Initiative to Establish a Priority Programme

Polarimetric Radar Observations meet Atmospheric Modelling (PROM)

Fusion of Radar Polarimetry and Numerical Atmospheric Modelling Towards an Improved Understanding of Cloud and Precipitation Processes

Photograph (left, courtesy of Dennis Oswald) and radar reflectivity $Z_H$ measurement (right) of the Pentecost storm on 9 June 2014 in North Rhine-Westphalia

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1 See Section 5.6 for more information about the members.
1. **Summary**

Cloud and precipitation processes are the main source of uncertainties in weather prediction and climate change projections since decades. A major part of these uncertainties can be attributed to missing observations suitable to challenge the representation of cloud and precipitation processes in atmospheric models. The whole atmosphere over Germany is since recently monitored by 17 state-of-the-art polarimetric Doppler weather radars, which provide every five minutes 3D information on the liquid and frozen precipitating particles and their movements on a sub-kilometer resolution, which is also approached by the atmospheric models for weather prediction and climate studies. Data assimilation merges observations and models for state estimation as a requisite for prediction and can be considered as a smart interpolation between observations while exploiting the physical consistency of atmospheric models as mathematical constraints. However, considerable knowledge gaps exist both in radar polarimetry and atmospheric models, which impede the full exploitation of the triangle radar polarimetry – atmospheric models – data assimilation and call for a coordinated interdisciplinary effort. The priority programme will exploit the synergy of the new observations and state-of-the-art atmospheric models to better understand moist processes in the atmosphere, and to improve their representation in climate- and weather prediction models. The programme will extend our scientific understanding at the verges of the three disciplines for better predictions of precipitating cloud systems by addressing the following objectives:

1. Exploitation of radar polarimetry for quantitative process detection in precipitating clouds and for model evaluation
2. Improvement of cloud and precipitation schemes in atmospheric models based on process fingerprints detectable in polarimetric observations
3. Monitoring of the energy budget evolution due to phase changes in the cloudy, precipitating atmosphere for a better understanding of its dynamics
4. Generation of precipitation system analyses by assimilation of polarimetric radar observations into atmospheric models for weather forecasting
5. Radar-based detection of the initiation of convection for the improvement of thunderstorm prediction

Research proposals will address science questions advancing at least one of the objectives and will be proposed by teams with expertise in at least two fields of the triangle to best leverage synergy. Its exploitation for profound improvements in the representation of clouds and precipitation processes in atmospheric modelling is an emerging research field, which demands the education of scientist still rarely available in Germany. In the first three-year period preferentially PhD students will be educated and trained in the development and exploitation of polarimetric radar data, and perform research in the interdisciplinary field, while the second period will preferably provide a postdoc phase for the most successful projects. The recruitment of suitable PhD candidates will be based on a common call and selection colloquium. The advancement of the PhD students will be monitored during two annual meetings and fostered by doctoral committees crossing disciplines and institutions.

2. **State of the art and preliminary work**

The representation of cloud- and precipitation processes in atmospheric models is a central challenge for numerical weather prediction and climate projections (e.g., Boucher et al. 2013; Bauer et al. 2015). In short-term weather prediction, the forecast of local convective precipitation events and thunderstorms with lifetimes of hours or less as experienced extensively during June 2016 is especially challenging due to their rapid development and our current inability to predict the time and location of their initiation. The relatively slow moving and frontal weather systems with lifetimes of days show reasonable predictability by numerical weather prediction (NWP, Alifieri et al. 2012), but high-resolution simulations and observations suggest that these systems are built of small-scale filament-type short-lived convective features and it is not clear yet how...
important they are for the system evolution. For isolated convective systems NWP is not yet applicable because of the still relatively coarse spatial model grids (Siccardy et al. 2005), inappropriately simulated convective cloud and precipitation processes, shortcomings in our understanding of polarimetric radar observations and their appropriate use in data assimilation systems, and last not least time constraints for delivering forecasts in due time. These constraints up to now favoured purely radar-observations-based nowcasting – an intelligent extrapolation of the path and evolution in time of events detected by radars. Considerable uncertainty with respect to their trajectory and evolution (Germann et al. 2009), however, strongly limits such methods. Thus, loose combinations of radar-based nowcasting and dynamical modelling have been proposed (e.g., Berenguer et al. 2005; Atencia et al. 2010). First attempts of radar data assimilation for addressing the very short time scales with NWP methods, e.g. by Bick et al. (2016), have shown success on larger scales, but the resolution of the observations had to be coarsened considerably to tens of kilometres before they could be digested by the prediction system.

Clouds and precipitation processes lead to large uncertainties in the predictions of climate change (Boucher et al. 2013). Anthropogenic pollution particles (aerosols) perturb the microphysical processes of clouds and precipitation (e.g., Quaas 2015). A particular uncertainty is the extent to which precipitation processes are altered by aerosol perturbations, especially in convective, mixed-phase clouds (e.g., Rosenfeld et al. 2014). Increasing levels of atmospheric carbon dioxide additionally influence cloud and precipitation evolutions at various timescales (Bony et al. 2013; Sherwood et al. 2015), and feedback to climate change (e.g., Klocke et al. 2011). Thus it is imperative to improve the representation of cloud- and precipitation processes in climate models to improve the prediction of climate change. New data sources are urgently required to address in particular the microphysical processes (e.g., Lohmann et al. 2007; Van Lier-Walqui et al. 2015).

The suggested Priority Programme builds upon the hypothesis that a coordinated effort in exploiting the nationwide availability of the polarimetric C-band (6 cm wavelength) weather radar observations in synergy with experimental radars at shorter wavelengths and atmospheric models will

- overcome current obstacles, which hinder the fusion of polarimetric radar observations and atmospheric models via data assimilation on scales which govern precipitating weather systems,
- provide a most effective research approach to cloud- and precipitation processes, that enables a thorough evaluation and improvement of parameterisations of moist processes in atmospheric models,
- allow for new insights into the atmospheric energy budget and the cycling between its different forms in moist atmospheric processes, and
- lead to innovations of our capabilities to predict convective cloud development and thunderstorms.

Radar polarimetry offers a wealth of still barely used information on cloud and precipitation microphysical composition and processes, which can be exploited for largely improving our understanding of moist processes in the atmosphere including thunderstorm development and evolution. Polarimetric radars emit horizontally and vertically linearly polarized electromagnetic wave trains; the returning wave trains scattered back from the cloud and precipitation particles are then analysed statistically with respect to their respective intensities, phase differences, correlations, and frequency shifts commonly called polarimetric radar moments explained in detail in Table 1. The cover figure shows a photo of the destructive Pentecost storm on 9 June 2014 over North Rhine-Westphalia together with a reflectivity cut through the storm performed by one of the new radars; the same cut but for another moment – differential reflectivity – is shown and discussed in Fig. 3. Observation examples for a more stratiform event including process indications are shown and discussed in Fig. 1. More radar-detectable processes are visible in Fig.2.
Figure 1: Stratiform rain event monitored at 09:44 UTC, 22 June 2011 with the polarimetric X-band radar in Bonn. Panels show horizontal reflectivity $Z_H$ (top left), differential reflectivity $Z_{DR}$ (top right), cross-correlation coefficient $\rho_{HV}$ (bottom left) and the radar-based hydrometeor classification (bottom right). The melting layer (0°C-level) was at around 3 km height during that day. The melting process is visible in the polarimetric measurements (enhanced $Z_H$ and $Z_{DR}$, reduced $\rho_{HV}$) due to the high particle diversity, and melting snow flakes appearing as big drops to the radar. The second visible process is size sorting. Since rain just starts, the reflectivity curtain does not reach the ground (insignificant $Z_H$) but $Z_{DR}$ increases at 1 km, which indicates size sorting (biggest drops fall faster). The hydrometeor classification shows at the melting layer the transition from dry snow (orange) to rimed particles (yellow) and bigger drops (light blue). Also the size sorting area shows the bigger drops (light blue) with the area of light rain (blue).

