Initial phase of the Hans-Ertel Centre for Weather Research – A virtual centre at the interface of basic and applied weather and climate research

Martin Weissmann[1,2,*], Martin Göber[1,3], Cathy Hohenegger[1,4], Tijana Janjic[1,3], Jan Keller[1,3], Christian Ohlwein[1,5], Axel Seifert[1,3], Silke Trömel[1,5], Thorsten Ulbrich[1,6], Kathrin Wapler[1,3], Christoph Bollmeyer[1,5], Hartwig Deneke[7]

[1]Hans-Ertel Centre for Weather Research, Germany

[2]Meteorologisches Institut, Ludwig-Maximilians-Universität München, Germany

[3]Deutscher Wetterdienst, Offenbach, Germany

[4]Max-Planck-Institut für Meteorologie, Hamburg, Germany

[5]Meteorologisches Institut, Universität Bonn, Germany

[6]Institut für Meteorologie, Freie Universität Berlin, Germany

[7]Leibnitz-Institut für Troposphärenforschung, Leipzig, Germany

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*Corresponding author: Martin Weissmann, LMU-Meteorologie, Theresienstr. 37, D-80333 München, Germany. E-mail: martin.weissmann@lmu.de

Abstract

The Hans-Ertel Centre for Weather Research is a network of German universities, research institutes and the German Weather Service (Deutscher Wetterdienst, DWD). It has been established to trigger and intensify basic research and education on weather forecasting and climate monitoring. The performed research ranges from nowcasting and short-term weather forecasting to convective-scale data assimilation, the development of parameterizations for numerical weather prediction models, climate monitoring and the communication and use of forecast information.

Scientific findings from the network contribute to better understanding of the life-cycle of shallow and deep convection, representation of uncertainty in ensemble systems, effects of unresolved variability, regional climate variability, perception of forecasts and vulnerability of society. Concrete developments within the research network include dual observation-microphysics composites, satellite forward operators, tools to estimate observation impact, cloud and precipitation system tracking algorithms, large-eddy-simulations, a regional reanalysis and a probabilistic forecast test product.

Within three years, the network has triggered a number of activities that include the training and education of young scientists besides the centre's core objective of complementing DWD's internal research with relevant basic research at universities and research institutes. The long term goal is to develop a self-sustaining research network that continues the close collaboration with DWD and the national and international research community.

1 Introduction

The increasing vulnerability of society to weather and natural disasters emphasizes the need for improved forecasts and warnings (IPCC, 2012). In addition, weather forecasts become increasingly important for economic applications, e.g. for predicting renewable energy production and energy demand. Climate change and its impact on local weather pose further risks to society and economy. The Hans-Ertel Centre for Weather Research (German: Hans-Ertel Zentrum für Wetterforschung[1], abbreviated as HErZ) initiated by Deutscher Wetterdienst (DWD) and its scientific advisory committee intends to trigger and intensify basic research in Germany that will, over the next decade, lead to an improved ability to predict weather- and climate-related risks and to improved warnings and communication of these predictions. In a round-table discussion in 2007 that included most major German meteorological research institutions, five key research areas for the further advancement of modelling, monitoring and forecasting systems were identified:

- Atmospheric dynamics and predictability;
- Data Assimilation;
- Model development;
- Climate monitoring and diagnostics;

[1] http://www.dwd.de/ertel-zentrum

- Optimal use of information from weather forecasting and climate monitoring for society.

In the first out of three four-year phases, these topics are addressed by five branches of HErZ (table 1), which together form a virtual centre for weather and climate research. This article presents the research objectives and scientific highlights of the current implementation of HErZ after the first three years since the centre was established in the beginning of 2011.

Research in the five scientific areas of HErZ has a long history. More than 100 years after Vilhelm Bjerknes first proposed the idea of a mathematical model of the atmosphere's dynamics (BJERKNES, 1904; GRAMELSBERGER, 2009) and after more than 60 years of numerical weather prediction (NWP), our ability to model the atmosphere has improved drastically (BENGTSSON, 2001; EDWARDS, 2010). However, fundamental advancement in our modelling capabilities requires time-scales of decades and therefore long-term and coordinated funding strategies. Significant shortcomings still exist, particularly in our ability to accurately predict specific regional weather events (e.g. severe convective systems) and the regional impact of climate change. Recent major German research activities addressed the first of these topics, particularly precipitation forecasts, predictability and atmospheric dynamics. These activities include the Priority Program Quantitative Precipitation Forecast (HENSE and WULFMEYER, 2008), the field campaign Convective and Orographically Induced Precipitation Study (COPS, WULFMEYER et al., 2008) and the research group PANDOWAE[2] (Predictability ANd Dynamics Of Weather Systems in the Atlantic-European Sector). HErZ builds upon expertise gained in these recent activities, but has a broader focus that inter alia also includes climate research and forecasts communication.

Overall, the development of NWP systems is challenging for many reasons: The complexity to combine observations with a model state for creating initial conditions, the requirement to include all relevant processes and phenomena, poor knowledge on several of these processes and technical limitations that prohibit the explicit representation of processes. Development of NWP systems may therefore be best achieved in a collaborative effort between the academic community and operational centres (JAKOB, 2010). In the United Kingdom, the Joint Centre for Mesoscale Meteorology which consists of staff from the University of Reading and the Met Office exhibits an example of the fruitful collaboration between academia and a weather service. HErZ addresses this need in Germany and aims at closing the gap between the academic community and DWD. It strengthens collaboration between universities, research institutes and DWD and complements more applied internal research at DWD with basic research at university and non-university institutions.

The intended combination of basic research with user oriented foci in weather and climate research will be demonstrated by a broad selection of research examples obtained during the initial phase of HErZ. Section 2 explains the implementation of HErZ as a virtual centre and section 3 presents the objectives

[2] http://www.pandowae.de

of the current five branches of HErZ together with highlights of their scientific findings. A summary and outlook follows in section 4.

2 Implementation of the virtual centre

HErZ currently consists of five branches which each have a size of about 5-6 positions (full-time equivalent) including two branch leaders, one from the host institution and one from DWD. Most branches complemented the funding provided by HErZ through the acquisition of other related research projects. The branches are located at one or multiple host institutions (table 1). Regular workshops and joint events ensure the interaction of different branches.

A key feature of HErZ is the close interaction between a national weather service and basic research at universities and research institutes. This makes the access to DWD facilities, data, products and end users much easier than in other projects and shall ensure that the findings and developments of HErZ feed into the operational modelling and forecasting chain of DWD in the longer term.

A further special feature for a research project is HErZ's dedication to the education and training of young scientists. One component is special training courses (summer or winter schools) that are also open to non-HErZ scientists. Past training courses covered large-eddy-simulations, data assimilation, remote sensing and forecast verification. In addition, all branches established special university courses on weather and climate-related topics that were previously underrepresented in the university curriculum. The integration of undergraduate and graduate students is also an important educational component.

German research is funded by two approaches, programmatic funding for applied research leading to specific developments (e.g. the base funding of DWD or research institutes) and funding for basic research in any research area (e.g. provided by the German Science Foundation DFG, see Volkert and Achermann (2012)). HErZ exhibits an intermediate approach for basic research that is geared towards long-term improvements of DWD systems.

3 The branches of HErZ: Goals and highlights

This section describes the research objectives of the current five branches of HErZ and provides highlights of their scientific results from phase 1. Each branch targets a different aspect of weather or climate research, but the branches share common foci as for example regional high-resolution (km-scale) modelling, the model representation of clouds and convection or probabilistic forecasting approaches.

