Title: Overview: Fusion of Radar Polarimetry and Numerical Atmospheric Modelling Towards an Improved Understanding of Cloud and Precipitation Processes.

General Comments: As the overview article for the PROM special issue, this manuscript provides a well-rounded description of the constituent PROM projects. Preliminary results and updates for each of the projects are included along with some context for where they fit into the current state-of-the-art understanding of combining radar polarimetry with models. Overall, the writing is clear and well-organized, with concise summaries of what has been found so far and what is planned for phase 2 of the project, although there are at times awkward phrasings and sentences that should be re-organized (some of which are addressed in the technical corrections). In general, given the scope of how many topics, projects, and data sources are covered in the paper, the large majority of comments are merely clarifying in nature, although some work is needed to make some of the formatting of the manuscript consistent throughout (e.g., abbreviations, date formatting, references, etc). Otherwise pending some of the requested clarifications I believe the manuscript can be published in the special issue.

We like to thank the reviewer for his time and valuable input which helps to improve our manuscript. Please see our replies highlighted in blue along with your suggestions. The revised manuscript is also provided with tracked-changes for clarity.

Specific Comments:

Line 24 (and 40): Is there evidence that can be provided that cloud and precipitation processes are “the” main source of uncertainty in NWP, or one among many? Consider changing “the” to “a”.

The reviewer is right in pointing to a sloppy formulation here. In the entire process, it is only one of several important aspects (e.g. initial conditions in NWP and boundary conditions in climate projects are also very uncertain). We chose to switch to “a” main source of uncertainty in the Abstract, and are now precise in what we mean in the opening sentence of the Introduction by clarifying we mean it is “the” main source within the models themselves (and also provide a reference for this assessment).

Line 53: I understand what the authors mean by “the triangle” of polarimetry, models, and DA, but this phrasing is a bit awkward. Perhaps “tripartite” might work better here, or “the triangle between radar polarimetry…”

Yes, we followed your second suggestion and changed to “..the triangle between radar polarimetry, atmospheric models, and data assimilation and called for a coordinated interdisciplinary effort.”

Line 62: Can the authors expand a bit on what is meant by “quantitative process detection”? Is this referring to things like Hydrometeor Classification Algorithms or more like a quantitative analysis of polarimetric fingerprints?

The focus is not on standard Hydrometeor Classification Algorithms (e.g. Dolan and Rutledge, 2009) providing the dominant hydrometeor type (ice, snow, rain, hail, or graupel) within a volume, but includes retrievals of more advanced hydrometeor partitioning ratios from radar observations, defined as the relative mass contribution of a specific hydrometeor type, or further development of polarimetric retrievals of hydrometeor mixing ratios, like liquid water content and ice water content including their accuracies. We also focus on a quantitative analysis of polarimetric fingerprints, e.g. aggregation and riming processes generate similar tendencies in ZH and ZDR. A more detailed quantitative analysis and/or the inclusion of additional (e.g. spectral) information may allow distinguishing between those processes exclusively based on weather radar observations. Another emerging field of research within the scope of SPP-PROM are thermodynamics, i.e. latent heat profile retrievals. We included in brackets for clarification in the manuscript: "(e.g. a quantitative analysis of polarimetric fingerprints enabling a distinction between aggregation and riming, microphysical retrievals like ice water content or latent heat profile retrievals)"

Line 76 and elsewhere: Inconsistent abbreviation for Section (e.g., Sec. vs. Sect.). I would tend toward not abbreviating it at all, but it should be consistent.

We cross-checked the guidelines of the journal: "The abbreviation "Sect." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence." We changed it accordingly throughout the text.

Line 99: Do the authors mean fronts themselves or frontal precipitation being composed of these filaments? Please clarify. It is also not immediately clear to the reviewer how this portion relates to the rest of the paragraph/work.

We agree with the reviewer that this statement is not very clear, and since indeed it is not essential for the understanding of what we want to convey, we delete it in the revised manuscript.

Line 104: Please define the acronym ECHAM.

ECHAM is a general circulation model developed by the Max Planck Institute for Meteorology in Hamburg by modifying global forecast models developed by ECMWF (European Centre for Medium-Range Weather Forecasts). The model was given its name as a combination of its origin (the 'EC' being short for 'ECMWF') and the place of development of its parameterisation package, Hamburg. In the manuscript, we included a short note, that the acronym is a combination of ECMWF and Hamburg.