We will partially build upon and extend earlier developments in the U.S.A. based on their longer-wavelength S-band (10-11 cm) radar network fostered by their earlier upgrade to polarimetry and take advantage of overlaps with existing research radar networks at K (cloud radars) and X-band also operating continuously in Germany (Haefelin et al. 2016). The synergetic exploitation of this new information source with the high-resolution modelling efforts currently pushed forward by the HD(CP)$^2$ research programme of BMBF will generate a new branch of research in atmospheric sciences in Germany, which is expected to

\textbf{accelerate an improved representation of cloud and precipitation processes in atmospheric models with strong repercussions on the quality of predictions ranging from short-term weather forecasts to centennial climate projections.}

The programme will approach this goal via fundamental research following the five scientific objectives detailed in the remainder of this chapter.
Table 1: The most important polarimetric variables, definitions and characteristics.

<table>
<thead>
<tr>
<th>Polarimetric variable</th>
<th>Definition</th>
<th>Characteristic</th>
</tr>
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<tbody>
<tr>
<td>Power measurements:</td>
<td>affected by misscalibration, partial beam blockage, attenuation</td>
<td></td>
</tr>
<tr>
<td>Horizontal/vertical reflectivity $Z_H / Z_V$</td>
<td>Backscatter in horiz./vertical polarization channel; for small drops the 6th moment of drop size distribution</td>
<td>Increases with horiz./vertical particle size, number concentration, density and water content (higher in rain than in ice)</td>
</tr>
<tr>
<td>Differential reflectivity $Z_{DR}$</td>
<td>Difference $Z_H - Z_V$</td>
<td>Increases with particle oblateness, measure for drop size ($Z_{DR}=0$ for small spherical drops); increases with density, independent of concentration; high for very anisotropic crystals</td>
</tr>
<tr>
<td>Cross-correlation coefficient $\rho_{HV}$</td>
<td>Correlation between back-scattered horizontally and vertically polarized waves</td>
<td>Measure for diversity of scatterers and quality of radar data, identifies non-meteorological signals</td>
</tr>
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Phase measurements: Not affected by misscalibration, partial beam blockage, attenuation

<table>
<thead>
<tr>
<th>Differential phase shift $\Phi_{DP}$</th>
<th>Cumulative phase shift between H and V pol. waves</th>
<th>Measure for path integrated attenuation; noisy in weak rain</th>
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<tbody>
<tr>
<td>Specific differential phase $K_{DP}$</td>
<td>Range derivative of $\Phi_{DP}$</td>
<td>Increases with oblateness, density, water cont. (similar to $Z_{DR}$); proportional to hydrometeor conc.; small/noisy in weak rain; $K_{DP}=0$ for spherical and randomly oriented hydrometeors</td>
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1. Exploitation of radar polarimetry for quantitative process detection in precipitating clouds including thunderstorms and model evaluation

Precipitation characteristics are notoriously poorly simulated in current atmospheric models (e.g., Stephens et al. 2010; Suzuki et al. 2011; Nam and Quaas 2012). One reason is the poor representation of subgrid-scale cloud variability in precipitation-formation processes (e.g., Weber and Quaas 2011), but much uncertainty is also related to the still poorly evaluated microphysical processes of precipitation formation. Models e.g. fail to realistically represent the partitioning of precipitation forming from ice vs. liquid phase clouds (e.g. Mülmenstädt et al. 2014). Polarimetric radar data provide highly relevant information about the evolution of cloud- and precipitation particle types and their size distributions, and the vast database now available from the DWD network allows for sound statistical analyses and conclusions about related processes. Examples include mass fluxes like rain and snow rates, information about the shape of the rain drop size distribution and the mean particle size $D_0$, classification of ice habits, and even mixing ratios of the different hydrometeor types. In the following, the latter three quite recently emerging research topics are elucidated in more detail.

Hydrometeor mixing ratios: Existing relations between radar reflectivity at horizontal polarization, $Z_H$ (intensity of the backscattered wave train) and mixing ratios for various hydrometeors (falling water/ice condensates) types, $q$, assume idealized size distributions (such as exponentials with fixed intercepts), typically neglect mixed-phase hydrometeors such as melting snow and graupel/hail. The relations also ignore particle shape diversity and radar wavelength-dependent resonance scattering effects (strong size-dependent signals caused by interferences of the waves within a particle), which might dominate the radar signal for certain size intervals. Dowell et al. (2011) formulated $Z_H$-$q$ relations specific for rain, hail, dry and wet snow. Since the actual particle size distribution is the prime uncertainty in these relations due to the strong particle-size-dependency of the radar reflectivity, reliable estimates are not possible from $Z_H$ alone. Radar polarimetry provides information that allows reducing these uncertainties.
Estimates of liquid water content (LWC, kg/m$^3$) in precipitation based on wave attenuation, $A$, which can be estimated e.g. from phase differences between the reflected waves of both polarizations (differential phase shift $\Phi_{DP}$), outperform estimates based on reflectivity alone (Carlin et al. 2016). If rain is mixed with hail, rain rate and rain specific water content $q_r$ (or LWC) can be estimated from the specific differential phase $K_{DP}$ (change of $\Phi_{DP}$ along the radar radial), which is much less affected by the presence of hail than $Z_H$ or $A$ (Doviak and Zrnić 1993). Relations between reflectivity $Z_H$ and specific hail content $q_h$ or ice water content (IWC, kg/m$^3$) require a separation into different hail classes and degrees of melting (Carlin et al. 2016), which can only be differentiated by radar polarimetry. Simulations of $q_r$, $q_h$, $Z_H$, and $K_{DP}$ using the Hebrew University Cloud Model combined with a polarimetric radar observation operator (simulation of radar observations from given sets of particles) described by Ryzhkov et al. (2011) suggest that such relations also depend on the stage of storm development. Since the mixing ratios occur as prognostic variables in the model, their reliable estimation from the radar observations would allow avoiding the compute-intensive forward operators in ensemble-based data assimilation.