3.1 Atmospheric Dynamics and Predictability

HErZ-OASE (Object-based Analysis and SEamless prediction) approaches seamless prediction of convective events from nowcasting to short-range forecasting by merging observation-based projections and NWP. The approach resides on and exploits a multi-sensor-based dual observations/microphysics 4D-composite based on ground and satellite-based active and passive sensors. An object-based approach to the composite allows for monitoring, characterization and an improved understanding of the dynamics and life cycles of convective events. Objects are identified and tracked in time by a multivariate 3D scale space algorithm. The resulting data provides the core information for observation-based nowcasting and NWP model initialisation and allows for its merging. A climatological exploitation of the data set shall elucidate the dynamics of convective events and lead to improved knowledge on predictability limits including their dependence on atmospheric conditions.

3.1.1 Synergistic use of multi-sensor data and its application

The national 3D composite area currently contains weather radar, geostationary satellite, and lightning detection network observations a common grid at a 5 min temporal resolution. Perfect model experiments are used to quantify the accuracy of radar and satellite products as well as their information content for nowcasting and data assimilation (SENF et al., 2012). The current 2D version contains the RADOLAN RX data from DWD’s weather radar network, METEOSAT SEVIRI observations and cloud products, as well as lightning frequencies from the LINET network (BETZ et al., 2009). A merging scheme projects dual radar observations onto a 3D polar-stereographic grid, compensates for observational errors (e.g. attenuation) and mitigates advection displacements caused by the 5-min volume scan intervals. The 3D high-resolution composite over the Bonn-Jülich area contains besides horizontal and vertical radar reflectivity Z_H and $Z_{V,}$ the differential reflectivity Z_{DR}, specific differential phase K_{DP}, co-polar correlation coefficient ρ_{HV}, quality indicators, minimum detectable Z_H threshold and surface rain rate (RYZHKOV et al., 2013). Physical downscaling is applied to enhance SEVIRI's standard 3x3 km^2 resolution to 1x1 km^2 (DENEKE and ROEBELING, 2010; BLEY and DENEKE, 2013). A multivariate 3D scale-space tracking algorithm based on the mean-shift method (COMANICIU and MEER, 2002) is applied to the composite and will evolve into a novel nowcasting framework. Its nowcasting skill is expected to outperform approaches residing on single data sources (WAPLER et al., 2012) and to increase the nowcasting horizon (SIEWERT et al., 2010; DIETZSCH, 2012). The data set allows also for a detailed regime-dependent analysis of the spatial and temporal occurrence of thunderstorms (WAPLER, 2013; WAPLER and JAMES, 2014) and reveals conditions and highlights regions favourable for thunderstorm development.

3.1.2 Object-based approach to weather analysis

Seam-less prediction is approached by the inclusion of process information in nowcasting and by assimilation of a highly-resolved radar data (MILAN et al, 2014). The Local Ensemble Transform Kalman Filter (LETKF; HUNT et al., 2007) within the experimental KENDA (KM-scale ENsemble-based Data Assimilation; REICH et al., 2011) system for the COSMO (Consortium for Small-scale MOdeling) model is applied to investigate the impact of radar observations on the representation of convective systems.

Current nowcasting strategies mostly follow advection-based strategies. Their major limitation is the disregard of life-cycle effects and the inability to consider emerging cells. Within HErZ-OASE an object-based analysis condenses the time-space distribution of observables and related microphysics into process-oriented descriptors, which may serve as proxies of the precipitation process and describe macrophysical structures and microphysical processes as the trend in brightband intensity or the efficiency of the raining system (e.g. TRÖMEL et al., 2009; Rosenfeld et al., 1990). These can be easily exploited in nowcasting methods. E.g. a reversal of the cloud-droplet effective radius (R_{eff}) tendency concurrent with increasing cloud optical thickness (COT) and liquid / ice water path (LWP, IWP) precedes thunderstorm intensification and lightning activity (HORVÁTH et al., 2012). KONRAD-derived (*KONvektionsentwicklung in RADarprodukten*, convection evolution in radar products) cell tracks during summer 2011 show a strong correlation between COT, LWP, IWP and total lightning during both the growing and the decaying phase of R_{eff}. Thus thicker, wetter clouds produce more lightning (Fig. 1a, c and d). The relationship between R_{eff} and total lightning, however, is more complex. Total lightning shows a strong increase after the trend reversal in R_{eff} (Fig. 1b and d). Some theories postulate an increase in lightning activity when large ice particles aloft precipitate in the lower mixed-phase cloud region, which is consistent with the observed negative correlation between flash count and cloud-top R_{eff} and the observed mean time difference between the peaks in lightning and R_{eff}. For stronger storms, peak lightning activity increasingly lags peak R_{eff} by up to 25-30 min for the most intense storms. The observed lags presumably correspond to the time required for large cloud-top ice particles to fall and intensify charge separation. Analyses of convective cells captured with the polarimetric X-band radar in Bonn (BoXPol) after the R_{eff}-maximum confirm the occurrence of graupel and support the hypothesis that the trend reversal in R_{eff} indicates the onset of the charge separation. Graupel is associated with high reflectivities Z_H and diminishing differential reflectivity Z_{DR} (Fig.2). The hydrometeor classification scheme (ZRNIĆ et al., 2001) confirms the presence of graupel in the mid and lower cloud region and smaller ice particles aloft. In agreement with the 3-body scattering signature visible in Fig. 2, a region with large hail particles has been identified. The signature appears as a radially oriented spike of weak Z_H protruding from the far side (relative to the radar) of the storm and a band of extremely large Z_{DR} values.

The comparison of object evolutions in observations and models can be applied for model evaluation, because deviations may hint at processes not adequately simulated (e.g. TRÖMEL and SIMMER, 2012). Polarimetry is expected to be particularly beneficial for the evaluation of microphysical processes. A prominent example is the backscatter differential phase δ, which is an indicator for the dominant size of rain drops or wet snowflakes. Its consideration allows for a better characterization of the brightband and can be utilized for improving microphysical models (TRÖMEL et al., 2013a, 2013b). Another example is the derivation of synthetic cloud products from model forecasts. The frequency and size of convective cells derived by the NWC SAF Rapidly Developing Thunderstorm product for observations and COSMO forecasts can be used as metric for the model's ability to simulate appropriate cell types (REMPEL, 2013).

3.2 Data Assimilation

Compared to global scales, research for convective-scale (km-resolution) data assimilation is at a much less mature stage and it remains to be answered which methods can cope with the strong non-linearities typically encountered on this scale while meeting the demands for computational efficiency and frequent analysis updates. Ensemble methods are seen as a promising approach to address the limited predictability of small-scale systems (e.g. convection), but knowledge is particularly missing on the appropriate representation of model error, the choice of specific observations for these scales and the best way to assimilate them. Satellite instruments nowadays provide a vast amount of information on the atmospheric state, but only a very small fraction is used in current convective-scale assimilation systems. Based on these shortcomings, HErZ Data Assimilation (HErZ-DA) addresses four research topics: Data assimilation methodology for strongly non-linear dynamics, the online estimation of the impact of different observations, the representation of uncertainty in ensemble systems and the improved use of cloud-related satellite observations. The satellite part comprises efforts to assimilate visible (VIS) and near-infrared (NIR) satellite reflectance and the development of a height correction for cloud motion vectors based on satellite lidar observations.

3.2.1 Data assimilation methodology

Limited computational resources prohibit testing multiple data assimilation methods extensively in a full NWP system and traditional test models for global-scale data assimilation (e.g. LORENZ, 1995) are missing key features of predominant convective-scale processes. To address this, a hierarchy of idealized models that resemble convective-scale dynamics has been developed. This hierarchy is used to test data assimilation algorithms that were generally not designed for the non-linearity and non-Gaussian error structures encountered on these scales. At the lowest level of complexity, CRAIG and WÜRSCH (2013) introduced a simple stochastic 1D cloud model based on a spatial Poisson birth-death process. At the second level, WÜRSCH and CRAIG (2014) modified the shallow-water equations to introduce convection. This model represents conditional instability whenever the water level exceeds a certain threshold and includes the negative buoyancy effect of rainwater that limits the growth of convective clouds. For both models, three data assimilation algorithms, the LETKF, Sequential Importance Resampling (SIR; VAN LEEUWEN, 2009) and the Efficient Particle Filter (VAN LEEUWEN, 2011) are being tested.