Line 113: I find the reference to the "ICON variants" confusing. Do the authors mean the NWP-scale ICON versions (i.e., those that inherited the COSMO microphysics)? Or do they mean the ICON model in general vs. either ECHAM or COSMO? Please clarify.

This was indeed an overly short and thus unclear formulation. We now write in a more precise formulation: "In PROM, primarily the ICON model is used, in its three different variants (ICON-LEM, ICON-NWP, and ICON-A/GCM)"

Line 118: Can the authors expand just a bit on what is meant by "intricate" here? Is it that the actual distributions are more intricate as is inherent to all spectral bin approaches or are there additional numbers of ice categories, etc?

We explain this now in a bracket, namely that ice - different from liquid-water droplets that are spherical and of constant density - may take different shapes and densities.

Line 132: This may be a bit pedantic, but I don't think it should be said that weather radars sample precipitation processes -- rather, they sample precipitation-sized particles from which ongoing microphysical processes can be inferred. Consider revising.

The text was revised accordingly: "… weather radars which provide a 3-D sampling of precipitation particles in the lower atmosphere above Germany every five minutes."

Line 144: While I understood the point, the phrasing "allow even more to zoom in" is a bit awkward. Consider "allow for a more granular look at"

The text was modified following the reviewer's suggestion.

Line 158 and elsewhere: There are various inconsistent date formats throughout the manuscript (e.g., line 917). Please make these consistent in "DD Month YYYY" format throughout.

The correct date format is used now.

Line 159 and elsewhere: There are repeated definitions of certain acronyms like JOYCE-cf, which has already been defined. Please revise so that each acronym is only defined once.

Thanks, we deleted the repeated definition.

Line 166: By "above -15C" I assume the authors mean (physically) above the -15C level rather than at temperatures above -15C, correct? Please clarify.

Correct, above -15°C refers to temperatures colder than -15°C (so at heights above the -15°C isotherm). This has been changed in the document.

Line 176: Please define acronyms "POLDIRAD", "DLR", "miraMACS", and "LMU".

POLDIRAD is the acronym for the C-band Polarization Diversity Doppler Radar at DLR, where DLR stands for Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center). The acronym miraMACS refers to the MIllimeter-wave cloud RAdar of the Munich Aerosol Cloud Scanner at LMU, where LMU stands for the Ludwig-Maximilians-University. We added this information where applicable.

Line 185: While it is still being developed, can a bit more be said about this retrieval algorithm -- what is it retrieving? IWC? Dm? Etc. What type of algorithm is it?

We added the missing details to the sentence describing the retrieval in development which now reads: "The measurements of Z, DWR and ZDR enter a retrieval algorithm currently in development where they are compared to T-matrix scattering simulations of horizontally oriented soft spheroids using a cost function minimization."

Line 191: What is meant here by "sound" statistical basis? Can more detail be provided?

Thank you for pointing out this inaccuracy! We replaced this adjective with a more explanatory sentence: “While previous studies only compared a limited number of microphysics schemes and days or were limited to case studies, the IcePolCKa project compiled over 50 convective days of polarimetric measurements and simulations with 5 different schemes over a 2-year period.”

Section 3.1: Overall, it is not entirely clear to me the differences between IMPRINT and IcePolCKa, as they both utilize DWR and multi-frequency measurements (while IMPRINT admittedly also uses spectral polarimetry) and focus on ice microphysical processes. Is the primary difference the wavelengths used (e.g., Ka-W vs. Ka-C), or the fact that models are only a component in IcePolCKa? I believe there is easily room for both projects to exist given outstanding uncertainties in ice microphysics, but it might be helpful if they were explicitly contrasted so readers can understand where each of them fits in. (This is done well in the HydroColumn section on lines 199-203, which specifically notes the use of spectral analysis at C band which makes that project unique).