Information about the rain drop size distribution: Polarimetric radar observations, especially differential reflectivity $Z_{DR}$ (the difference between the backscatter in the horizontal and vertical polarization channel), provide information about the mean particle size of the rain drop size distribution (e.g., Zrnić and Ryzhkov 1999; Bringi and Chandrasekar 2001) and is often used to retrieve the slope parameter of the drop size distribution (e.g., Zhang et al. 2001). However, also the polarimetric variable backscatter differential phase $\delta$ (a phase shift between horizontal and vertical wave train due to backscatter from Mie-sized particles) relates to the mean particle size that could be exploited for better characterizing drop sizes, especially when $Z_{DR}$ is affected by attenuation (Trömel et al. 2013). While formerly, in coarse-resolved models precipitation was considered to fall from the clouds to the ground in one model time-step in a single column, increasing model resolutions in space and time have to resolve the falling of particles as well as their horizontal advection (e.g. Forbes et al. 2012). Thus, observations of precipitation particle sizes are crucial to evaluate new parameterisations in atmospheric models that increasingly include prognostic equations for precipitation water and particle sizes.

Quantification and classification of ice: In midlatitudes strong precipitation and thunderstorms always involve so-called cold precipitation processes (e.g., Mülmenstädt et al. 2014), i.e. precipitation is primarily generated above the 0°C level and thus depends on frozen hydrometeors (by so-called Wegener-Bergeron-Findeisen processes) with their wide range of sizes and shapes. Updrafts lead to super-cooled cloud droplets due to missing ice nuclei, transport existing liquid hydrometeors from lower levels into heights at subfreezing temperatures, and thus initiate a most complex mixture of particles with various interaction processes depending – besides temperature, humidity and wind profiles - on the size, shape and composition of these particles. Atmospheric models parameterize these processes largely based on assumed particle size and shape distributions, if not simply based on local temperature (e.g., Doutriaux-Boucher and Quaas 2004). Only radar polarimetry, which exhibits specific fingerprints for particle types and exchange processes in their moments, can validate and/or challenge these assumptions. Thus radar polarimetry allows evaluating and eventually improving the representation of mixed-phase clouds in atmospheric models to which many important questions such as the aerosol-cloud-climate forcing (e.g., Storelvmo et al. 2008) or the cloud-climate feedback (Tan et al. 2016) are highly sensitive. The assimilation of such observations into atmospheric models requires that the model is able to simulate these real-world processes. Multivariate polarimetric fingerprints allow to retrieve size sorting, evaporation, aggregation, riming, melting and dendritic growth (Kennedy and Rutledge 2011; Andric et al. 2010; Moisseev et al. 2015, Trömel et al. 2013; 2014).
As an example Fig. 2 illustrates the polarimetric fingerprints of dendritic growth and riming. Around -15°C (at around 5 km height in this case) dendritic growth results in an increase in $Z_{DR}$ but also in $K_{DP}$, indicating high number concentrations. Below the dendritic growth area, the combination of increasing $Z_{H}$ due to increasing particle size and decreasing $Z_{DR}$ due to decrease in anisotropy of the particles indicates ongoing riming processes. Aggregation processes generate similar tendencies in $Z_{H}$ and $Z_{DR}$, but the $Z_{DR}$ reduction differs in magnitude. $Z_{DR}$ is expected to be 0.1-0.3 dB lower just above the melting layer in case of riming. In Fig. 2 the sagging of the melting layer puts another weight to ongoing riming processes. Rimed snow particles fall with higher fall velocity due their higher density and thus melt at lower heights compared to unrimed snow (e.g., Zawadski et al. 2005; Trömel et al. 2014). A dedicated analysis of polarimetric observations has thus a huge potential for classifying ice and the distinction at least between pristine crystals, lightly rimed ice, heavily rimed ice, and aggregates. Ryzhkov et al. (2016) suggest the use of so-called Quasi-Vertical-Profiles (QVPs, compare Fig. 2), generated via azimuthally averaging of high-elevation conical scans (varying azimuth while keeping the radar elevation angle constant) for monitoring and detection of microphysical processes in polarimetric radar data; these QVPs largely reduce the often disruptive noisiness in radar measurements and allow for a quite direct comparison with other vertically profiling sensors (e.g. cloud radars or microwave radiometric profilers) and atmospheric model output. Most polarimetric fingerprints for microphysical processes are qualitatively known or anticipated; however, small changes in polarimetric moments can be crucial to distinguish between two processes (e.g. aggregation and riming) and thus different classes of ice. In addition the quantification of ice depends on a correct particle classification. E.g. IWC can be estimated either from specific differential phase $K_{DP}$ or from the combination of $K_{DP}$ and differential reflectivity $Z_{DR}$ (difference in the intensity of the reflected horizontally and vertically polarized wave trains, $Z_{H}-Z_{V}$) in the areas of pristine or lightly aggregated ice where $K_{DP}$ and $Z_{DR}$ attain significant values (Ryzhkov et al. 1998). Different approaches must be evaluated to narrow down probabilities. Polarimetric information on microphysical processes in the ice phase emerges as one of the central research areas in the radar community (e.g. Giangrande et al. 2016; Schrom et al. 2015; Xie et al. 2016a/b; Trömel et al. 2016a/b). At the same time, ice- and mixed-phase cloud- and precipitation processes are particularly poorly parameterized in current atmospheric models.
2. Improvement of cloud and precipitation schemes in atmospheric models based on process fingerprints detectable in polarimetric observations

Cloud and precipitation processes are a significant source of uncertainty in numerical weather prediction and climate models (e.g., Stevens and Bony 2013). The related water phase transitions are accompanied by heating or cooling, drying or moistening of the atmosphere and constitute main driving forces for atmospheric motions at a wide range of scales reaching from individual clouds to the global circulation. The response of these processes to anthropogenic perturbations of the atmosphere is the main uncertainty in global climate change (Boucher et al. 2013). Polarimetric radar observations contain signatures of both, phase transitions (melting, evaporation, freezing) and hydrometeor mass redistributions (coalescence, differential sedimentation). Polarimetric observation operators implemented in atmospheric models generate virtual observations from the models, which enable a direct comparison of observed and simulated signatures of microphysical processes including their temporal evolution/lifecycles (e.g. Bodas-Salcedo et al. 2011; Ryzhkov et al. 2011; Nam and Quaas 2012; Kumjian et al. 2014). Thus deficiencies in model representations of microphysical processes can be uncovered and differing pathways of precipitation generation in the observations and the model identified.

However, in bulk parameterizations, which need to be used in current atmospheric models due to compute-time restrictions, the information required for the correct representation of radiation interaction with radar waves is largely missing and thus must be assumed. Bulk parameterizations are 0-dimensional box models, which simulate microphysical processes on the model grid-scale and represent e.g. hydrometeor size distributions only by one to three moments of assumed theoretical functions and neglect the natural shape variability within the different hydrometeor classes. In particular for parameterized convection (vertical mass, momentum and energy redistributions over stacks of layers are parameterized instead of simulated from first principles), the embedded microphysical processes are particularly poorly represented (e.g., Yano et al. 2014), sometimes using a simple conversion rate from condensed water to precipitation flux (e.g. Tiedtke 1989). Another particular shortcoming of such parameterizations are so-called trigger algorithms that have a large influence on the intensity of simulated convective events (Küll and Bott 2009; 2011). The validation of a given convection parameterization would be facilitated if observation operators would be directly implemented in such schemes.