At the third level, idealized perfect model experiments are performed using the experimental KENDA-COSMO system with 2 km grid spacing. These studies focus on radar assimilation and the preservation of physical properties following JANJIC et al. (2014). A model run with idealized initial conditions is taken as “truth” (referred to as nature run) and observations simulated from this nature run are used to investigate different settings or implementations of KENDA.

LANGE and CRAIG (2014) tested the assimilation of radar reflectivity and Doppler velocity in KENDA using a nature run initialized with one vertical sounding and small random perturbations to trigger convection. The major focus was the comparison of the following two setups: One producing initial conditions with high-resolution fine assimilation (FA) settings every 5 min and the other producing initial conditions with spatially coarse assimilation (CA) settings every 20 min. The fine assimilation converged closely to the observations whereas the coarse analysis was not able to resolve all storm details (compare Figs. 3a, b and c). However, due to the limited predictability of convective-scale dynamics and imbalances in the strongly forced fine assimilation, the forecasts initialized from fine initial conditions quickly lost their superiority and the errors of vertical velocity were similar for both experiments after 1-2 h lead time (Fig. 3d).

3.2.2 Observation impact

Knowledge about the contribution of different observations to the reduction of forecast errors (referred to as observation impact) is crucial for both the refinement of observing as well as data assimilation systems. However, the direct calculation through numerical data denial experiments (i.e. parallel experiments) is only feasible for specific applications and data sets due to computational expenses. Therefore, a computationally inexpensive ensemble-based method for estimating observation impact following KALNAY et al. (2012) has been implemented in KENDA-COSMO (SOMMER and WEISSMANN, 2014).

Figs. 4a and b exemplarily illustrate the (positive and negative, respectively) impact values of all observations in one particular assimilation cycle. Consistent with previous studies using adjoint estimation methods (e.g. WEISSMANN et al., 2012), only slightly over 50% of the observations (on average 54%) contribute to an improved forecast due to the statistical nature of observation impact.

The ensemble impact estimation has been systematically tested by comparison to data denial experiments that exclude particular observation types (SOMMER and WEISSMANN, 2014). Fig. 4c shows the estimated radiosondes impact and their impact in data denial experiments. Overall, the method is able to reproduce the general behaviour of the impact despite deviations for individual analysis cycles. Averaged over all observations during nine analysis cycles, the relative deviation between the estimated and the data denial impact is about 10% for different observation types. In addition, the differences were shown to be statistically not significant.

3.2.3 Representation of uncertainty

This part of HErZ-DA intends to improve the representation of uncertainty in ensemble systems. A first study examined the relative contribution of different perturbations in the current regional COSMO ensemble prediction system of DWD (KÜHNLEIN et al., 2014). The impact of initial condition perturbations that are downscaled from a global multi-model ensemble was largest in the first six forecast hours. Thereafter, lateral boundary condition and physical parameter perturbations become more important. The impact of parameter perturbations is particularly important during weak large-scale forcing of precipitation (KEIL et al., 2014). Ensemble assimilation systems as KENDA directly provide an estimate of initial condition uncertainty. Ongoing studies investigate the structure and growth of KENDA perturbations and test different methods to account for model errors, e.g. relaxation to prior spread and a stochastic boundary layer scheme.

3.2.4 Satellite cloud observations

Traditionally, VIS and NIR satellite channels have been neglected for data assimilation due to the lack of suitable fast observation. Given that convective systems are much earlier discernible through their cloud signal than through radar observations of precipitation, these cloud-related observations are seen to be particularly valuable for convective-scale modelling. HErZ-DA has developed a suitable operator for assimilating VIS and NIR satellite reflectance in KENDA (KOSTKA et al., 2014) and the assessment of their impact in KENDA is ongoing. In addition, research in HErZ-DA uses CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) information to correct the height assignment of cloud motion vectors. A method has been developed to directly correct motion vectors heights with nearby lidar cloud top observations, at first in an experimental framework with airborne observations during a field campaign (WEISSMANN et al., 2013) and subsequently using CALIPSO observations (FOLGER and WEISSMANN, 2014). The developed lidar correction leads to a significant reduction of motion vector wind errors by 12-17%. Further studies will assess the benefit of such a correction for data assimilation, both by directly assimilating height-corrected motion vectors and through the development of situation-dependent correction functions.

3.3 Model Development

The overall aim of the HErZ Clouds and Convection (HErZ-CC) branch is to better understand the physical processes that control the lifecycle of clouds and convection and to use this understanding to improve their representations in NWP models. Clouds are a decisive part of NWP and climate models. They interconnect the land surface, planetary boundary layer and the deeper atmosphere and allow for a range of complex scale interactions. As some of these processes can be explicitly represented whereas other ones have to be parameterized, the treatment of clouds, even in high-resolution weather forecasts, essentially remains an unsolved problem. Most existing parameterizations make either explicitly or implicitly assumptions about scale-separation, convective quasi-equilibrium and sub-grid homogeneity which are becoming a road block for further improvements of NWP and climate models.

3.3.1 Large-eddy simulations (LESs)

Improving parameterizations requires better understanding of the processes at work as parameterizations encapsulate an idealization of our understanding. Today supercomputers make it possible to perform LESs with grid spacings of some 10-100 m on mesoscale domains over periods of several days. Such simulations provide the data to develop and test new parameterization hypotheses and they may also be used to estimate necessary parameters or functions. Process studies with LESs constitute the first line of research in HErZ-

CC. It is here to emphasize that the best use of LESs is in improving our understanding of the processes and their interactions, not in reproducing reality.

Figure 5 shows the result of such an LES of precipitating shallow cumulus clouds on a domain of 50^2 km^2 with an isotropic grid spacing of 25 m. Such a setup is able to resolve the larger turbulent eddies in the boundary layer, the internal circulations of the clouds as well as the mesoscale flow which leads to the self-organization of the cloud field (SEIFERT and HEUS, 2013). Figure 5 shows the simulated albedo of a cumulus field with the typical cloud patterns as observed in the trade wind zones. These are the cloud streets that are due to along-wind oriented boundary layer rolls, the so-called mesoscale arcs, regions of deeper congestus-type clouds which may reach 4-6 km cloud top height and can produce locally intense precipitation and cloud-free areas in between. The LES data and additional sensitivity studies suggest that the main cause of the organization are cold pools originating from the most intense rain events. However, the cold pools are relatively weak and short lived, i.e. the mesoscale patterns do not so much establish themselves in the temperature field, but only in the moisture field itself. Hence, modelling the structure and statistics of the sub-cloud layer moisture field as it evolves due to the effects of precipitation is key for a parameterization which aims at representing the effect of cloud organization.

The cloud microphysics and radiation scheme of the LES model have also been extended to allow the simulation of deep convection (HOHENEGGER and STEVENS, 2013; SCHLEMMER and HOHENEGGER, 2014) and a simple land surface model (RIECK et al., 2014) has been introduced. This enables the investigation of the full diurnal cycle of convection, from shallow to deep, including the interaction with the land surface.