We thank the reviewer for this important comment. One new component of the IMPRINT project is indeed the combination of triple-frequency zenith pointing observations with spectral cloud radar polarimetry (as opposed to the C-band polarimetric radar of IcePolCKa). The use of W-band polarimetry allows as to be much more sensitive to smaller ice particles and lower particle concentrations as for example KDP scales with 1/wavelength. Furthermore, we are also using three vertically pointing radars at X, Ka and W-band frequencies, which provide us with additional spectral information, and a wider range of particle sizes can be characterized (DWR-KaW is sensitive to the early growth of aggregates, whereas DWR-XKa for the later growth). The IMPRINT project focuses on the understanding of ice microphysical processes, mainly secondary ice production and aggregation by combining the radar observations with a 1D Monte-Carlo Lagragian super-particle model, with which the processes of ice formation and growth can be studied in detail. The lagrangian nature of the model used allows us to track the particles formation and growth history, and with the newly implemented habit prediction scheme and fragmentation scheme we are able to test hypotheses which were made from studying the observations.

In contrast to IMPRINT, the IcePolCKa project explores the feasibility to narrow down ice crystal properties from spatially separated weather and cloud radars. Coordinated Range-Height-Indicator (RHI, varying elevation at constant azimuth) scans along the 23 km long cross-section between the two radar instruments allow to track and observe DWR and Z_{DR} fingerprints of individual cells. *In IcePolCKa we furthermore study the ice particle growth and its role in precipitation formation within convective cells, while the IMPRINT project focuses on typical mid-latitude frontal clouds which occur most frequently during winter time. Convection would simply limit the use of Doppler spectral information (due to dynamical broadening, smoothing effects) which is one of the key approaches in IMPRINT. In IcePolCKa we currently develop an algorithm which combines Z, Z_{DR} and DWR measurements from the spatially separated radars to retrieve IWC, D_m and the aspect ratio of ice crystals. These parameters are retrieved iteratively using a least-squares fit between our measurements and T-matrix scattering simulations. Since we tried to find the simplest ice particle model, which is still able to explain our measurements, we used the model of horizontally aligned spheroids in combination with an effective medium approximation following Hogan et al (2012). In contrast to other studies our approach allows us to study the covariance of DWR and Z_{DR} while* *seamlessly varying the particle density, D_m and the aspect ratio. For this task, more sophisticated models, like DDA simulations of specific ice crystals, would introduce additional challenges to define the aspect ratio in the first place and make it hard to sort a collection of ice shapes along these free variables.*

We introduced the above mentioned explanations in the manuscript and tried to clarify the different focus areas of the two projects and hope it is now more clear to the readers.

Line 263: Is this cross-section reconstructed from a PPI or a true RHI? It appears to be the former but this should be added.

Yes, the cross-section is reconstructed from a measured volume scan. Following text has been added in the revised manuscript:

"Fig. 5 shows vertical cross-sections reconstructed from volume scans measured with BoXPol …"

Line 266: I am a bit confused by the sudden introduction of B-PRO, especially given the subsequent space dedicated to the polarimetric EMVORADO in 4.1. What are their differences and why would one be used over the other (e.g., in section 4.2.1)? A bit more info might be helpful here and explain why they are switched between.

Selection of B-PRO for this study was driven by availability: B-PRO was already available at the start of the PROM project, while Pol-EMVORADO has been developed within the project. Hence, the FO processing in the ILACPR sub-project was carried out using B-PRO (with some refinements done during PROM and benefitting from experiences and findings of the parallel Pol-EMVORADO development). Differences within the actual polarimetric FO parts of B-PRO and (Pol-)EMVORADO are rather minor. Preliminary comparisons exhibit only small differences that do not affect the conclusions of the ILACPR study.

However, EMVORADO itself has evolved significantly between the version B-PRO is based on and the current one, Pol-EMVORADO has been developed for and is integrated into. This includes all sensor characteristics: B-PRO is only capable of calculating radar parameters at (NWP) model grid points, and any sensor characteristics (other than radar frequency) have to be implemented by the users themselves. EMVORADO on the other hand considers the actual observation setup incl. tracing of the bending ray(s) through the 3D model fields, the beam pattern and beam broadening, allowing to consider the effects of attenuation. Furthermore, the current EMVORADO is much more computationally efficient by applying lookup tables that get calculated once if necessary (all described in detail in Zeng et al., 2016). Pol-EMVORADO makes all these new(er) EMVORADO features available also for polarimetric calculations.