However, forward operators in models are not an easy solution for a perfect model-data comparison. Differences in polarimetric fingerprints between observations and models may result both from model deficiencies and faulty assumptions in observation operators. This problem also has obvious repercussions in radar data assimilation, which tries to match real and virtual observations for the generation of optimal initial model states. Consequently, it is necessary to develop observation operators, which include the error statistics produced by the inherent assumptions. With these uncertainties known, parameterization schemes used in the models can be objectively evaluated and eventually revised or improved. Deficiencies in the representation of certain microphysical processes may be identified and different lifecycles in observations and simulations (e.g., Gehlot and Quaas 2012; Trömel and Simmer 2012) may uncover different pathways of precipitation generation in the observations and the model.

For the improvement of convection and grid-scale microphysics parameterizations, bin microphysical models may be employed, which simulate transformation processes based on particle size intervals (bins) instead of treating the hydrometeor classes as the smallest entities and thus dispose of the necessity to assume certain types of size distributions (e.g., Bott 2000; Kerkweg et al. 2003; Khain et al. 2015; Ilotoviz et al. 2016). Simulations of mid-latitude storms using the Hebrew University Cloud Model (HUCM) with polarimetric forward operator showed very high correlations between differential reflectivity, on one hand, and vertical velocity, hail mass and hail size near the surface, on the other hand. Such dependencies can be used for the
improvement of the representation of hail formation in deep convective clouds and for calibration of bulk-parameterization schemes.

Simulations with HUCM also show dramatic effects of aerosol concentration on hail size and the fields of differential reflectivity. These results are important for the improvement of bulk models regarding their response to aerosols. The exploitation of polarimetric observations for the validation of these schemes requires a particularly careful processing and calibration of the radars, and a large data set with radar-monitored processes has to be collected to analyse, interpret, and categorize the fingerprints. In this respect, detailed ground-based measurements can also be used to assess the capabilities of space-borne radars for analyzing microphysical processes on a global scale (Maahn et al. 2014). Synergistic measurements from other remote sensing instruments, like cloud radars and micro-rain radars can contribute and/or corroborate the quantification of the fingerprints and the resulting classification. Here atmospheric profiling sites such as the Jülich Observatory for Cloud Evolution (JOYCE, Löhntet al. 2015) that combine a multitude of remote sensing instruments, e.g. cloud radars, lidars, radiometers at multiple frequencies - often with polarimetric capabilites, play an important role to constrain the microphysical processes within a column as good as possible (Haeffelin et al. 2016) and to serve as a reference for operational scanning radars. Furthermore, they provide important information on wind and thermodynamic profiles of the atmosphere (Barrera et al. 2016) which are important for process understanding.

3. Monitoring of the energy budget evolution due to phase changes in the cloudy, precipitating atmosphere

Phase transitions, especially in deep convective clouds, are accompanied by heating or cooling, and drying or moistening of the atmosphere, which largely drive the dynamics of convection. These processes are besides radiative effects the most important local drivers of atmospheric motion on all scales but in particular for convective events. Their quantification is particularly important for parameterizations of convective processes such as updrafts and cold pools, which play a decisive role in storm development. Polarimetric radars are capable to distinguish between different hydrometeor habits and the processes of melting/refreezing, deposition/sublimation, and evaporation based on their polarimetric multi-variate fingerprints as discussed in Section 1. Consequently, they have a tremendous potential to quantify latent heat release and accumulation associated with phase transitions.

Latent heat retrieval on the global scale has been addressed e.g. in Tao et al. (1990; 2001; 2006) and was one of the goals of the Tropical Rainfall Measuring Mission (TRMM). Most algorithms use TRMM microwave imager brightness temperatures and precipitation radar reflectivity observations, where the discrimination between different hydrometeors is based on a model and not on the radar measurements (Tao et al. 1990). Most observational estimates of latent heating are from satellites with coarse resolution in space and time and thus cannot be used for the convective events, which are one focus of this research programme.

For storm-scale applications “latent heat nudging” is commonly used for the assimilation of radar data into NWP models (e.g., Jones and Macpherson 1997; Stephan et al. 2008, Milan et al. 2008; 2014), which assumes that the majority of water vapor which condenses in the cloud is precipitated out and only a small amount of water and ice is stored in the cloud. Therefore, the vertically integrated latent heating rate due to condensation must be approximately proportional to the net precipitation rate. Latent heat nudging scales the latent heating profile in the NWP model according to the radar-estimated rain rate. This technique has several limitations when only based on non-polarimetric radars and needs to be improved. First, the quite inaccurate $Z_{H}$-estimates of surface rain rates can be improved by radar polarimetry. Second, this method cannot provide accurate estimates of latent heat at the initial stage of convective development.
Figure 3: Vertical cross-section of the Pentecost storm at 18:30 UTC 9 June 2014 measured with the polarimetric X-band radar of the University of Bonn. Shown is differential reflectivity $Z_{DR}$, which complements the information obtained from the reflectivity $Z_{H}$ measurement for the same cross section (title page, right panel).

Figure 4: 2D field of $Z_{DR}$ (colored shading; dB) simulated by HUCM. The white arrows indicate the wind field. Ellipses at $x=61.5$ km and $z=3$ km, 4 km and 5 km show locations for which particle mass distributions are plotted on both side panels. The red dashed line shows the 0°C isotherm. The liquid-drops mass distributions on the left side panels are plotted in black, hail distributions in red curves, and freezing-drops in blue. The right panels show the hail mass distributions. Blue parts correspond to the wet growth regime and red parts to the dry growth regime. Courtesy of A. Khain (figure will be included in Ilotoviz et al. (2016) close to submission).
when precipitation has not yet been formed. Some researchers use “first-guess” heating profiles obtained from the simple pseudo-adiabatic parcel model of convective updrafts and then try to utilize either radar reflectivity or vertical velocity retrieved through multiple Doppler radar analysis to adjust the “first guess” profile of latent heat (Tong et al. 1998; Brewster 2002). One promising strategy could be to compute vertical profiles of latent heating/cooling and associated mass fluxes by applying spectral bin models and link them with the vertical profiles or fields of polarimetric radar variables obtained with polarimetric radar observation operators (e.g. Ryzhkov et al. 2011). Kumjian et al. (2012) and Ryzhkov et al. (2013) describe 1D column models focused on individual microphysical processes of melting, freezing, and evaporation and Khain et al. (2014) established the more sophisticated Hebrew University Cloud Model (HUCM). Simulations with HUCM indicate a close relationship between polarimetric parameters and convective heating. Most recent research at NOAA/NSSL (private communication A. Ryzhkov) identified plumes of strong warming within the updraft approximately coincident with both columns of enhanced differential reflectivity $Z_{DR}$ and specific differential phase $K_{DP}$, with the maximal heating rate strongly correlated with the height and size of both columns. As an example, Fig. 3 illustrates at distances of about 28, 36, and 40 to 44 km from the radar, the appearance of $Z_{DR}$-columns. Since high $Z_{DR}$-values indicate large liquid drops, enhanced $Z_{DR}$ above the 0°C level (at around 3.8 km height during that day), which sometimes appears as vertically extended $Z_{DR}$-columns, is currently thought to be associated with supercooled liquid rain drops lofted by intense updrafts (Kumjian et al. 2014; Trömel et al. 2016a). The HUCM is capable to simulate $Z_{DR}$ columns realistically. Fig. 4 shows a simulated $Z_{DR}$ column including the full analysis of its anatomy: types of particles forming the $Z_{DR}$ column, their size distributions and the regime of hail growth (i.e. whether hail is covered by liquid or not). Thus radar polarimetry provides an opportunity to estimate for the first time the heating profiles in deep convective clouds, which is needed in convection parametrizations in atmospheric models.