3.3.2 Understanding and parameterizing the cloud size distribution

The cloud size distribution (CSD) constitutes the second line of research in HErZ-CC. By providing explicit information about the size of all clouds, the goal is to derive parameterizations that are appropriate for a given mesh size and are at the same time able to provide information about sub-grid variability. It is worth noting that the original proposal of the mass flux convection scheme by ARAKAWA and SCHUBERT (1974) included the explicit prediction of different cloud sizes, i.e. a cloud size distribution. This concept has later been largely abandoned and replaced by the simpler bulk mass flux scheme (TIEDTKE, 1989; PLANT, 2010). Including explicit assumptions about the size, life time and life cycle of convective clouds may also be a necessary pre-requisite for a consistent treatment of cloud microphysics and rain formation. For example, SEIFERT and STEVENS (2010) suggested that the use of dynamical and microphysical timescales may be a viable and promising alternative to the current formulation of microphysical parameterizations within convection schemes.

Having large-eddy simulations for several cloud regimes makes it possible to improve our understanding of small-scale variability and hence, to formulate improved parameterizations. Based on such data, NAUMANN et al. (2013) derived a refined cloud closure, which has now been handled over to DWD for practical implementation and testing. Another major effort has been the development of a cloud tracking algorithm which is able to handle extensive datasets and at the same time includes a physically-based definition of cloud objects (HEUS and SEIFERT, 2013). The clustering of clouds, which becomes especially pronounced in the presence of precipitation, requires splitting clouds into dynamically meaningful entities which is done based on the buoyant cloud cores. Using cloud tracking, a power law size distribution for the instantaneous shallow cumulus cloud field is found as it is also found based on satellite observations. At the same time, LES data provide detailed information on the cloud lifetime and cloud life-cycle which is necessary for the formulation of a stochastic cloud scheme, e.g. following PLANT and CRAIG (2008).

Changes in the CSD as the clouds transition to deep convection or due to heterogeneous surface conditions have also been investigated. In general, it is thought that a widening of the clouds as the diurnal cycle proceeds constitutes one of the necessary ingredients for transition to deep convection (e.g. KHAIROUTDINOV and RANDALL 2006; KUANG and BRETHERTON 2006). Understanding mechanisms that influence the size of the largest clouds is therefore crucial. As soon as clouds begin to precipitate, the formation of cold pools shifts the CSD to larger scales and promotes the transition to deep convection (SCHLEMMER and HOHENEGGER, 2014). Figure 6 shows a snapshot of a cloud field transitioning to deep convection. New clouds form on the rim of the cold pools (visible as circular dry areas in Fig. 6), where moisture has been accumulated. The size of the largest clouds seems to correlate with the size of these moist patches. Likewise, surface heterogeneities can affect the formation of larger clouds (RIECK et al., 2014). Except for such changes in the scale break (i.e. largest clouds), the CSD remains remarkably similar over homogeneous and heterogeneous surfaces. Accurately representing the effects of cold pools and surface heterogeneity in convective parameterizations is thus important to capture a correct timing of the development of convection. The transition time from shallow to deep convection was for instance reduced by half in a simulation performed over a heterogeneous surface with a heterogeneity length scale of 12.8 km. Such effects are unlikely to be correctly represented, even in cloud-resolving NWP models and may explain a delayed onset of precipitation in such models.

3.4 Climate Monitoring and Diagnostics

The overall aim of HErZ-Climate is to develop and improve methods for the self-consistent assessment and analysis of regional climate in Germany and Europe over the past decades at an appropriate spatial and temporal resolution. The central approach to this is the development and evaluation of a model-based, high-resolution regional reanalysis system which encompasses the synergetic use of heterogeneous monitoring networks while providing detailed diagnostics of the energy, water and momentum cycles of the reanalysed climate state.

In the scope of climate monitoring, reanalyses are becoming more and more important for the assessment of climate variability and climate change. The European Union Global Monitoring for Environment and Security (GMES) initiative has recently started funding for generating reanalyses and the verification of the corresponding data sets. These efforts are directed towards establishing climate services based on reanalyses. HErZ-Climate takes part in the EU-FP7 funded projects UERRA (Uncertainties in Ensembles of Regional Reanalysis) as well as CORE-CLIMAX in order to provide impetus for the continuous development, production and dissemination of regional reanalyses towards a climate services framework.

3.4.2 Criteria for regional reanalyses

Within the meteorological and climate community, the term reanalysis is commonly understood as the synthesis of past observations – heterogeneous in space and time – into a physical model using a state-of-the-art assimilation system. By freezing the model and data assimilation system, it avoids systematic variations that otherwise appear in operational NWP analyses. Such a model-based approach yields the advantage of generating 4D fields for a large number of atmospheric variables, which are physically consistent in space and time as well as between the parameters.

Gridded climate data products based on alternative approaches such as spatio-temporal interpolation methods do not meet these criteria. Commonly used atmospheric reanalyses include ERA-Interim (ECMWF Re-Analysis, DEE et al., 2011) and MERRA (Modern-Era Retrospective analysis for Research and Applications, RIENECKER et al., 2011) by the National Oceanic and Atmospheric Administration (NOAA). Such reanalyses facilitate a large observational data set, a global circulation model and a corresponding data assimilation scheme. The horizontal grid-spacing of global reanalyses is usually in the range of 70-125 km and the temporal resolution of the output normally coincides with the 6-h interval between two assimilation cycles, sometimes complemented by the output of 3-h forecasts. For a better representation of spatio-temporal variability including local extreme events, the regional enhancement of global reanalysis data has become an important task. An approach for the European region is presented in sections 3.4.3 and 3.4.4.

The added value of high-resolution regional reanalyses lies in the enhanced representation of spatio-temporal variability and extremes and, most importantly, in the spatio-temporal coherence with independent observations. SIMON et al. (2013) showed that regional dynamical downscaling methods generate variability in the inner-domain by itself, whereas data assimilation on regional scales suppresses this freely developing variability.

Such regional reanalysis systems provide a quality-controlled and homogenised data set for the detection and assessment of regional climate change in the past and the future, the statistical post-processing of operational forecasts, the analysis of systematic model errors of the respective regional model as well as the verification and calibration of climate impact models.

3.4.3 Regional reanalysis for the European CORDEX domain

HErZ-Climate generated a high-resolution regional reanalysis for the CORDEX EUR-11 domain (COordinated Regional Downscaling Experiment, cf. Fig. 7), but with an increased resolution of the horizontal grid to 0.055° (~6 km). The reanalysis consists of the DWD COSMO model and its nudging (or dynamical relaxation) assimilation system. The atmospheric analysis is complemented by a soil moisture, a sea surface temperature and a snow analysis module. In a first stream, reanalysis data have been produced for the period 2007-2011. The following part of this section provides findings from the comparison of COSMO-REA6 and ERA-Interim. A detailed analysis including various parameters can be found in BOLLMEYER et al. (2014).

At first, precipitation estimates of the two reanalyses against rain gauge observations over Germany have been evaluated. The difficulty when evaluating the quality of precipitation estimates is that it follows a non-Gaussian distribution and therefore standard scores such as bias or RMSE are inadequate. Therefore, histograms of 3-hourly precipitation over Germany were analysed in order to investigate the quality of precipitation reanalyses.

Histograms for the observations, COMSO-REA6 and ERA-Interim are presented in Figure 8. The diagrams show the frequency of occurrence for weak (upper panel) and heavy precipitation events (lower panel). For the frequent weak precipitation events, COSMO-REA6 performs well compared to observations while ERA-Interim shows an underestimation of event frequency for values below 0.1 mm and above 5 mm per 3 h. For values of 0.1-5 mm per 3 h, ERA-Interim overestimates the frequencies of events.

For the less frequent heavy precipitation events, the histogram bins are restricted to values above 20 mm per 3 h. COSMO-REA6 underestimates the frequencies of the observed precipitation, especially in the range of 20-30 mm. However, COSMO-REA6 still represents extreme precipitation events, with the frequency of occurrence being well-estimated for precipitation events of 50 mm and beyond. In contrast, ERA-Interim does not exhibit values that exceed 22 mm in 3 h at all. This is in accordance with the change of support as rain gauge observations are point measurements while reanalyses represent area-averaged values.