Particularly at this place in the manuscript, we consider these details in history as of minor interest for the reader, hence prefer(red) to leave them out here. The features of (current) EMVORADO are listed in Sect 4.1 that covers the (primary) forward operator development within the PROM project. Following text has been added in the revised manuscript to clarify the reviewer's concern:

"To generate the synthetic radar observations the Bonn Polarimetric Radar forward Operator, B-PRO, (Xie et al., 2021; Xie et al., 2016; Heinze et al., 2017) has been applied. B-PRO is based on an early fork of the non-polarimetric version of EMVORADO (Zeng et al. 2016) and expands its code part for computing unattenuated radar reflectivity on the original model grid (Blahak, 2016) to unattenuated polarimetric variables based on spheroidal shape assumptions (T-matrix). Because the full polarimetric version of EMVORADO (Pol-EMVORADO) as described below in Section 4.1 was only released very recently, the model data in this sub-project was processed using B-PRO. Preliminary comparisons between B-PRO and Pol-EMVORADO (not shown here) exhibit negligible differences in their results on the model grid, but Pol-EMVORADO would have been much more computationally efficient and would have allowed to take effects of beam broadening and attenuation along the actual radar ray paths into account."

Lines 275-277: Please move this information up to line 265 where the perturbed CN and INP are first mentioned.

Thanks, we followed your suggestion.

Lines 273-275, 277-279: These are interesting results -- can the authors add a bit about what they might imply, as is done for the subsequent ZDR column discussion? I would have expected higher CN to result in higher Z due to suppressed warm rain processes and enhanced growth of hail due to the availability of SLW which would cause higher Z as earlier studies have implied, but it seems this is not the case here. Also, the finding that IN doesn't seem to change the simulated polarimetric variables while Continental vs. maritime does (lines 277-279) is interesting and deserves further exploration, even if brief.

Based on the 2-moment cloud microphysics scheme with fixed shape parameters for the hydrometeor size distribution, we find that "high CN resulting in high Z", does not seem to apply for this case. The simulations with maritime CN produce low cloud droplet concentrations with relatively larger mean diameter compared to the continental CN. Accompanied by strong updraft, this also leads to high concentrations of supercooled raindrops above the melting layer with broader spatial extent (due to broader updraft region) compared to continental simulations. In terms of ice processes, the maritime simulation with low IN has a higher mean ice particle diameter, and also produces large size hail particles compared to the continental runs, resulting in higher Z.

Also, as shown in the time-series of the CAF, simulations with continental aerosol and default/high IN tend to exhibit similar behaviour in radar space, with the latter exhibiting higher CAF only at latter stages of the storm. The continental CN simulations with default and high IN differ in terms of simulated updraft speed and total hydrometeor content, being higher for the latter one. However, Cont-highIN produces relatively smaller size graupel and hail particles compared to Cont-defIN, resulting in similar Z.

The following text has been added in the revised manuscript:

"The simulations with maritime CN produce low cloud droplet concentrations with relatively larger mean diameter compared to the continental CN. Accompanied by very strong updraft, this also leads to high concentrations of supercooled raindrops above the melting layer with broader spatial extent (due to broader updraft region) compared to continental simulations. This contributes to enhanced growth of hail, producing larger size hail particles compared to the continental runs, resulting in higher Z. Also, as shown in the time-series of the CAF, simulations with continental aerosol and default/high IN tend to exhibit similar behaviour in radar space, with the latter exhibiting higher CAF only at latter stages of the storm. The continental CN simulations with default and high IN differ in terms of simulated updraft speed and total hydrometeor content, being higher for the latter one. However, Cont-highIN produces smaller graupel and hail particles compared to Cont-defIN, resulting in similar Z."

Line 305-306: This sentence ("An example…") seems out of place with the surrounding discussion since an example is already referenced in an earlier sentence.