4. Generation of precipitation system analyses by assimilation of polarimetric radar observations into atmospheric models

An analysis is the best estimate of the complete current or past 3D state of the atmosphere at a specific time. Due to necessarily coarse observations networks, analyses are generated by data assimilation into a numerical model, which employs physical consistency as a strong interpolation constraint. Given a perfect model and perfect observations, an analysis would provide an initial state starting from which a perfect model could produce a forecast by integration forward in time, the quality of which would only be limited by the predictability of the system itself. The combination of model errors and observation errors not accounted for in the data assimilation scheme (and shortcomings of the type of data assimilation used) lead to unbalanced system states (e.g. unrealistic pressure gradients, supersaturations, etc.), to which a model may react by non-meteorological state changes like extensive sound and/or gravity wave generation. The result is eventually a balanced state after a spin-up phase of several hours, which might, however, significantly divert from the observations. Thus the capability of a model in reproducing reality can be estimated by its ability to stay close to the observations within their errors over a period of time small compared to the system predictability limit and also by short spin-up times (e.g., Rodwell and Palmer 2007). Accordingly, any fruitful developments in objectives 1 - 3 will result in a measurable coherence increase between real observations and virtual observations created from the model state with observation operators.

Polarimetric radar observations provide by their high-resolution (in space and time) 3D information on the true system state very strong constraints on the initial state of any model. It is still undecided, which type of data assimilation system – nudging, variational or ensemble-based is most suitable for the wet atmospheric processes most relevant on the convective scale. Up to now, only measurements from a single radar site are assimilated (e.g. Dowell et al. 2004; Tong and Xue 2005). Bick et al. (2016) assimilated for the first time 3D reflectivity observations from the entire national radar network of the German Weather Service (DWD) in the COSMO (COnsortium for Small-Scale Modelling) model based on the experimental Kilometer-scale
Ensemble Data Assimilation system (KENDA) of DWD. They demonstrated improvements in precipitation location in the analysis and forecasts for lead times up to four hours. Bick et al. (2016) also tested the impact of different assimilation update frequencies (how often the model is dragged to the observations). On the one hand, the model was successfully pushed closer to the observations with higher update frequencies, but on the other hand the forecast quality for lead times beyond 1 h decreased due to increasingly still unbalanced states. The study puts another weight to the argument that numerical models are not yet at a state to adequately reproduce the reality observed by radars.

Worldwide, the exploitation of polarimetric weather radars is still in its infancy concerning its use for assimilation into NWP models. Single pioneering studies in the U.S.A. are ongoing regarding e.g. the assimilation of radar-derived mixing ratios (Carlin et al. 2016). Their approach represents a first step towards polarimetric radar data assimilation, which can be performed without a polarimetric forward operator at hand. Reliably estimated, mixing ratios will help to evaluate the model state and reduce model spin-up times. Other preliminary studies to exploit polarimetry aim at the assimilation of signals of enhanced differential reflectivity $Z_{DR}$ above the melting layer as a descriptor of precipitation intensification and hail (Picca et al. 2010; Kumjian et al. 2014; Weissmann et al. 2014).

5. Radar-based detection of the initiation of convection for the improvement of thunderstorm prediction

Current deficiencies in observation-based nowcasting applications are the disregard of life cycle effects of convection and missing information on convection initiation (CI), which may lead to missed alarm rates above 40 % (Silvestro and Rebora 2012). To include the formation of new cells in nowcasting strategies with viable precision in space and time, different research scenarios have been approached.

Advanced radar techniques: For reduced 3D scan schedules with a smaller number of elevations but slower antenna rotations, more power per unit volume is transmitted, which results in finer spatial resolution and signal accuracy (Crum and Alberty 1993). This clear-air scan mode allows for the monitoring of so-called clear-air echoes e.g. caused by biota and/or strong refractive index inhomogeneities (Campistron 1975; Wilson 1994; Rabin and Doviak 1989). These echoes often occur near fronts, convergence lines, thunderstorm cold air outflow and strong updrafts and can be exploited to better tackle the CI issue. Also so-called Quasi-Vertical Profiles (QVPs, Ryzhkov et al. 2016) of the pre-storm environment produced via azimuthally averaging of scans at higher elevation angles may help to identify meteorological situations relevant for the development of high-impact weather. Next generation phased array radars will offer higher scan rates because a range of elevation angles can be measured in parallel. While their polarimetric properties are still far from comparable with current pulsed radar systems, the more frequent measurement rates of better than a minute has the potential to advance CI detection considerably.

Large-Eddy-Simulations: Early signs of potentially severe convection are observable by atmospheric boundary layer (ABL) observations of water vapor and wind. Such ABL structures are adequately addressed by Large-Eddy-Simulation (LES) models, which are, however, prohibitive in current NWP due to time constraints. Accordingly, a fusion of synoptically-forced (lateral boundary conditions taken from lower-resolution NWP models) LES modelling on convection-covering domain sizes with RANS (Reynolds-Averaged Navier Stokes) models used in NWP is promising. In convection-prone areas, which could be either fixed or following convective phenomena as identified by tracking of radar-detected phenomena with potential CI, LES simulations could initiated with the radar information and results could be assimilated into large-scale forecast as ‘super-observations’ in order to improve the representation of convective events in the larger-scale model.
Cumulus convection schemes: The accurate description of deep cumulus convection in NWP models is still one of the most challenging tasks (see objective 2). In the so-called convection-permitting high-resolution NWP models, dynamically driven convection events, e.g. at frontal zones, may be explicitly simulated with acceptable accuracy. However, in these models air mass convection, which is largely thermodynamically driven, is often insufficiently predicted. Here, the application of convection schemes which are especially designed for use in high resolution NWP models, such as the HYMACS scheme of Küll and Bott (2009; 2011; 2014), could distinctly improve the prediction quality of local convection events. Particularly the parameterization of these air-mass convection events would certainly benefit from radar information yielding a clearly improved spatio-temporal description of the convective cells.

Statistical approaches: Inspection of radar images indicate regularities where new cells form and how they develop over time. New cells initiate less likely close to a developing or mature cell; at some distance the probability rises and decreases again e.g. by cold-pool triggered updrafts. Statistical analyses of radar observations might allow to suggest a strategy to introduce new cells e.g. by a convective cell generator in form of a checkerboard where each field holds a probability \( p \) that a new cell develops; if this probability exceeds a threshold \( t \) a cell is introduced. The point process might include a clustering mechanism depending on the mesoscale situation (Marsham and Parker 2006). Once \( p > t \) (threshold probability) a new cell is introduced, its spatio-temporal development follows statistics of lifecycles typical for the synoptic condition. Larsen (1995) models image sequences as a set of individual rain cells as a realization of 2+1D spatial point process. To each point defined by location and time of maturation of a precipitation cell a vector is assigned with time-varying features such as intensity, duration, extent, shape and velocity. Such an approach can be optimized and extended and used to mathematically describe the lifecycle of a new-born cell.