The results from the first stream of COSMO-REA6 underline the added value of high-resolution regional reanalyses as a tool to monitor regional climate. The increased resolution allows a better representation of surface parameters and meso-scale processes leading to an improved reproduction of local variability of the climate such as extreme events. Especially in the context of severe weather, the understanding of climate variability on these scales is becoming more and more important.

3.4.4 Towards a regional reanalysis on the convection-permitting scale

Currently, the production of a horizontally refined convection-permitting scale reanalysis is under way. With 2-km grid size for a domain covering Germany and adjacent areas (Fig. 7), the reanalysis COSMO-REA2 allows the direct representation of deep convection. The reanalysis is supported by a latent heat nudging (LHN) scheme which assimilates radar data to allow for a better representation of rainfall.

First results of COSMO-REA2 for summer 2011 indicate that the precipitation analysis is further improved, especially with regard to the diurnal cycle. Figure 9 shows the precipitation intensity for all 3-h intervals of the day for June, July and August 2011. In comparison to the observed precipitation, it can be observed that ERA-Interim does not represent the diurnal cycle with precipitation intensities remaining nearly constant throughout the day. In COSMO-REA6, a diurnal cycle is present with the correct amplitude but lagged by approximately 3 h while in COSMO-REA2 the diurnal cycle is reproduced nearly perfectly, thereby showing the benefits of a convection-permitting reanalysis.

3.5 Communication and Use of Forecasts and Warnings

At the end of the forecasting process, the value of forecasts is only accomplished if end users make better decisions, e.g. to mitigate the impact of hazardous weather. In order to be able to make optimal use of the information contained in the forecast, the users' vulnerability must be known and suitable mitigation measures must be available. Furthermore, forecasting products must be disseminated reliably, they must be understood and accepted. All these aspects of optimal forecast usage can only be investigated by a transdisciplinary approach including social sciences, relevant institutions and stakeholders.

Research on this final step of the forecasting process has been scarce in Germany, yet there have been some efforts in the United States and Australia (e.g. the "Weather And Society - Integrated Studies" (WAS-IS) initiative) or in the United Kingdom (ROULSTON et al., 2006) and the topic has been addressed in the World Weather Research Programme (WWRP) and the THORPEX programme of the World Meteorological Organization (WMO, 2004).

HErZ-Application investigates weather warnings and their perception and use by emergency managers and the public. The applied methods range from statistical modelling to surveys, direct observations of emergency managers and stakeholder interviews. The main focus in the initial phase of HErZ are warnings for wind storms and thunderstorms in Berlin. The goal is to improve the warning process and the communication of warnings and to develop recommendations for user-oriented information products. One overarching aspect is the treatment of uncertainty information.

3.5.1 Estimation and perception of uncertainty

Although weather warnings are uncertain, they are still delivered without an explicit indication of their weather-dependent uncertainty. To investigate the usefulness of uncertainty information for emergency managers, a test product has been designed with the help of DWD's regional office responsible for Berlin. It consists of probabilistic short range forecasts of warning events for 6-h time intervals. As a first step, this human-made forecast has been verified and compared to a statistical forecast. Both forecasts were very reliable, at least for moderately severe events. Note, that this good calibration of the forecasters has been achieved without providing feedback to them yet.

DWD provides weather warning information to emergency managers via the online platform FeWIS (Feuerwehr-Wetterinformationssystem). Access to this platform is limited to emergency managers from dispatch centres, professional, voluntary and private fire brigades and other relief units. An online survey on this platform has been conducted to assess how much emergency managers are aware of uncertainties, how much trust they put in the information and how they are affected by failed weather warnings. In a previous survey, FRICK and HEGG (2011) investigated the users' assessment of and trust in a similar Swiss online platform for hydrologic and atmospheric hazards. 174 FeWIS users responded: 59% represent fire brigades and dispatch centres, 26% are emergency managers and 14% belong to other relief units. The survey showed that 60% of respondents rated the frequency of false alarms at least as "acceptable". Only 13% of participants replied that false alarms are too frequent or much too frequent.

Another question was how participants estimated the frequency of false alarms. The vast majority of emergency managers expects thunderstorms to occur for 60-90% of warnings (Fig. 10). The objectively verified rate of occurrence of an event after a thunderstorm warning was issued by DWD however, is significantly lower. Depending on the regional forecast centre, the rate is in the range of 40-55% (GÖBER, 2012). It is unclear whether meteorologists and emergency managers define false alarms in the same way. A thunderstorm for example, that hits uninhabited regions or does not cause missions might not be perceived as an event by EMs. Thus, emergency managers put high trust into weather warnings issued by DWD although they are aware of uncertainties.

An open question was posed about the consequences of false alarms. 35% of responders claimed to suffer no consequences. About two thirds prepared for an event, mostly by reinforcing staff for relief missions and dispatch centres by prolonging work shifts, setting up standby duty or calling in voluntary fire brigades. One quarter of survey participants reported that they took precautionary measures, which then turned out to be not needed. Those measures included cancelling outdoor events, checking equipment and installing defences. Roughly 20% of emergency managers raised the concern that false alarms cause reduced trust in warnings by both DWD and their own institution.

Complementary to the effects of false alarms, the consequences of missed events have been investigated. Here, only 10% of respondents claimed to suffer no consequences. 35% of respondents were troubled by lacking of staff in dispatch centres and for rescue forces. The former is particularly critical if it leads to a queuing of emergency calls. The latter means to alert and wait for reinforcements and therefore causes a delay of counter measures and emergency responses. Additionally, reinforcing personnel might be obstructed by weather effects.

Another 35% of respondents suffered from being unprepared. Resources and material were not available and emergency managers struggled to keep track of the situation and to plan missions. Probably the most severe consequence is putting people at risk (when not sending out warnings, e.g. to outdoor events) and suffering avoidable damage. This was named in 20% of the answers. Loss of trust was listed only by 3% of responders.

Another online survey aimed at a larger audience within the emergency management community: KOX et al. (2014) investigated the perception and use of uncertainty information in severe weather warnings. The results showed that the emergency service personnel who participated in this survey generally had a good appraisal of uncertainty in weather forecasts. When asking for a probability threshold at which mitigation actions would start, a broad range of values was mentioned and a tendency to avoid decisions based on low probabilities was detected. Furthermore, additional uncertainty was noted to arise from linguistic origins, e.g. context dependence, underspecificity, ambiguity and vagueness.

3.5.2 Risk analysis and risk communication

The vulnerability of people and infrastructure plays a major part in the analysis of risks, especially for large cities. One important aspect of risk mapping is the distribution of trees, since storm damaged trees pose a major thread, e.g. to people, cars or rail tracks. Here, Berlin is particularly vulnerable since its 5342 km of streets are lined, on average, by about 80 trees per km. Trees are stressed in cities because of water deficiency, heat, pollution, bad soil conditions, small rooting spaces, etc. Inter alia, this leads to a weakening of wood or defence against insect attacks. Vulnerability is dependent on tree species and age (wood flexibility), size (height, crown), foliation and other factors.

Mass media are the major public source of information about impending severe weather (ULBRICH, 2013). A content analysis of television weather reports of the 26 most severe winter storms has been conducted with the goal to relate the information and its quality to observed and modelled losses (DONAT et al., 2011). In a semi-experimental setting, the understanding of TV weather reports has been tested with about 200 students in order to investigate how they perceived and understood the information and whether they derived actions from it.

4 Summary and outlook

The initial phase of HErZ has triggered a number of activities in the areas of weather forecasting and climate research. Basic research within HErZ complements more applied internal research at DWD. In addition, HErZ significantly intensifies the collaboration between universities, research institutions and DWD. This is seen as a benefit for both the host institutions and DWD. Training young scientist is also a key component of HErZ. All branches are actively involved in course teaching and several special training events have been conducted. In addition, a number of doctoral, master and bachelor students have completed or are working on their thesis in the framework of HErZ.