We agree, these lines were disordered and related to 2 aspects: 1) uncertainties in bulk models in general and 2) determination of parameters that are not constrained by the model but are relevant to the forward operator. We revised as follows:

"However, bulk cloud microphysical parametrizations required for NWP models include assumptions on several critical parameters and processes which are not explicitly prognosed respectively resolved by the governing numerical model. An example are the inherently assumed particle size distributions and their relations to the prognostic moments (hydrometeor mass- and number densities). Another challenge is the handling of hydrometeor parameters which are insufficiently or not at all constrained by the model's microphysics but are highly relevant for the calculation of virtual observations in the (radar) forward operator. For example, in most operational bulk schemes the melting state as well as shape, microstructure, spatial orientation and melting state of the different hydrometeors are not prognostic (or not even implicitly assumed), so that, as a way out, meaningful assumptions need to be made in observation operators in order to compute meaningful virtual observations."

Line 330: What is meant by "reflectivity weighting" here?

The beam pattern (or antenna pattern or instrumental function), ie. the different weight of the measured parameter depending on where within the sensor's (non-infinitesimal) field of view the signal is arriving. Reformulated as follows:

"The effects of neglecting radar beam pattern and broadening..."

Line 354: "Typical features" is a bit vague. Can the authors describe the features in Fig. 7 a bit more specifically?

We extended the sentence with the information "i.e. bands of enhanced Z_{DR} and K_{DP} in the DGL and decreasing but mostly positive values downwards to the melting layer."

Line 380: Isn't the DGL typically defined with its center around -15C (as stated on line 210)?

Yes, you are right. It is corrected in the revised manuscript.

Line 382: The polarimetric variables (e.g., ZDR and KDP) were defined early on but then occasionally re-defined throughout the manuscript (E.g., lines 382, 948, 959). These should be made consistent to (generally) always use the abbreviation once introduced.

Thanks, we clarified the distinction between the differential reflectivity in logarithmic scale Z_{DR} and the differential reflectivity in linear scale Z_{dr}. However, to our knowledge it is fine, and sometimes also wanted, to repeat the definitions in figure captions, to enable the understanding of figures without the text.

Lines 391-393: Am I understanding correctly that this then implies a deficiency in the radar operator? That is, if the model is actually simulating significant graupel (even if erroneously) but the HMC applied to the simulated polarimetric observations does not identify graupel, that implies that there is an incongruence between the operator and the model physics, correct? This is an interesting finding but a bit more detail might be helpful.

There are deficiencies in the operator, but mostly regarding the representation of snow and more pristine ice particles (as outlined in the manuscript). Regarding the point the reviewer is addressing, we reformulated the sentence in the manuscript for clarification: "Applying the HMC, which is based on clustering, to the virtual observations, however, it does not reproduce a graupel layer of similar intensity (Fig. 8c), probably caused by a too strong ZH and temperature influence (compare with Fig. 7) relative to the polarimetric variables in the classification scheme which needs further investigation. A persistent challenge in according routines is, that clusters are always separated by the 0°C-level (e.g. Ribaud et al., 2019), i.e. hail or graupel are identified as clusters only below or above the melting layer."

Reference:

Ribaud, J.-F., L. A. T. Machado, and T. Biscaro: X-band dual-polarization radar-based hydrometeor classification for Brazilian tropical precipitation systems. Atmos. Meas. Tech. 12, 811–837, 2019.

Lines 406-407: The relevant letters in the full name of the project should be capitalized with the acronym wrapped in parentheses to match the other projects.

Yes, we changed it accordingly.

Line 477: Can the issues encountered with KDP data be briefly explained?

The authors studied a supercell case observed in Oklahoma and KDP values showed high observation errors as a result of contamination from wet hail, dust and debris and nonuniform beam filling. We added this information in the manuscript.

Line 488-489: This again may be pedantic, but I would rephrase this slightly. We have had 3- and 4-D mosaics of Z for a while now which do contain microphysical information about hydrometeors' size, concentration, and phase -- these are just severely underconstrained and underdetermined. Perhaps instead of "for the first time" the authors can say something like, "modellers now hold an unprecedented amount of microphysics-related…"

We like to make the comment that the microphysical information content of mosaics of Z regarding ongoing precipitation generating processes is very limited compared to polarimetric mosaics and also reflectivity-based microphysical retrievals like LWC and IWC show higher uncertainties compared to their polarimetric counterparts. However, we are also fine with your formulation and revised the sentence accordingly.