3. Project-related publications by members of the programme committee

3.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published


Quaas, J., 2015: Approaches to observe effects of anthropogenic aerosols on clouds and radiation. Current Climate Change Reports, 1, 297-304.


4 Bibliography


Williams, J., 1994: Doppler effects. Weather, August/September, 43-46.


5 Merits of the proposal taking into account the objectives of the programme

5.1 Originality of research questions in terms of topic and/or methodology

The German scientific community since recently has the probably best C-band polarimetric radar network in the world at its disposition, which practically turns the whole of Germany into a research testbed for cloud and precipitation-related research. Given the vast information on cloud and precipitation processes contained in this data, which is available every five minutes at almost every volume of the German sky, a range of scientific questions can now be addressed, which could not be approached before. Prior to the era of polarimetry, only one information – radar reflectivity, proportional to the 6th moment of raindrop size distribution in the radar volume – was available, which provided besides the structure of the precipitation-bearing air only crude estimates of rainfall intensity. In addition to large uncertainties of rain retrievals caused by unknown hydrometeor type, the high sensitivity to variations in the size distribution of the hydrometeors and attenuation effects, reflectivity-based estimates are burdened with many artefacts due to ground echoes, melting-layer effects, and partial beam-blocking due to topography and man-made structures. Now in addition to reflectivity a set of independently derived observables of hydrometeors is available, which provide rainfall estimates less sensitive to variations in the hydrometeor size distribution, and the possibility to correct for attenuation. They enable a substantial reduction of the impacts of the artefacts mentioned above and allow us to map the type of hydrometeors including phase and shape, which provides a handle to better estimate condensed phase fluxes and mixing ratios of different hydrometeors. A holistic analysis of the different polarimetric measurements allows to uncover acting microphysical processes like riming, coalescence or breakup during the lifetime of precipitation systems. The new observations also reveal information on additional parameters of the size distributions of the hydrometeors such as mean particle size or shape.

At the same time atmospheric models approach the simulation of the atmosphere on similar spatial scales as the polarimetric radar observations and more clearly unveil shortcomings of bulk microphysical and convection parameterizations developed over the past decades by comparison with observations. Given the new observations by a Germany-wide network of polarimetric radars, we are now in the position to effectively fuse the information content of polarimetry with atmospheric models to improve the representation of clouds and precipitation generating processes in atmospheric models in general and to advance them to a state, which allows to assimilate this new observation data base for an improved prediction of precipitating clouds including the locations, timing and development of convection and severe thunderstorms.

5.2 Delimitation of scope taking into account the duration of a Priority Programme

The scope of the programme is limited to the exploitation of the synergy of radar polarimetry, atmospheric modelling, and data assimilation with a focus on high-impact weather with short forecast horizons. We exclude climatological studies with radar observations, fundamental cloud and aerosol research not exploiting radar polarimetry, and any model and data assimilation research along the lines of classical numerical weather prediction. Any project proposed to the priority programme must be oriented towards exploiting or extending the use of the new polarimetric radar observations and models for an improved cloud/precipitation process understanding, for the development of improved or new parameterizations of moist processes in the atmospheric models, or for data assimilation striving for an improved prediction of convective events.
5.3 Coherence of planned research activities

The exploitation of the synergy between the new polarimetric radar observations and atmospheric models requires critical progress in the individual disciplines. The proposed programme will spurn this progress by advancing radar polarimetry from a so far more purely data-based nowcasting-oriented and guessing avenue to a more quantitative and at the same time probabilistic path, which develops clear bounds on atmospheric states and challenges atmospheric models. At the same time atmospheric models will be further developed such that measurement operators, which simulate virtual radar observations from the model states, become that advanced that also retrievals of fluxes and states from the radar observations can be challenged. Model evaluation strategies will be developed that enable detailed assessments and improvements of specific cloud- and precipitation parameterisations. Finally, data assimilation techniques will be extended, such that the full information from the polarimetric radar observations can be digested to take full advantage of these data for weather prediction especially for short-term high-impact weather development, which we experienced extensively in early summer 2016. Thus the central goal of the programme will be approached from three different aspects, which have in common the exploitation of the synergy between the vast amount of polarimetric radar observations available and state-of-the-art atmospheric models.

5.4 Strategies for collaborating / networking across disciplines and locations

The research programme is organized along the five objectives developed in the state-of-art section. Research along these objectives will be coordinated by the programme committee members as a group. Research proposals must address science questions advancing at least one of the objectives and must be proposed by teams with expertise in at least two fields of the triangle radar polarimetry – atmospheric modelling – data assimilation. The research groups addressing the individual objectives will meet biannually to discuss and exploit their findings. All programme members will meet once a year to monitor progress and readjust their path of research if necessary. In the first of the two three-year periods preferentially PhD students should be educated and do their research in the interdisciplinary field, while the second period should provide a postdoc phase for the PhD projects oriented most closely to the central common goal.

5.5 Early career support, promotion of female researchers, family-friendly policies

The recruitment of suitable PhD candidates will be based on a common call and common selection colloquium. The advancement of the PhD students will be monitored during two annual meetings and fostered by doctoral committees crossing disciplines and institutions. Since in the field of research female students are about as frequent as male students there is no extra need at that stage. During the second phase, however, there is a clear need to advance promising female Postdocs and prepare them for their next step in their scientific career, because female scientists are still a clear minority at the professor level. The programme committee sees it as its responsibility to identify potential candidates and to aid them in structuring their developments including research visits at other institutes contributing to the programme and/or exchange with international institutions. We will apply for funding in the module Gender Equality Measures in Research Networks to finance the travel costs of female PhD students and Postdocs and to provide family support for young-scientist parents by funding of travel expenses for children arising in connection with project-related trips, and childcare during conferences.
5.6 Networking of planned research activities within the international research system

The existing strong collaboration with international groups on radar polarimetry especially in the U.S.A. will be further exploited for the programme. The Meteorological Institute of the University of Bonn (MIUB) collaborates since many years with Alexander Ryzhkov (member of the advisory board). He is senior research scientist and Affiliate Professor at CIMMS/NSSL (Cooperative Institute for Mesoscale Meteorological Studies/NOAA Severe Storms Laboratory) in Norman, Oklahoma, and an outstanding radar expert documented by more than 130 publications and many awards. The intense collaboration with A. Ryzhkov is documented by many joint publications (e.g., Borowska et al. 2011a; 2011b; Diederich et al. 2015a; 2015b; Ryzhkov et al. 2014; Trömel et al. 2013; 2014a; 2014b), regular visits, guest lectures and a Memorandum of Agreement between CIMMS, the University of Oklahoma and the MIUB. He is also actively involved in collaborations with cloud modelers in the US and abroad (e.g., Israel and Germany) in the framework of the US Department of Energy Atmospheric System Research (DOE ASR) programme and the Aerosol, Clouds, Precipitation, Climate (ACPC) international research initiative.