HErZ has been established as a virtual research centre and contributes to better understanding of atmospheric processes, ways to observe and represent them in numerical models and ways to forecast them to mitigate their impact. Specific contributions of the current HErZ to improved understanding address:

- The structure, life-cycle, precipitation efficiency and organization of shallow and deep convection;
- The differences between convective-scale and synoptic-scale data assimilation;

- Representation of different sources of uncertainty in ensemble systems;
- The effects of land surface heterogeneities and soil moisture on the formation of convective clouds;
- Regional and local climate variability;
- The perception and use of forecasts.

In addition to an improved understanding, a number of specific methods, tools and data sets have been developed in HErZ. In the course of future phases of HErZ, the research shall feed into improved modelling, monitoring and forecasting capabilities. More specifically, research of HErZ shall lead to:

- Seamless short-term weather prediction by means of a more detailed process description in nowcasting and high-resolution data assimilation;
- Improved assimilation systems through additional observations and new tools;
- Improved and scale-adaptive parameterizations of clouds and convection;
- Improved monitoring of past weather and climate;
- Improved communication and use of forecast uncertainty and weather warnings.

The five branches of HErZ address different aspects of weather or climate research, but they share common research topics as for example regional high-resolution (km-scale) modelling. Clouds, convection and hydrometeors are another important aspect for the first four branches and research ranges from polarimetric radar observations to cloud tracking, cloud motion vectors, assimilation of cloud observations, idealized LES of cloud regimes, suitable parameterizations and cloud validation. Further joint research areas include observation forward operators, data assimilation, probabilistic forecasting and the verification and validation of analyses and forecasts.

The current HErZ research covers the whole chain of topics relevant for weather forecasting and climate monitoring ranging from understanding of processes over methods to represent these in observation-based nowcasting and numerical models to ways of condensing and communicating the observational and model-based information to end users. By this, it brings together basic with applied research, observational with modelling expertise, academic with weather service experience and scientists with end users.

HErZ has overcome the difficulty of initiating and establishing such an unprecedented collaboration of DWD, universities and research institutes. It has triggered and intensified research in important, as yet underrepresented subjects at universities. The remaining challenges for the long-term success of HErZ will be to develop sustainable structures based on currently limited-term funding for the branches and long-term career perspectives for people working in HErZ. Establishing the centre has also been accompanied by comparably high management efforts given the centre’s strategic and structural goals in addition to research objectives. Thus, finding a good balance between structural demands and the focus on its primary objective of excellent science as well as a good balance of fundamental research and research motivated by and focused on needs of a weather service are seen as crucial tasks for lasting scientific success.

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Tables

Branch topic and affiliated authors	**Project title, research topics and host institutions**	**Branch short name**
Atmospheric dynamics and predictability; *S. Trömel,* *K. Wapler,* *H. Deneke*	**Object-based Analysis and SEamless prediction (OASE);** • Synergistic use of multi-sensor observations • Analysis of the structure and life-cycle of deep convection • Nowcasting and (very) short-term forecasting of severe weather events *Universität Bonn, Leibniz-Institut für Troposphärenforschung Leipzig*	Branch 1: HErZ-OASE
Data Assimilation; *M. Weissmann,* *T. Janjic*	**Ensemble-based convective-scale data assimilation and the use of remote sensing observations** • Methods and tools for convective-scale data assimilation • Use of cloud-related satellite observations • Representing uncertainty in ensemble systems *Ludwig-Maximilians-Universität München*	Branch 2: Data Assimilation (HErZ-DA)
Model development; *C. Hohenegger,* *A. Seifert*	**Clouds and convection** • Process studies with large-eddy simulations • Analysis and characterization of the cloud size distribution • Improved parameterizations of subgrid processes *Max-Planck Institut für Meteorologie, Hamburg*	Branch 3: Clouds and Convection (HErZ-CC)
Climate monitoring and diagnostics; *C. Ohlwein,* *J. Keller,* *C. Bollmeyer*	**Retrospective analysis of regional climate;** • Development of a regional reanalysis system • Assimilation techniques for historical observation systems • Diagnostics of the energy, water, and momentum cycles *Universität Bonn, Universität zu Köln*	Branch 4: HErZ-Climate
Communication and use of forecasts and warnings; *T. Ulbrich,* *M. Göber*	**Improving the process of weather warnings and extreme weather information in the chain from the meteorological forecasts to their communication for the Berlin conurbation (WEXICOM)** • Assessment of uncertainty of weather warnings • Analysis of risk communication and perception • Analysis of vulnerability and risk management *Freie Universität Berlin, Forschungsforum Öffentliche Sicherheit, Deutsches Komitee Katastrophenvorsorge*	Branch 5: HErZ-Application

Table 1: The five branches of HErZ in the initial funding phase 2011-2014.

Figures

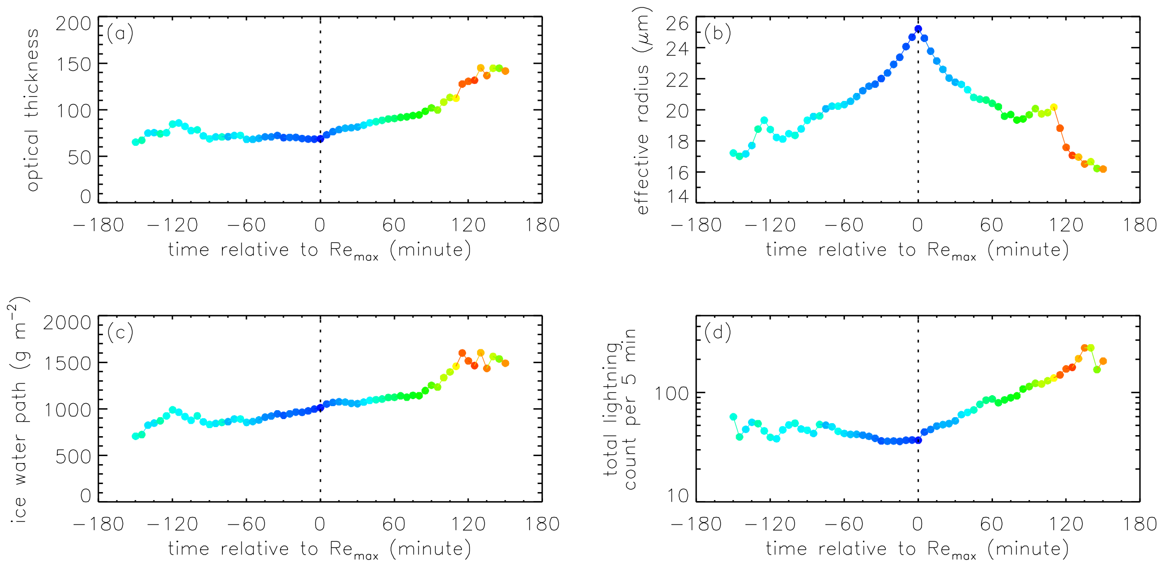

Figure 1: Evolution of satellite-retrieved cloud properties and ground-based total lightning count per 5 min time interval averaged over ~1700 systems tracked with KONRAD and synchronized to the time of maximum effective radius (vertical dotted line). The colour indicates the KONRAD cell size, i.e. number of radar pixels (1 km²) with reflectivity greater 46 dBZ, ranging from less than or equal to 30 (blue) to greater than or equal to 120 (red).