References: There are some inconsistencies regarding the formatting of the references (e.g. journal abbreviations (Monthly Weather Review vs. Mon. Wea. Rev, lines 836 vs. 840.), occasionally “pp.” before the page ranges, missing trailing periods, missing commas (E.g., line 740), etc).

Thanks, we went again through the references and we hope all inconsistencies are corrected now.

Figure 2: I believe the caption here is wrong, with b) and c) switched compared to the figure labeling.

Yes, we corrected it.

Figure 5: It was hard for me to see the grey lines in panel (a). Can these be made much bolder/wider?

Done.

Technical Corrections:

Line 26: Remove comma after “hypothesis” ->Ok

Line 28-29: “C band” → “C-band”-> OK

Line 32: “still considerable knowledge gaps exist” → “considerable knowledge gaps still exist”-> OK

Line 37: “it” → “this manuscript” or “this article”-> OK

Line 42: Remove “Since several years”-> OK

Line 46: “parallel to” → “parallel with”-> OK

Line 53: “called” → “call”-> OK

Line 56: “started” → “began in”-> OK

Line 83, 117: “cloud-” → “cloud”-> OK

Line 93: “still rudimentary” → “still-rudimentary”-> OK

Line 105 and elsewhere (e.g., line 423): “of the order” → “on the order”-> OK

Line 107 and elsewhere (e.g., line 418, 457): “currently replaced” → “currently being replaced”-> OK

Line 108: Add “the” before Max-Planck.-> OK

Line 118: “Hebrew University cloud model” → “Hebrew University Cloud Model”-> OK

Line 120: “by” → “to”-> OK

Line 136: Think an “and” is needed before “their observations”.-> We suggest to include “but”

Line 142: Consider changing “strength” to “magnitude”.-> We followed your suggestion.

Line 143: “differential change” → “differential phase” or “differential phase shift”-> Corrected.

Line 149: “at improving” → “to improve”-> OK

Line 153: “polarimetric” → “polarimetry”-> OK

Line 155: Should “Ze” be “Ze” here (as on line 232)?-> Yes, we adapted the formatting.

Line 160: “in about” → “at about”-> OK

Line 161: “in case” → “in the case”-> OK

Line 179: “23 km long” → “23-km-long”-> We think this is not correct?!

Line 182: “wavelength” → “wavelengths”-> The text is revised.

Line 191: Remove “E.g.”-> OK

Line 191: “Predicted Particle Properties” should be capitalized.-> OK

Line 210: No hyphen needed between Z and increase. -> Hyphen deleted.

Line 221: “thrives” → “seeks”-> OK

Line 237, 240, 255: “allow(s)” → “allow(s) us”-> OK

Line 238: Should “slanding” be “slanting” or “shifting”?-> Yes, slanting.

Line 268: Should 3.1 refer to section 4.1 instead? -> Removed.

Line 280, 282, 283, etc: No hyphen needed in ZDR column. Also remove “those”. -> Done.

Line 307: “interaction” → “interactions” -> Done.

Line 311: “Central” → “The central” -> Done.

Line 315: “up to now” → “up-to-now” -> Done.

Line 320: Should “access” be “accesses”? -> Done.

Line 331: “fall speed” → “hydrometeor fall speeds” -> Done.

Line 349: “as” → “are” -> “Assuming hydrometeors as” changed to “Modeling hydrometeors as”

Line 356: “in large” → “into large” -> Done.

Line 373: “grid-point” → “gridpoint” -> Changed to “grid point”.

Line 375: “within and below the melting layer (ML)” to the end of sentence -> Done.

Line 377: “leading in” → “leading too” -> Reformulated.

Line 380: “centred” → “centered” -> We are using British English.

Line 383: hyphenate “COSMO-simulated” -> Reformulated.

Line 387: “NWC” → “NWP” -> Done.

Line 401: Change hyphen to comma. -> Done.

Line 466: Remove comma after “Both”-> OK

Line 485: Hyphenate “as-complete-as-possible”-> OK

Line 486: Missing “-art”-> Included

Line 494: “microphysic” → “microphysics”-> OK

Line 496: Add “The” before “Developed”-> Included

Line 505: “made progress” → “progress made”-> OK

Line 958: “imulated” → “simulated”-> Corrected

Line 960: “together” → “together with”-> Corrected