Existing collaborations with the Atmospheric Radiation Measurement (ARM) community are valuable for the Priority Programme and will be extended. Since July 2012 S. Trömel is member of the ARM Radar Science steering committee headed by Pavlos Kollias (Professor at Stony Brook University). P. Kollias, who is affiliated to the University of Cologne as International faculty, is a renowned expert in the application of short wavelength radars for cloud and precipitation research from ground-based and space-based platforms and a member in the Mission Advisory Group for ESA EarthCARE (European Space Agency Earth Clouds Aerosols Radiation Experiment). Exchange with D. McLaughlin (former Director of NSF CASA), P. Kollias (Stony Brook) and A. Ryzhkov (NOAA/NSSL) on the benefit of phased array radars for research on convective initiation is anticipated. The deployment of a phased array radar in Bonn for testing purposes is under discussion.

Collaborations are already established with Alexander Khain (Hebrew University, member of the advisory board) concerning the polarimetric radar forward operator, which is fundamental for practically all objectives of the programme. Also, his expertise in cloud microphysics is of great relevance for the Priority Programme suggested. He is a Full Professor at the Department of Atmospheric Sciences of The Hebrew University of Jerusalem and published about 180 scientific papers on, amongst others, cloud microphysics and cloud-aerosol interaction. He developed the probably most advanced spectral bin microphysics (SBM) cloud model known as the Hebrew University Cloud Model (HUCM). The HUCM and the SBM package of HUCM is implemented e.g. in Pacific National North-West Laboratory (PNNL) (models WRF/SBM; SAM/SBM), NASA Goddard (GCE/SBM), NSSL (Oklahoma University), and Pennsylvanian State University. His expertise in modelling of cloud microphysics is highly valuable for the suggested Priority Programme.

Dmitri Moisseev is an Associate Professor of radar meteorology at University of Helsinki with profound expertise in microphysics of clouds and precipitation and engaged to improve our understanding of cloud and precipitation formation processes and thus the accuracy of weather and climate forecasts. During his visit of the Meteorological Institute in Bonn in summer 2016, the plan was made to pool the European radar community and submit together near the end of 2016 an innovative training network (ITN) within the Marie Curie action.

Dr. Ann Fridlind (member of the advisory board) and her group at the NASA Goddard Institute for Space Studies (New York) are pioneering the use of polarimetric radar data for the evaluation of processes in atmospheric models. A close collaboration is active with the team in Leipzig (e.g. research semester by J. Quaas in New York in 2015). A. Fridlind and J. Quaas together serve on the steering committee of the Aerosols, Cloud, Precipitation and Climate initiative by
GEWEX and iLEAPS in the context of which the exploitation of polarimetric radar observations for a better process understanding and model improvements is actively promoted.

Dr. Matthew Kumjian (member of the advisory board) is an Assistant Professor at the Pennsylvania State University. A main thrust of his research involves understanding the impact of precipitation processes on the polarimetric radar variables. As part of this work, Matthew Kumjian contributed the idea of “microphysical fingerprints” in polarimetric radar data, quantifying processes such as evaporation, size sorting, collision-coalescence-breakup, melting, and freezing using simplified models. Additionally, he worked with storm-scale numerical models, modifying microphysics parameterizations and using these simulations as tools to understand microphysics in deep convective storms (including rain and hail production in supercell storms). He is well suited to contribute to the exciting priority programme on synthesizing polarimetric radar observations and atmospheric modeling.

The members of the programme committee are already networking with the international radar and microphysics community. These collaborations will be fostered, exploited and extended within the Priority Programme. A joint conference is envisioned in the second year of the potential funding period, inviting in addition to the scientists already mentioned especially the European radar community, like e.g. Prof. H. Russchenberg (TU-Delft), Prof. A. Berne (École Polytechnique Fédérale de Lausanne), and Prof. P. Tabary (Météo France, Toulouse) as well as microphysicists, and modelers, like Dr. Axel Seifert (DWD), Dr. Ulrich Blahak (DWD), Prof. Corinna Hoose (KIT), or Prof. Bjorn Stevens (MPI).

6 Differentiation from other on-going programmes on related topics, e.g. Collaborative Research Centres, Research Units, programmes by other funding agencies

The BMBF-funded research programme High-Definition Clouds and Precipitation for Climate Prediction (HD(CP)) on clouds and precipitation in the climate system, which entered its second phase in 2016 addresses as its central goal the development and exploitation of a high-resolution (100 m) version of the ICOsahedral Non-hydrostatic General Circulation Model (ICON) to improve cloud parameterizations in climate models. Radar polarimetry, convection initiation, data assimilation and weather forecasting are not addressed in any current project within the programme.

A preproposal has been submitted to DFG for the research unit RealPEP (Near-Realtime Quantitative Precipitation Estimation and Prediction) on the use of polarimetric radar observations for improving quantitative precipitation estimation and its nowcasting for hydrological forecasts. The central goal is an observation-based nowcasting by seeking predictors in the radar observations for convection intensification and by extrapolating these. These extrapolations will be used in one data assimilation subproject. The exploitation of radar polarimetry for data assimilation and the improvement of parameterizations are not addressed. Convective initiation is only approached via satellite measurements. No atmospheric modelers – a key group in the planned programme - are part of RealPEP.

In the Transregional Collaborative Research Centre 32 (TR32) on “Patterns in Landsurface-Vegetation-Atmosphere Systems – Monitoring Modelling and Data Assimilation” radar polarimetry is addressed in one project for improving quantitative precipitation estimation at the surface for hydrological purposes. Data assimilation is applied for improving the state and parameters of the subsurface for an improved representation of exchange fluxes.

The Transregional Collaborative Research Centre “Arctic Amplification: Climate relevant atmospheric and surface processes and feedback mechanisms” (AC³, TR172) as one of its themes assesses cloud- and precipitation processes. However, the focus is on the specific
region of the Arctic, and does not involve polarimetric radar observations nor data assimilation as core topics.

The Research Unit FOR2131 on Data Assimilation for Improved Characterization of Fluxes across Compartmental Interfaces focuses on strongly coupled data assimilation in the terrestrial system. Similar to TR32 non-polarimetric radar observations are used for surface rain rate retrievals. Radar polarimetry, convection, clouds and precipitation processes are not addressed.

The Transregional Collaborative Research Centre 165 (TR165) Waves to Weather addresses weather predictability in general. The development of larger synoptic systems like midlatitude low-pressure systems is the focus; one project addresses convection initiation from a theoretical perspective. Ensemble data assimilation is a central tool, which will be further developed. Radar polarimetry and the improvement of cloud and precipitation processes in models are not addressed.

Radar polarimetry has been a component in the first phase of the Hans-Ertel-Zentrum für Wetterforschung (HErZ) of Ministry of transportation and Infrastructure (BMVI) and DWD. The current research topics focus on data assimilation as in TR165, a high-resolution reanalysis, boundary-layer and convection processes with high-resolution models, and the use of weather information for the public. Radar polarimetry is not used in any of the projects.