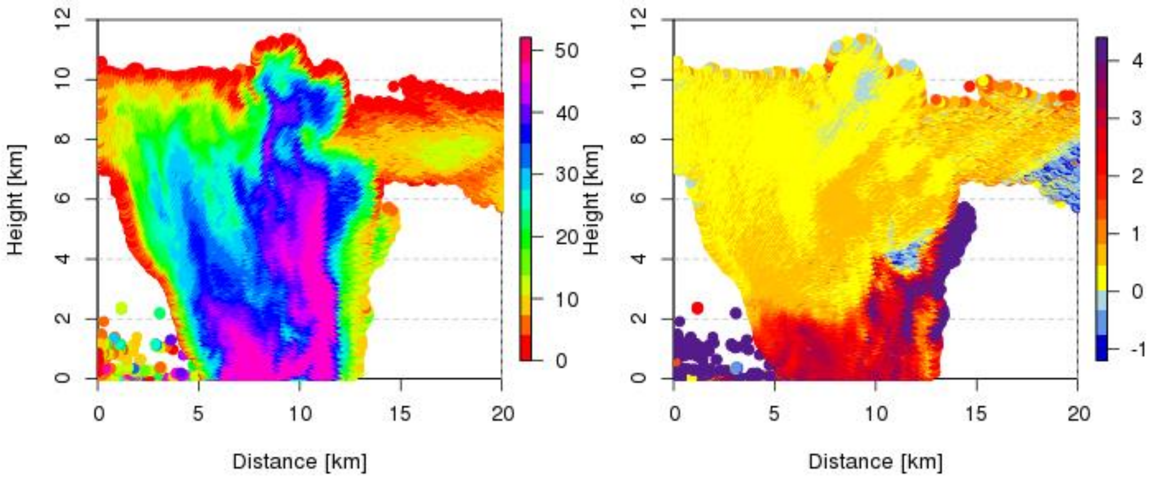

Figure 2: Vertical cross-section of a storm during intense lightning activity from measurements of the polarimetric X band radar in Bonn (BoxPo) on 5 June 2011 at 1359 UTC. The left panel shows the horizontal reflectivity Z_H (in dBZ) and the right panel the differential reflectivity Z_{DR} (in dB).

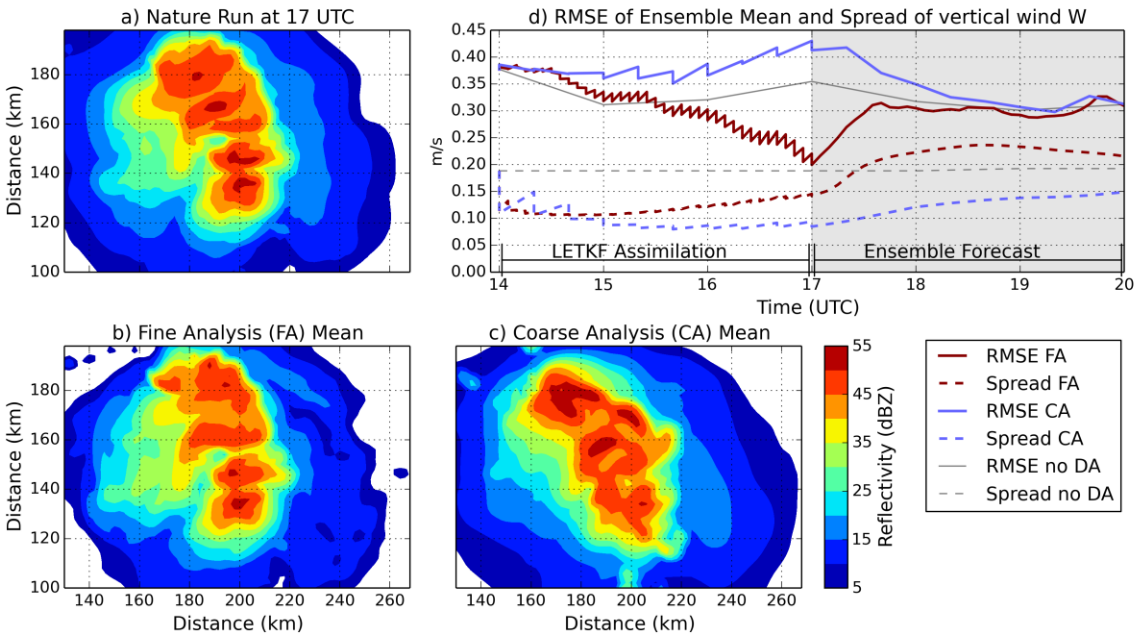

Figure 3: Idealized experiments to investigate convective-scale radar assimilation with an ensemble Kalman filter. (a) Composite radar reflectivity of the nature ("truth") run, (b) the corresponding ensemble mean of the fine analysis (FA) and (c) of the coarse analysis scheme (CA) after 3 h of cycled data assimilation. (d) RMSE and spread of vertical velocity of FA (red) CA (blue) and the experiment without data assimilation (no DA, grey) during cycled assimilation (white area) and free forecast (grey area).

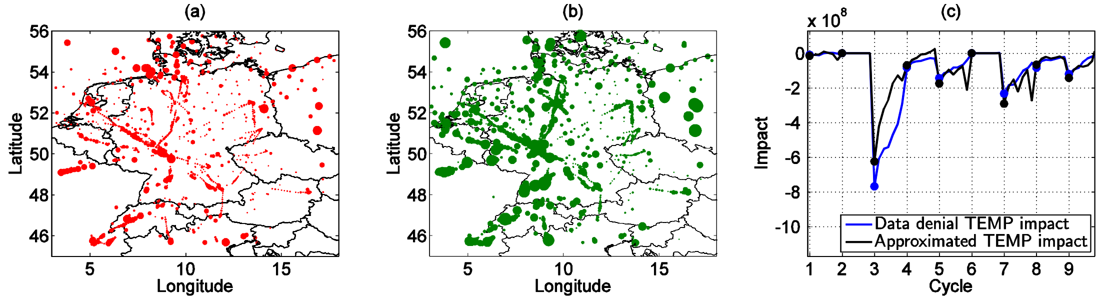

Figure 4: Spatial distribution of approximated impact for all observations with beneficial (a) and detrimental (b) impact with marker size proportional to the impact values. Forecast time 6 h from initialization at 8 August 2009 1200 UTC. (c) Data denial (blue) and approximated (black) impact of radiosonde observations. Dots represent the analysis influence and lines the evolution of the observation impact for forecast lead times up to 6 h from every analysis cycle.

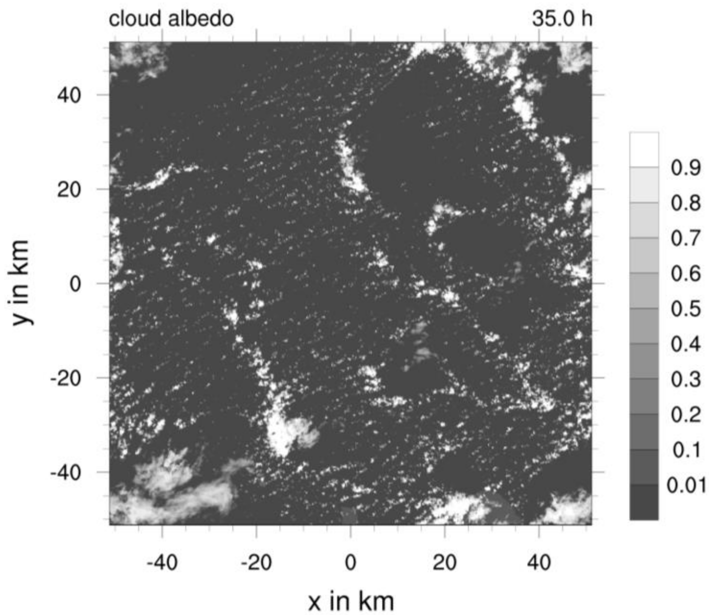

Figure 5: Synthetic cloud albedo for the RICO LES case as calculated from simulated cloud liquid water path after 35 h. Shown is the result of a simulation with the UCLA-LES model using 4096 × 4096 × 160 grid points with an isotropic mesh of 25 m grid spacing. The resulting domain has a horizontal size of 100 × 100 km and can therefore include mesoscale cloud structures as the mesoscale arcs that are typically observed in precipitating shallow convection in the trade wind zone.

