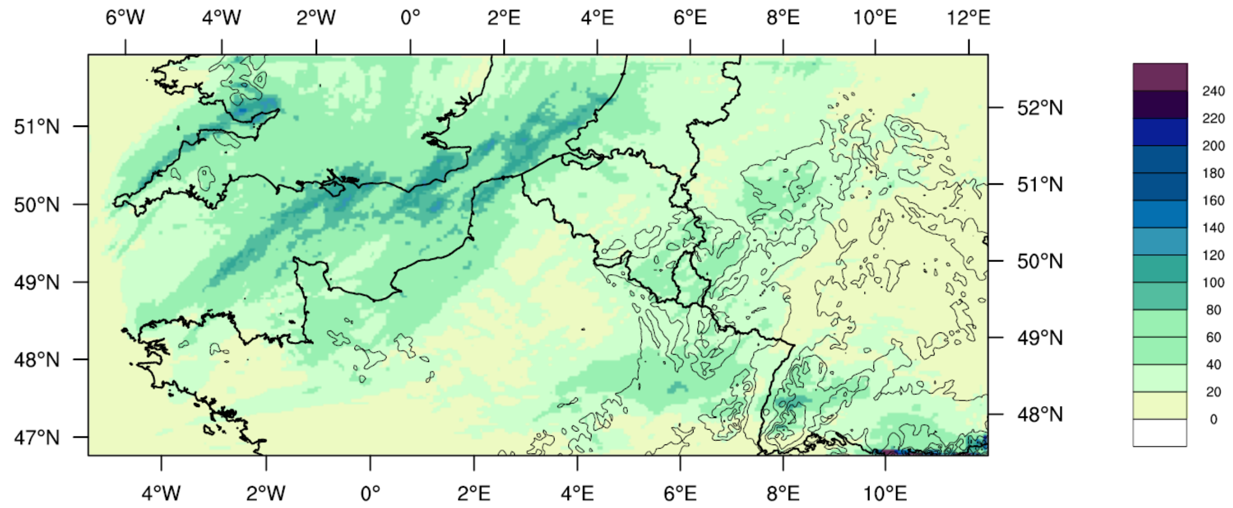

Figure 16: Monthly precipitation sum in September 2012 in the 3 km annual WRF simulation.

References

Bakhshaii, A., Y. Jung, T. Schwitalla, H.-S. Bauer, and V. Wulfmeyer, 2014: WRF dual polarized radar forward operator evaluation on a supercell event in Central Europe. The World Weather Open Science Conference, 16-21 August, 2014, Montreal, Canada.

Bauer, H.-S., T. Weusthoff, M. Dorninger, V. Wulfmeyer, T. Schwitalla, T. Gorgas, M. Arpagaus, and K. Warrach-Sagi, 2011: Predictive Skill of a Subset of the D-PHASE Multi-Model Ensemble in the COPS Region. COPS Special Issue of the *Q. J. R. Meteorol. Soc.* **137**, 287-305, DOI: 10.1002/qj.715.

Bauer, H.-S., T. Schwitalla, V. Wulfmeyer, A. Bakhshaii, U. Ehret, M. Neuper and O. Caumont, 2015: QPE based on high-resolution numerical weather prediction and data assimilation with WRF – a performance test, Tellus A, 67*, http://dx.doi.org/10.3402/tellusa.v67.25047*

Barker, D. M., Huang, X.-Y., Lui, Z., Auglіné, T., Zhang, Z. and co-authors. 2012. The weather research and forecasting model's variational/ensemble data assimilation system WRFDA. Bull. Am. Meteorol. Soc. 93(6), 831_843.

Grzeschik, M., H.-S. Bauer, and V. Wulfmeyer, 2008: Four-dimensional analysis of water-vapor Raman lidar data and their impact on mesoscale forecasts. *J. Atmos. Oceanic Tech.*, **25**, 1437-1453, DOI:10.1175/2007JTECHA974.1.

Huang, Xiang-Yu, and Coauthors, 2009: Four-dimensional variational data assimilation for WRF: formulation and preliminary results. *Mon. Wea. Rev.,* **137**, 299–314. doi: 10.1175/2008MWR2577.1.

Kawabata, T., H. Seko, K. Saito, 2007: An assimilation and forecasting experiment of the Nerima heavy rainfall with a cloud-resolving nonhydrostatic 4-dimensional variational data assimilation system. *J. Meoteorol. Soc. Japan*, **85**, 255-276.

Kawabata, T., T. Kuroda, H. Seko, and K. Saito, 2011: A cloud resolving 4DVAR assimilation experiment for a local heavy rainfall experiment in the Tokyo metropolitan area. *Mon. Wea. Rev.* **139**, 1911-1931.