The current Extramural Research Programme of the German Weather Service funds research towards an integrated forecasting system and seamless prediction from nowcasting to short-time forecasting. One PhD-project (HailSize) employs radar polarimetry for a radar-based hail-size discrimination algorithm for hail nowcasting. A second PhD-project (BlackIce) aims at the nowcasting of situations, when liquid rain hits the surface at sub-freezing temperatures by combining information from polarimetric radar, model predictions and in-situ observations. The improvement of cloud and precipitation processes in models is not addressed in both projects.

7 Qualification of coordinator to manage a research network

Silke Trömel, assistant professor (AOR) at the Meteorological Institute of University Bonn, has a strong background in radar polarimetry, the synergistic use of different observations, compositing, quantitative rainfall estimation based on radar polarimetry and microwave backhaul links, as well as the detection of microphysical processes in radar measurements and microphysical characterization. From September 2011 to December 2014 she led together with Kathrin Wapler (DWD) the research group on Object-based Analysis and SEamless prediction (HErZ-OASE) of the Hans-Ertel-Centre for Weather Research (HErZ, http://www.dwd.de/ertel-zentrum). HErZ-OASE built upon achievements from the project cluster AQUARadar (seven projects from different institutes), also coordinated by Silke Trömel in the framework of SPP1167 “Quantitative Precipitation Forecasting” from May 2006 to April 2009.

Johannes Quaas, Professor for Theoretical Meteorology at the University of Leipzig, has led research research groups for more than ten year (DFG-Emmy Noether Junior Research Group at Max Planck Institute for Meteorology in Hamburg, 2006 – 2011; research group on Clouds and Global Climate, University of Leipzig, since 2011). He has served as work package coordinator for different EU projects (COMBINE, GA 226520, 2009 -2013; EUCLIPSE, GA 244067, 2010 – 2013) and national projects (HD(CP)^2, BMBF-funded; 2012 – 2016 and in its second phase since 2016) and led many smaller projects funded by DFG, ERC, DWD and other agencies. He is actively contributing to SPP 1689 “Climate engineering” and SPP 1294 “HALO” and to the TR 172 “Arctic Amplification”. He was vice chair and working group leader of COST Action ES0905 on Convection Parameterisations, and co-leads the international Aerosols, Clouds, Precipitation and Climate (ACPC) initiative (by GEWEX and iLEAPS).
8 List of potential applicants

Radar meteorology
Prof. Dr. Felix Ament, University Hamburg, Hamburg
Dr. Marco Clemens, University Hamburg, Hamburg
Dr. Michael Frech, Deutscher Wetterdienst (DWD), Offenbach
Dr. Silke Groß, German Aerospace Centre (DLR), Oberpfaffenhofen
Dr. Martin Hagen, German Aerospace Centre (DLR), Oberpfaffenhofen
Dr. Jan Handwerker, Karlsruhe Institute for Technology (KIT), Karlsruhe
Dr. Norbert Kalthoff, Karlsruhe Institute for Technology (KIT), Karlsruhe
Dr. Stefan Kneifel, University Cologne, Cologne
Dr. Michael Kunz, Karlsruhe Institute for Technology (KIT), Karlsruhe
Dr. Ulrich Löhnert, University Cologne, Cologne
Dr. Patric Seifert, Leibniz Institute for Tropospheric Research (TROPOS), Leipzig
Dr. Jörg Seltmann, Deutscher Wetterdienst (DWD), Offenbach
Prof. Dr. Clemens Simmer, University Bonn, Bonn
PD Dr. Silke Trömel, University Bonn, Bonn

Convection, cloud and precipitation modelling
Dr. Ulrich Blahak, Deutscher Wetterdienst (DWD), Offenbach
Prof. Dr. Andreas Bott, University Bonn
Dr. Ulrike Burkhardt, German Aerospace Centre (DLR), Oberpfaffenhofen
Dr. Ulrich Corrmeier, Karlsruhe Institute for Technology (KIT), Karlsruhe
Dr. Cathy Hohenegger, Hans-Ertel Centre for Weather Research, Hamburg
Prof. Dr. Corinna Hoose, Karlsruhe Institute for Technology (KIT), Karlsruhe
Dr. Daniel Klocke, Hans-Ertel Centre for Weather Research, Hamburg
Dr. Martin Köhler, Deutscher Wetterdienst (DWD), Offenbach
Dr. Oswald Knoth, Leipniz Institute for Tropospheric Research (TROPOS), Leipzig
Prof. Dr. Roel Neggers, University Cologne, Cologne
Dr. Axel Seifert, Deutscher Wetterdienst (DWD), Offenbach
Prof. Dr. Yaping Shao, University Cologne, Cologne
Prof. Dr. Peter Spichtinger, University Mainz, Mainz
Prof. Dr. Bjorn Stevens, Max-Planck-Institute for Meteorology, Hamburg
Prof. Dr. Christiane Voigt, German Aerospace Centre (DLR), Oberpfaffenhofen

Data assimilation
Prof. Dr. George Craig, Ludwig-Maximilian-University, Munich
Prof. Dr. Andreas Hense, University Bonn, Bonn
Dr. Tijana Janjic-Pfander, Deutscher Wetterdienst, Offenbach
Dr. Jan Keller, Deutscher Wetterdienst (DWD), Offenbach
Prof. Dr. Roland Potthast, Deutscher Wetterdienst (DWD), Offenbach
Dr. Christoph Schraff, Deutscher Wetterdienst (DWD) Offenbach
Dr. Martin Weissmann, Ludwig-Maximilian-University, Munich

9 Justification of requested annual funding amount for the first funding period of one, two or three years

The Priority Programme PROM is proposed for two 3-year periods from 2017 to 2023. The programme aims at funding 12 science teams uniting each expertise from at least two fields of the triangle polarimetric radar, atmospheric modelling, and data assimilation (24 partners).
The following annual costs are estimated:
Personnel: Funding for one PhD student (75% TVL E13, 46,350 € annually) or Post-Doc (66,600 € annually) for each partner. With a total of 24 partners, and 3/4 of the project staff PhD students, this amounts to
1,233,900 € annually.

Additional costs: for travel (participation to three international conferences per partner – one for PI and one for PhD/Post-Doc, at 1,500 € each), publications (per partner 750 €), and student work (per partner 3,600 €) are estimated at
176,400 € annually.

Young Scientists exchange: Support for PhD students and Post-docs to spend 6 months at a partner institution during each 3 years (1,000 € per month for living, plus 200 € for travel) totals 148,800 € per funding period, or
49,600 € annually.

Bi-annual science workshops: Support for workshop logistics (5,000 € each), travel support for one PI and Phd/Post-Doc per partner (600 € per participant), invitation of advisory board members (1200 € on average per flight plus 400 € allowance) totalling
80,400 € annually.

The project coordination includes the organisation of the PhD student and Post-doc exchanges, support with international advertisement and candidate selection for the project staff, organisation of the workshops, as well as outreach including maintenance of a project web site and wiki pages. For this, an administrator position (TVL E13) and support for a student worker (6,000 €) are requested.
72,600 € annually.

Financial means from the special DFG funding for gender equality measures are requested; as detailed above, we expect these to be particularly relevant in the second 3-year period.
First period: 2,000 annually.

Total
1,614,900 € annually.
4,844,700 € total sum.