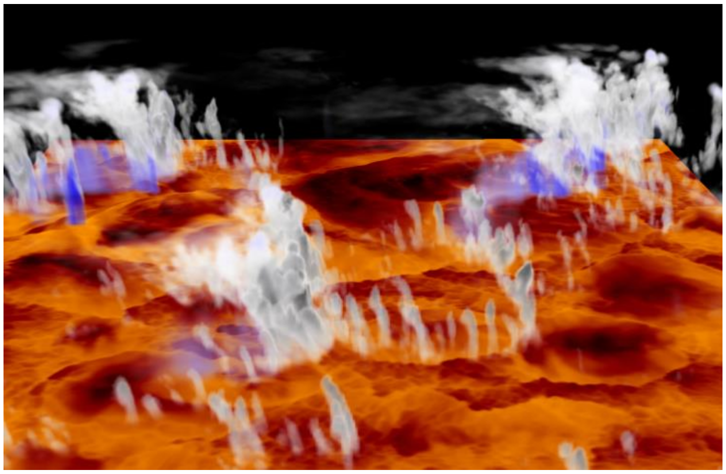

Figure 6: 3D snapshot of developing deep convection with cloud (white), precipitation (blue) and near-surface humidity (from low to high: black-red-orange) from a LES simulation (grid spacing 100 m, domain size 125 x 125 km).

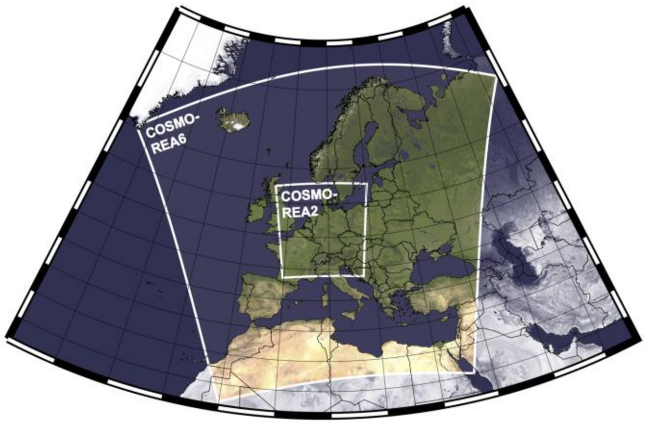

Figure 7: A map of Europe showing the domains for the European reanalysis (COSMO-REA6, approx. 6 km resolution, 880x856 grid points) and the German reanalysis (COSMO-REA2, approx. 2 km resolution, 724x780 grid points).

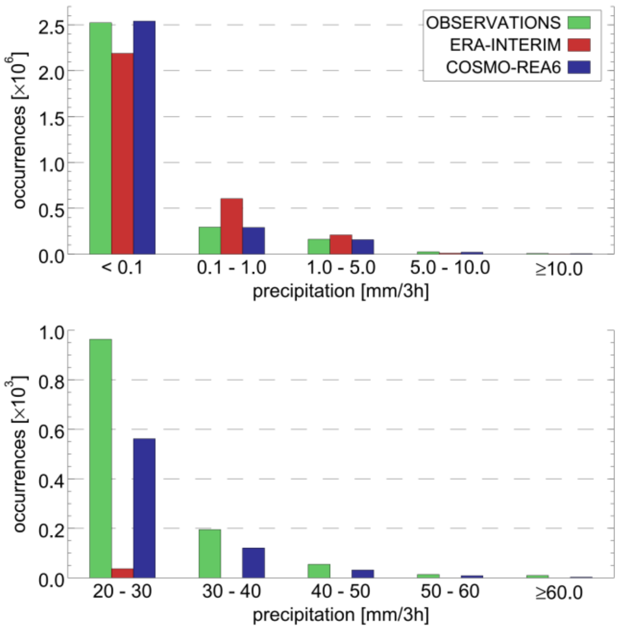

Figure 8: Histograms of 3-hourly precipitation over Germany for 2011 for rain gauge observations (green), ERA-Interim (red) and COSMO-REA6 (blue) for weak (upper diagram) and heavy (lower diagram) precipitation events.

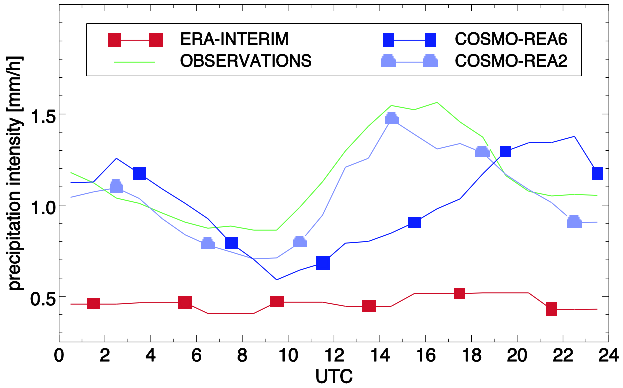

Figure 9: Diurnal cycle of precipitation intensity (3-hourly averages) for June 2011 over Germany. Values for the observations (green), ERA-Interim (red), COSMO-REA6 (dark blue) and COSMO-REA2 are shown.

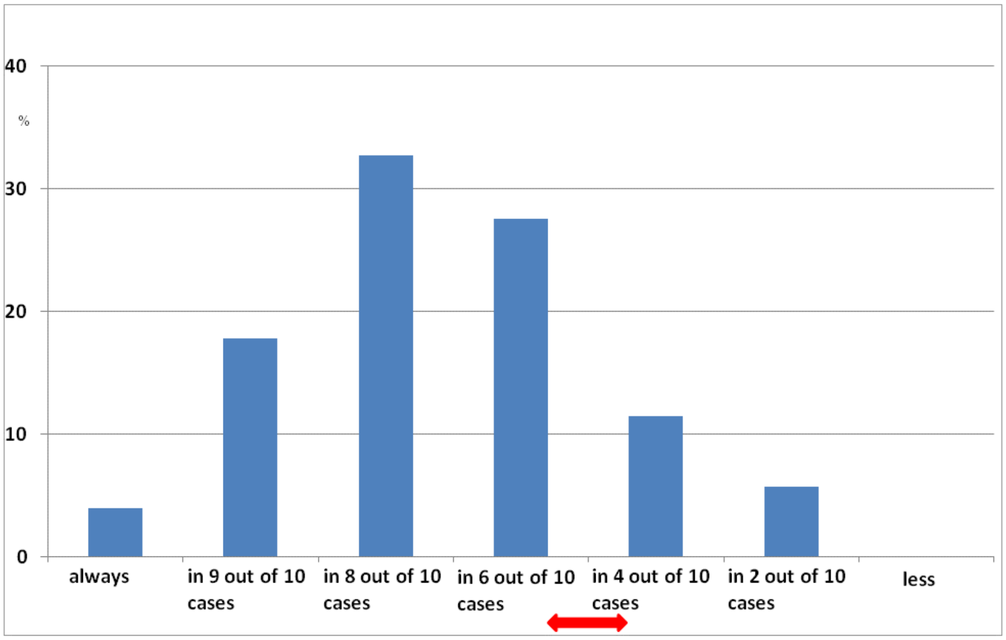

Figure 10: Participants of the online survey were asked: "When receiving a thunderstorm warning via FeWIS, how often do you expect a thunderstorm to actually happen?" The red arrow indicates the range of the objectively verified rate of occurrence of an event in a county after a thunderstorm warning was issued (GÖBER, 2012).