Morrison, H., Thompson, G. and Tatarskii, V. 2009. Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: comparison of one- and two-moment schemes. Mon. Weather Rev. 137, 991_1007.

Schwitalla, T., G. Zängl, H.-S. Bauer, and V. Wulfmeyer, 2008: Systematic errors of QPF in low-mountain regions. Special Issue on Quantitative Precipitation Forecasting, *Met. Z.*, **17**, 903-919, DOI: 10.1127/0941-2948/2008/0338.

Schwitalla, T., H.-S. Bauer, V. Wulfmeyer, and F. Aoshima, 2011: High-resolution simulation over central Europe: Assimilation experiments with WRF 3DVAR during COPS IOP9c*. Q. J. R. Meteorol. Soc.* **137**, 156-175, DOI:10.1002/qj.721.

Schwitalla, T. and Wulfmeyer, V. 2014. Radar data assimilation experiments using the IPM WRF rapid update cycle. Meteorol. Zeitschrift. 23, 79_102. DOI: 10.1127/0941-2948/2014/0513.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X-Y. Huang, W. Wang and J. G. Powers, 2008: A Description of the Advanced Research WRF Version 3, *NCAR Technical Note*, **NCAR/TN–475+STR**, 123 pp. Available on-line at: http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf

Wang, X., D. A. Barker, C. Snyder, and T. A. Hamill, 2008a: A hybrid ETKF-3DVAR data assimilation scheme for the WRF model. Part I: Observing system simulation experiment. *Mon. Wea. Rev.* **136**, 5116-5131.

Wang, X., D. A. Barker, C. Snyder, and T. A. Hamill, 2008b: A hybrid ETKF-3DVAR data assimilation scheme for the WRF model. Part II: Real observation experiments. *Mon. Wea. Rev.* **136**, 5132-5147.

Weusthoff, T., Ament, F. Arpagaus, M. and Rotach, M.W., 2010: Assessing the benefits of convection permitting models by Neighborhood Verification - examples from MAP D-PHASE. *Mon. Wea. Rev. 138, 3418-3433,* DOI: 10.1175/2010MWR3380.1

WMO, 2010: Strategic Plan for Implementation of WMOs World Weather Research Programme 2009-2017, World Meteorological Organization: Geneva, Switzerland: Available at: http://www.wmo.int/pages/prog/arep/wwrp/new/documentsfinal_WWRP_SP_6_Oct.pdf

Wulfmeyer, V., H.-S. Bauer, M. Grzeschik, A. Behrendt, F. Vandenberghe, E. V. Browell, S. Ismail, and R. Ferrare, 2006: four-dimensional variational assimilation of water vapor differential absorption lidar data. The first case study within IHOP 2002. *Mon. Wea. Rev.*, **134** (1), 209-230, DOI: 10.1175/MWR3070.1.

Wulfmeyer, V., A. Behrendt, Ch. Kottmeier, U. Corsmeier, C. Barthlott, G.C. Craig, M. Hagen, D. Althausen, F. Aoshima, M. Arpagaus, H.-S. Bauer, L. Bennett, A. Blyth, C. Brandau, C. Champollion, S. Crewell, G. Dick, P. Di Girolamo, M. Dorninger, Y. Dufournet, R. Eigenmann, R. Engelmann, C. Flamant, T. Foken, T. Gorgas, M. Grzeschik, J. Handwerker, C. Hauck, H. Höller, W. Junkermann, N. Kalthoff, C. Kiemle, S. Klink, M. König, L. Krauss, C.N. Long, F. Madonna, S. Mobbs, B. Neininger, S. Pal, G. Peters, G. Pigeon, E. Richard, M.W. Rotach, H. Russchenberg, T. Schwitalla, V. Smith, R. Steinacker, J. Trentmann, D.D. Turner, J. van Baelen, S. Vogt, H. Volkert, T. Weckwerth, H. Wernli, A. Wieser, M. Wirth, 2011: The Convective and Orographically Induced Precipitation Study (COPS): The Scientific Strategy, the Field Phase, and First Highlights. COPS Special Issue of the *Q. J. R. Meteorol. Soc*. **137**, 3-30, DOI:10.1002/qj.752.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. Meteor. Atmos. Physics, 82, 139-170

Zus, F., M. Grzeschik, H.-S. Bauer, and V. Wulfmeyer, 2008: Design and optimization of the IPM GPS slant path 4DVAR system. Special Issue on Quantitative Precipitation Forecasting, *Met. Z.*, **17**, 867-885.